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Research in the spotlight

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LATEST ARTICLE

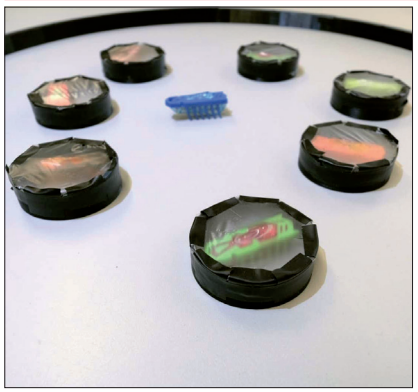
Chiral bristlebots
A toy model for active matter

Heat-transfer fins
Giving phase change materials a boost

Ocean waves
Shedding light on pollution spread

Animate droplets
From active to autonomous

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On the cover
A typical Hexbug Nano
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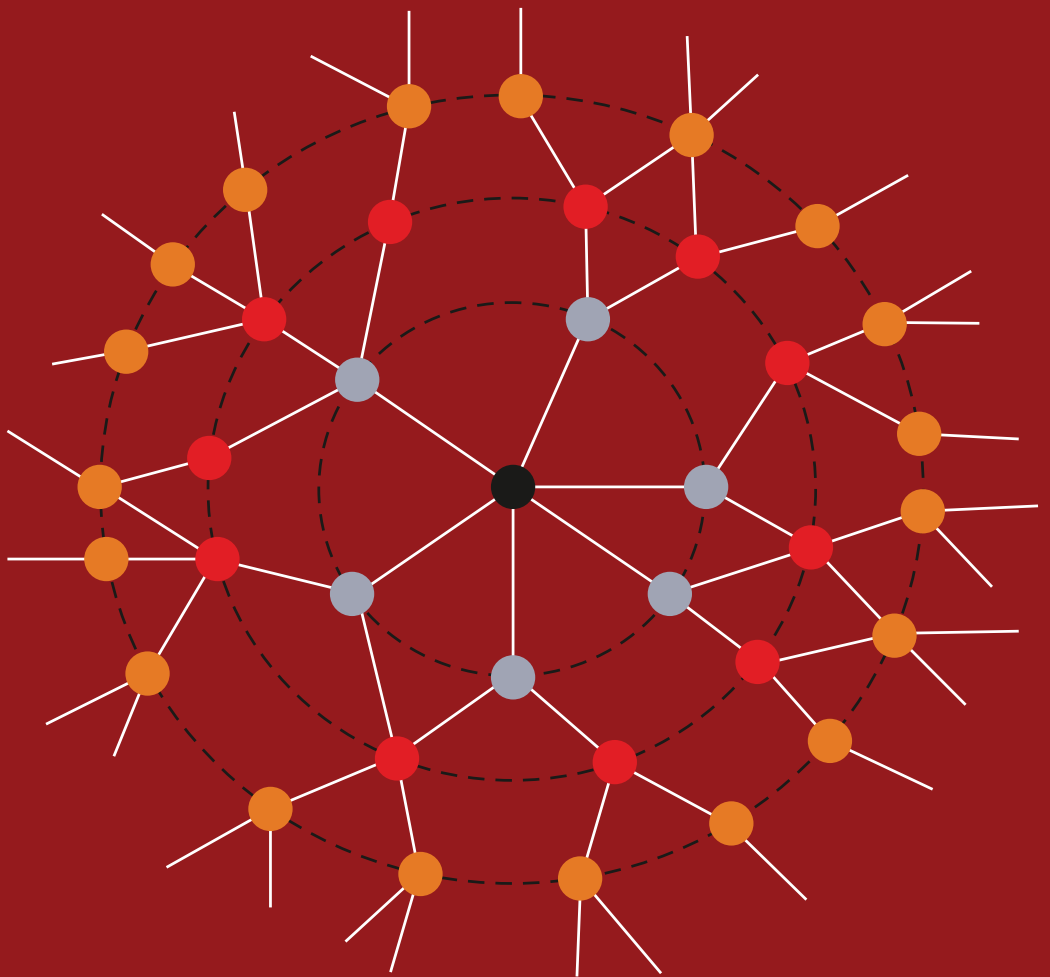
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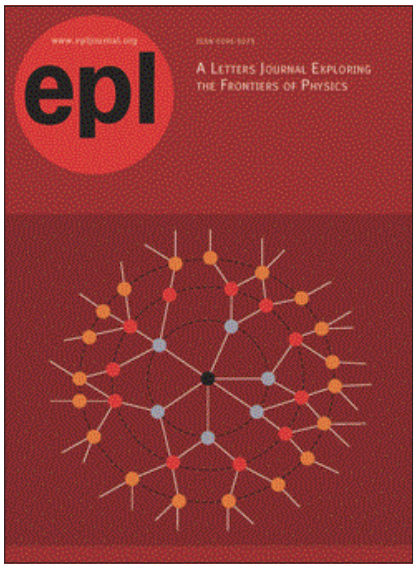
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Cover image: Inspired by a figure showing an example for the reachable subgraph of a node. **Yong Lu *et al*** 2025 *EPL* **152** 31004



