Instructor’s Corner

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Why do rocks curl?
—Rowan D. Conner

You have to admit that curling is a very strange sport. You push a 40-pound granite stone down a painstakingly prepared ice surface, with a specific direction and amount of rotation, and the darned thing doesn’t even travel in a straight line. To a non-curler, this surely seems plain daffy. So why don’t curling rocks travel in a straight line? It turns out that there have been numerous attempts to answer this question, most of which have not been very successful. Indeed, curling rocks seem to support Howe’s Law: “Every man has a scheme which will not work.” Fortunately for us, stones *do* curl, and that makes the game challenging and fun.

Historical investigations of curling stones

Among the earliest systematic investigations of curling stones goes back to 1924 (E.L. Harrington, *Trans. Royal Soc. Canada* **1924**, *18*, 247) in which the author observed the motion of curling stones on the ice, and examined the torque applied to a curling stone by a rotating sheet of ice. Harrington concluded that rocks curl because the friction between the stone and the ice is strongly velocity-dependent, increasing dramatically as the velocity of the stone decreases relative to the ice it is traveling over. In the case of a rotating curling stone, the leading edge (left side for a clockwise rotation) travels faster over the ice than the retreating edge (right side for a clockwise rotation). As the stone slows down near the end of its travel, the retreating edge of the stone has a velocity over the ice that approaches zero, and therefore friction on that side of the stone increases compared to the friction of the leading edge of the stone. This asymmetry of friction on the stone is supposed to induce the stone to curl to the right—except the physics doesn’t work! This type of friction asymmetry cannot exert any *sideward* force on the stone, which is required to make it curl. So back to the drawing board.

W.H. Macaulay and G.E. Smith (*Nature* **1930**, *125*, 408) made a number of cogent observations about curling stones that are still accurate today. Specifically, they noted that stones thrown with normal rotation (3-5 rotations release to stop) vary in curl very little if at all with rotational speed. Only stones thrown with much less rotation (they curl more) or much more rotation (they curl less) will vary significantly in curl. Macaulay and Smith also realized that any friction theory to account for curl would have to be accounted for by a difference in friction between the *front* and *rear* of the stone and not between the left and right sides. Only thus can a sideward force be generated. (Now you wish hadn’t slept through vectors in physics, eh?) When they calculated the maximum possible sideward force that could be generated by a stone rotating 5 times from release to stop, they calculated an approximate curl of slightly less than 2 feet, much smaller than that observed for real curling stones. And that is assuming that all the rotational energy was channeled into differential friction, which is clearly not going to happen. Even worse, this model predicts that curl will increase with increasing rotation, which is contrary to the observed behavior of curling stones. Macaulay and Smith described their calculation as a “disconcerting result.” They considered the possibility that there was a significant change in friction between ice and stone with pressure—a possibility if the stone “tips” slightly as it slows down, much like a car tips forward when you brake, but in fact they could measure no difference in friction between ice and stone with pressure. The authors concluded that "we have failed to take account of some important feature of the motion" [of curling stones].

Differential Friction Models

Another serious attempt to explain the motion of curling stones came from Mark Shegelski at the University of Northern British Columbia. In his 1996 paper (M.A. Shegelski *et al*., *Can. J. Phys* **1996**, *74*, 663), even he acknowledges that "there is no simple explanation that accounts…for the motion of the curling rock." Of course, being an academic, he does go on with a theory for exactly that. The "Shegelski model" evolved a bit over time, but the fundamental mechanism is that somehow the front half of the rock experiences less friction on the ice that the back half of the rock. This left-right difference in friction, as originally proposed by Macaulay and Smith, produces a sideward force that can at least qualitatively account for the proper direction of curl. Shegelski *et al.* propose that the differential friction is due to the "melting" of ice underneath the front of the stone as it plows down the ice: they hypothesize that a thin film of water forms under the leading half of the stone, reducing friction. As this liquid film rotates around the running band to the rear of the stone, it cools and freezes increasing friction at the rear of the stone. Voila! Curl! Using this model, Shegelski *et al.* make some rather impressive-looking mathematical calculations to estimate how much sideward force can be developed, and estimate the amount of total curl for a stone thrown to tee line. Remarkably, this model predicts an amount of curl that closely matches that of the much simpler calculations of Macaulay and Smith: about 1 ½ feet. This model suffers from a lack of any experimental evidence that liquid water actually forms under any part of the stone during its travel down the ice, and of course does not quantitatively account for the actual amount of curl of curling stones, which can be 3 feet or more.

