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The Science of the Curl

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Abstract

A century after the first scientific inquiry, tribologists are finally closing in on why a rotating granite stone traces a gentle arc across the ice – and the answer is far stranger than anyone expected.

A Century of Inquiry

The first scientific paper on the subject was published in 1924 by E. L. Harrington of the University of Saskatchewan — the same institution that, a century later, would use infrared cameras and surface-roughness profilometers to study the same problem with far more sophisticated tools [1]. In the intervening hundred years, dozens of peer-reviewed articles have emerged from Canada, Sweden, Finland, Japan, South Korea and China. They frequently contradict one another's mathematical models and none fully accounts for every observed behavior of a stone in motion.

That is not unusual in tribology. Friction at the nanoscale, especially on a material as structurally peculiar as ice, resists simple models. But the gap between the sport's practical sophistication — elite curlers can place an almost twenty-kilogram stone within centimeters over twenty eight meters — and the incompleteness of the theoretical framework is striking. Recently, it has recently begun to narrow.

What is in Touch?

Before addressing why stones curl, it is worth establishing precisely what is in contact. The bottom of a curling stone is not flat. A concave hollow leaves only an annular ring, the running band roughly 6–8 mm wide, in contact with the ice surface. This geometry concentrates load onto a narrow, predictable zone and makes the stone's motion far more reproducible than a flat-bottomed object would be.

The ice surface, meanwhile, is deliberately not smooth. Before play, the ice is repeatedly sprayed with fine droplets of water that freeze into rounded protrusions – the pebble – standing roughly 0.3–0.5 mm above the surrounding surface. These are then mechanically scraped by a process called nipping to flatten their crowns. The stone therefore rests not on a continuous film but on an array of small, consistent contact points.

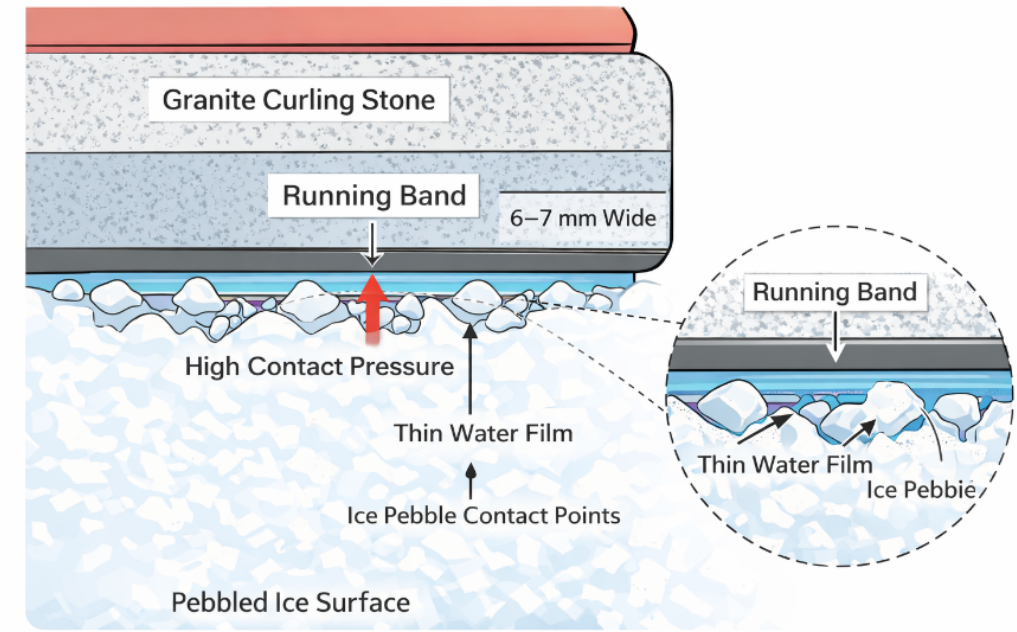

Figure 1: Illustration of curling stone contacting ice surface.

This architecture is engineered tribology, whether or not the ice technicians who developed it over generations would use that term. As Michigan Metrology has noted, a flat stone on flat ice would be nearly unplayable: the real contact area would be so large that friction would be unmanageably high and inconsistent [2]. Instead, every spatial wavelength of surface texture, from the large-scale levelness of the sheet to the microscopic roughness of the running band itself, is managed to produce a specific, reproducible friction response.