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Europhysics Letters (EPL) publishes the highest quality research from around the world, and provides authors with fast, fair and constructive peer review thanks to an Editorial Board of active scientists, who are experts in their respective fields.

EPL celebrates 40 years

We are pleased to present this collection of articles that showcase thought-provoking physics research recently published in EPL, a letters journal at the frontiers of physics that operates under the scientific direction of the European Physical Society.



Richard Blythe
Editor-in-chief
Europhysics Letters

Despite the many changes in scientific publishing since the journal was founded 40 years ago, EPL has been unwavering in its commitment to the international community of physics researchers. Key to this support is an editorial board drawn from this self-same community: practising research physicists whose expertise allows them to spot the most exciting developments in their field. Regular renewal of the board ensures that we constantly move with the times.

One of the most important trends that we have identified recently is that as more and more scientific research is conducted and published, it is becoming increasingly easy for readers to miss important developments, and increasingly hard for authors to be heard. It is in this spirit that EPL's editors are now working with *Physics World* to draw greater attention to certain papers that are both scientifically strong and likely to resonate with a broad spectrum of physicists.

This collection brings together the articles that have been published so far as part of this collaboration, and will be updated as the programme continues. As you will see, the topics covered range from fundamental theories about the universe to practical applications of contemporary physics research across multiple disciplines. This reflects EPL's mission as a journal that spans the whole of physics, including ways in which physics thinking is brought to bear on important questions in other fields.

