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**The author declares no competing interests.**

**Mathematics**

# Shaped to roll along a programmed path

### Elisabetta Matsumoto & Henry Segerman

An algorithm has been developed for constructing a 3D shape that follows an infinitely repeating path as it rolls under gravity. The approach could have applications in quantum computing and medical imaging. **See p.310**

A single wheel follows a straight line as it rolls downhill, but can change direction by rotating about its contact point with the ground. Two wheels connected by an axle have much less freedom — with no common point about which to rotate, they are forced to move along parallel straight lines forever. Trains use an ingenious method to solve this problem: their wheels are conical, so the wheel on the outside edge of a turn can keep up with the other wheel by riding the train track at the wide end of the cone. The outside wheel spins at the same rate as the inside wheel, but travels farther (see go.nature.com/3jjykjc). In this way, the track's shape controls the train's path.

On page 310, Sobolev *et al.*[1] have turned this relationship around by designing an object whose path is determined by its own shape, instead of by the shape of the ground. The authors term these objects trajectoids, and then 3D print trajectoids to show that the objects follow a pre-programmed periodic path down a gently sloping plane. In some cases, the paths of these objects match the desired trajectories even when they are made to roll briefly uphill.

To understand how such a shape could be created, imagine rolling a clay ball along a path that has been drawn on a tabletop, flattening a version of the path into the clay (Fig. 1). The shape of the ball now encodes both the trajectory across the table and the way in which the ball must rotate as it moves along the drawn path. But the ball's surface area is limited, so the shape can program tabletop trajectories only up to a certain length. Beyond this point, the ball would stop following the desired path, unless the path on the tabletop repeats itself, as in the case of Sobolev and colleagues' periodic paths.

Trajectoid-like objects have been reported previously, but not with this level of generality — existing attempts have looked at objects that roll along relatively simple repeating paths. One example is the sphericon, a shape that follows a wiggling trajectory, which is encoded in a spherical path that looks similar to the seam of a baseball[2]. Another example was devised by one of us in response to a question a circus performer asked us at a juggling convention: his giant sphericon-like apparatus could zigzag acrobats across a stage, but they would have to stop and go backwards at the edge of the stage[3]. The modified design that enabled the apparatus to turn in a circle is perhaps the previous effort that came closest to Sobolev and colleagues' trajectoids.

Spheres have a peculiar property that makes closing the path of a trajectoid difficult. Imagine that the ball of clay on the table is a globe. The north pole points upwards; Asia is to the left and the Americas to the right. Now imagine rolling it around on the table along any path until the north pole points upwards again. You'll almost certainly find that a different part of Earth faces you. But if a path on this globe is to trace out a repeating path on the table, it must have a special condition: not only does it need to return the north pole to the top, it also needs to align the continents with their initial positions.

Sobolev *et al.* took this idea and devised an algorithm for creating a shape that follows the

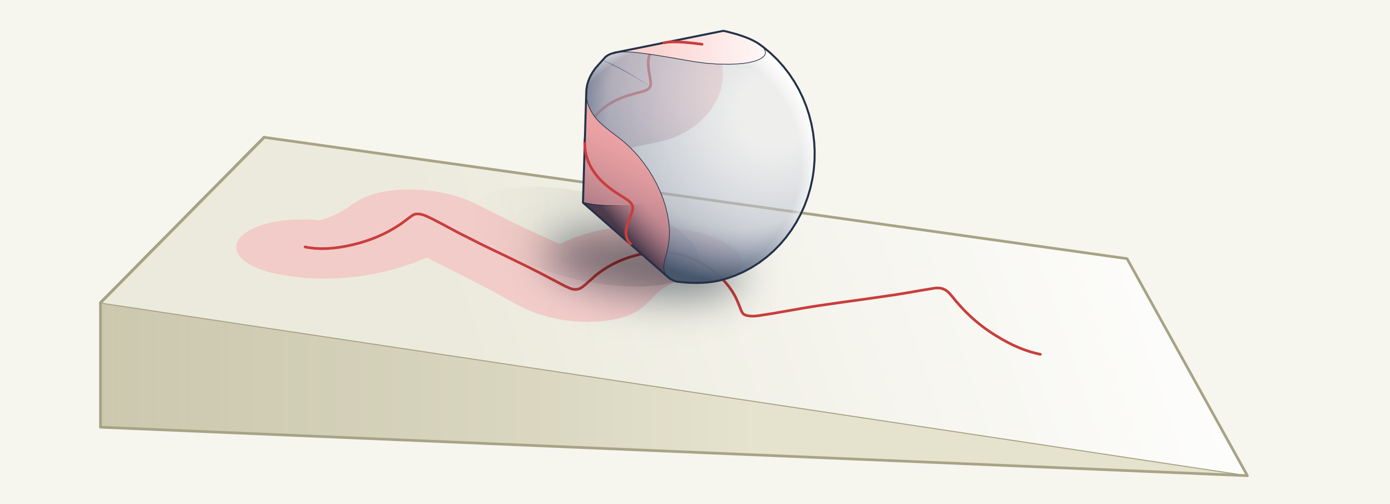

**Figure 1 | How to roll on a periodic path.** Sobolev *et al.*[1] devised an algorithm for constructing 3D shapes (called trajectoids) that follow periodic paths simply by rolling down a slope. The authors' approach can be understood by analogy with a clay ball rolling along a path on a tabletop. If the ball is flattened into the table as it rolls, its shape will encode the path, and it will follow this path when it rolls down a slope.

periodic path imprinted into the clay sphere, simply by rolling as a result of gravity. Much like the case of the globe, closing the path of one of these objects is challenging, even when its 'north pole' is returned to its initial position. However, the authors were (almost always) able to circumvent this problem by creating trajectoids that trace out not one, but two periods of a repeating path as they roll once around.

