Natural architectural design

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1. Introduction

Science, engineering and medicine are three rather distinct disciplines. However, encounters between researchers in these fields often result in dialogues and exchanges on how their different worlds are not that dissimilar. Frequently they discuss how the world that surrounds them is full of inspiration to them in their respective fields. Indeed, in seeking solutions to our problems and research questions, we often ignore the obvious and forget that, through time, nature has probably already found a way of solving most of the problems we will ever encounter. Indeed, nature has its own way of solving complex problems in an exceptionally smart manner that we can only but admire and let ourselves be inspired by.

This work, dedicated to a very dear person of exceptional gentleness, integrity and wisdom, who one of the co-authors is fortunate enough to have as his uncle, will look at how nature has solved some real important problems through a process that is being referred to as 'natural architectural design'. The aim is not to provide an extensive or thorough review of the state of the art of matters discussed, but more to share some of the interests of the co-authors with the wider community. It will also attempt to show how nature has inspired the authors and guided them in their process of understanding some of the more pertinent issues related to their work.

In particular, this article will look at the architectures of the human rib cage and chest and how these are designed for optimal function. It will also look at how the actual chest shape can be modelled using classical pressure vessel theory so as to predict stress concentrations and also the propensity for certain medical conditions to occur. It will then look at another marvellous natural construct: the shells of turtles and molluscs, and how nature can achieve exceptional mechanical properties in natural hierarchical biomaterials. Finally, it will look at how nature can achieve a highly unusual mechanical property, that of auxeticity, meaning the ability of becoming thicker rather than thinner when stretched, and how this is realized in tendons, including human ones, and crystals.

2. The Architecture and Mechanics of Living Beings: An example of natural optimization for better functionality

2.1 Natural Architectures and Body Armour

2.1.1 Shells: Enhanced protection and perfection for the simple creatures

The bodies of humans and other vertebrates hang on an internal skeleton. But in nature this is not always the case and some living creatures, such as turtles and molluscs, have external skeletons. Such exoskeletons ("shells" in common language) of snails and clams are some of the best examples of how nature can achieve extremely superior natural material architectures.[1]

Exoskeletons of molluscs such as snails, clams, oysters and many others have three distinct layers and consist mainly of calcium carbonate with small amounts of protein (up to 2%). The shells, in contradistinction to typical animal structures, are not made up of cells. Instead, mantle tissue located under the shell secretes proteins and minerals extracellularly, forming the shell. In a building technology analogy, proteins correspond to steel rods, while mineral substance plays the role of concrete. The seashells grow from the bottom up, adding material at the margins. Since their exoskeleton is not shed, molluscan shells must grow to allow body growth. Such manner of growth results in three

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[1] See John D. Currey, “Mechanical Properties of Mollusc Shell”, in *The Mechanical Properties of Biological Materials,* Symposia of the Society for Experimental Biology 34, ed. J.F.V. Vincent and J.D. Currey (Cambridge: Cambridge University Press, 1980), 75-97; M. Sarikaya, H. Fong, J. M. Sopp, K. S. Katti and G. Mayer, “Biomimetics: Nanomechanical Design of Materials through Biology”, in *15th ASCE Engineering Mechanics Conference Proceedings* (New York: Columbia University, 2002); M. A. Meyers, A.Y.M. Lin, Y. Seki, P. Chen, B.K. Kad and S. Bodde, “Structural Biological Composites: An Overview”, *JOM* 58 (2006): 35-41. *JOM* is a technical trade magazine published by The Minerals, Metals & Materials Society (TMS). From 1949 through 1988, the journal was named *Journal of Metals*. With materials systems becoming commonplace and with the journal frequently covering composites, plastics and other materials, the journal’s name was changed to *JOM*.

different shell layers: an outer proteinaceous periosteum (uncalcified), a prismatic layer (calcified) and an inner pearly layer of nacre (calcified).

On the other hand, turtle shells are a part of the vertebrate endoskeleton (a skeleton within the animal's body). Surface scutes are epidermal structures made of the tough protein keratin (as found in our fingernails). Underneath these scutes are the dermal tissue and calcified shell, the latter being formed by the fusion of ribs and vertebrae during the animal's growth. Turtle shells are composed of about 33% weight of proteins and about 66% weight of hydroxyapatite (a mineral consisting mainly of calcium phosphate with some addition of calcium carbonate).

Unlike seashells, turtle shells contain living cells, blood vessels and nerves. Their bone can grow and reshape continuously and nature has discovered a very smart way to repair any damage sustained. In fact, turtle shell can grow from within just like leg bones in humans; when a bone breaks, cells can be activated to repair and hence undo any damage. In such systems, nutrients such as calcium and protein can be supplied through blood vessels within the bone itself. In contrast to this, damaged seashells obtain the essential nutrients needed for any shell repair from the mantle cells underneath the shell. The protein matrix of turtles' external bone and seashell is secreted out of the cells. The proteins can bind calcium ions, which leads to calcification. Binding of calcium ions to the protein matrix promotes crystal formation in a hierarchical pattern. The chemical structure of proteins determines whether the calcium carbonate crystal is calcite (forming a prismatic layer), or aragonite (forming the seashell nacre).

Both kinds of shells, i.e. those of molluscs and turtles, are strong, do not dissolve in water, provide excellent mechanical protection and allow for firm attachment of muscles. Shells reveal enormous strength and fracture toughness if compared to their single constituents.

