

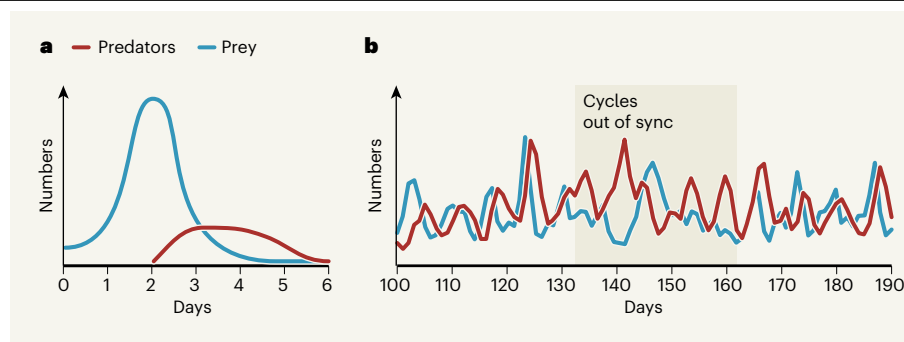


Figure 1 | A difficult balance to strike. Ecological theory predicts that the relative numbers of a predator and its prey should oscillate in persistent cycles, but demonstrating this in the laboratory has been hard. **a**, Classic experiments⁴ from the 1930s failed to achieve cycles, because predators were either too inefficient at eating prey (not shown) or too efficient, and ate them all. Either way, predator numbers dwindled. **b**, Blasius *et al.*² have succeeded in achieving persistent predator–prey cycles in the laboratory. They found that cycles were mostly in phase, with predator cycles slightly lagging behind prey cycles. However, there were transient periods in which the two – for unknown reasons – fell out of sync. (Adapted from Fig. 2b of the paper.)

However, these oscillations would undergo sudden shifts, without any external driver. During these transient periods, both populations would oscillate out of sync with one another, before the in-phase cyclic dynamic resumed (Fig. 1b).

The authors also performed experiments in which they introduced pulses of nutrients to the species' environment. This mimics seasonal environmental changes experienced in many natural systems. The overall dynamics of the predator–prey cycle remained the same in these conditions, indicating that predator–prey interactions can govern cycle dynamics, even in a seasonally varying environment.

Although Blasius and colleagues' work answers one question, it raises others. First and foremost, why are the results so different from those of earlier experiments? It is not just a quirk of the species used, because the authors repeated the experiment using a different prey species and achieved the same result. One contributing factor could be that the researchers used a predator that has a complex life history involving transitions through several stages, from egg to adulthood. Another could be that persistence depends on the specific amplitude of oscillation in the cycle.

In support of these ideas, previous work involving a predator with a simpler life cycle demonstrated that populations of predators, prey or both went extinct if cycles reached an amplitude at which population numbers become low⁴. In addition, analysis of a different marine predator–prey combination⁸ showed that cyclic dynamics eventually gave way either to extinction or to persistence of the two populations in equilibrium. And mathematical theory¹ suggests that the small-amplitude cycles observed by Blasius and colleagues would occur only under very specific conditions. Demonstrating persistent cycles in other systems is therefore a key challenge for the future. The life-history characteristics of the predator used by Blasius and colleagues

could be a starting point in the search for systems that show similar behaviour.

Another intriguing avenue for future study is to determine the relationship between transient dynamics and switches in system behaviour. Does a sudden change in the dynamics of a cycling system reflect changing environmental conditions, or is it an intrinsic phenomenon? The existence of unexpected, transient shifts in predator–prey dynamics limits the predictability of ecological systems⁹. In the real world, sudden shifts of this nature could spur an erroneous quest to identify drivers of the change, whereas the current

study indicates that there may be none. The possibility of transient dynamics could also make it more difficult to predict the effect of ecological-management strategies.