This approach is surprising, and suggests that there should be a precise mathematical statement saying exactly when a two-period trajectoid exists. The authors provide an example curve that doesn't work, but also show that tiny modifications to that curve make it work. They conjecture that paths that don't work are infinitely rare. It therefore seems likely that any designer wanting to use a trajectoid in a real-world application would not run into problems in constructing one. However, future work developing a more precise mathematical understanding of the issue would help to connect this work to applications, as well as to open up more purely mathematical veins of research.

Even in the absence of a rigorous proof, it seems clear that Sobolev and colleagues' algorithm will find applications in robotics. Sphericon-shaped microrobots that follow simple curving trajectories have already been shown to be stable, and able to move on arbitrary surfaces[4,5]. Deformable robots[6,7] could implement trajectoid geometries to navigate complex landscapes and obstacles.

Beyond robotics, this research has promising applications in fields as far-ranging as quantum computing and medical imaging. In physics, many systems are represented by a point on a sphere. For example, the intrinsic angular momentum (or spin) of an electron can point in any direction, so the curved 'tabletop' trajectory of a trajectoid could represent the orientation of a spin as a function of time[8]. In quantum computing, this representation could be used to control the evolution of a quantum bit[9] — the basic unit of quantum information, which can be encoded in spin.

Similar techniques could be used to help mitigate the effects of unwanted signals in magnetic resonance imaging machines. Trajectoids that have been engineered to control the spin dynamics — and therefore the magnetic fields — in these devices could be used to help separate useful signals from noise[10]. Whether or not these applications materialize, Sobolev and colleagues' algorithm offers an insightful answer to the problem of how to encode an object's trajectory using its shape alone.

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**The authors declare no competing interests.**

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Microbiology

# Harnessing a gut bacterial team for human health

**Yolanda Sanz**

Understanding how our gut bacteria combine forces to co-exist and produce beneficial molecules will be crucial for developing next-generation probiotics. Key progress towards achieving this goal has been made. **See p.381**

The microbial communities in the human gut function as a bioreactor that breaks down nutrients (mainly complex indigestible carbohydrates) and liberates bioactive substances to drive microbe–host interactions and shape host health and disease. Bacteria inhabiting the gut also interact to increase their ability to survive as a team. Disentangling this complex, symbiotic relationship should provide opportunities to promote health. On page 381, Khan *et al.*[1] report efforts to harness a beneficial partnership between species of gut bacteria.

The re-establishment of depleted bacterial species is, theoretically, a straightforward approach to rescuing a perturbed gut ecosystem that has been affected by disease, antibiotics or poor diets that endanger health[2,3]. However, this approach brings specific challenges in terms of growing bacteria for transfer to humans, because most gut-dwelling bacteria live in the absence of oxygen (that is, they are strict anaerobes) and, therefore, require special conditions to grow in the aerobic, *in vitro* world. Also, one species might require others to provide the nutrients for their subsistence inside the gut and for optimal effectiveness in the human host.

> **"Researchers need to learn how to better cultivate and preserve bacteria outside the gut."**

To harness the interactions between collaborating bacteria in the human gut, Khan and colleagues co-isolated strains of two bacterial species that interact through a cross-feeding mechanism involving the exchange of nutrients (Fig. 1a). Specifically, the authors isolated an anaerobic bacterial strain of *Desulfovibrio piger*, together with an anaerobic strain of *Faecalibacterium prausnitzii*, one of the first bacterial species (of a type normally resident in the gut and thus called a commensal species) reported to be depleted in people with Crohn's disease and proposed to act as a driver of health[4].

The two species have complementary nutritional requirements that make them indispensable partners. *Faecalibacterium prausnitzii* consumes the molecule glucose to produce lactate that, in turn, is used by *D. piger* to produce acetate, which is ultimately used by *F. prausnitzii* to produce butyrate. The authors found that *D. piger* enhances carbohydrate fermentation, which is the main metabolic pathway used to obtain energy for many commensal gut bacteria, such as *F. prausnitzii*, by consuming end products such as lactate.

By comparing the metabolite molecules produced in co-culture and monoculture of *F. prausnitzii*, the authors found that the presence of *D. piger* promoted butyrate production by *F. prausnitzii*, enhancing its fermentative capacity. This type of metabolic cooperation is similar to the arrangement that exists for other specialized commensal species such as *Bacteroides uniformis*, which degrades complex carbohydrates and provides substrates for butyrate-producing species such as *Eubacterium rectale*[5]. Such cooperation contributes to the resilience of the gut ecosystem through nutrient exchange[5] and control of the substrates available, which prevents