It is only recently that the mechanical properties of sea shells are being systematically investigated. Several species of molluscs have shells that are lined with an inner, iridescent layer of nacre, which is also known as mother-of-pearl. The nacre layer consists of many hard plates of calcium carbonate that are cushioned by an organic matrix of proteins. While the organic matrix is weaker than the hard chalk-like plates, the organic matrix actually adds to the strength of shells through its ability to trap and prevent any cracks that form from spreading. This makes the shells much less brittle. Inspired by the above mechanism, one can add some powdered seashells to glass in order to make it less brittle and thus to improve its toughness. Another invention based on biomimicry (i.e. on imitating nature) recently observed is the reinforcement of concrete by merely substituting 2-4% of sand with powdered seashells.

The observed layered structure of molluscs and shells has proved to be an important source of inspiration for engineers. A self-constraining strengthening mechanism for multilayered brittle materials was proposed. The strengthening is a result of the self-constraint of the individual layers on each other. No additional reinforcements are needed. The proposed model predicts that when individual brittle layers are stacked and properly "glued" together with a weak interphase, each layer will be ensured a minimum tensile strength, regardless of the flaw size in the individual layers. It is also predicted that low-strength ceramic sheets might be produced by low-cost production techniques, which can be used to construct high-strength man-made nacreous ceramics.[2]

2.1.2 The Human Rib Cage for enhanced organ protection and functionality

The human rib cage, arguably one of the most efficient body armours ever developed, is a complex structure made of twelve vertebrae, twelve pairs of ribs and a breastbone. The shape of the rib cage is a complicated three-dimensional structure and would seemingly take a lot of genetic encoding. But since Nature tends to be very economical, how does it encode the rib cage economically?

The rib cage of a human foetus has a different shape to that of a human adult. It resembles that of a primate in that it is conical rather than ellipsoid. Similar to the simian shape, the foetal ribs are horizontal and identical to each other with regard to external rib thickness and width, and internal cortical thickness and radio-density. Evidence suggests that adult human external and internal rib morphology are influenced by post-partum factors, most probably pressures developed by ventilation and coughing, leading to changes in external and internal rib dimensions and bone density. Another factor is the requirement of a stable centre of gravity with an upright biped stance, which leads to invagination of the vertebral column into the trunk.

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[2] See G. Mayer and M. Sarikaya, "Rigid Biological Composite Materials: Structural Examples For Biomimetic Design", *Experimental Mechanics* 42/4 (2002): 395-403; Ahmed A. Abdala, David L. Milius, Douglas H. Adamson, Ilhan A. Aksay and Robert K. Prud'homme, "Inspired by Abalone Shell: Strengthening of Porous Ceramics with Polymers", *Polymeric Materials: Science and Engineering* 90 (2004) 384-385; Kenneth S. Vecchio, "Synthetic Multifunctional Metallic-Intermetallic Laminate Composites", *JOM* 57 (2005): 25-31; F. A. Burgman, X.L. Xaio, D.G. McCulloch, D.R. McKenzie, M.M.M. Bilek, B.K. Gan and L. Ryves, "Relationship Between Microstructure, Stress and Hardness in Multilayer Coatings", *Micros Microanal* 11 (2005), Suppl. 2; G. Mayer, "New classes of tough composite materials - Lessons from natural rigid biological systems", *Materials Science and Engineering* C 26 (2006): 1261-1268; P. Podsiadlo, Z. Liu, D. Paterson, P.B. Messersmith and N. A. Kotov, "Fusion of Seashell Nacre and Marine Bioadhesive Analogs: High-Strength Nanocomposite by Layer-by-Layer Assembly of Clay and L-3,4-Dihydroxyphenylalanine Polymer", *Advanced Materials* 19/7 (2007): 949–955; F.D. Fleischli, M. Dietiker, C. Borgia and R. Spolenak, "The influence of internal length scales on mechanical properties in natural nanocomposites: A comparative study on inner layers of seashells", *Acta Biomineralia* 4/6 (2008): 1694-1706

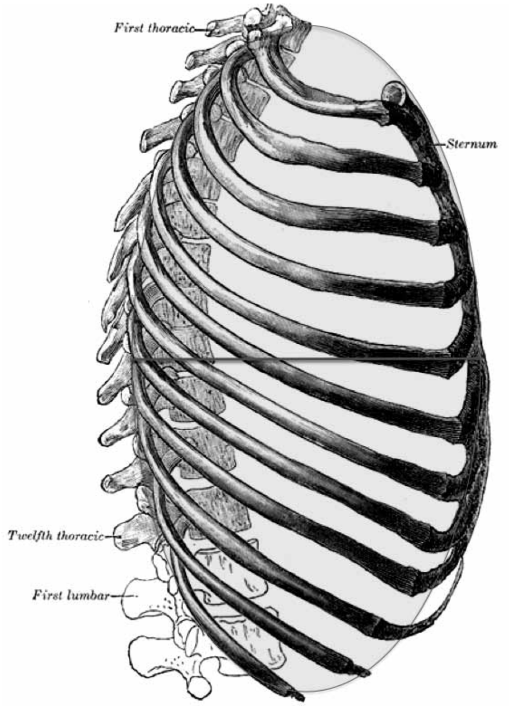

Figure 1: *Lateral view of adult human rib cage, with superimposed ellipsoid*
[Adapted from *Grey's Anatomy*]

