**Anne Neville's fascination with nature**

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## Abstract

Biomimetics is an interdisciplinary field in which principles from engineering, chemistry and biology are applied to the synthesis of materials, synthetic systems or machines that have functions that mimic biological processes. In this paper, we want to capture the fascination nature held for Anne Neville, and the way she used biomimetics to inform her research. We are briefly reviewing Anne's work involving natural systems, then look at biological systems that rely on lubrication, and finally, we summarise how Anne's research might have expanded and influenced the implementation of concepts leading to preservation of natural resources.

## Introduction

In February 2005, one of the authors (TWL), arrived in the UK to join the University of Leeds as a Research Associate on the Engineering and Physical Sciences Research Council (EPSRC) funded project "Designing New Generation Lubricant Additive Technology Using Nature's Lead" led by Professor Anne Neville [1]. Fresh after his PhD viva at the École Centrale de Lyon in France, he was keen to work on this exciting project under the mentorship of such a energetic and visionary research leader.

In the proposal, Anne was postulating that nature produces complex nanocomposite structures, which are self-healing, functionally graded and smart, to a degree. These properties are all required of tribofilms in the field of lubrication technology where their structure, formation and removal rate and smartness are key to their ability to maintain fuel economy and durability. This was the first proposal to explore the potential of biomimetics for the development of tribofilms, representing a radical shift from current lubrication technology research and, as such, was highly speculative.

One of the first milestones in the proposal was to visit Professor Julian Vincent, a biologist in the Department of Mechanical Engineering at the University of Bath. His remit in that post was to show engineers the tricks nature uses. That meeting took place in Spring 2005, and was the first time Anne, Julian and Tomasz met together. Judging by the topics quoted in both [1] and [2] Anne was already familiar with Julian's work, and it obviously coloured her early exploration of natural systems.

## Anne's work involving links to nature

The first evidence of Anne referring to nature in her research can be found in her PhD thesis entitled "An investigation of the corrosion behaviour of a range of engineering materials in marine environments", which was submitted to the University of Glasgow in 1995 [3]. In this work, Anne investigated corrosion behaviour of high-grade alloys in marine environments of varying severity using electrochemical methods. She looked at the effects of micro and macro fouling on corrosion in the presence and activity of sulphate reducing bacteria. She included microscopic images of a biofilm and diatoms (microorganisms comprising several genera of algae, specifically microalgae), and on several occasions she reflected how much joy she found in collecting and characterising the diatom samples. Anne investigated the effect of the macrofouling layers on the electrochemical behaviour of studied materials. She observed the evolution of the diatom concentration with time and made comments about the effect of the marine organism settlement being a major issue in marine systems from the point of view of environmental factors and economic considerations regarding material replacement due to irreversible fouling.

Anne devoted a lot of attention to, and produced a significant body of work related to the mechanism of formation of a tribofilm [e.g. 4-8]. In the aforementioned proposal [1], Anne was challenging the current conventional approach to lubricant additive design by attempting to use biomimetics to develop a new generation of lubricant chemistry. She provided examples of the successful use of biomimetics for the derivation of new structural materials, and she specifically referred to the strain gauging based on receptors in insects [9], deployable structures based on flowers and leaves [10], tough ceramics based on mother of pearl [11], drag reduction based on dermal riblets on shark skin [12], tough composites based on fibre orientations in wood [13], underwater glues based on mussel adhesives [14], flight mechanisms based on insect flight [15], extrusion technology based on the spinneret of the spider [16], and self-cleaning surfaces based on the surface of the lotus leaf [17]. As a rationale for using nature as lead in designing new lubricants, Anne argued that nano-biotechnology would ultimately lead to the integration of artificial and biological materials – a concept of enormous technological potential.

Anne also learned from nature to formulate a novel strategy for controlling scale deposition and adhesion. She was of the opinion that nature produces the most elegant of surface structures with nanoscale patterning exhibiting a complex range of physical and chemical properties resulting in self-cleaning. She was making the point that despite the properties of natural surfaces being mimicked to design functional surfaces in some fields of science and technology, the biomimetic approach was not used for the control of the wide-spread problem of mineral scale deposition and adhesion. This philosophy for designing surface treatments for scale control inspired several projects led by Anne, including [18-22].

