Institution:
University of Cambridge

Unit of Assessment:
UoA10

Title of case study:
Statistical Physics of Hair

1. Summary of the impact (indicative maximum 100 words)

Research conducted at the University of Cambridge yielded a theory for the energy of hair arrays and a differential equation for the shape of the envelope of a bundle ("Ponytail Shape Equation"). It enabled Unilever to address quantitatively a number of "what if" questions about how properties of individual hairs are reflected in those of bundles, an important component of product development. Novel imaging techniques have been developed that allow for quantitative studies of hair properties. Finally, the story of this research generated worldwide attention, in its original announcement and also through the award of the 2012 Ig Nobel Prize in physics to this team. It has featured on international radio programs (Canada, Germany, UK), on worldwide press, and has led to invited presentations in schools and universities internationally.

2. Underpinning research (indicative maximum 500 words)

The underpinning research on the statistical physics of hair was carried out from 2009 to 2012 in collaboration between Professor Raymond E. Goldstein, the Schlumberger Professor of Complex Physical Systems at the Department of Applied Mathematics and Theoretical Physics, University of Cambridge (DAMTP) throughout this time, and Dr Patrick B. Warren of Unilever Research and Development, Port Sunlight. The research involved combined experimental and theoretical investigation of the properties of hair fibre bundles. The two researchers worked closely on all aspects of the theoretical analysis, and Goldstein led the experimental work. The key issues addressed were the quantification of the random curvatures of real hairs and the incorporation of the effects of those curvatures into a continuum theory for the energy of a bundle. This was essential for a range of problems in hair physics, including the elasticity of bundles, their dynamics, and understanding the physics of hair tangling. The quantification problem was solved by the development of a stereoscopic imaging system combined with a statistical reconstruction algorithm to give highly reliable representations of the shapes of individual hair fibres in three dimensions. This allowed extraction of the locally varying intrinsic curvatures of the filaments. Knowledge of the statistical properties of these curvatures provided a way to distinguish different hair types and to assess the effects of various treatments on hair. The theoretical problem was solved by developing a density functional theory of hair arrays by analogy to the theory of liquid crystals, and using methods from fluid dynamics to simplify the mathematics to the point that analytical progress could be made. This resulted in the derivation of a fourth-order ordinary differential equation for the envelope of a ponytail, known now as the "Ponytail Shape Equation". From this came a direct way of determining the "equation of state" of hair from the shapes of bundles hanging under gravity. Tests of this method of analysis using real human hair bundles showed that the amplitude and characteristic length scale of the variations in bundle pressure could be related directly to the spectrum of random curvatures of the individual hairs.

3. References to the research (indicative maximum of six references)

Goldstein, R.E., Warren, P.B. & Ball, R.C. 2012 Shape of a ponytail and the statistical physics of hair fiber bundles. *Phys. Rev. Lett.*, **108**, 038103, DOI: 10.1103/PhysRevLett.108.078101.

4. Details of the impact (indicative maximum 750 words)

There are two important contributions of the research of direct interest to Unilever, a global manufacturer of personal care products, including shampoos and conditioners, which has clear interests in understanding quantitatively the properties of hair.

Unilever Global Senior Vice President for Home and Personal Care R&D confirms these impacts in a letter, saying:

"The first is the differential equation now known as the 'Ponytail Shape Equation', whose solutions describe the envelope of a hair bundle as a balance between elastic, gravitational, and random curvature effects. This has allowed Unilever to address a number of "what if" questions about hair in a very straightforward way. Since this is coded in Matlab, which is a standard Unilever application, it has been circulated widely and can be used by all researchers in house."

The second important contribution is the suite of image analysis protocols that Goldstein and Warren developed to image both single hairs and bundles reliably and to extract from stereoscopic images their three-dimensional shapes. The strong verification that the team did with these protocols gives Unilever confidence in their accuracy.

Unilever Global Senior Vice President for Home and Personal Care R&D, adds "In a Fast Moving Consumer Goods business such as ours, we know that even just a three-month reduction in time to market for an innovation in one of leading billion Euro brands could readily correspond to an incremental turnover of the order of several hundred thousand Euro, if not more."

In 2012 the team was awarded an Ig Nobel Prize for this research. The Ig Nobel Prizes honour achievements that first make people laugh, and then make them think. The prizes are intended to spur people's interest in science, medicine, and technology. The original announcement of the research, followed by the Ig Nobel Prize award, generated worldwide media attention. The research has featured on international radio programs (Canada, Germany, UK), on worldwide press, and has led to invited presentations in schools and universities internationally.

5. Sources to corroborate the impact (indicative maximum of 10 references)
Letter from Unilever Global Senior Vice President for Home and Personal Care R&D

Both the original publication and the Ig Nobel award received extensive media coverage: for example

New York Times: 10th Feb 2012: *Like How Your Hair Hangs? Praise the Laws of Physics*
http://www.nytimes.com/2012/02/11/science/ponytail-shape-is-determined-by-complex-physics.html

BBC Web coverage 13th Feb 2012 *Science behind ponytail revealed*
http://www.bbc.co.uk/news/science-environment-17012795

BBC Web coverage 21st Sept 2012 *Ig Nobel honours ponytail physics*:
http://www.bbc.co.uk/news/science-environment-19667664