The action of the muscles of respiration results in changes in pressure between the inside of the chest and the surrounding air, leading to ventilation. Coughing results in a large pressure differential across the thoracic wall, similar to that of a pressure vessel like a boiler.[3] The stresses in the thoracic wall should mimic those in a pressure vessel, resulting in a gradient from the internal to external aspect of the thoracic wall, with stress related to the diameter of the pressure vessel. As the shape of the front and sides of the chest resemble closely the shape of an American football, the front and sides of the chest can be elegantly described mathematically as a scalene ellipsoid, see Figure 1, which in cross section is identified as an oval.[4] This shape is similar to a dome shape, ever since Michelangelo described his

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[3] See A.R. Casha, A. Manché , M. Gauci, M.T. Camilleri-Podestà, P. Schembri-Wismayer, Z. Sant, R. Gatt and J.N. Grima, "Placement of trans-sternal wires according to an ellipsoid pressure vessel model of sternal forces", *Interactive Cardiovascular and Thoracic Surgery* 14/3 (2012):283-287.

[4] See A.R. Casha, A. Manché, R. Gatt, E. Duca, M. Gauci, P. Schembri-Wismayer, M.T. Camilleri-Podestà and J.N. Grima, "Mechanism of sternotomy dehiscence", *Interactive Cardiovascular and Thoracic Surgery* 19 (2014): 617-621.

perfect dome as the inverted shape traced by a piece of rope dangling between his hands. But the rib cage is really two domes attached together at their widest plane, with the lowest dome incomplete, producing the typically narrow waist, lower down in the trunk. This allows Nature to bypass the problem of high stresses in the mouth of a dome or any bell-shaped structure. Bells crack at their mouths, and man-made domes often need iron chains around their base to prevent them from cracking, as Brunelleschi used in the base of the dome of the Santa Maria del Fiore Duomo of Florence.

Dome builders learned through their craft and experience how to build domes. The chest distributes stresses similarly, with ribs that are taller and thicker from the base or equator of the chest upwards. The lower ribs' measurements are a mirror image of the upper ribs, as expected by the ellipsoid (oval) shape. The internal rib cortex is thicker from the equator upwards, and also traces an ellipsoid shape. Similarly the external rib cortex is also thicker from the equator upwards, and traces an ellipsoid shape too. The same also applies for both the internal and external radio-density levels, a measure of calcification.

Mathematical equations can model many aspects of rib morphology,[5] even internal aspects that are visible only on computerized tomography (CT) scanning. Yet the genetic encoding is simple, producing horizontal featureless ribs, with growth and the response of bone to stress (Wolff's Law) resulting in the complex adult configuration of the rib cage.

2.2 Models of Pathogenesis resulting from Mathematical Modelling of the Lung and Chest Shape

Mathematical modelling, apart from being useful in describing the internal aspect of the rib cage or surface of the lung, can provide a model to explain the pathogenesis of certain conditions, including primary spontaneous pneumothorax and reactivation of tuberculosis (TB) or secondary TB infection, which occurs after the initial exposure and primary TB infection.

Primary spontaneous pneumothorax is a disease where the lung deflates spontaneously due to a bulla in the lung bursting. Symptoms include shortness of breath due to air trapped between the lung and chest wall. However, if the air that escapes from the lung is pressurized, the lung collapses completely and may displace the contralateral lung, resulting in cardiac embarrassment and collapse of the circulation. Spontaneous pneumothorax carries a mortality of 1%.

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[5] See A.R. Casha, L. Camilleri , A. Manché , R. Gatt, D. Attard, M. Gauci, M.T. Camilleri-Podestà and J.N. Grima, "External rib structure can be predicted using mathematical models: An anatomical study with application to understanding fractures and intercostal muscle function", *Clinical Anatomy* 28/4 (2015): 512-519.

Although labelled a disease without a cause, a biomechanical hypothesis for its pathogenesis has now been proposed.[6],[7] First, the shape of the lung was measured using CT scans, which was found to have prominent rib grooves especially for the first rib. The tall lobular shape of the lung apex was found to be unstable from a wall tension point-of-view such that it would technically lead to wall disruption due to stress inversion.

Secondly, the lung shape was modelled using computer simulation techniques and exposed to a distending pressure equivalent to coughing. Stress was measured and found to be the highest in the apex of the lung. Thirdly, the computer model was then altered to mimic different chest shapes and a flattened chest shape was associated with a ten-fold increase in stress. Fourthly, a study of Maltese spontaneous pneumothorax patients showed that these had statistically significantly flattened chests as compared to controls. This suggested that spontaneous pneumothorax patients suffered from high apical stress levels that may cause rupture. Finally, a literature review confirmed the flattened chest wall shape in pneumothorax patients, and showed that spontaneous pneumothorax occurred in the lung apices of young males.

Now every hypothesis should be complete, encompassing, non-discordant with present knowledge and explain circumstances without exceptions. It should also be predictive. Our hypothesis easily explained the lung apex, and also the rare occurrences of pneumothorax in the apex of the lower lobe. What about the age and gender characteristics of the patients? The ratio of the diameters of the chest changes with development. Babies have a round chest, which becomes antero-posteriorly flatter up to adolescence, and then again becomes rounder with maturing age. This explains the age range of pneumothorax patients, as spontaneous pneumothoraxes are typically found in adolescents and young adults. The male characteristics could similarly be explained by the chest wall shape that is flatter than in females. A combination of subclinical congenital apical lung bullae and low Body Mass Index (BMI) is present in an otherwise normal fifteen per cent of the population.[8] A low body mass index was found by our group to be associated with a flattened chest shape, thereby demonstrating non-discordance with previous knowledge.

