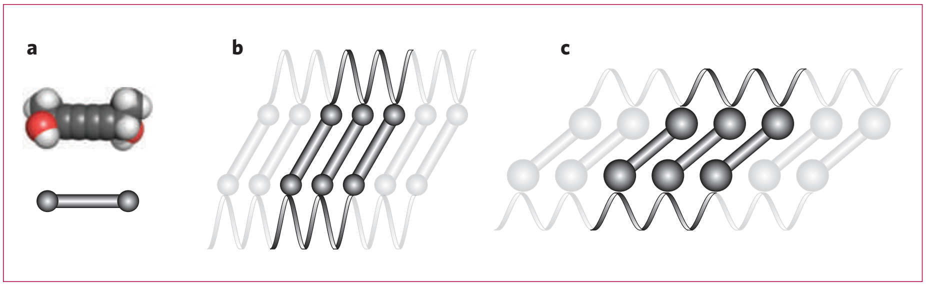

Figure 2 | Schematic of thermal expansion. **a**,**b**, Dumbbell-shaped (*S*,*S*)-octa-3,5-diyn-2,7-diol molecules (**a**) form pillar-like crystals (**b**) that are held together by means of helical networks of hydrogen-bonding interactions. **c**, On heating, the effective space occupied by each molecule increases, which extends the helices along their axes and causes a contraction in a perpendicular direction.

in the separations between functionalized substituents. For example, electronically functionalized molecules could form crystals that switch from absorbing to transmitting certain frequencies of light at different temperatures.

The extreme NTE seen in this molecular crystal already suggests a range of other bizarre physical properties even without chemical modification. Under hydrostatic pressure, where the same pressure is applied in all directions, the crystals should reduce their volume by actually expanding in some directions. This phenomenon, known as negative linear compressibility, has applications in high-performance pressure sensors[6]. Moreover, the crystals should function as so-called auxetic materials, which when stretched along a particular axis expand in a perpendicular direction. In any case, the results of Barbour and co-workers highlight the importance of looking to weakly bound materials for extreme, and extremely useful, mechanical behaviour. ❐

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NANOTRIBOLOGY

The renaissance of friction

500 years after the first studies on friction, the concepts of superlubricity, wearless sliding and friction control are being realized in laboratories and have become predictable by adequate modelling. The challenge now is to bridge the gap between what is known about these processes on the microscopic and macroscopic scales.

Michael Urbakh and Ernst Meyer

Friction is present in a great number of physical systems and plays a central part in phenomena that occur at all length scales, from micro- and nanomachines[1] or biological molecular motors[2] to the geophysical scales characteristic for earthquakes[3]. Despite the practical and fundamental importance of friction and the growing efforts in the field, many key aspects of the dynamics of this phenomenon are still not well understood. The main challenge is posed by the complexity of highly non-equilibrium processes occurring in any tribological situation, which includes detachment and re-attachment of several microscopic contacts between the surfaces in relative motion. Friction is not simply the sum of single asperity responses, but is influenced by temporal and spatial dynamics across the entire ensemble of asperities that form the frictional interface.

The recent developments in understanding friction and the leading factors that determine the frictional response at the nanoscale (see Fig. 1), were the main topics of debate at the recent Trends in Nanotribology conference, held at the International Centre for Theoretical Physics, Trieste, on 19–23 October 2009. Some 500 years after Leonardo da Vinci's studies, scientists are again actively working on the topic. The reasons for this 'renaissance of friction' are the development of highly sensitive experimental tools, such as friction force microscopes, surface force apparatus or quartz microbalances, and the availability of advanced computational methods, which give access to nanoscale friction and wear phenomena. The conference was part of the series of activities coordinated by the European Science Foundation (ESF), in which groups from 16 different European countries collaborate in the ESF-FANAS programme — Friction and Adhesion in Nanomechanical Systems (FANAS) — and try to answer some of the fundamental questions of tribology.