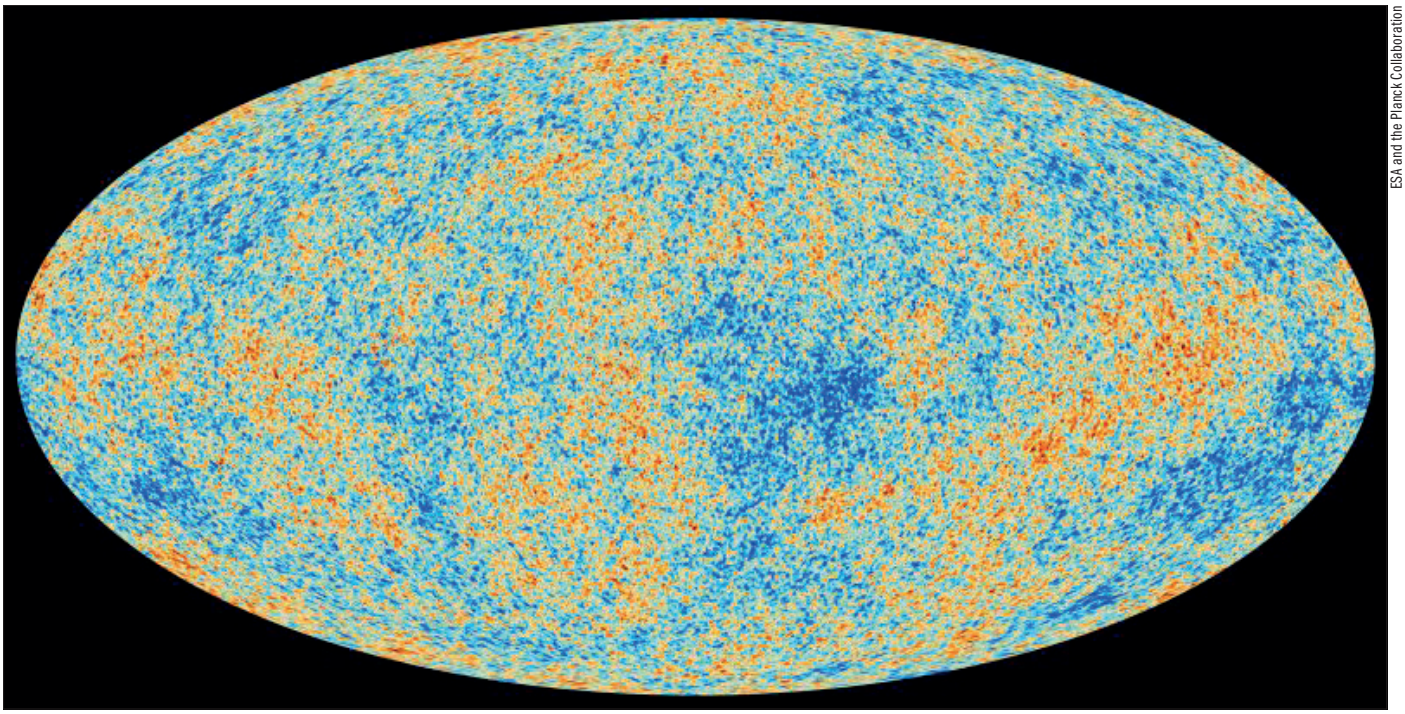


Margaret Harris
Online editor
Physics World

The crowded research landscape that Richard describes is a challenge for science journalists, too. Fortunately, EPL attracts authors who are passionate about physics and skilled in explaining it; for *Physics World*, making their acquaintance has been a highlight of this programme. I hope you enjoy reading about the work of these standout scientists as much as I enjoyed discussing it with them – and, based on their feedback to EPL, as much as they enjoyed the chance to share it with a wider audience.

Loop quantum cosmology may explain smoothness of cosmic microwave background

Repulsive gravity at the quantum scale would have flattened out inhomogeneities in the early universe



ESA and the Planck Collaboration

First light The cosmic microwave background, as imaged by the European Space Agency's Planck mission.

In classical physics, gravity is universally attractive. At the quantum level, however, this may not always be the case. If vast quantities of matter are present within an infinitesimally small volume – at the centre of a black hole, for example, or during the very earliest moments of the universe – space–time becomes curved at scales that approach the Planck length. This is the fundamental quantum unit of distance, and is around 10^{20} times smaller than a proton.

In these extremely curved regions, the classical theory of gravity – Einstein's general theory of relativity – breaks down. However, research on loop quantum cosmology offers a possible solution. It suggests that gravity, in effect, becomes repulsive. Consequently, loop quantum cosmology predicts that our present universe began in a so-called "cosmic bounce", rather than the Big Bang singularity predicted by general relativity.

In a recent paper published in *EPL*, Edward Wilson-Ewing, a mathematical physicist at the University of New Brunswick, Canada, explores the interplay between loop quantum cosmology and a phenomenon sometimes described as "the echo of the Big Bang": the cosmic microwave background (CMB). This background radiation pervades the entire visible universe, and it stems from the moment the universe became cool enough for neutral atoms to form. At this point, light was suddenly able to travel through space without being continually scattered by the plasma of electrons and light nuclei that existed before. It is this freshly liberated light that makes up the CMB, so studying it offers clues to what the early universe was like.

What was the motivation for your research?

Observations of the CMB show that the early universe (that is, the universe as it was when the CMB formed) was extremely homogeneous, with relative anisotropies of the order of one part in 10^4. Classical general relativity has trouble explaining this homogeneity on its own, because a purely attractive version of gravity tends to drive things in the opposite direction. This is because if a region has a higher density than the surrounding area, then according to general relativity, that region will become even denser; there is more mass in that region and therefore particles surrounding it will be attracted to it. Indeed, this is how the small inhomogeneities we do see in the CMB grew over time to form stars and galaxies today.

The main way this gets resolved in classical general relativity is to suggest that the universe experienced an episode of super-rapid growth in its earliest moments. This super-rapid growth is known as inflation, and it can suffice to generate homogeneous regions. However, in general, this requires a very large amount of inflation (much more than is typically considered in most models).

Alternately, if for some reason there happens to be a region that is moderately homogeneous when inflation starts, this region will increase exponentially in size while also becoming further homogenized.


University of New Brunswick

Cosmologist Edward Wilson-Ewing uses loop quantum gravity to study quantum effects in the very early universe.