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[6] See A.R. Casha, A. Manché, M. Gauci, W. Wolak, K. Dudek, P. Schembri-Wismayer, M.T. Camilleri-Podestà, R. Gatt and J.N. Grima, “Is there a biomechanical cause for spontaneous pneumothorax?”, *European Journal of Cardiothoracic Surgery* 45 (2014): 1011-1016.

[7] See A.R. Casha, M. Gauci, R. Gatt and J.N. Grima, “Spontaneous pneumothorax”, *British Medical Journal* 348 (2014): 348. http://www.bmj.com/content/348/bmj.g2928/rr/698923

[8] See K. Amjadi, G.G. Alvarez, E. Vanderhelst, B. Velkeniers, M. Lam and M. Noppen, “The prevalence of blebs and bullae among young healthy adults: a thoracoscopic evaluation”, *Chest* 132/4 (2007): 1140–1145.

Once the concept of a biomechanical cause for spontaneous pneumothorax had been developed, the idea gradually dawned that tall thin young males with antero-posteriorly flattened chest walls could be walking around without realizing that they carried a subclinical lung bulla that could burst the very next day. Would carrying a cavity in the lung apex predispose to further lung pathology? The notion germinated that such a lung would be at higher risk of super-infection. Which condition could act as a super-infection? The lung infection with the longest and widest literature is undoubtedly tuberculosis. So an exercise was performed to see if our hypothesis was inclusive for tuberculosis.

Tuberculosis starts with a primary infection. Then a secondary infection occurs after an interval, when the tuberculosis infection is reactivated. Reactivation of tuberculosis is unusual in that, in contrast with primary tuberculosis, there is a strong logarithmic association between body mass index and rate of reactivation that spans different countries and differing incidence levels of tuberculosis within the population. The incidence of new pulmonary TB is five times higher in a low BMI group (BMI <21) as compared to a high BMI group (BMI >31).[9] Hitherto, this association could not be explained in medical literature.[10] However this remarkable association was not observed for extra-pulmonary tuberculosis,[11] suggesting that low BMI predisposed to an increased risk for pulmonary TB only, but not for non-pulmonary TB. Further, the reactivation of pulmonary TB increases in adolescence and young adults, and in males more than females, in contrast with the reactivation of non-pulmonary TB, which remains constant.[12]

The conventional explanation for the apical localization of reactivation of tuberculosis is that of high oxygen levels[13] and gravity affecting lymphatic drainage. However, these reasons do not explain localization of tuberculosis on the apex of the lower lobe. Clearly some other factors must be at play,

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[9] See K. Lonnroth, B.G. Williams, J.P. Cegielski and C. Dye, "A consistent log-linear relationship between tuberculosis incidence and body mass index", *International Journal of Epidemiology* 39 (2010): 149–155.

[10] See J.P. Cegielski, L. Arab and J. Cornoni-Huntley, "Nutritional risk factors for tuberculosis among adults in the United States, 1971-1992", *American Journal of Epidemiology* 176/5 (1 September 2012): 409-422.

[11] See A. Tverdal, "Body mass index and incidence of tuberculosis", *European Journal of Respiratory Diseases* 69/5 (November 1986): 355-362.

[12] See P.R. Donald, B.J. Marais and C.E. Barry III, "Age and the epidemiology and pathogenesis of tuberculosis", *The Lancet* 375 (2010):1852–1854.

[13] See D.W. Fitzgerald, T.R. Sterling and D.W. Haas, "Mycobacterium tuberculosis", in J.E. Bennett, R. Dolin and M.J. Blaser, ed., *Mandell, Douglas and Bennett's Principles and Practice of Infectious Diseases* (Philadelphia: Elsevier, 2014), 2787–2818.

since tuberculosis affecting the apex of the lower lobe is well documented.[14] Our hypothesis,[15] based on the idea that certain lung shapes result in high pleural stress with tissue destruction and cavitation, predisposing to tuberculosis superinfection at a later stage, can explain several factors associated with reactivation of tuberculosis. The antero-posterior flattened chest shape and resultant high stress levels explain the low BMI, the young age, the apical location, and the tendentially male gender of tuberculosis patients.

However, a hypothesis is most useful in science if it is predictive and can anticipate changes or events that can be measured. If tuberculosis and spontaneous pneumothorax share a common pathogenesis, then one would expect these two different pathologies to occur concurrently fairly frequently. Both pathologies are fairly rare, with the incidence of TB at about 7:100,000[16] and that of spontaneous pneumothorax of 18:100,000,[17] suggesting that concurrent disease should be multiple and very rare. However Freixinet *et al.* reported in 2011 that 5.4% of spontaneous pneumothorax patients had TB and 2.1% of TB patients suffered from spontaneous pneumothorax.[18] This fits in with our hypothesis and cannot be explained with conventional knowledge, further bolstering the validity of our model.

It appears a very flattened chest wall shape, predisposes to development of disease in adolescence and afterwards, and may justify screening to prevent disease especially in high risk individuals like airline pilots and divers since these individuals work in hazardous environments with regard to spontaneous pneumothorax. Thoracic ultrasound has been used to diagnose apical bullae,[19] although its false negative pick-up rate vis-à-vis the more established computerized tomography is unknown. However, ultrasound is free of radiation and can therefore be performed repeatedly, whereas computerized tomography delivers approximately the equivalent of six months of background radiation. Thoracic ultrasound may well

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[14] See Y.G. Jeong and S.K. Lee, "Pulmonary tuberculosis: Up-to-date imaging and management", *American Journal of Roentgenology* 191 (2008): 834-844.