One of the main challenges in the field is linking the results obtained at the nanoscale with friction phenomena occurring in the macroscopic world, mainly because atomistic models do not seem directly scalable. From a practical point of view, the conditions in which nanotribology and tribology tests take place — using, for example atomic force microscopes (AFMs) for nanotribology and pin-on-disk or V-block-on-cylinder testers for tribology — are very different. AFM tips induce stresses in the gigapascal range, whereas macroscale testers operate in the kilopascal range. Atomic force microscopes typically operate at sliding amplitudes of a few micrometres, whereas macroscale testers operate at sliding amplitudes ranging from hundreds of micrometres up to tens of centimetres. Several ways to address the problem of bridging the gap between the nano-, micro- and macroscales in friction were discussed at the conference. Oded Ben-David (from Jay Fineberg's group at the Hebrew University of Jerusalem, Israel) as well as Roland Bennewitz (Leibnitz Institute, Saarbrucken, Germany) and Oleg Braun (Academy of Sciences, Ukraine) studied the tribological properties of large ensembles of asperities; Lydéric Bocquet (Université Claude Bernard, Lyon, France) looked at the effects of confinement on the properties of embedded liquids; Merlijn van Spengen (Leiden University, The Netherlands) studied the frictional response of microelectromechanical systems; and Bernd Gotsmann from IBM Zurich investigated wear at the nano- and mesoscales under dry and wet sliding conditions.

Significant progress in understanding the relationship between the dynamics of individual contacts and macroscopic frictional motion has been achieved with the development of a new real-time visualization method of the net area of contact along the entire interface, as discussed by Oded Ben-David. This method has enabled a number of key conclusions on the mechanism of transition from static to kinetic friction in macroscopic systems to be made[4]: (1) the onset of sliding is preceded by a discrete sequence of crack-like precursors (collective modes of the entire ensemble of asperities); (2) the transition is governed by the interplay between three types of fronts: sub-Rayleigh, intersonic and slow fronts; and (3) a sequence of 'precursor' events gives rise to a highly inhomogeneous spatial distribution of contacts before the overall sliding occurs. The collective behaviour of the asperity ensemble that composes a frictional interface therefore determines the transition mechanism from static to dynamic friction. A complete understanding and, possibly, control of the frictional characteristics of these systems necessitates integrating and modelling contact dynamics at all scales — from the single contact (nano-) scale to macroscopic scales.

An alternative approach to the study of friction at the nanoscale is by means of controlled manipulation of nanoparticles, which are known to be formed in tribological contacts. The nanoparticles may either form a third body between the tip and the surface or they may be incorporated into the surface layer, thus forming a different compound. If the tip is operated in tapping mode, relatively small particles with weak interfacial strengths can be imaged and manipulated in a controlled way. Andre Schirmeisen from Münster University (Germany) presented the results of experiments with antimony particles on graphite that showed two distinct types of motion under ultrahigh-vacuum conditions[5]. Type I shows a clear particle-size dependence, where the observed dissipated energies are proportional to the area of the particles with a shear strength of about 1 MPa. Type II shows practically zero friction, which is independent of the size of the particles. A possible explanation is related to the phenomenon of structural lubricity: type II particles presumably form an incommensurable contact, whereas type I particles form a commensurate contact. It is rather remarkable that the state of superlow friction (superlubricity) is maintained across long distances of several hundreds of nanometres, at least under relatively clean vacuum conditions. However, the researchers also observed that the number of non-superlubric events increases with contamination, which would indicate the influence of interfacial mobile molecules. So far, the role of these contaminants is still unclear. Manipulation experiments with nanoparticles can be either performed sequentially (one particle after the other) or in a parallel mode, in which the tip is continuously scanned across the surface. The manipulated nanoparticles move in well-defined directions, where the angle of the trace of the particle is characteristic of its size[6,7].

