The geometry of Nature's stingers is universal due to stochastic mechanical wear

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A brief stroll through the museum halls suffices to discern the prevalence of polearms in the history of human weaponry. A shorter walk in a garden is perhaps adequate to notice that the case is no different in Nature. Stingers – pointed appendages – are widespread in organisms across different branches of the tree of life, from tiny zooplankton to the familiar bee to the mighty narwhal. Often cited as an example of convergent evolution, biological stingers are believed to have evolved independently across species - a simple yet efficient defence strategy. Remarkably, the commonalities do not end there. At first glance, most stinger tips may appear to be a regular cone. But zoom in and take a closer look - you'd see a rounded tip. Not a sharp "spinose" tip that we may intuitively attribute to a weapon. In a 2024 study, Quan et al. (PNAS)[1] reported that regardless of organismic size or the material the stingers are made of, the rounded tip follows the expression $z \sim radius^n$ with $n \approx 2$. This means that if one looked at the outline of the stinger tip, it would the humble parabola! But why is this so? They argued that the paraboloid tip shape results from evolutionary pressures selecting the optimal shape suited for piercing into soft tissues, without buckling or bending instantly before any damage can be made. However, they also showed through experiments that tip shapes with n lying between 2 and 6 are equally suitable shapes where piercing outcompetes buckling. Then, of all suitable shapes, why do biological stingers universally possess the parabolic profile or $n \approx 2$? If evolutionary selection is at play, are stingers 'born' with this shape?

Coming from fluid mechanics, this was not the first time we encountered parabolic tip shapes in the literature. For example, the tip of icicles which are shaped by the physics of melting[2], the apex of a cylinder of sugar melting in a tank of water shaped by flow driven by dissolution[3], are both paraboloid. What if the stingers are also shaped by some erosive mechanism, where material is removed rather than added? To verify this notion, we decided to look for newly formed stingers. Unsurprisingly perhaps, finding well preserved stingers that have never been used turned out to be quite the ordeal. Fortunately, around the same time Ryderheim et al. (PNAS 2024)[4] published images of the microscopic mandibles of larval copepods – of pristine, unused marine 'teeth' and those of used mandibles later in their lifetime. These newly minted stinger tips were sharp "spinose" cones, whereas the used stingers were reminiscent of the universal parabolic geometry. This observation affirmed our hypothesis that the universality of stinger shapes stem not from a biological driver, rather, it is simply geometry and mechanics at play.

To validate our idea, we used pencil tips as stand-ins for their biological counterparts, simulating mechanical interactions by placing them on a vibrating plate, allowing them to collide with one another stochastically. After tracking the change in their geometries for about four and a half hours, we found that pencils of different grades (that is, with different material properties) and of different initial shapes (the tip does not have to be well-sharpened, or could even be broken) all morphed over a few hours of collisional activity. In addition to control experiments in the lab, we were amused enough to put sharpened pencils in a little box and carry it around in our pockets as we'd walk around for several days! The pencils would audibly rattle around, and took merely 20k steps to start conforming to the expression for the universal paraboloid.

The relation between form and function has long inspired scientists from various disciplines. And it is quite compelling to take a functional view of surprising commonalities in Nature. However, the formation or development of shapes in biology is both driven by and limited by underlying physical principles rather than an end-use function. The emergence of a universal geometry as an inevitable mechanical consequence of use, which coincidentally takes the guise of an optimized shape, offers a cautionary tale in biomimetics and suggests that temporal stochastic processes may play a more fundamental role in shaping form in Nature than adaptive narratives alone would imply.

References

(1) Quan, H.; Liang, X.; Zhang, X.; Meyers, M. A.; McMeeking, R. M.; Arzt, E. *Proceedings of the National Academy of Sciences* **2024**, *121*, e2316320121.

(2) Huang, J. M.; Moore, M. N. J.; Ristroph, L. *Journal of Fluid Mechanics* **2015**, *765*, R3.

(3) Nakouzi, E.; Goldstein, R. E.; Steinbock, O. *Langmuir* **2015**, *31*, 4145–4150.

(4) Ryderheim, F.; Olesen, J.; Kiørboe, T. *Proceedings of the National Academy of Sciences* **2024**, *121*, e2407876121.