Blasius *et al.* have provided one of the clearest demonstrations so far of transient dynamics in the laboratory, where it is absolutely certain that no external influences caused the change. It will be important to bring together this work (and another convincing experimental demonstration¹⁰) with theoretical models that are currently being developed⁹. Doing so should provide more insights into the role of transient dynamics in natural systems.

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This article was published online on 18 December 2019.

Materials science

The physics of ice skating

Daniel Bonn

The slipperiness of ice is poorly understood at a microscopic level. Experiments that probe how the surface of ice melts and flows in response to wear help to explain the exceptionally low friction that underpins winter sports.

It is widely thought that ice skating is enabled by the formation of a layer of water on the surface of ice, which lubricates the skate. Writing in *Physical Review X*, Canale *et al.*¹ report that, although there is indeed a layer of something, it is not simply water – the lubricating layer has surprising flow properties that are very different from those of bulk water, and are intermediate between those of liquid water and ice.

The idea that a thin film of meltwater wets the surface of ice has been accepted since the nineteenth century². This layer should

be present beneath skates or other objects sliding on ice. Most of the debate about this topic, therefore, deals with the origin of the layer – is it the result of surface melting, heating associated with friction generated by the skate, or pressure-induced melting? Pressure melting has largely been discounted, because this process is impossible for ice below about –20 °C, whereas skating is possible at such low temperatures. Surface melting and frictional heating also seem unlikely explanations because these phenomena are not specific to solid water ice, yet ice is almost the only

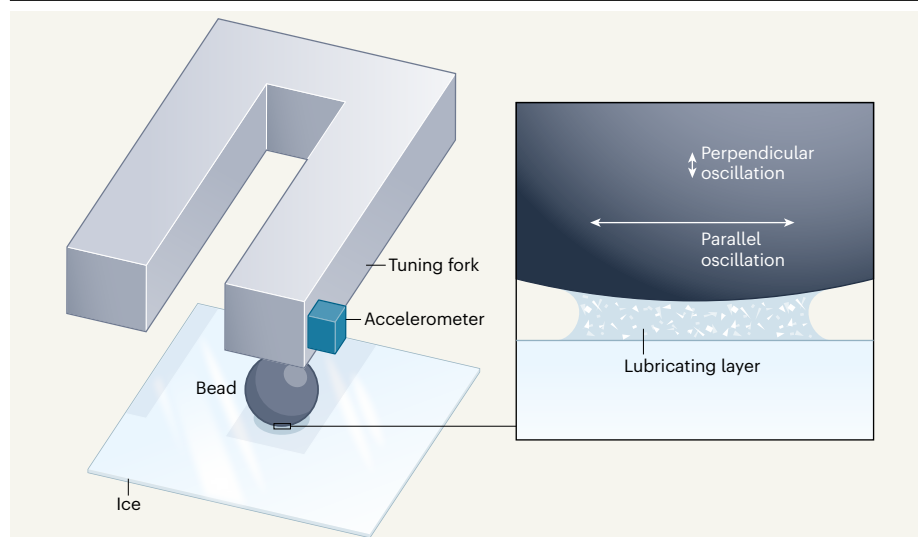


Figure 1 | Probing the lubricating layer of ice. Canale *et al.*¹ investigated the thin layer of melt water that lubricates the slipping of objects on ice. The authors attached a millimetre-scale glass bead to a prong of a macroscopic aluminium tuning fork. The fork was made to vibrate, causing the bead to oscillate over the ice surface. An accelerometer on the fork measured the amplitude of the bead's oscillations parallel and perpendicular to the surface. From these measurements, the friction between the bead and the ice, and the flow properties (rheology) of the lubrication layer, could be calculated. The observed viscosity and elasticity of the layer suggest that it consists of a mixture of water and ice particles.

material that it is possible to skate on.

Also unknown are the mechanical properties of the meltwater layer. Whether a liquid lubricates or not is mostly determined by its resistance to being squeezed out from the gap between the two rubbing surfaces – thick grease is usually needed for good lubrication. Water is not a good lubricant, because its low viscosity means that it is easily squeezed out of gaps. The idea that a layer of water is sufficient to lubricate a skate on ice is therefore strange. It doesn't even make intuitive sense, given that it is impossible to skate on a road or a kitchen floor with a layer of water on it.

