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Tiny Knots, Untold Possibilities

by Timothy Erick | February 2017

Knot tying is a simple, yet extremely useful skill. We use knots to tie our shoes, to put surgical stitches in place, and to keep boats from drifting away from their moorings. However, knots are not necessarily a human invention. "Molecular knots" are knot-like structures found in molecules too small to be seen with the naked eye. Some molecular knots occur naturally in biological molecules such as DNA and proteins. Yet, scientists do not fully understand how molecular knots are formed, or what purposes they might serve.

Stuart Jantzen/www.biocinematics.com

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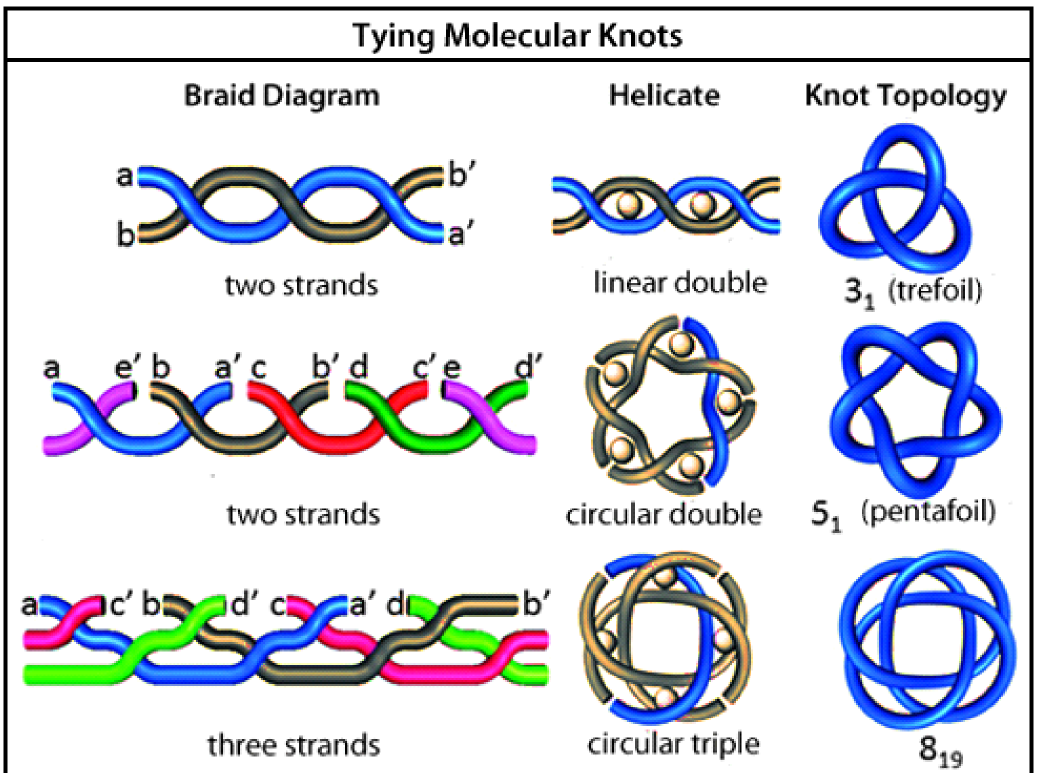
In order to learn more about these mysterious, microscopic knots, scientists have been working to recreate them in the lab. For decades, they have been able to produce only a handful of simple molecular knots, despite knowing of at least six billion possibilities. Recently, however, a group of researchers at the University of Manchester in England generated a new molecular knot that is much more complex than any of its predecessors. The researchers intend to study this knot in detail, and use it to try to produce strong, flexible, lightweight materials. Just as knots in ropes serve all sorts of purposes, molecular knots might also end up having various uses. This study was published in the journal *Science*, with David A. Leigh as the corresponding author.

Tying Up Loose Ends

In simple terms, a knot is a looped structure in a string that will not become untangled by tugging the free ends in opposite directions. In order to untie a knot in a rope, for instance, you have to pull one of the ends of the rope through the knot itself. DNA, proteins and other biological molecules consist of long chains of atoms called polymers, which resemble molecular strings. Polymers can become entwined into structures called molecular knots, which are not exactly like knots tied in ropes. Molecular knots require at least two polymer strands, so they resemble a braid more than a typical knot. Also, the polymer ends fuse after a molecular knot is formed, creating a closed loop. Thus, molecular knots cannot be untangled without breaking the polymer strands.