It is important to extend this work in several directions to check the robustness of the homogenization effect in loop quantum cosmology

This second possibility requires a little more than a minimal amount of inflation, but not much more.

My goal in this work was to explore whether, if gravity becomes repulsive in the deep quantum regime (as is the case in loop quantum cosmology), this will tend to dilute regions of higher density, leading to inhomogeneities being smoothed out. In other words, one of the main objectives of this work was to find out whether quantum gravity could be the source of the high degree of homogeneity observed in the CMB.

What did you do in the paper?

In this paper, I studied spherically symmetric space–times coupled to dust (a simple model for matter) in loop quantum cosmology. These space–times are known as Lemaître–Tolman–Bondi space–times, and they allow arbitrarily large inhomogeneities in the radial direction. They therefore provide an ideal arena to explore whether homogenization can occur: they are simple enough to be mathematically tractable, while still allowing for large inhomogeneities (which, in general, are very hard to handle).

Loop quantum cosmology predicts several leading-order quantum effects. One of these effects is that space–time, at the quantum level, is discrete: there are quanta of geometry just as there are quanta of matter. This has implications for the equations of motion, which relate the geometry of space–time to the matter in it: if we take into account the discrete nature of quantum geometry, we have to modify the equations of motion.

These modifications are captured by so-called effective equations, and in the paper I solved these equations numerically for a wide range of initial conditions. From this, I found that while homogenization doesn't occur everywhere, it always occurs in some regions. These homogenized regions can then be blown up to cosmological scales by inflation (and inflation will further homogenize them). Therefore, this quantum gravity homogenization process could indeed explain the homogeneity observed in the CMB.

What do you plan to do next?

It is important to extend this work in several directions to check the robustness of the homogenization effect in loop quantum cosmology. The restriction to spherical symmetry should be relaxed, although this will be challenging from a mathematical perspective. It will also be important to go beyond dust as a description of matter. The simplicity of dust makes calculations easier, but it is not particularly realistic.

Other relevant forms of matter include radiation and the so-called inflaton field, which is a type of matter that can cause inflation to occur. That said, in cosmology, the physics is to some extent independent of the universe's matter content, at least at a qualitative level. This is because while different types of matter content may dilute more rapidly than others in an expanding universe, and the universe may expand at different rates depending on its matter content, the main properties of the cosmological dynamics (for example, the expanding universe, the occurrence of an initial singularity and so on) within general relativity are independent of the specific matter being considered.

I therefore think it is reasonable to expect that the quantitative predictions will depend on the matter content, but the qualitative features (in particular, that small regions are homogenized by quantum gravity) will remain the same. Still, further research is needed to test this expectation will depend on the matter content, but the qualitative features (in particular, that small regions are homogenized by quantum gravity) will remain the same. Still, further research is needed to test this expectation.

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From rabbits and foxes to the human gut microbiome, physics is helping us understand the natural world

This episode of the *Physics World Weekly* podcast is a conversation with two physicists, **Ada Altieri** and **Silvia De Monte**, who are using their expertise in statistical physics to understand the behaviour of ecological communities.

A century ago, pioneering scientists such as Alfred Lotka and Vito Volterra showed that statistical physics techniques could explain – and even predict – patterns that ecologists observe in nature. At first, this work focused on simple ecosystems containing just one or two species (such as rabbits and foxes), which are relatively easy to model.

Nowadays, though, researchers such as Altieri and De Monte are turning their attention to far more complex communities. One example is the collection of unicellular organisms known as protists that live among plankton in the ocean. Another, closer to home, is the "microbiome" in the human gut, which may contain hundreds or even thousands of species of bacteria.

Modelling these highly interconnected communities is hugely challenging. But as Altieri and De Monte explain, the potential rewards – from identifying "tipping points" in fragile ecosystems to developing new treatments for gut disorders such as irritable bowel syndrome and Crohn's disease – are great.

This discussion is based on a Perspective article that Altieri (an associate professor at the Laboratory for Matter and Complex Systems at the Université Paris Cité, France) and De Monte (a senior research scientist at the Institute of Biology in the École Normale Supérieure in Paris and the Max Planck Institute for Evolutionary Biology in Ploen, Germany) wrote for the journal *EPL*, which sponsors this episode of the podcast.