Another important topic, particularly for applications, is the ability to control frictional forces. It might be desirable to reduce or enhance friction, or to eliminate the chaotic and stick–slip regimes of motion, and achieve smooth sliding. Once again the main problem is the complexity of the physical systems of interest that typically involve many degrees of freedom under a strict size confinement, which leaves very limited access to external action. An approach that has attracted considerable recent interest is the mechanical control of a system through externally imposed vibrations of small amplitude and energy[8,9]. In this case, the idea is not to change the physical properties of interfaces but to reduce the frictional force or to eliminate stick–slip motion through the dynamical stabilization of desirable modes of motion, which are unstable in the absence of control. Experimental (Anisoara Socoliuc, SPECS-Zurich) and theoretical (Stefano Zapperi, Consiglio Nazionale delle Ricerche, Rome) studies presented at the conference have demonstrated that oscillations of the normal load can lead to a transition from a state of high-friction stick–slip dynamics to a low-friction, smoothly sliding one. Manipulation by mechanical excitations, when applied at the correct frequency, amplitude and direction, can drive a system out of its potential energy minima and thereby reduce friction. At other frequencies or amplitudes the friction can be increased. Even more exciting is an observation of elimination of wear[10] on a tip

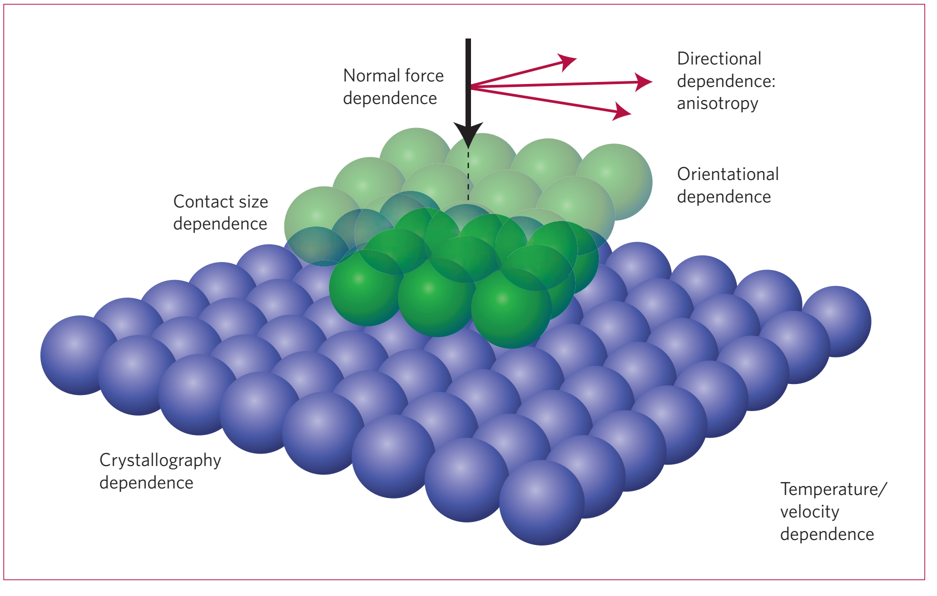

Figure 1 | Scheme of a typical experiment to study friction at the nanoscale, in which an AFM tip is driven along a surface. The main factors that contribute to the determination of friction between a tip and a surface (as discussed at the conference by Joost W. M. Frenken from Leiden University) are also shown. The purple and green spheres represent the atoms in the underlying surface and those in the AFM tip, respectively; the black arrow indicates the effect of normal load, and the red arrows show the possible directions of tip motion and indicate the possible rotation of the tip with respect to the surface.

sliding on a polymer surface over a distance of 750 m by modulating the normal force acting on the tip–sample contact. This approach could lead to parallel-probe storage systems that are competitive with existing storage technologies in terms of lifetime requirements, and has the potential for reducing wear in other applications such as probe-based nanolithography, nanomanufacturing and high-speed metrology systems. It may also be relevant to the design of micro- and nanoelectromechanical systems, for which the wear of contacting and sliding parts can impose severe limitations on device lifetime.

Although the possibility of mechanical control of friction and wear has been demonstrated, there are fundamental questions that still need answering. For example, we do not know what the fundamental mechanisms behind these phenomena are. Also, it is unclear as to what types of system the different manipulation methods can be applied. Finally, the relationships between optimal values of the control parameters and the physical properties of the tribological system are unknown at this stage.

Despite the many open and unanswered questions, it was clear from the conference that substantial progress in understanding friction has been made in the past few years. The challenges outlined by the various presentations and partly summarized in this article have a principal role in determining the excitement of the field and contribute in drawing the roadmap for the future studies on friction. ❐

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