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Molecular knots are relatively common in DNA, and are also found in roughly 1% of all known proteins. Only recently have scientists begun to understand the functions that molecular knots serve in biological molecules. For instance, molecular knots in a protein can help to stabilize its overall structure, or improve its biological activity. In an effort to further understand the formation and purpose of natural molecular knots, researchers have been trying to generate synthetic molecular knots in the lab. Unfortunately, this is much more difficult than tying a knot in a rope. The polymers that make up DNA and proteins are too small to be seen with all but the most powerful microscopes. Thus, researchers cannot simply grab the ends of polymer strands and braid them together. Instead, they need to create the right conditions for the polymer strands to braid themselves into knots, sort of like Marty McFly's self-tying shoes from "Back to the Future II."

Slow Progress

Scientists have been working on producing synthetic molecular knots for decades. In 1989, a group of researchers led by Nobel Prize winner Jean-Pierre Sauvage created the first synthetic molecular knot. They made a knot called a trefoil, which consists of two polymer strands intertwined at three cross points. The ends of these strands are then joined together, creating a knot that cannot be unraveled without breaking the strands. In the years since, researchers have built upon Sauvage's techniques to synthesize other molecular knots of increasing complexity. In addition to furthering our knowledge about how molecular knots are formed, some of these knots have had unexpected uses. For instance, a synthetic knot with five cross points was recently found to act as a catalyst (catalysts are substances that improve the rate of specific chemical reactions).

University of Manchester

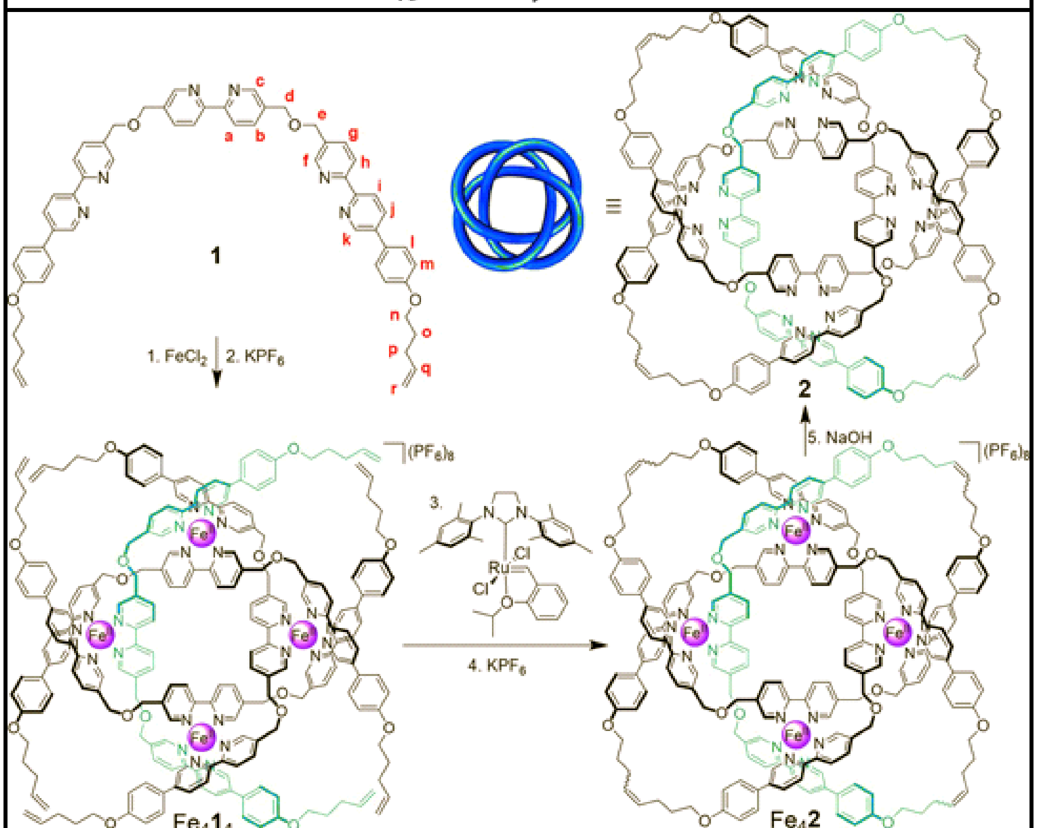
David Leigh (above) and his colleagues set out to synthesize a molecular knot with three polymer strands. Their goal was to generate a specific molecular knot called the "8_{19}" knot, with 8 indicating the total number of cross points, and 19 specifying it as the 19th of a group of 21 possible knots with eight crossings.