The quasi-liquid surface

Ice is not merely a solid. Its surface, at temperatures near freezing, supports a nanometer-thin quasi-liquid layer – a disordered region of water molecules whose hydrogen-bonding is intermediate between bulk ice and liquid water. These molecules are in constant motion relative to one another, providing intrinsic lubricity even before any frictional heating occurs [3]. At -4 °C, the operating temperature of curling ice, this layer is more developed than at the -7 °C preferred by speed skaters. Its precise role in curling has not been quantified, but it sets the baseline lubrication on which everything else acts.

The Stribeck Framework

The Stribeck curve – named after Richard Stribeck, who described it in 1902 – plots the coefficient of friction against a dimensionless parameter combining lubricant viscosity, sliding speed, liquid film thickness and contact pressure. As speed decreases, friction first falls (hydrodynamic regime), then rises again as the lubricant film breaks down (mixed and boundary regimes). It is a foundational concept in bearing and engine design, but until Brown's 2024 paper, nobody had applied it systematically to curling.

Brown argues that the logarithmic deceleration of a curling stone – its initial mild slowdown followed by an increased rate of deceleration near the end of its travel – is precisely the signature of a system moving through these three regimes [4]. A constant coefficient of friction would produce linear deceleration. The observed behavior requires a friction force that changes as a function of velocity, which the Stribeck model provides naturally. The framework also explains where the lubricating water comes from at -4 °C. Sean Maw and his research team at the University of Saskatchewan have demonstrated, using a highly sensitive infrared camera, that the passage of a curling stone over pebble causes localized frictional warming – sufficient

to produce a transient water film at the contact interface even well below freezing. The stone is, in effect, skating on the heat it generates [4].

Three Friction Phases of a Curling Stone	
Phase I Hydrodynamic	Frictional heat from shear stress within a thin water film maintains near-hydroplaning conditions. Coefficient of friction on the order of 10^{-2}. No striations form on pebble. Deceleration mild and approximately constant.
Phase II Mixed	Water film thins; running-band asperities begin mechanically abrading pebble crowns. Striations appear. CoF rises sharply. This is the "break point" – curl intensifies. Sweeping has maximum effect here.
Phase III Boundary/Dry	Lubrication essentially absent. Friction rises steeply and the stone decelerates rapidly to rest. Sweeping has limited effect.

Brown's analysis confirms earlier work by Nyberg showing an absence of striations when stones travel at higher velocities: the hydroplaning interpretation makes this absence expected rather than anomalous [5].

