Silica microspheres in liquid crystals offer the possibility of creating every knot conceivable

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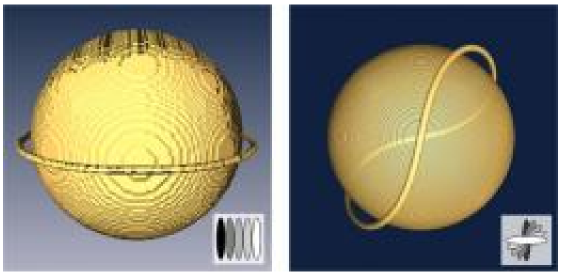


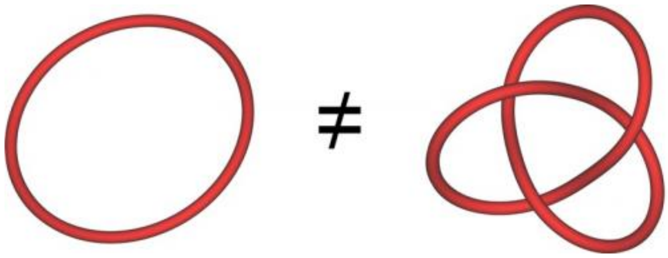
Connection points for knots: Left: In a homogeneously aligned nematic liquid crystal, the defect line surrounds the microsphere like a Saturn’s ring. Right: In a so-called chiral nematic crystal the ring is buckled like the twisted wheel of a bicycle. © Miha Ravnik

Knots can now be tied systematically in the microscopic world. A team of scientists led by Uros Tkalec from the Jozef Stefan Institute in Ljubljana (Slovenia), who has been working at the Max Planck Institute for Dynamics and Self-Organization in Gottingen (Germany) since September 2010, has now found a way to create every imaginable knot inside a liquid crystal. Starting points of the new method are tiny silica microspheres confined in thin liquid crystal layers. Surrounding these microspheres, a net of fine lines is formed where the molecular orientation of the liquid crystal is altered. The researchers discovered a method to twist and link these lines in such a manner as to create every knot imaginable.

Knots are ubiquitous: We encounter them in woven materials, in the numerous sailors' knots, and in constantly entangled electric cables and extension cords. When putting on their shoes, even small children learn to master their first knots - long before they can read and write. Even our DNA can be complicatedly knotted. From a mathematical point of view, knots that seem completely different at first sight can belong to the same class. The essential criterion is that one knot can be transformed into another by means of simple deformations. The most simple example is a rubber band. Topologically speaking, every shape you can create from it without cutting open the loop and joining it back together is equivalent to the initial rubber band. A completely different knot, for example, is the trefoil knot (see figure 1). This knot cannot easily be tied from an intact rubber band. Furthermore, several interlocked loops can constitute even more complex structures.

Despite this tidy mathematical system organizing the general jumble of knots, one question remains: Can every conceivable knot be implemented in a microscopic, physical system? In his most recent study Uroš Tkalec found such a system, in which complex knots can be created systematically: silica microspheres within an only slightly thicker nematic liquid crystal film confined between two glass plates. Such liquid crystals also pose the basis of common LCD displays.

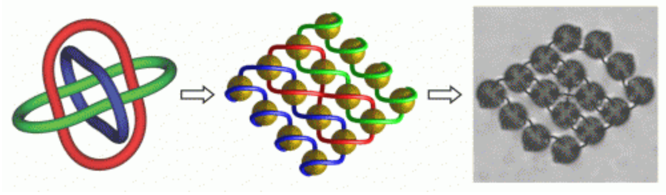
"The glass plates were treated in such a manner as to force the liquid crystalline molecules to align parallel to the surface", explains Tkalec. A single silica microsphere entering the layer changes the surrounding alignment substantially: around the sphere a ring-shaped region forms in which no preferred direction can be discerned. Scientists refer to such disruptions in the molecular order as defect lines. Since the defect ring surrounding a microsphere reflects light differently than the rest of the liquid crystal, it can be easily detected. "It looks as if every microsphere were surrounded by its own ring - similar to the planet Saturn", explains Tkalec (see figure 2, left). These Saturn's rings are oriented perpendicularly to the average orientation of molecules between the glass plates. If several microspheres are confined to such thin nematic layers, they can be moved together and arranged in lines by using a laser, much like using a pair of tweezers. The rings then join to form more complex, entangled lines surrounding the aligned spheres.



A simple loop cannot easily be transformed into a trefoil knot. It would be necessary to cut it open and then paste it back to together. © Max Planck Institute for Dynamics and Self-Organization

"However, in such rows of spheres no knots can be assembled", says Tkalec. Creating knots requires the defect rings of neighbouring microspheres to be able to attach to each other in two directions. In order to achieve this, the scientists used a "trick": if the upper plate confining the liquid crystal layer is turned by 90 degrees, the alignment of the molecules is changed. While the lower molecules still point in the same direction as before, the upper ones are also rotated by 90 degrees. In between, the transition is gradual. Scientists refer to this as a twisted or chiral nematic liquid crystal. "In this experimental set-up, the defect rings surrounding the spheres are slightly buckled - like a buckled wheel of a bicycle", says Tkalec (see figure 2, right). The rings of neighbouring spheres can therefore cross and link: a crucial requirement for creating knots.

In an essential step, the researchers discovered a way of manipulating the regions between the spheres by joining and separating neighbouring rings. First, they heated the region between the spheres with a laser. This destroys the characteristic alignment of the molecules. After switching off the laser, the alignment is re-established - but often in a different way than before. Thus, it is possible to join rings that bypassed each other before or reconnect rings in a different way.



For every knot (left) an equivalent interpretation with the help silica microspheres can be found (centre). The right image shows the real experimental result. © AAAS / Science

But the researchers not only proved sleight of hand in the experimental handling of microspheres and lasers. In the theoretical part of their study they showed that for every conceivable knot a mathematically equivalent knot can be found which can be implemented in this way. "With the help of microspheres in a chiral nematic liquid crystal, we can create practically every knot that you can imagine", says Tkalec.

The researchers now hope that these findings will help to better understand the complex knotting of DNA. "The knotting of DNA molecules, for example, plays an important role in many vital processes such as replication or transcription of DNA", says Uroš Tkalec. In addition, the strategy may boost the assembly of reconfigurable optical circuits in soft materials which would guide a light in future photonic applications.

More information: Uroš Tkalec, Miha Ravnik, Simon ?opar, Slobodan Žumer und Igor Muševi?, Reconfigurable Knots and Links in Chiral Nematic Colloids, *Science*, 1 July 2011.
www.sciencemag.org/content/333/6038/62.abstract

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