How Paramecium protozoa claw their way to the top

September 19 2014

How some organisms are able to find upwards for their survival – as shown here symbolically from below – was until now a mystery. An international research team now found out, that simply their asymmetrical shape could enable them to swim upwards in a stable fashion. Credit: Roland Wengenmayr

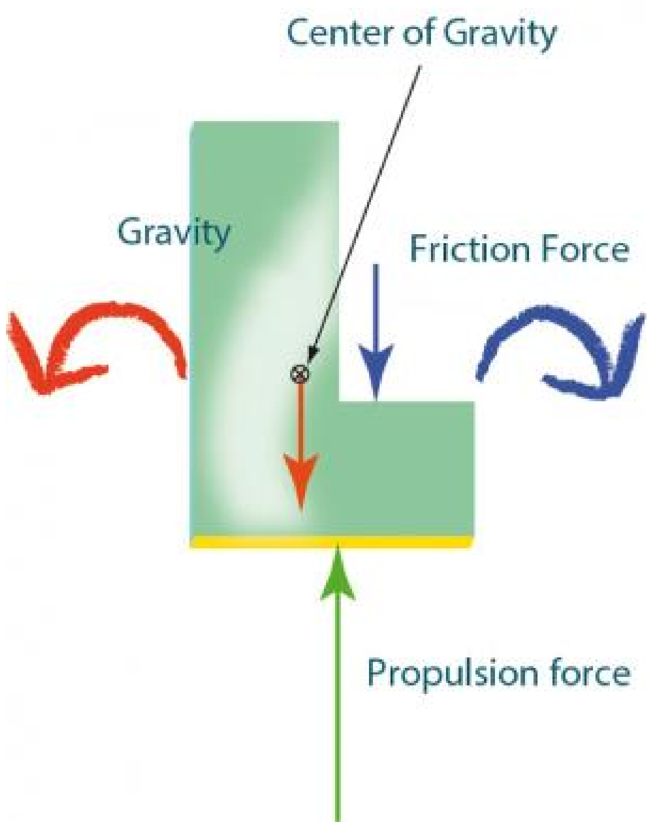
The ability to swim upwards – towards the sun and food supplies – is vital for many aquatic microorganisms. Exactly how they are able to differentiate between above and below in often murky waters is still not understood today. An extremely simple trick of physics involving the self-organised balancing of two forces could offer a reliable and effective explanation of this phenomenon. This has been demonstrated by an international research team headed by Clemens Bechinger from the Max Planck Institute for Intelligent Systems and the University of Stuttgart. Their discovery not only provides a plausible and elegant explanation for this natural behaviour called Gravitaxis, it could also be used to enable the self-organised steering of swimming microrobot swarms in the future.

Life is hard for small organisms - at least when it comes to swimming. Stuttgart-based physicist and Max Planck Fellow Clemens Bechinger recalls swimming in a quarry pond in summer: "If you perform a strong breaststroke and then place your arms by your side," says the Professor, "you will move a few metres forward in the water." Our relatively massive body is only slightly decelerated by the water, which we experience as a fluid medium. For microorganisms, however, water is viscous, like honey. In addition to developing an adapted swimming technique, many microswimmers must overcome a second challenge in their – often murky – aquatic environment: they must be able to make their way safely to the surface of the water. Precisely how they succeed in doing this is being researched by Bechinger as part of an international cooperative project.

The ability to move in the right direction is a matter of survival for many aquatic organisms. Deeper zones can be fatal due to the lack of oxygen – and the journey to the surface promises food and light for photosynthesis, for example. Unlike fish with a swim bladder, smaller swimmers are often heavier than water and thus risk sinking to the bottom. Avoiding this "sedimentation" is as important for many bacteria as it is for larger single-celled organisms, e.g. microalgae or, familiar to many from biology lessons, paramecia. The technical term for this behaviour is "negative gravitaxis", which can be described as directed movement against gravity. The question remains, however, as to how these microscopic swimmers find their way upwards. Bechinger explains that some scientists speculate about the existence of receptors that direct the minute swimmers to the surface based on the reduction in the water pressure. However, the change in the water pressure along the microscopic body length of such organisms is minimal. Therefore, the question as to whether such a relatively complex mechanism actually exists remains open.