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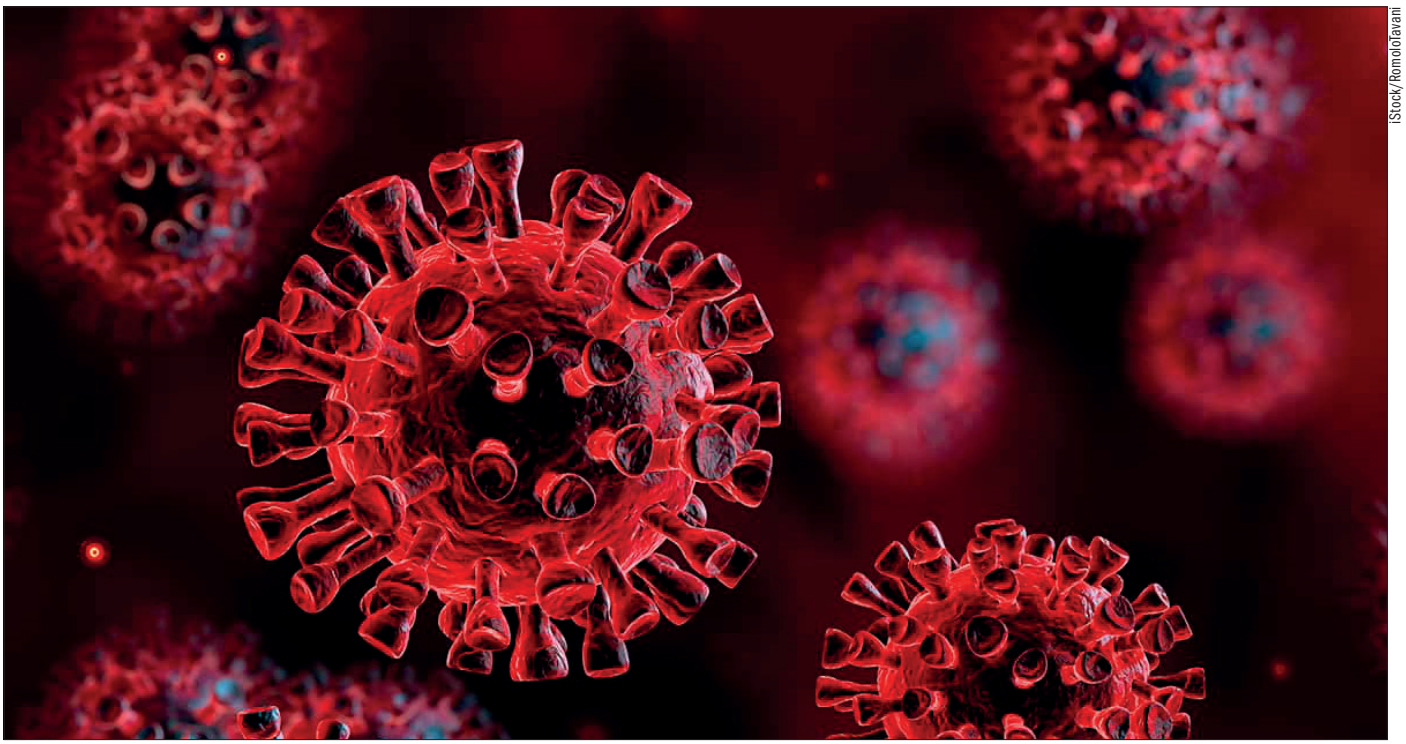
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Staying the course with lockdowns could end future pandemics in months



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Survivors Artist's impression of Sars-CoV-2 virions, which cause COVID-19.

As a theoretical and mathematical physicist at Imperial College London, UK, Bhavin Khatri spent years using statistical physics to understand how organisms evolve. Then the COVID-19 pandemic struck, and like many other scientists, he began searching for ways to apply his skills to the crisis. This led him to realize that the equations he was using to study evolution could be repurposed to model the spread of the virus – and, crucially, to understand how it could be curtailed.

In a paper published in *EPL*, Khatri models the spread of a SARS-CoV-2-like virus using branching process theory, which he'd previously used to study how advantageous alleles (variations in a genetic sequence) become more prevalent in a population. He then uses this model to assess the duration that interventions such as lockdowns would need to be applied in order to completely eliminate infections, with the strength of the intervention measured in terms of the number of people each infected person goes on to infect (the virus' effective reproduction number, R).