Up until recently, all of the molecular knots generated in the lab have incorporated only two polymer strands. This has frustrated scientists, since they are aware of at least six billion possible molecular knots, most of which require more than two polymer strands. Spurred on by the desire to delve into new territory, a team of scientists led by Leigh recently set out to synthesize a molecular knot with three polymer strands. Their goal was to generate a specific molecular knot called the "8_{19}" knot, with 8 indicating the total number of cross points, and 19 specifying it as the 19th of a group of 21 possible knots with eight crossings.

Some Assembly Required

Synthesizing the 8_{19} knot required the researchers to perform some very precise chemistry. They started with polymer strands made up of carbon, hydrogen, nitrogen and oxygen. The polymer strands were combined with iron and chlorine ions in a particular solvent (a liquid meant to foster chemical interactions). This mixture was heated to 130 degrees centigrade (about 266 degrees Fahrenheit) for 24 hours, which caused the iron ions to bind to the polymer strands in particular locations. Specifically, four iron ions each bound to three polymer strands near their intended cross points. This had the effect of holding the strands together so that the knot could form. The researchers then changed the reaction conditions in a stepwise manner, adding in a new catalyst, modulating the temperature, or changing the solvent as needed. Each of these changes helped the polymer strands to braid around the metal ions and get closer to forming the 8_{19} knot. Some of the steps took 24 hours or more, so the researchers had to be patient.

8_{19} Knot Synthesis



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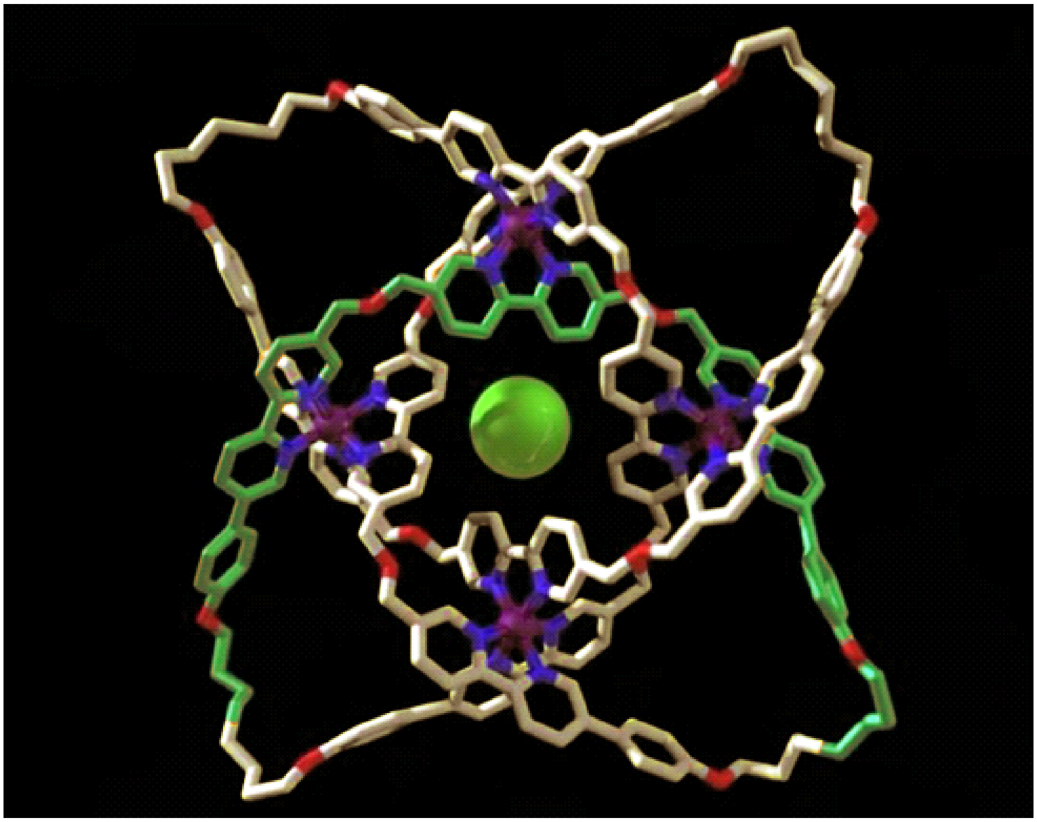
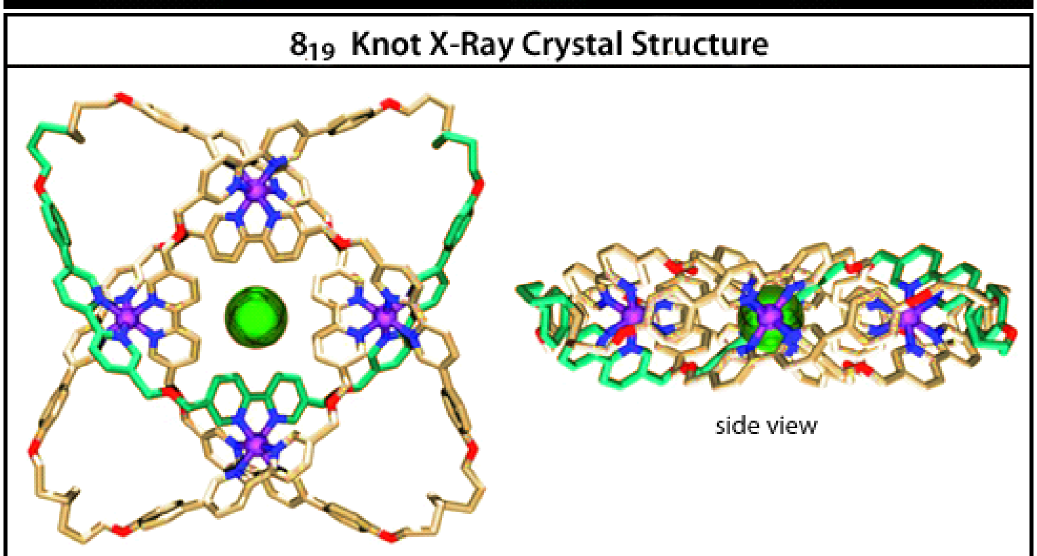
After completing this painstaking process, the researchers' patience was rewarded: they had finally synthesized a complete 8_{19} knot. The knot included one chlorine ion in the center, and four iron ions at the polymer cross points. A final, 30-minute chemical reaction removed these metal ions, resulting in a pure 8_{19} knot consisting of only the three polymer strands.