[15] See A.R. Casha, L. Camilleri, A. Manché, R. Gatt, D. Attard, W. Wolak, K. Dudek, C. Gauci, C. Giordimaina and J.N. Grima, "A hypothesis for reactivation of pulmonary tuberculosis: How thoracic wall shape affects the epidemiology of tuberculosis", *Clinical Anatomy* 28 (2015): 614–620.

[16] See World Bank, "Incidence of tuberculosis" (2015), in URL: http://data.worldbank.org/indicator/SH.TBS.INCD/countries [Accessed 13 January 2015].

[17] See M. Noppen, "Spontaneous pneumothorax: Epidemiology, pathophysiology and cause", European *Respiratory Review* 19 (2010): 217–219.

[18] See J.L. Freixinet, J.A. Caminero, J. Marchena, P.M. Rodríguez, J.A. Casimiro and M. Hussein, "Spontaneous pneumothorax and tuberculosis: long-term follow-up", *European Respiratory Journal* 38 (2011): 126–131.

[19] See F. Sandionigi, F. Cortellaro, E. Forni and D. Coen, "Lung ultrasound: a valid help in the differential diagnosis between pneumothorax and pulmonary blebs", *Emergency Care Journal* 9 (2013): 3.

develop into an important screening tool in the global fight against tuberculosis (and also for spontaneous pneumothorax), since cavitation is the major route of spread for this disease.

3. Auxetic Architectures

If the macrostructure of the human body can be considered as a *magnum opus* in architecture and functional design, the micro and nanostructure of naturally occurring materials are equally remarkable in both magnificence and impressiveness. Naturally occurring materials are typically classified according to their origin as 'abiotic' or 'biotic' where the latter originate from once living organisms and include wood, natural fibres and petroleum products, whilst the former, which include metals, glass and rocks, sometimes referred to as inorganic compounds, are traditionally viewed as those having an inanimate, not biological, origin.[20]

The actual chemical composition of a material is known to impart to it a number of its macroscopic properties. However, it is now also known that some other important properties are primarily dependent on the internal micro- or nanostructure of the materials, i.e. its micro and/or nanoarchitecture, and of how this responds to changes in its surroundings. One such property, which is predominantly dependent on the internal structure of a material, is the manner in which materials change their shape and size when uniaxially stretched or compressed.

It is a common perception that when a material is stretched in one direction, it must necessarily contract in the other directions, a notion which is probably the result of observing the behavior of soft rubber-like materials being stretched. In fact, rubber contracts significantly in its thickness when unidirectionally stretched, since rubber has the tendency to preserve its volume when subjected to a uniaxial stress. Nevertheless, not all materials behave like this, and the ability to preserve volume upon stretching on compression is not a universal or common property in materials. Instead, most materials will change their thickness upon stretching in a manner that is dependent on the particular internal nano- or microscale structure of the material. The extent to which this happens is quantified by the so-called "Poisson's ratio."[21]

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[20] The 19th century chemist, Jöns Jacob Berzelius (1779-1848) described inorganic compounds as inanimate, not biological, origin (J. J. Berzelius, *Lehrbuch der Chemie*, 1st edn [Dresden and Leipzig: Arnoldischen Buchhandlung, 1827]). This definition is however not perfect as many minerals are known to be of biological origin.

[21] Siméon Denis Poisson (1787–1840) was a French mathematician who devoted most of his

The Poisson's ratio of a material is mathematically defined as the negative of the ratio of the transverse strain and the uniaxially applied strain,[22] or, in more lay terms, as the negative of the percentage change in dimension in the thickness of a sample of material divided by the percentage change in dimension in the length of a sample in the direction it is stretched or compressed. Since most materials become thinner when stretched, this Poisson's ratio typically assumes positive values, achieved by reversing the sign of a negative quantity (the percentage shrinkage of a material) divided by a positive quantity (the percentage increase in length when the material is stretched). In fact, the Poisson's ratios of most typically encountered materials typically range between 0 and 0.5, where the higher the value, the more pronounced is the extent of thinning when the material is stretched. For example, rubber has a Poisson's ratio of *ca.* 0.5, whilst the more common metals have Poisson's ratios of *ca.* 0.3. Cork has a Poisson's ratio of 0, meaning that it neither thins nor fattens when stretched or compressed, a property which is rather exceptional and useful. It is also known that the Poisson's ratio need not be positive, a result which has been well known since the development of the classical theory of elasticity. In fact, theory suggests that the Poisson's ratio for isotropic materials, i.e. materials which have the same properties for testing in any directions, may range between -1 and +0.5, a range wider for anisotropic materials.[23] This opens up the possibility that materials can have a negative Poisson's ratio, meaning that they can get thicker rather than thinner when stretched, and thinner rather than wider when compressed. Such materials are now commonly referred to as 'auxetic materials', a term which was coined in 1991 by British physicist Kenneth E. Evans and derives from the Greek word *auxetos*, meaning "that may be increased."[24]

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adult life to mathematical physics and mechanics. In 1811, he published his two-volume *Traité de Mécanique*, one of the classical texts in mechanics. In the second volume of this text, Poisson presents an analysis of the shape and volume changes of a fluid under arbitrary loading. Building on an earlier work by the French engineer and physicist Navier, in 1827, Poisson proposed an expression for the change in cross-sectional area resulting from the elongation of an elastic wire (i.e. what we now refer to as the "Poisson's ratio"). It later became clear, through work by Cauchy in his *Exercices de Mathématiques* and by Voigt, that the Poisson's ratio may differ from one material to another, and is now considered to be one of the fundamental mechanical properties which characterize materials.