Biotribology, i.e. the science of biological surfaces in sliding contact, is a topic that was of high interest to Anne. She regarded the synovial joint as an example of beautiful and excellent tribological systems. Anne worked with late professor Duncan Dowson, who was her friend and mentor, and in 2006 they published a paper "Bio-tribology and bio-mimetics in the operating environment", where they explained the exciting prospects of close association between bio-tribology and biomimetics [23]. They gave an account of a wide range of fascinating tribological features of natural tribological systems, including animal locomotion, swimming, adhesion and attachment to adjacent surfaces, oral tribology, skin and ocular tribology. Duncan inspired Anne to expand her research interest further into biotribology, and biotribocorrosion specifically, i.e. the topic of material degradation due to the combined effect of corrosion and wear in the biological environment. Anne and Duncan argued that the effects of bodily fluids on hard-on-hard hip replacement joints (i.e. metal-on-metal and metal-on-ceramic) are the primary concern and that the issues relating to their durability need to be addressed [24-32]. They also looked at the role of proteins and adsorbed protein layers in wear, corrosion and tribocorrosion processes in artificial joints [33], and used in-situ electrochemical methods to assess the corrosion behaviour of hip components in real time [34].

Anne derived inspiration from nature to inform her work on functional surfaces in other areas, including investigation of wet adhesion of micro-structured surface to peritoneal tissue [35], surfaces modified and textured by anti-freeze protein [36-37], and lubrication of soft oral surfaces [38]. She also systematically reviewed frictional systems in nature [39].

**Joints and sliding surfaces in biology**

In this section, Julian takes a wider view and reflects on biological systems that rely on lubrication [40]. The purpose is to provide a brief review of other lubrication systems that Anne and her group might have progressed to.

The most obvious, lubricated biological systems are the joints of arthropods in which the outer covering is a fibrous composite ('cuticle') of chitin microfibrils in a protein matrix assuming a wide variety of structures, a modulus varying over seven orders of magnitude, with a wide variety of additives [41]. In the main joint of the jumping leg of a katydid (a form of grasshopper) a hard cuticle with microscopic ridges on the surface rolls over the other side of the joint which has a softer surface that can release a lipid from sub-surface lacunae [42]. It's a little like our own joints with weeping lubrication, except that it's external and exposed. An intriguing factor is that the soft surface is hydrophilic (yet produces the lipid) whilst the hard surface, being phenolically tanned, is hydrophobic. The significance of this difference to the functioning of the joint is obscure. The soft surface can be repaired and controlled by the cells beneath, which may be part of the maintenance schedule. And many of these joints, especially on larger insects, and crustaceans that live in muddy and sandy areas, have brushes that wipe the surface clean whenever the joint moves. Smaller insects don't have them – perhaps the edge of the joint has some sort of compliant barrier. It seems not to be reported in the literature.

Plants have lubricants too. Seeds in fruit usually have a slippery coat, presumably to make it harder for the animal eating the fruit to bite into them, and the shoots and roots penetrating the soil have a surface lubricant to help them on their way [43]. Probably better known are the slippery surfaces of pitcher plant traps down which unfortunate insects slide to their doom. An unusual (perhaps 'unusual' simply because it hasn't been much studied) is a lubricant on the surface of cells of the alga *Porphyridium* [44]. A very large polysaccharide (2.3 MDa) strongly holds a thin layer of water. It's tempting to think that it stabilises the liquid crystalline morphology of water on a surface and that it's the deformation of that organised structure that gives the low friction.

Biological lubricants are all based on the retention and (probably) organisation of water on a surface. Whilst water and metals mostly don't mix well, the concept of using the molecular organisation of the lubricant has not been explored extensively in technology. Perhaps temperatures and shear rates are too high for the biological systems that are found commonly, but the reader must be aware that organisms abound around the hot 'smokers' where the earth's crust has fractured and continental drift originates [45]. In these deep and hot (well over 100degC) waters, conditions similar to those in a hard-working bearing may be approached.

**Summary**

Anne, like most who apply biological concepts to technology, especially engineering, necessarily needed a good biologist to expand her horizons. She was able to do this effectively, as she was strong advocate of cross-disciplinary collaboration, believing that it is only by doing this that scientists and engineers will solve the major technological challenges.

Anne was concerned about the environmental impact of humanity and the way nature is affected by exploration of natural resources. Anne always pointed out that, although tribological processes cause billions of pounds of energy losses per year, we still have very limited understanding of friction and wear phenomena. She was also advocating for reducing reliance on petrochemicals and improvements to the circular economy. At the time of her retirement, she had applied for and was shortlisted for a Royal Society Chair to study triboelectric nanogenerators (TENGs) as solutions for challenges in energy and global emissions leading to £7M EPSRC Programme Grant to investigate fundamentals of friction [46].

Anne will be remembered for her seminal contributions to the materials science community through her fundamental understanding of functional surfaces, including biological surfaces. She will also be remembered for her warm human qualities and for transforming lives of many young researchers. Her legacy will live on in the staff and students she has inspired and worked with.

The authors declare that they have no conflict of interests.

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