Tantalizingly, the paper concludes that applying such interventions worldwide in June 2020 could have eliminated the COVID virus by January 2021, several months before the widespread availability of vaccines reduced its impact on healthcare systems and led governments to lift restrictions on social contact. *Physics World* spoke to Khatri to learn more about his research and its implications for future pandemics.

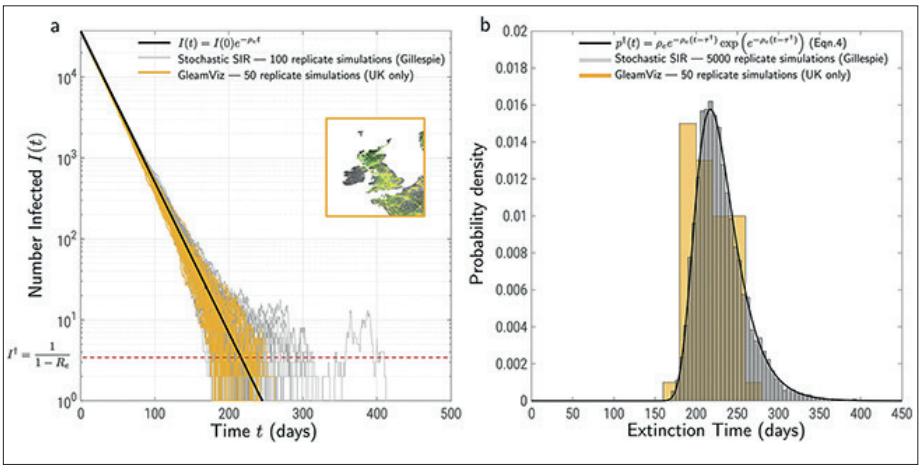
What are the most important findings in your work?

One important finding is that we can accurately calculate the distribution of times required for a virus to become extinct by making a relatively simple approximation. This approximation amounts to assuming that people have relatively little population-level "herd" immunity to the virus – exactly the situation that many countries, including the UK, faced in March 2020.

Making this approximation meant I could reduce the three coupled differential equations of the well-known SIR model (which models pandemics via the interplay between Susceptible, Infected and Recovered individuals) to a single differential equation for the number of infected individuals in the population. This single equation turned out to be the same one that physics students learn when studying radioactive decay. I then used the discrete stochastic version of exponential decay and standard approaches in branching process theory to calculate the distribution of extinction times.

Alongside the formal theory, I also used my experience in population genetic theory to develop an intuitive approach for calculating the mean of this extinction time distribution. In population genetics, when a mutation is sufficiently rare, changes in its number of copies in the population are dominated by randomness. This is true even if the mutation has a large selective advantage: it has to grow by chance to sufficient critical size – on the order of 1/(selection strength) – for selection to take hold.

The same logic works in reverse when applied to a declining number of infec-



Simulation trajectories a) A plot of the decline in the number of infected individuals over time. b) Probability density of extinction times for the same parameters as in a), showing that the most likely extinction times are measured in months. (Courtesy: Bhavin S. Khatri 2025 *EPL* **152** 11003 DOI 10.1209/0295-5075/ae0c31 CC-BY 4.0 https://creativecommons.org/licenses/by/4.0/).

tions. Initially, they will decline deterministically, but once they go below a threshold number of individuals, changes in infection numbers become random. Using the properties of such random walks, I calculated an expression for the threshold number and the mean duration of the stochastic phase. These agree well with the formal branching process calculation.

In practical terms, the main result of this theoretical work is to show that for sufficiently strong lockdowns (where, on average, only one of every two infected individuals goes on to infect another person, R=0.5), this distribution of extinction times was narrow enough to ensure that the COVID pandemic virus would have gone extinct in a matter of months, or at most a year.

How realistic is this counterfactual scenario of eliminating SARS-CoV-2 within a year?

Leaving politics and the likelihood of social acceptance aside for the moment, *if* a sufficiently strong lockdown could have been maintained for a period of roughly six months across the globe, then I am confident that the virus could have been reduced to very low levels, or even made extinct.

The question then is: is this a stable situation? From the perspective of a single nation, if the rest of the world still has infections, then that nation either needs to maintain its lockdown or be prepared to re-impose it if there are new imported cases. From a global perspective, a COVID-free world should be a stable state, unless an animal reservoir of infections causes re-infections in humans.



Bhavin Khatri

Modelling the decline of a virus Theoretical physicist and biologist Bhavin Khatri.