[22] See Siméon Denis Poisson, *Annales de Chimie et de Phyique*, ed. L.J. Gay-Lussac and F. Arago, 36 (1827): 384–385; B.M. Lempriere, "Poisson's ratio in orthotropic materials", *American Institute of Aeronautics and Astronautics Journal* 6/11 (1968): 2226-2227. doi: 10.2514/3.4974

[23] See Augustus E.H. Love, A Treatise on the Mathematical Theory of Elasticity (Cambridge: Cambridge University Press, 1944); L.D. Landau and E.M. Lifshitz, Theory of Elasticity, 3rd edn (Oxford: Butterworth Heinemann, 1986).

[24] See K.E. Evans, M.A. Nkansah, I.J. Hutchinson and S.C. Rogers, "Molecular network design", *Nature* 353 (1991), 124.

It is now known that by having a negative Poisson's ratio, materials can achieve a number of improved properties, which may surpass those of their conventional counterparts.[25] For example, auxetics are ideal in making products such as nails, screws or press-fit fasteners: the compressive force used to insert the fastener into a hole causes a lateral contraction, hence facilitating insertion. However, any attempts to re-pull out the nail or fastener back demonstrate that the stretching force will cause the auxetic material to expand laterally within the hole, thus proving an even better grip. Auxetics also can be used in seat belts to reduce the pressure exerted upon impact when the passenger is thrown forward in a collision. There are also a number of other advantages in having a negative Poisson's ratio which range from an increased resistance indentation and the natural ability to form dome-shaped surfaces (synclastic curvatures) as opposed to conventional materials, which tend to take on a more classical saddle-shaped conformation. These two properties are particularly desirable in the manufacture of seats, which can be more comfortable and provide a better cushioning effect, thus enhancing their comfort and safety characteristics.[26]

At this point an important question arises: if auxetics can benefit from so many enhanced characteristics, why has nature, in its long and *quasi*-perfect evolutionary process, not provided us with natural materials having this property? Or have natural auxetic materials been around us all the time, but we simply did not recognize or discover them?

Probably the first report of a naturally occurring auxetic material was made in 1921 by Voigt who discovered this property in iron pyrite crystals, a result which is now thought to have arisen from twinning defects in the samples. In the 1970s and early 1980s there were a number of other isolated reports of natural materials with a negative Poisson's ratio, but in all cases, such reports were not given much publicity and were merely hidden within the text of published works, probably from fear of rejection of the unknown and the unusual. All this changed when in the 1980s synthetic auxetic materials started to be produced[27] and materials with this property were put in the limelight. We started to look closer at natural materials that could possibly exhibit this property, and indeed we found them … much closer to us than we thought they were!

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[25] Kenneth E. Evans and Andrew Alderson, "Auxetic materials: functional materials and structures from lateral thinking", *Advanced Materials* 12/9 (2000): 617-628.

[26] See Joseph N. Grima, Daphne Attard, Ruben Gatt and Richard N. Cassar, "A Novel Process for the Manufacture of Auxetic Foams and for their re-Conversion to Conventional Form", *Advanced Engineering Materials* 11 (2009): 533-535.

[27] See R.S. Lakes, "Foam structures with a negative Poisson's ratio", *Science* 235 (1987): 1038-1040.

3.1 Auxetic Tendons

Tendons are the tough bands of fibrous connective tissue that usually connects muscle to bone and one of nature's most fascinating materials, capable of withstanding significant stresses and tension. In view of their biological importance, the biomechanical properties of tendons have been the subject of intensive research with early research focusing more on rat and horse tendons, with later studies also considering a number of human tendons, particularly those susceptible to injury. From a structural perspective, tendons possess a remarkable nano and micro-architecture. They are in fact hierarchical structures having triple helices of tropo-collagen form fibres, which in turn form fibrils, fascicles and eventually tendons. On the micro-scale, they also display a wavy crimped structure when relaxed which becomes flat when stretching tendons at low strain results due to the disappearance of this crimping. Recent ex-vivo and in-vivo studies carried out in Malta have shown that that healthy tendons of both human and animal origin have a negative Poisson's ratio when stretched along their length, in the plane of the width of the tendon, i.e. for example the coronal plane in the case of the Achilles tendon (see Figure 2).[28] In fact, ex-vivo experiments carried out on a number of tendons, in humans, pigs and sheep, have all indicated that healthy tendons are likely to exhibit a negative Poisson's ratio and get wider in the direction parallel to the surface of the bone when stretched, a result which was confirmed by in-vivo magnetic resonance imaging (MRI) observations on the human Achilles tendon. Moreover, the strain region tested corresponded to the strains at normal activity, meaning that every muscle movement is likely to be accompanied by the manifestation of auxeticity.

It is not easy to identify what gives rise to this effect and the actual magnitude of the Poisson's ratio in the different species, since a multitude of factors, ranging from evolution to the lifestyle could have an effect. However, it is probable that auxeticity is a consequence of the actual microscopic design, with the highly characteristic crimped microstructure playing a very important role. In fact, this crimp structure is similar to the crumpled paper model, which was used by Grima *et al.* to describe auxetic behaviour in graphene with defects,[29] and is easy to visualize at the macroscale.

