PHOTO: V. P. PATIL *ET AL.* (1)

PHYSICS

Following the entangled state of filaments

California blackworms serve as a template for the topological design of active matter

By **Eleni Panagiotou**

Many physical systems, from human cells to bird nests, are composed of entangled filamentous matter. The entangled state of filaments, whether through intentional tying or by natural occurrence, is particularly hard to unravel. Nature, however, has means to efficiently control the organization of material, including filaments, in contexts where it is beneficial for function and survival. For example, multiple macromolecules actively organize to drive major functions such as cell division. How do filaments entangle and disentangle, thereby controlling their function and mechanical properties, in the appropriate space and time? On page 392 of this issue, Patil *et al.* (*1*) describe their study of California blackworms, a fascinating system in which the organisms entangle and spontaneously disentangle. The authors show that single-chain locomotion at specific frequencies is at the core of collective entanglement and disentanglement. This may point to methods for controlling and engineering entanglement in many contexts.

California blackworms assemble in minutes and disentangle in milliseconds to control, for example, their temperature or to escape predators. By using ultrasound imaging, the conformations of blackworms can be visualized. The snapshots of their tangled state can be used in mathematical modeling. But what is the best way to describe such an entangled state, and how can it be quantified? Physical entanglement has been formally studied in polymer physics to describe the viscoelastic properties of polymer melts and solutions (*2*). In those contexts, entanglement is typically understood as a discrete number of local obstacles that a polymer chain meets, according to Edwards's tube model (*3*–*5*). This viewpoint, however, cannot measure the complexity of the collective entanglement as a whole. Indeed, Edwards already had pointed out both that entanglement is something more complex and the relevance of mathematical topology in this context (*6*).

In mathematics, topology and, in particular, knot theory focus on characterizing and classifying the conformations of simple closed curves in three-dimensional (3D) space (*7*). In this scenario, two knots or links are equivalent if one can be deformed into the other without cutting and pasting. However, under this notion of topological equivalence, linear filaments (seen as open curves in 3D space), whose endpoints can be different and lie anywhere, are all trivial (every open mathematical curve in 3D space can be untied without cutting and pasting). This barrier has been one of the reasons why mathematical topol-

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Understanding how California blackworms (*Lumbriculus variegatus*) form a topologically complex tangle may guide the development of tangling and untangling strategies for filaments.

ogy has not been used to study polymer entanglement more broadly, despite the success that traditional knot theory has provided to enzymology since the 1980s to study circular DNA (*8–10*). Topologists and polymer physicists have tried to measure the entanglement of linear polymers by artificially closing the linear chains to identify knot types. Such tools have led to the identification of knots in proteins (*11*). It is only recently that methods to define knotting and linking have appeared without any approximation, extending the theory of knots and links to open curves in 3D space (*12*).

Patil *et al.* used topology to capture both local and global pairwise entanglement in a system of worms—information that can serve as a characterization of the system's overall topological state. More precisely, the authors used the Gauss linking integral of linear chains—a measure of the degree that one filament turns around the other—to capture pairwise entanglement of filaments. They propose a method to bridge the local versus global pairwise linking effects by introducing the contact linking number. The latter reflects the degree of interwinding of two worms that are in physical contact. This approach quantifies topological entanglement and thus enables an assessment of the mechanical implications of entanglement on the system. By characterizing the entangled state of a system with rigorous mathematical methods, Patil *et al.* are able to model entanglement and address the question of how filaments attain such a conformation and how active matter regulates it.

It is known that entanglement varies with the stiffness and length of filaments. Theoretical results predict how the probability of knotting varies as a function of the length of mathematical curves (*13*). However, these results do not explain how an initially unentangled system will entangle or subsequently disentangle. Recent results suggest that activity and fluid-structure interactions can alter the topological state of a system (*14*, *15*). For example, molecular simulations of dense solutions of circular polymers containing (active) segments, modeled at thermal fluctuations of uneven temperature, have revealed that the interplay of the activity and the topology of polymers generates an unprecedented glassy state of matter, which bears similarities to the conformation and dynamics of a DNA fiber in the living nucleus of a higher eukaryotic cell (*14*). As another example, simulations of chromatin as a confined flexible chain acted upon by molecular motors show that coherent motions emerge and are accompanied by large-scale chain reconfigurations and nematic ordering (*15*).

Patil *et al.* propose a new way to advance these ideas by looking for answers in a real system of California blackworms. They demonstrate how experimentally obtained trajectories of the worms can be mapped on a full 3D filament model of Kirchhoff filaments (elastic rods) with heads moving at varying turning angular speed and direction. This reproduces the collective slow entangling and fast untangling behavior of the worms, as measured by the contact linking number. Moreover, Patil *et al.* could derive a mean field model for the system (based on a 2D approximation of it) as a snakelike motion around an array of obstacles. Their results predict a large space of tangling and untangling strategies. They also predict that there are stable tangle topologies that are not accessed by the worm tangles, which indicates a space of unexplored possibilities.

Through a combination of methods from topology, applied mathematics, and engineering, Patil *et al.* derive a general model of active entanglement and disentanglement that provides new insights into the organization of active matter. The generality of the model prompts the question of whether it can be applied to systems at different lengths and timescales. If so, the approach could give rise to new materials that markedly change their mechanical properties when their topology is modulated. Furthermore, one might examine whether the same model could apply to macromolecules in confined environments, such as chromatin in a cell's nucleus. One could envision new means to control DNA structure and function, opening new biotechnological interfaces related to the design of dynamic DNA topology in cells. ■

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10.1126/science.adh4055

NANOPHOTONICS

Learning photons go backward

Efficient learning algorithms are implemented in a silicon photonic neural network chip

By **Charles Roques-Carmes**

Since the invention of the laser, it has been known that light can carry information. Light beams can be mixed and processed at speeds that far exceed those of electronics, an observation that initiated the field of optical computing in the 1960s (*1*, *2*). Recent technological achievements in photonic circuits (*3*, *4*), as well as the necessity to develop alternative hardware platforms for artificial intelligence (AI), have reawakened interest in photonic and hybrid optoelectronic computing platforms. However, the path toward realistic applications of photonic circuits in AI was hindered by the absence of at least two key ingredients: the demonstration of on-chip nonlinear operations (required in AI neural networks); and the ability to efficiently train photonic chips to learn a specific task. On page 398 of this issue, Pai *et al.* (*5*) make progress on the training problem by implementing a method called "backpropagation" on a photonic chip.

The motivation behind photonic computing finds its roots in fundamental physics: At low optical intensities, photons typically do not interact with one another, remaining in the regime of so-called "linear optics." This behavior enables the parallel and energy-efficient implementation of linear operations (such as vector-to-matrix multiplications). Most neural network architectures rely on a combination of two types of transformations: vector-to-matrix multiplications, where the vector represents input data and the matrix is composed of trained weights of the network; and nonlinear activation functions, which enable the network to learn complex patterns in the training data.

One of the most popular photonic architectures for optical vector-to-matrix

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Science, **380** (6643), .
DOI: 10.1126/science.adh4055

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