Canale *et al.* report clever experiments that investigate the microscopic mechanisms responsible for the slipperiness of ice (Fig. 1). The authors measured the coefficient of friction (a measure of the friction produced at a surface) of ice and the properties of the lubrication layer simultaneously, using an experimental set-up that resembles a large tuning fork. The fork was made to vibrate, so that a millimetre-scale glass bead attached to one of its prongs oscillated across an ice surface. The bead thus functioned as a tiny ice skate, gliding for distances of the order of tens of micrometres across the same region of ice.

An accelerometer attached to the same prong of the fork as the bead measured the amplitude of the bead's oscillations parallel to the surface, and compared them with the amplitude of the driving force. Canale *et al.* used the difference in amplitude to calculate the friction force between the bead and the ice. Simultaneously, tiny oscillations of the bead (restricted to just a few tens of nanometres, so as not to influence the friction measurements)

perpendicular to the ice surface allowed the authors to probe the properties of the lubrication layer. The authors used a similar procedure to the one used to measure parallel movements to measure the forces acting on the bead perpendicular to the surface. The coefficient of friction between glass and ice could then be calculated from the ratio of the two measured forces.

Canale and colleagues' procedure not only measured the amplitude change of the perpendicular movements, but also the time taken for the driving force to produce these oscillations of the bead (the phase shift). This allowed the authors to measure the mechanical impedance of the lubricating layer on the ice – a measure of its resistance to forces applied by the bead. These measurements, in turn, correlate with the flow properties (rheology) of the lubrication layer.

Taken together, the authors' measurements allowed the friction and rheology of the lubrication layer to be probed simultaneously. The experiments show that the lubrication layer has both viscous and elastic responses to an object sliding on top of it. This is not only different from the behaviour of bulk water, but also to that of ice. The results, therefore, reveal that skating requires more than just a layer of water.

So what is happening? Sophisticated spectroscopy techniques have previously been used to study the surface of ice at different temperatures³, and revealed that melting occurs discontinuously through successive bilayers of ice molecules – the first bilayer melts at about -70°C , and the second one at -20°C . Friction measurements over that same temperature range have shown, however, that friction at the

surface doesn't change as the bilayers melt⁴. It therefore seems that the slipperiness of ice does not just depend on its surface properties during melting, but also on its interaction with the skate.

Canale and co-workers' experiments support that idea. The authors suggest that repeated sliding over the same spot generates a mixture of ice and water, which displays both elastic behaviour (from the ice) and viscous behaviour (from the water) in response to a load. The resulting layer of material would be more difficult to squeeze out of gaps than ordinary water. This could – at least in part – explain the layer's excellent lubrication properties.

The new study also provides the beginning of an explanation of why skating is so specific to ice. Lubricated friction and concomitant wear often lead to the formation of a layer of different material, known as a third body, between the two rubbing objects. Because this process relies on the specific ways in which the surfaces of rubbing objects wear away, and often even on friction-induced chemistry, the formation of a third body is largely system-specific. In other words, few materials can form a visco-elastic, liquid–solid third body in response to friction and wear, such as that observed in Canale and colleagues' experiments.

Interesting questions remain. For example, does the observed layer form rapidly enough on pristine ice to lubricate on contact? And how does the presence of the layer explain that the optimal ice temperature for skating^{4,5} is about -7°C ? (The temperature at which all speed-skating rinks are kept.) Beyond ice skating, detailed measurements of the properties of thin lubrication films are likely to be useful, because many such films do not show the same properties as the bulk lubricant⁶, and because the origin and effects of the third body in lubrication remain a largely open question. These are important issues because lubrication is often the only way to reduce friction, which is responsible for an estimated 20% of the world's energy consumption⁷.

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This article was published online on 16 December 2019.