The asymmetric pear shape brought about an upward orientation

Purely physical solutions are far simpler and more elegant. This kind of solution is used by the unicellular green algae of the Chlamydomonas genus, for example. One part of these organisms is slightly heavier than the rest so that this end always points downwards, thereby ensuring their stable positioning – similar to a buoy. If a flagellum is attached to this end of the organism, it automatically propels it upwards.



Balance of forces: Because the centre of gravity of the L-shaped swimming body is shifted to the massive long arm on the left, gravity tends to rotate it in this direction (red). However, this anti-clockwise rotation counteracts the friction force of the water when the propulsion mechanism (green) is activated: the latter aims to rotate the swimming body in a clockwise direction (blue). At a suitable swimming speed, the two torques rise upwards and the microswimmer is propelled upward in a stable fashion. Credit: Roland Wengenmayr

However, there are a large number of microswimmers in which the existence of this kind of buoy effect can be excluded; they nevertheless do not have any problem swimming in an upward direction. The physicists involved in the cooperative project believe that the body shape of these organisms plays a crucial role in this process. Paramecia, for example, look like elongated pears. The scientists suspected that this asymmetrical shape could ensure a stable upward orientation.

In order to be able to study this phenomenon in detail, the researchers developed an experiment using L-shaped model bodies made of a synthetic material that is heavier than water. Compared with living organisms, this model had the advantage that the scientists could control the shape and weight of the body down to the last detail. The L-shape they used had one six-micrometre-long (millionths of a metre) arm and a second nine-micrometre-long one. The researchers chose this shape, as it provides maximum asymmetry in two dimensions – that is on the flat. They produced their swimmers using a process similar to that used by the semi-conductor industry to produce microchips.

Gravity and friction act on L-shaped micro-swimmers against each other

The scientists in Stuttgart developed an ingenious solution for the propulsion mechanism. They coated the front side of the short arm with a layer of gold, which was so thin that it only increased the weight of this end of the swimmer negligibly. In this way, they excluded the possibility of the buoy effect. The physicists then focused a laser beam at a certain wavelength on the layer of gold. The liquid there warmed up and generated a propulsive force at the lower end of the L.

The experiments in fact showed that the L-shape ensures stable swimming in an upward direction. Despite the complexity of the researchers' model, it provides an easily understood explanation of the microswimmers' behaviour. As soon as the researchers "activated" the propulsion mechanism, its force took effect from below the middle of the short L arm.

ten Hagen, a doctoral student who, together with his supervisor, Professor Hartmut Löwen, carried out the computer simulation at the University of Düsseldorf explains how this works: "This causes the L to rotate in the direction of the long arm." The reason for this is that gravity wants to tip the L, which is balanced delicately by the propulsion force like a pencil tip, to the heavy side. However, the movement resulting from this anti-clockwise rotation counteracts a second force, the friction force of the water flowing from above. This force would like to turn the L in a clockwise direction, as its shorter lower arm acts like a brake standing upright in the current. "It would be like a moving rowing boat with a left-hand twist," says Bechinger, "which I counteract by submerging the right oar."

A self-organising control system for microrobots

If the ascent velocity is right, the two counteracting "torques" rise straight up and the L-shape swims stably upwards counter to gravity. In addition, as the researchers discovered, the range of velocities, within which this effect functions, is relatively extensive. "So the effect is robust," says Bechinger. The movement only becomes unstable above a certain critical velocity and the swimmers tumble down along a spiral trajectory. The theoretical calculations, on which a physicist from the University of Edinburgh and a flow mathematician from Honolulu collaborated with the two physicists from the University of Düsseldorf, tally fully with the experiments.

Above all, the effect is universal because it is purely physical. It applies to all microswimmers whose body shapes deviate from a spherical form. "The asymmetry ensures the upward movement," emphasises Felix Kümmel, a doctoral student in Stuttgart who is working on the project: "Scientists had already speculated about such a mechanism, but our experiments alone show that it actually works." This self-organising effect is of interest to the researchers for other reasons, as it could be adopted as a simple way of controlling the movement of microrobot swarms. Such systems are currently undergoing intensive tests. They may be used one day for the targeted delivery of drugs in the body and the purification of bodies of water, for example.

More information: Borge ten Hagen, Felix Kümmel, Raphael Wittkowski, Daisuke Takagi, Hartmut Löwen und Clemens Bechinger. "Gravitaxis of asymmetric self-propelled colloidal particles" *Nature Communications*, 19. September 2014; [DOI: 10.1038/ncomms5829](https://dx.doi.org/10.1038/ncomms5829)

Provided by Max Planck Society