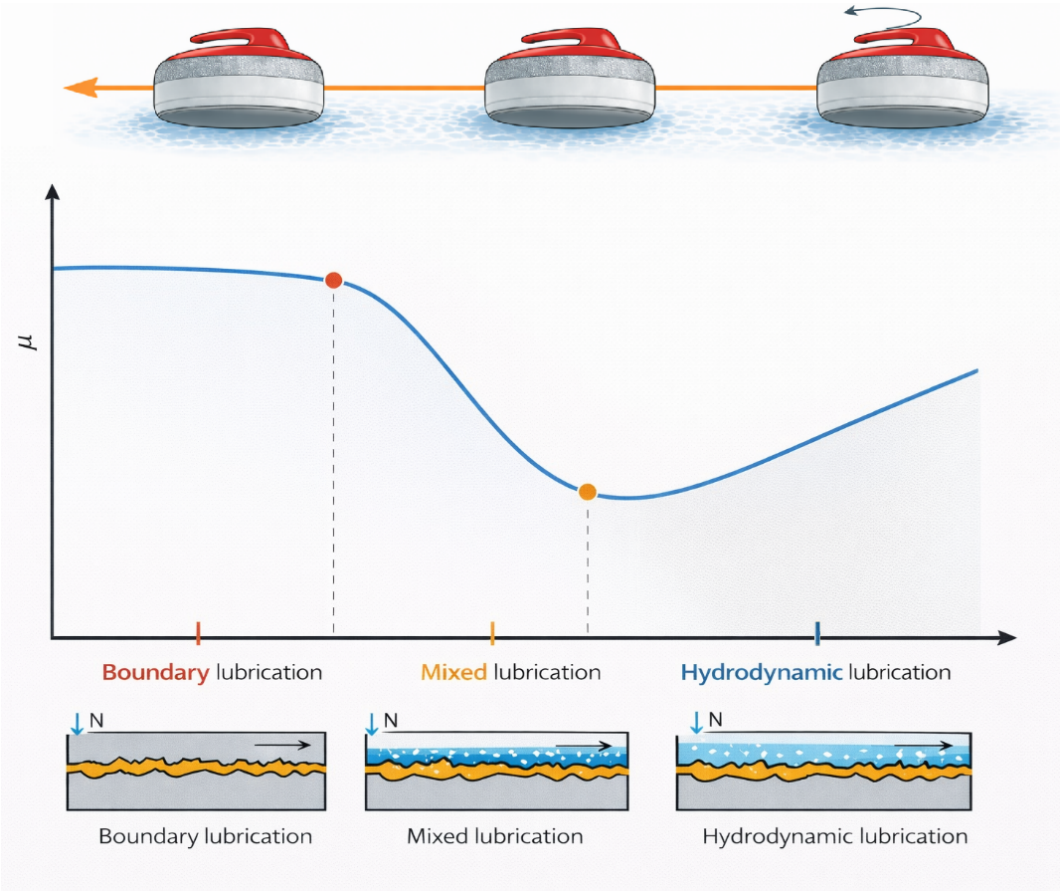

Figure 2: Stribeck curve - Friction coefficient depending on dynamic viscosity, speed and load at boundary, mixed and hydrodynamic regimes. The curling stone shown above travels from the throw (hydrodynamic mode) through (mixed) to stopping (boundary).

Why Does It Curl? Competing Theories

The Stribeck framework clarifies how friction changes during a stone's travel. It does not, by itself, explain the lateral force that produces the curl. For that, separate mechanisms have been proposed over the decades. And this is where tribologists have disagreed most sharply.

Left–right asymmetry

The intuitive explanation for curl is that a rotating stone experiences different friction on its two sides because one side moves faster relative to the ice than the other. The side where rotation aids forward motion moves faster, friction is generally higher at higher speeds. Therefore that side drags more and therefore the stone veers toward the slower side, which is opposite to the observed curl direction.

This inconsistency (classical rotation theory predicts curl in the wrong direction) has driven decades of alternative proposals. One version, advanced by physicist Mark Denny, invokes a snowplow effect in which ice debris accumulates asymmetrically. Another, proposed by Mark Shegelski at the University of Northern British Columbia, suggests that the increased downward pressure at the front of a decelerating stone causes local melting, reducing friction, so the stone steers toward its front edge rather than away from it.

The scratch-guide model

One of the most experimentally investigated mechanism to date comes from a 2013 paper by Nyberg, Alfredson, Hogmark and Jacobson at Uppsala University, published in the journal Wear [5]. Their proposal, developed using white-light interferometry and pressure-sensitive Fuji Prescale film to visualize actual contact, is deceptively elegant.

As the stone traverses the ice, its running band scratches microscopic grooves into the crowns of the pebble. These grooves are oriented in the direction of the stone's travel at each contact point. The trailing portion of the running band then encounters these fresh scratches at a small angle, because the stone has rotated slightly by the time the back of the band crosses the same pebble. The scratches act as micro-guides, exerting a lateral force on the trailing contact that is consistently directed toward the curl side.

Three properties of this mechanism are particularly important. First, curl varies less strongly with spin than simple friction models predict, which explains the well-documented observation that stones with very different amounts of spin (provided they have at least some) curl by roughly the same amount. Second, it depends strongly on the roughness of the running band: a smoother band leaves shallower scratches and produces less curl. Third, it operates through the geometry of micro-scale contact rather than through differential macroscopic velocities, which is why classical friction analysis points in the wrong direction.

Grit, debris, and the Penner model

A. R. Penner (2019, 2022) has extended the scratch-guide concept into a first-principles model in which the key actors are tiny particles of ice and grit liberated from the pebble surface as the stone passes over it [6]. Because the stone rotates, these particles are distributed asymmetrically beneath the running band in a way that creates a measurable lateral normal force. Penner's model operates without free parameters tuned to the data and produces trajectory predictions that match observations well – a significant achievement given the complexity of the underlying contact mechanics.

The isotropic model

Most recently, Ziegler (2025) proposes that the curl originates from isotropic friction combined with asymmetric accumulation of the lubricating water film [7]. One particularly promising feature of this model is that it can account for the behavior of "spinner" shots – deliveries made with substantially more rotation than is standard in competitive play – which other models struggle to predict accurately.

Sweeping: Real-Time Surface Engineering

The sweepers who follow a stone down the ice are, in tribological terms, modifying the contact interface in real time. Their nylon fabric brooms interact with the pebble in at least two distinct ways.