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[28] See Ruben Gatt, Michelle Vella Wood, Alfred Gatt, Francis Zarb, Cynthia Formosa, Keith M. Azzopardi, Aaron Casha, Tonio P. Agius, Pierre Schembri-Wismayer, Lucienne Attard, Nachiappan Chockalingam and Joseph N. Grima, "Negative Poisson's ratios in tendons: an unexpected mechanical response", *Acta Biomaterialia* (2015). In press. doi:10.1016/j.actbio.2015.06.018.

[29] See Joseph N. Grima, Szymon Winczewski, Luke Mizzi, Michael C. Grech, Reuben Cauchi, Ruben Gatt, Daphne Attard, Krzysztof W. Wojciechowski and Jarosław Rybicki, "Tailoring Graphene to Achieve Negative Poisson's Ratio Properties", *Advanced Materials* 27 (2015): 1455-1459.

Auxeticity in these bio-structures is most probably an evolved trait. This is because negative Poisson's ratios may give tendons a number of functional advantages ranging from an enhanced damping capability to a reduction in stress at the points of contact between the tendon and the underlying structures. Also, knowledge that healthy tendons exhibit a negative Poisson's ratio could have a number of implications which may result in the development of better synthetic allografts to replace injured tendons and a better understanding of tendon health. This would be especially useful in persons performing highly demanding physical activities, such as top athletes and professional football players, who frequently suffer from tendon injuries such as Achilles heel, patellar, quadriceps and hamstring tendinopathies. It is also possible that tendons could provide us with a blue-print for the design of new man-made auxetic materials and metamaterials, which mimic the behaviour of these biological systems.

3.2 Auxetic Crystals

Crystals are solid materials whose constituents, such as atoms, molecules or ions, are arranged in a highly ordered and symmetric nanoscopic formation to produce a periodic lattice that extends and repeats in all directions. The word crystal derives from the ancient Greek word κρύσταλλος (kristallos), meaning both "ice" and "rock crystal." The symmetry of a crystal is constrained by the requirement that the unit cells stack perfectly with no gaps. It is now known that there are more than 200 possible crystal symmetries which are grouped into seven crystal systems (cubic, hexagonal, etc.).

The structure and symmetry of crystals play a role in determining many of their physical and macroscopic properties, including their mechanical properties. With the variety of such geometries, one may argue that it is likely that a number of crystalline systems should exhibit auxetic behaviour. In fact, recent research has confirmed this hypothesis and a number of naturally occurring auxetic crystalline materials have been identified.

Of these, natrolite is probably the best example of crystals which can exhibit a negative Poisson's ratio. This result was first indicated through modelling studies which indicated the potential for zeolitic-like structures to exhibit negative Poisson's ratios.[30] In fact, with the help of computer simulations, it was suggested that various idealized versions of zeolite frameworks, including the SiO_2 equivalent of natrolite NAT, were likely to exhibit negative Poisson's ratios, a property which can generally be explained in terms of the geometry of their nanoporous frameworks. More recently, experimental elastic constants of

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[30] See J.N. Grima, R. Jackson, A. Alderson and K.E. Evans, "Do zeolites have negative Poisson's ratios?", *Advanced Materials* 12 (2000): 1912-1918.

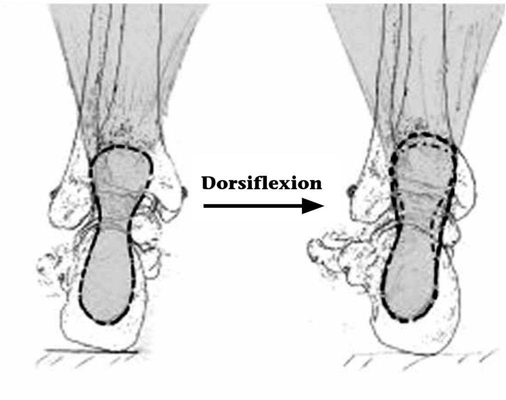

Figure 2: *A pictorial (exaggerated) illustration of auxeticity in a human tendon* *(Taken from Gatt et al., 2015)*

the naturally occurring orthorhombic aluminosilicate NAT single crystals were measured from the acoustic velocities using Brillouin-scattering spectroscopy at ambient conditions, that confirmed the results of the earlier simulations and definitely confirmed auxeticity in natrolite.[31] In fact, a mathematical analysis of the full set of experimentally-obtained data clearly indicates that this zeolite exhibits negative Poisson's ratios in its (001) plane for loading in certain directions.[32] More interestingly, as illustrated in Figure 3, the natrolite framework in this 'auxetic plane' is such that its geometry may be trivially described in terms of "connected squares", the corners of which correspond to the oxygen atoms of the Si-O-Al linking bonds. Such constructs, apart from being highly aesthetically pleasing, are known to be able to exhibit auxetic behavior.[33] The fact that the direction of maximum auxeticity in the crystal corresponds to the main axis of a 'rotating squares' model, confirms this. This clearly indicates that nature has found its own way to achieve the desired macroscopic property through the use of smart nanoarchitectures.

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[31] See Carmen Sanchez-Valle, Stanislav V. Sinogeikin, Zoe A. D. Lethbridge, Richard I. Walton, Christopher W. Smith, Kenneth E. Evans and Jay D. Bass, "Brillouin scattering study on the single-crystal elastic properties of natrolite and analcime zeolites", *Journal of Applied Physics* 98 (2005), Art. 053508.

[32] See Joseph N. Grima, Ruben Gatt, Victor Zammit, Jennifer J. Williams, Kenneth E. Evans, Andrew Alderson and Richard I. Walton, "Natrolite: A zeolite with negative Poisson's ratios", *Journal of Applied Physics* 101 (2007), Art. 086102.

