The mechanics of slender structures

Modern physics edged mechanics out into the wilds of engineering. But multidisciplinary interest in pattern formation has moved it back into the mainstream, bringing with it interest from other fields — as this summer's Solvay Workshop demonstrated.

Pedro M. Reis, Fabian Brau and Pascal Damman

At the turn of last century, the Belgian chemist, industrialist and philanthropist Ernest Solvay organized a conference to enable the most prominent scientists of the time to meet and address contemporary challenges in physics and chemistry. The first Solvay conference took place in Brussels in 1911 and is still considered a turning point from classical to modern physics. Subsequent meetings have continued this tradition, catalysing significant advances in solid-state, particle, chemical and biological physics. In August this year, a cohort of leading experts and young researchers from physics, mechanics, biomechanics, locomotion, materials science, engineering, architecture and art converged in Brussels for a Solvay workshop to explore new opportunities in understanding the mechanics of slender structures — from their failure to their functionality[1].

Participants of the Solvay workshop on the 'Mechanics of slender structures in physics, biology, and engineering: from failure to functionality' that took place at the Université libre de Bruxelles (ULB), from 27–29 August 2018. Credit: Victor Levy

Within the new paradigm of modern physics, the mechanics of fluids and solids slipped away from the physics mainstream and moved closer to the realm of engineering. But the new field of pattern formation was quietly gaining prominence in the physics community, with the realization that order, form and function can emerge spontaneously from a featureless or disordered system. Early examples, including the Liesegang ring precipitation patterns[2], Rayleigh–Bénard convection[3], Turing patterns[4] and the Belousov–Zhabotinsky reaction[5,6], revived concepts from classical physics, powered by novel analysis tools rooted in nonlinear dynamics and statistical mechanics. Efforts to rationalize pattern formation in these systems eventually led to the emergence of a new paradigm based on far-from-equilibrium thermodynamics and dissipative structures[7] — recognized in Ilya Prigogine's 1977 Nobel Prize in Chemistry.

As the understanding of pattern-forming systems evolved, it became apparent that systems in equilibrium can also generate complex patterns. Instead of energy dissipation, complex structures can result from the interplay of competing physical ingredients. Elastic deformation, fluid flow, electromagnetic forces and surface energy, together with geometric confinement, can often pair to generate patterns in solids and fluids. Pattern-forming systems, involving thin layers of fluids or slender solid objects, for example, tend to require a delicate balance of the various, often antagonistic, forces at play, so as to prevent the domination of bulk energy terms. Within this paradigm, mechanical instabilities in thin elastic sheets emerged rapidly as a canonical system to investigate how geometry can couple to nonlinearities to produce intricate patterns[8–10].

The formation of wrinkles in bilayers is now considered an archetypal process for illustrating this pattern-formation mechanism; the buckling of the thin sheet is balanced by the deformation of the soft foundation to produce regular patterns[11]. In the realm of materials science, these buckling instabilities, previously considered the first route toward failure in engineering structures, are now being used to functionalize materials and structures[12]. For example, wrinkles are used to tune the wetting[13] and adhesion[14] properties of a surface; to improve OLED light extraction[15] and increase the efficiency of photovoltaics[16]; or to impart flexibility in otherwise rigid materials, as in stretchable electronics[17] and soft implantable prosthesis[18].

We organized a Solvay workshop this year with the central goal of providing a platform for exchange, discussion, cross-pollination and synthesis for this growing community. The multidisciplinary footprint of the attendees demonstrates how active and porous the boundaries are within this community, but also highlights the common themes that traverse seemingly disparate fields.

The workshop was organized in a series of topical sessions, covering the elastic instabilities of slender objects; elastocapillarity and fluid–structure interaction; foldable structures, origami and kirigami; biomechanics; bio-inspired robotics and stretchable electronics; and soft matter, structures and art. The presentations and discussions during the workshop highlighted the following challenges, which will doubtless keep the community active, vibrant and engaged for years to come.

First, the field needs effective analytical and computational tools to provide a more intuitive understanding of the crucial geometric nonlinearities that underlie slender systems. More direct bridges to the field of differential geometry might be one way of accomplishing this. Even though differential geometry is well established for continuum systems, devising equivalent approaches for discrete systems is still an active field in mathematics and computer graphics, and geometrical singularities, for example, are particularly relevant for our understanding of slender structures.

Theoretical frameworks to describe slender systems are still relatively rudimentary, primarily centred on the simple engineering elements of beams, rods, plates and shells. This language needs to be extended to more intricate structures that consist of assemblies of slender elements, and include the possibility of coupling to bulk materials. Here, coarse graining and homogenization can provide effective descriptions that are more amenable to the analysis and design of heterogeneous and hierarchical systems, similar to the role that amplitude equations have played in the field of nonlinear pattern formation[19].

Another promising avenue for research on the physics of thin objects stems from the ability to travel across dimensions. For example, reduction of three-dimensional bulk objects down to two- or one-dimensional theoretical descriptions has been powerful in providing efficient and effective analysis toolboxes. Conversely, starting from low-dimensional structural systems that spontaneously morph into complex three-dimensional structures is common in origami and kirigami. Developing a better and more predictive understanding in this domain remains a theoretical challenge that may enable the design of novel deployable structures in aerospace engineering, architectural and microstructural systems.

Finally, innovation will no doubt continue to emerge from coupling the mechanics of slender structures with other phenomena, such as nonlinear material behaviour, fluid–structure interactions, adhesion, fracture, electromagnetic effects and growth. In the context of biological systems, the proliferation of D'Arcy Thompson's doctrine[20] on the mechanics of growth is an exciting direction for future research, now supported by modern advances in mechanobiology and microbiology.

There is a bright future ahead for curiosity-driven research on the mechanics of slender structures. Ultimately, the golden goal is to aim for a level of fundamental understanding that facilitates the predictive design of innovative engineering mechanical devices and the rationalization of natural processes and systems. ❐

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A machine of superlatives

The Large Hadron Collider has completed its second data-taking period. For the next two years, the accelerator will shut down and the experiments will undergo major upgrades. Here's a take on our past achievements — and a preview of the future.

Niels Tuning

The first run of the Large Hadron Collider (LHC) started in 2009 after decades of designing, developing and constructing — a process that involved thousands of dedicated particle physicists and engineers. Run 1 culminated in the 2012 discovery of the Higgs boson, but many open questions remain: are there new particles, forces or even several Higgs bosons that can help explain the nature of dark matter or the disappearance of antimatter? Finding answers to these questions requires precise measurements — and precise measurements require a powerful accelerator combined with state-of-the-art particle detectors.

Run 1, lasting from 2009 to 2013, superseded the expectations of many, with numerous discoveries making headlines. We found that quarks and gluons behave as a perfect liquid[1], revealed particles consisting of five quarks (rather than the standard two or three)[2] and measured the decay of the B_s meson into two muons, which is as rare as three in a billion[3].

But discovering the Higgs was certainly a highlight[4,5]. Far from being just another matter particle or another fundamental force, the Higgs is an entire category on its own. A formidable particle by any standards, it impacts the origin of mass, the properties of the vacuum and even the fate of the Universe. And the Lagrangian of the standard model of particle physics makes clear the central role this particle plays, as half of its terms contain the Higgs field[6].