Norikazu Maeno (*Sports Eng.* **2013**, DOI 10.1007/s12283-013-0129-8) proposed a hypothesis similar to that to Shegelski *et al*., but invokes instead an ice-evaporation model to account for the difference in friction between the front and back halves of the running band of the stone. In this model, the front of the curling stone is hypothesized to melt the ice as it passes over pebbles on the ice. The thin layer of water formed is then thought to evaporate in 10-100 milliseconds, cooling the pebble so that it becomes more slippery. While this model can predict a quantity of curl that matches that of real curling stones, it does so only at high rates of stone rotation. In addition, it also predicts that curl will increase with rotation speed, and nearly all curlers know that "spinners" if anything, run straighter than a normally thrown stone. And of course there is no experimental data that shows that the ice changes temperature dramatically during the passage of a stone over it.

Also in this camp is a Russian study (A. P. Ivanov & N. D. Shuvalov, *Reg. Chaotic Dynam.* **2013**, *17*, 97) that thoroughly investigated through a series of calculations what conditions were required to make a stone curl. Not surprisingly, they discovered that some sort of differential friction was required between the front and rear of the stone. Again, they propose that the origin of the friction differential must arise form a film of liquid water that forms at the leading edge of the stone.

Ice-Scratching Model

Nyberg et al. (*Tribol. Lett.* **2013**, *50*, 379) did a thorough quantitative analysis of all models of front-rear asymmetric friction models and found that none were satisfactory to account for the motions of curling stones. The most problematic feature of all these models is a strong dependence of curl on the rotational velocity of the stone, which is counter to experience. In addition, the amount of curl predicted by these models generally falls short of that of real curling stones.

These deficiencies prompted the Nyberg group to propose a completely novel, and rather simple model for why stones curl. In their most recent paper (Nyberg *et al*., *Wear* **2013**, *301*, 583) it is proposed that stones curl because they *scratch the ice*. This model has some satisfying features. For one thing, it accounts for why "textured" stones curl more than smooth and polished ones. In this model, the microscopic irregularities in the roughened surface of the running band scribes scratches on the surface of the ice, more specifically, the tops of the pebbles. As a stone rotates slowly during delivery, these scratches will track in a curved direction. For example, a microscopic bump on a stone thrown with a clockwise rotation will scribe an arc that gently bends to the right as the bump advances from the rear of the stone to the front of the stone. The scratch will effectively end when the bump starts retreating and then a second arc will be traced out when it rotates around again. The key event occurs when the microscopic projections of the running band interact with the curved scratches when they come around to the rear half of the stone. Because of the curvature of the scratch that has been laid down, the irregularities of the stone will directly cross these scratches at a nearly right angle, creating significant resistance, much like rubbing your fingers across, rather than along the wales of corduroy. The increased friction when crossing these scratches produces the sideward motion required for curl.

Nyberg *et al.* were able to verify many aspects of their hypothesis. Using a surface-conforming resin (kind of an advanced form of silly putty) they were able to take impressions of the ice and precisely visualize the topography of the surface using scanning electron microscopy. Freshly prepared and nipped ice reveals little round, mounded pebbles with smooth, flat tops created by the nipper blade. Pebbles which rocks have passed over show numerous scratches, maybe several dozen per pebble, that are about 10 micrometers (0.004") deep. The depth of these scratches match the average roughness of the running band of a curling stone. In addition, some pebbles were observed to be fractured on their edges. The sideward force of the roughened stone "bumps" as they cross the scratches can be calculated, and the number of scratches observed in the ice, multiplied by the number of pebbles that a stone interacts with when it sits on a typically prepared ice surface, is sufficient to predict the amount of curl observed for real stones, about 3 ½ feet. Essentially, the stones are attempting to "follow" the scratches. This model predicts very little variation in curl for stones thrown with moderate amounts of rotation. To test their hypothesis, Nyberg *et al.* carefully manipulated both stones and the ice surface. In one experiment ice was "pre-scratched" with emery paper and stones thrown over the ice without rotation. Stones thrown in this fashion deviated in the direction of the scratches. If a "zigzag" pattern was scratched into the ice, the stones (thrown without rotation) veered back and forth, again following the scratches. When stones were repeatedly thrown over the pre-scratched ice, the effect grew weaker as scratches were worn away by the travel of the stone. Stones whose running bands were polished smooth did not follow pre-scratched ice and ran straight.

The "scratch-guiding" mechanism for curling stones, if correct, has significant implications for both play and for ice-making. Good curling ice has to be soft enough to be scratched, but not so soft that pebbles fracture and disintegrate during play. Rocks need to have sufficient roughness to create approximately 10 micrometer deep scratches in the ice. Finally, sweeping, which reduces the effect of curl, achieves its effect by polishing out scratches left in the ice by stones. To achieve the best results, curling brushes should be designed to efficiently remove these microscopic scratches.

So there you have it. Believe it or not!

Good curling! Have a question for Instructor's Corner?
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