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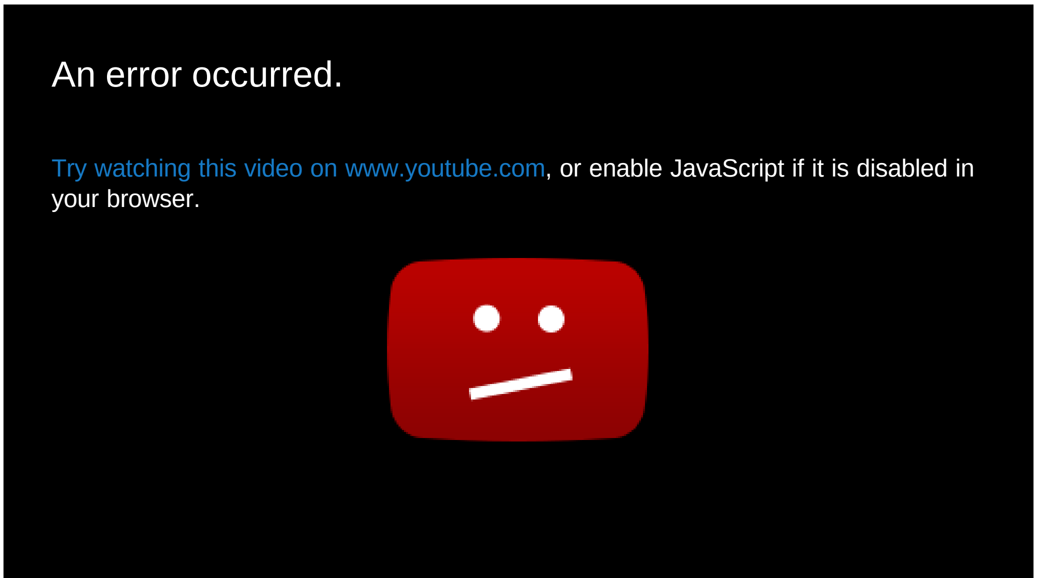
The final 8_{19} knot included one chlorine ion in the center, and four iron ions at the polymer cross points. A final, 30-minute chemical reaction removed these metal ions, resulting in a pure 8_{19} knot consisting of only the three polymer strands.