As for the practical success of such a strategy, that depends on politics and the willingness of individuals to remain in lockdown. Clearly, this is not in the model. One thing I do discuss, though, is that this strategy becomes far more difficult once more infectious variants of SARS-CoV-2 evolve. However, the problem I was working on before this one (which I eventually published in *PNAS*) concerned the probability of evolutionary rescue or resistance, and that work suggests that evolution of new COVID variants reduces significantly when there are fewer infections. So an elimination strategy should also be more robust against the evolution of new variants. What lessons would you like experts (and the public) to take from this work when considering future pandemic scenarios?

I'd like them to conclude that pandemics with similar properties are, in principle, controllable to small levels of infection – or complete extinction – on timescales of months, not years, and that controlling them minimizes the chance of new variants evolving. So, although the question of the political and social will to enact such an elimination strategy is not in the scope of the paper, I think if epidemiologists, policy experts, politicians and the public understood that lockdowns have a finite time horizon, then it is more likely that this strategy could be adopted in the future.

I should also say that my work makes no comment on the social harms of lockdowns, which shouldn't be minimized and would need to be weighed against the potential benefits.

What do you plan to do next?

I think the most interesting next avenue will be to develop theory that lets us better understand the stability of the extinct state at the national and global level, under various assumptions about declining infections in other countries that adopted different strategies and the role of an animal reservoir.

It would also be interesting to explore the role of "superspreaders", or infected individuals who infect many other people. There's evidence that many infections spread primarily through relatively few superspreaders, and heuristic arguments suggest that taking this into account would decrease the time to extinction compared to the estimates in this paper.

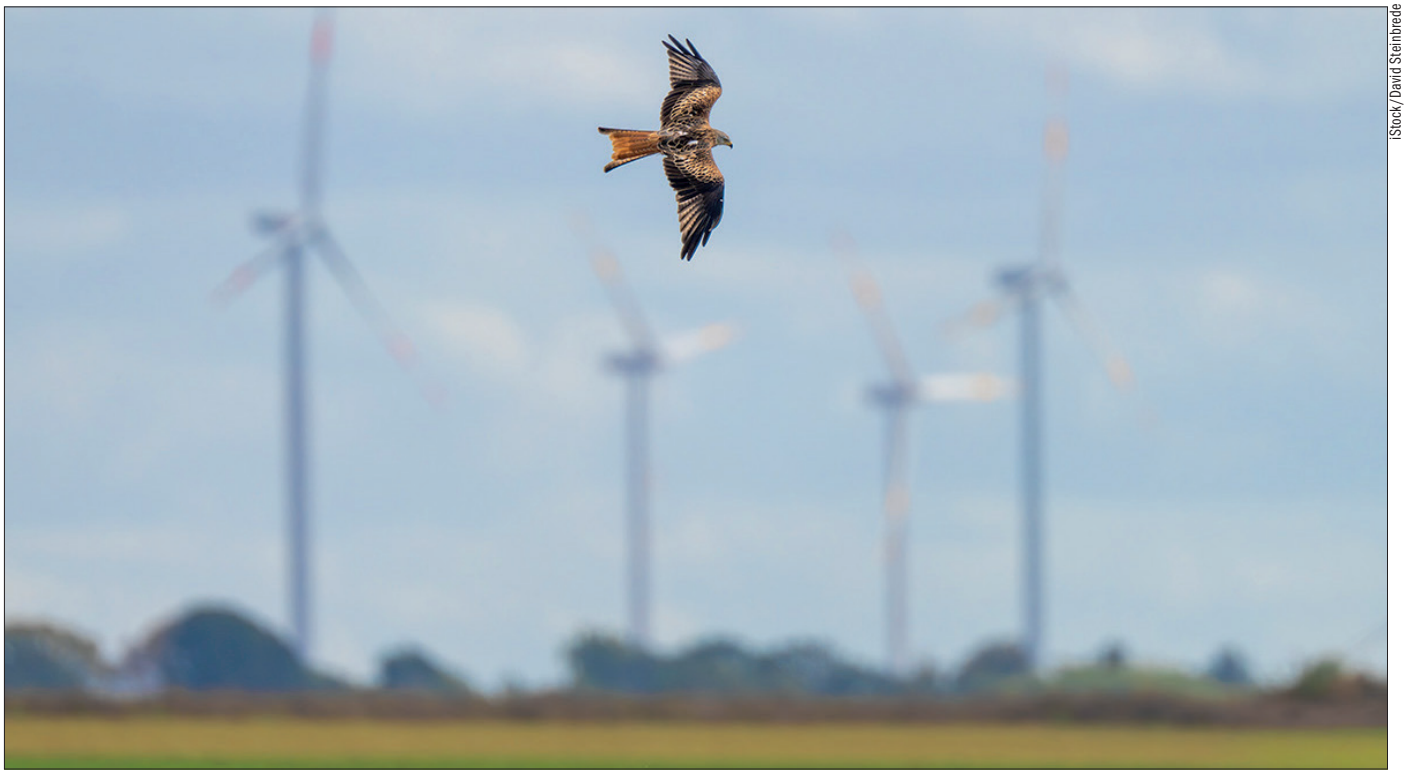
I've also had a long-term interest in understanding the evolution of viruses from the lens of what are known as genotype phenotype maps, where we consider the non-trivial and often redundant mapping from genetic sequences to function, where the role of stochasticity in evolution can be described by statistical physics analogies. For the evolution of the antibodies that help us avoid virus antigens, this would be a driven system, and theories of non-equilibrium statistical physics could play a role in answering questions about the evolution of new variants.

