3D strand of curly hair is analogue for curved thin rod

PROBLEM
The steel pipe used in oil fields, as well as most other industrial tubing, is generally coiled for transport and storage. Unfortunately, the coiling can create intrinsic natural curvature that affects mechanical behavior. In industrial tubing or any thin rod-like structure, this curvature can unpredictably anticipate or postpone undesirable mechanical instabilities when the structure is placed under a compressive load or torsion.

APPROACH
Professor Pedro Reis has been working on the development of a predictive framework for the mechanics of thin rods that would be applicable at any scale: from flagella of bacteria at the microscopic to steel pipes and fiber-optic cables at the kilometer. For straight thin rods, descriptive equations, as well as mathematical solutions to the governing equations, exist. But for naturally curved rods, most existing explicit solutions are for helices with a highly symmetrical external load.

Reis designed a lab experiment to create and study rod-like, flexible strands of vinylpolysiloxane (a silicone-based rubber) bearing different degrees of natural curvature. He noted that these strands hanging from a small beam — suspended under their own weight — were similar to strands of curly hair hanging from a head. Making use of this analogy, he contacted Basile Audoly at the Centre National de la Recherche Scientifique (CNRS), who had previously used engineering mechanics to explain the 2D shape of human hair. Audoly also had been involved in, and Reis familiar with, recent efforts in computer-generated imagery to simulate the precise physical movements of straight hair that swings to and fro. Simulation tools that mathematically represent curly hair — and the collisions of many hairs — are at their infancy, and a complete detailed model for the 3D shape of a strand of curly hair had not been created. So, together with Audoly, graduate student James Miller, and postdoctoral associate Arnaud Lazarus, Reis set out to create the first detailed model for the 3D shape of a strand of curly hair — a model that could serve as an analogue for a slender rod with natural curvature.

FINDINGS
For low values of natural curvature, the researchers describe a strand of hair as a 2D hook weighted by gravity so that the top of the strand carries more weight than the tip, which can therefore curl. As the curvature increases, the curled hook grows larger and eventually becomes unstable under its own weight. When this occurs, it falls out of plane and takes on a 3D configuration. Depending on the strand’s length and stiffness, 3D curls can be described as either a localized helix, where only a portion of the strand is curled, or a global helix, if the curliness extends the entire length up to the head. A curl can change phase — from 2D to 3D local helix, and then to 3D global helix, and back again — if its parameters change. Using lab experimentation, computer simulation and (with Audoly) mathematical theory, the MIT team identified the main parameters for curly hair and simplified them into two dimensionless parameters: curvature (relating to the ratio of curvature and length) and weight (relating to the ratio of weight and stiffness). Given curvature, length, weight and stiffness, the model will predict the shape of a hair, steel pipe or Internet cable suspended under its own weight.

IMPACT
Following a dimensionless approach to describe innate curvature, which typically has not been considered as a systematic control parameter in thin rods, means the equation remains valid over a wide range of scales. Regarding a single curly hair as a building block could be useful in the computer animation industry for generating characters with more complex and realistic hairstyles. This framework could also be used in reverse as a measuring technique to determine the natural curvature of engineering tubular systems. The work is part of a vibrant movement that is reviving structural mechanics, a discipline that was developed in the 19th century, matured in the 20th century, and is being reanimated in the 21st century as an enabling discipline in a variety of new contexts.

MORE
A paper on this work by Pedro Reis, James Miller Ph.D. ’14 (now a research associate at Schlumberger-Doll Research), Basile Audoly and Arnaud Lazarus (now at CNRS) appeared in the Feb. 14 issue of Physical Review Letters.