[33] See J.N. Grima and K.E. Evans, "Auxetic Behavior from Rotating Squares", *Journal of Materials Science Letters* 19 (2000): 1563-1565.

4. Some Final Comments

If Nature is so perfect, why should mankind develop new materials and architectures rather than rely on the naturally existing ones which took millions of years of evolution to produce and perfect? The answer is simple: evolution has worked in a highly economical manner and has optimized its architectures and materials for the specific use they were designed for. Thus, for example, the wood in a tree trunk was never intended in the evolutionary process to be optimized as a material for the design of boats or furniture. Instead, it was designed to support the branches, leaves, flowers and fruits of the tree itself. Nevertheless, Nature seems to have significantly inspired us in the design of man-made architectures and materials that can be customized for some specific purpose or application.

To be able to fully describe natural materials and architectures, man has often relied on mathematics to provide a detailed and expandable description of the world that surrounds us. We are governed by mathematics and live in a mathematical world. One may argue that our God must be a mathematical multi-tasking genius, who created mathematics and should be considered as the first mathematician. As the mathematician Roger Penrose stated, does the human mind develop mathematical ideas or does the physical world actually obey mathematical laws? The authors take the empirical view that since mathematics is a very useful tool in a number of disciplines, it makes our lives simpler by explaining some very complicated branches of Science, ranging from astronomy to quantum physics, and from chemistry to biology, right up to economics and statistics, in a rather simple and yet effective manner. Mathematics can be a powerful tool that allows problem solving instead of being an eternal self-assuming truth.

The question as to whether God is a mathematician is interesting, because it raises mathematics to the level of godliness. Just like belief in God requires faith, similarly the nature of mathematics remains, at least for some, a mystery. As John D. Barrow wrote, “All our surest statements about the nature of the world are mathematical statements, yet we do not know what mathematics ‘is’… and so we find that we have adapted a religion strikingly similar to many traditional faiths. Change ‘mathematics’ to ‘God’ and little else might seem to change.” Similar to godliness, a belief in Mathematics is self-fulfilling in that it can provide a proof for itself and does not require external measurements; for example the proof of Pythagoras’ theorem can be proven with different mathematical methods. It led Galileo Galilei to write that “Mathematics is the language with which God has written the universe” and “the great book of nature is written in mathematical symbols.” Even Plato, over two thousand years ago, said that “the knowledge of which geometry aims is the knowledge of the eternal.”

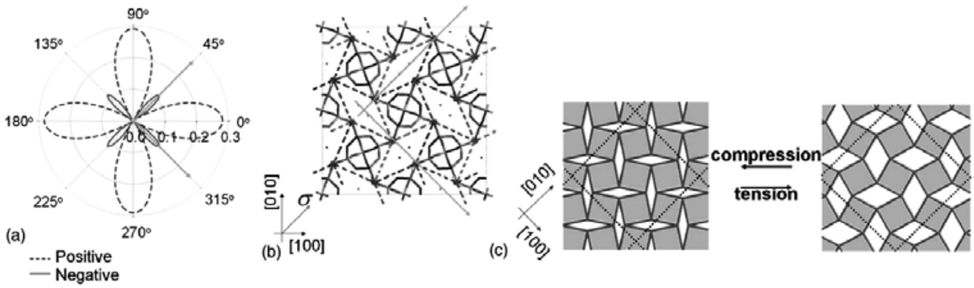

Figure 3: *(a) The Poisson's ratios in the 001 plane of the zeolite natrolite (NAT) which confirms that NAT is auxetic in the 001 plane with maximum auxeticity* $v=-0.12$ *being exhibited at ±45° to the [100] and [010] crystallographic axes. Note that the crystal structure of NAT projects in its (001) plane, as shown in (b), as a motif describable through the "connected squares" model, which in its idealized form, shown in (c), exhibits negative Poisson's ratios of –1. Note that the directions of maximum auxeticity may be directly mapped to the nanostructure of NAT. (Adapted from Grima et al., Journal of Applied Physics 101 [2007], Art. 086102.)*

It is uncanny how a few mathematical symbols arranged in the form of an equation can model the world and unlock great truths. However, mathematics has the ability to act as a two-edged sword in human hands. Einstein's simple equation $E=mc^2$ led to the discovery of nuclear energy, but also to nuclear bombs that threaten to render our own world into an apocalyptic post-nuclear desert.

Does Mathematics entice us with the ability to play God? Mathematics can be used to model complex interactions and then it can be used to further explore possibilities in the future, or, generate predictions. The fact that predictions can further science allows for scientific prophecies and an ability to peer into the future. Many human inventions are so rooted in mathematics, like rockets and space travel, that it may have encouraged an exaggerated belief in the success of human endeavours that makes humankind believe that it can reach and achieve godliness. Yet how mistaken we are! Charles Darwin said that "a mathematician is a blind man in a dark room looking for a black cat which isn't there." Whilst it is commonly known that the careful observation of the natural world, with the right mathematical tools, can lead to improved man-made designs and products, we should keep our feet on the ground. We should remember that there is still a long way to go in scientific discoveries, even though we seem to be able to do so much more, as compared to a century ago. More importantly, it is the opinion of the authors, that the more new science is discovered, the more we feel there must be a chosen path through the randomness of the universe and the evolutionary process. In this path, we seem to be so exceptionally well-guided, and for this we are truly grateful.

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