The final knot was only 192 atoms long, which is hundreds of times smaller than a mammalian cell. The 8_{19} knot is also the most complicated molecular knot yet synthesized in the laboratory. The researchers are excited by the opportunity to study it in more detail, and intend to use the techniques involved in its creation to synthesize other molecular knots with three or more polymer strands.

Casting a Wide Net

In addition to figuring out their purpose in nature, scientists are discovering useful applications for molecular knots. For instance, the molecules that make up most materials are linked by chemical bonds. These bonds create rigid connections between molecules, resulting in materials that are relatively inflexible. Some researchers have been working to weave polymer strands together the way we might create a net out of rope.



University of Manchester

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In a "molecular weave," the polymers would be linked without the constraints of chemical bonds. This would leave them free to stretch and slide around, which would result in strong, yet light and flexible materials. The techniques used to produce the 8_{19} knot could help scientists to create molecular weaves, as well as other materials with useful new properties. This is new territory for chemists, and the possibilities are almost boundless.

Discussion Questions

In a molecule like DNA, how might molecular knots be beneficial? Could they also be a detriment?

What sort of uses could we find for synthetic materials that incorporate molecular weaves?

Journal Abstracts and Articles

(Researchers' own descriptions of their work, summary or full-text, on scientific journal websites.)

Danon, J.J., et al. "Braiding a molecular knot with eight crossings." *Science* (January 13, 2017) [accessed January 20, 2017]: http://science.sciencemag.org/content/355/6321/159.

Bibliography

Ayme, J.F., et al. "A synthetic molecular pentafoil knot." *Nature Chemistry* (November 6, 2011) [accessed January 21, 2017]: http://www.nature.com/nchem/journal/v4/n1/full/nchem.1193.html.

Danon, J.J., et al. "Braiding a molecular knot with eight crossings." *Science* (January 13, 2017) [accessed January 20, 2017]: http://science.sciencemag.org/content/355/6321/159.

Dietrich-Buchecker, C.O., and Sauvage, J.P. "A Synthetic Molecular Trefoil Knot." *Angewandte Chemie* (February 1989) [accessed January 21, 2017]: http://onlinelibrary.wiley.com/doi/10.1002/anie.198901891/epdf.

Forgan, R.S., Sauvage, J.P., and Stoddart, J.F. "Chemical Topology: Complex Molecular Knots, Links, and Entanglements." *Chemical Reviews* (January 24, 2011) [accessed January 21, 2017]: http://pubs.acs.org/doi/full/10.1021/cr200034u.

Gutierrez-Puebla, E. "Interlacing molecular threads." *Science* (January 22, 2016) [accessed January 28, 2017]: http://science.sciencemag.org/content/351/6271/336.full.

Lim, N.C.H., and Jackson, S.E. "Molecular knots in biology and chemistry." *Journal of Physics: Condensed Matter* (August 20, 2015) [accessed January 21, 2017]: http://iopscience.iop.org/article/10.1088/0953-8984/27/35/354101/meta.

Liu, Y., et al. "Weaving of organic threads into a crystalline covalent organic framework." *Science* (January 22, 2016) [accessed January 21, 2017]: http://science.sciencemag.org/content/351/6271/365.full.

Marcos, V., et al. "Allosteric initiation and regulation of catalysis with a molecular knot." *Science* (June 24, 2016) [accessed January 21, 2017]: http://science.sciencemag.org/content/352/6293/1555.

Sulkowska, J.I., et al. "Conservation of complex knotting and slipknotting patterns in proteins." *Proceedings of the National Academy of Sciences of the United States of America* (June 8, 2012) [accessed January 21, 2017]: http://www.pnas.org/content/109/26/E1715.full.

Taylor, W.R. "A deeply knotted protein structure and how it might fold." *Nature* (August 24, 2000) [accessed January 21, 2017]: http://www.nature.com/nature/journal/v406/n6798/full/406916a0.html.

Keywords

molecular knot, polymer, synthetic material, trefoil, catalyst, 8_{19} knot, ion, solvent, molecular weave, David A. Leigh, Jean-Pierre Sauvage

Citation Information (MLA)

Erick, Timothy. "Tiny Knots, Untold Possibilities." *Today's Science.* Infobase Learning, Feb. 2017. Web. 16 Feb. 2017. <http://tsof.infobaselearning.com/recordurl.aspx?wid=99270&ID=37262>.