The heating effect

The heating effect has been studied since at least 2006, when Marmo, Farrow, Buckingham and Blackford at the University of Edinburgh used thermocouples to measure the temperature rise produced by sweeping [8]. The increase is modest (tenths to single-digit degrees Celsius) but it is sufficient to shift the stone from a boundary-friction state back into a mixed or even hydrodynamic regime. The practical effect is that the stone travels further and curls less: two independent variables that a skilled team can exploit tactically.

The abrasive effect

What has only recently been appreciated is that sweeping also has a mechanical, abrasive effect on the pebble. Research by Sean Maw's group (2024–25) evaluated pebble modification on a four-point scale ranging from minor edge smoothing to complete elimination of the nipped crown — a process they call erasure [9]. This matters because the pebble geometry directly determines the real contact area between stone and ice and therefore the friction response. A swept path is not just warmer than an unswept one, it is physically different at the micrometer scale.

Pebble wear from stones

Yanagi, Kameda, Harada and Sado (2024) quantified the progressive wear of pebble across a game, using polymer replicas that could be analyzed under a profilometer away from the ice [10]. Pebble height decreases with each stone passage, and the contact area with the running band increases correspondingly. A track that has been played repeatedly becomes what curlers call keen – faster, with altered curl behavior – because its tribological character has genuinely changed.

Knifing

These findings have direct implications for the controversial technique of knifing, in which a sweeper rotates the brush head ninety degrees so its fabric moves across rather than along the path of travel. Experienced players have confirmed that knifing slows a stone. The mechanism is not yet fully understood, but the Maw group's work on mechanical abrasion provides a plausible starting point: a ninety-degree brush orientation may alter the directionality of pebble damage in a way that increases effective friction.

The Ice Itself

Curling ice is not arena ice repurposed. It is an engineered tribological surface built up in dozens of thin layers to achieve planarity, then textured to specification. The ice technician – a skilled and underappreciated figure in competitive curling – manages, in the language of surface metrology, every spatial frequency of the surface from the macro (overall flatness) to the micro (pebble roughness and nip height) [2].

One persistent puzzle is the choice of operating temperature. The minimum coefficient of friction for ice is known to occur at approximately -7 °C, which is why speed skating rinks operate at that temperature. Curling ice is maintained at -4 °C, three degrees warmer, apparently for reasons related to the behavior of the pebble and the curl response of stones rather than simple energy minimisation. The precise physical reason for this preference has not been rigorously established in the literature.

Another unresolved phenomenon is the well-known effect of rest on ice condition. A sheet that has been played heavily and then left alone for a period – say, during the fifth-end break in a championship – will revert toward a slower, less-keen state. The surface appears to heal. The underlying mechanism, presumably involving surface sintering, recrystallisation

or changes in the quasi-liquid layer, has not been systematically studied in the curling context.

Conclusion

Curling is unusual among sports in that friction is not an obstacle to be minimised but the central variable to be managed. The stone, the ice, the sweepers' brooms and the ice technician's spray bottle are all instruments in a system whose behavior is governed by contact mechanics at scales from nanometers to millimeters.

The emergence of the Stribeck framework — bringing together the hydrodynamic, mixed and boundary regimes that tribologists have studied in bearings and engines for over a century — offers the first genuinely unifying language for describing what happens during a stone's trajectory. The scratch-guide and grit-debris models provide the most credible accounts of the lateral force behind the curl. And the work on pebble abrasion, both from stones and from brooms, is beginning to explain why the ice changes over the course of a game.

What remains remarkable, a hundred years after Harrington's first paper, is how much productive mystery remains in 42.5 meters of ice and a polished ring of granite. The next decade of research, aided by infrared cameras, surface-roughness profilometers and precision kinematic sensors, will very likely resolve the central questions. Until then, every competitive end played is, among other things, an uncontrolled but richly informative tribological experiment.

About the Author

Jakub Grunt currently serves as Technical Manager for the Central Europe HUB at TotalEnergies in Prague, where he oversees technical operations and support across the region. Prior to this role, he was the Head of the Tribotechnical Laboratory at KOMA Commercial s.r.o. in Ostrava, Czech Republic, leading laboratory activities and ensuring high standards in materials and lubrication analysis. Jakub holds an engineering degree (Ing.) in Consumer Chemistry from Brno University of Technology (Vysoké učení technické v Brně), which provided a strong foundation for his expertise in tribology and technical management.

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