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Reinforcement learning could help airborne wind energy take off

When people think of wind energy, they usually think of windmill-like turbines dotted among hills or lined up on offshore platforms. But there is also another kind of wind energy, one that replaces stationary, earthbound generators with tethered kites that harvest energy as they soar through the sky



iStock/David Steinbrede

Sophisticated control mechanisms Airborne wind energy systems generate electricity from devices that soar through the sky like birds, in contrast to conventional, Earth-bound turbines, but controlling them is a challenge.

This airborne form of wind energy, or AWE, is not as well-developed as the terrestrial version, but in principle it has several advantages. Power-generating kites are much less massive than ground-based turbines, which reduces both their production costs and their impact on the landscape. They are also far easier to install in areas that lack well-developed road infrastructure. Finally, and perhaps most importantly, wind speeds are many times greater at high altitudes than they are near the ground, significantly enhancing the power densities available for kites to harvest.

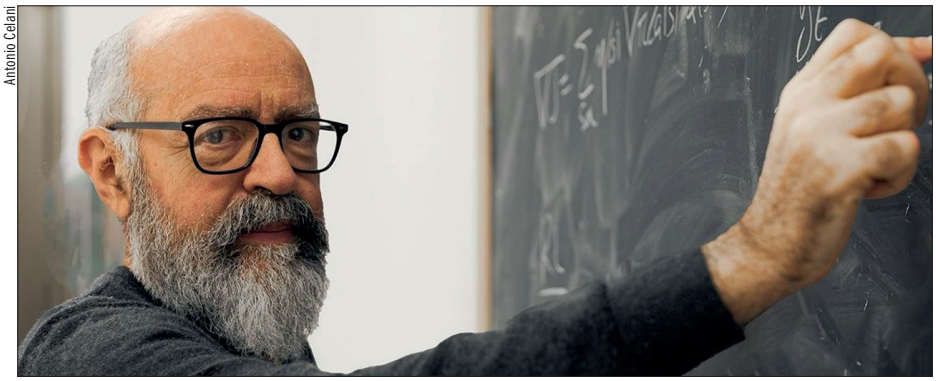
There is, however, one major technical challenge for AWE, and it can be summed up in a single word: control. AWE technology is operationally more complex than conventional turbines, and the traditional method of controlling kites (known as model-predictive control) struggles to adapt to turbulent wind conditions. At best, this reduces the efficiency of energy generation. At worst, it makes it challenging to keep devices safe, stable and airborne.

In a paper published in *EPL*, Antonio Celani and his colleagues Lorenzo Basile and Maria Grazia Berni of the University of Trieste, Italy, and the Abdus Salam International Centre for Theoretical Physics (ICTP) propose an alternative control method based on reinforcement learning. In this form of machine learning, an agent learns to make decisions by interacting with its environment and receiving feedback in the form of "rewards" for good performance. This form of control, they say, should be better at adapting to the variable and uncertain conditions that power-generating kites encounter while airborne.

What was your motivation for doing this work?

Our interest originated from some previous work where we studied a fascinating bird behaviour called thermal soaring. Many birds, from the humble seagull to birds of prey and frigatebirds, exploit atmospheric currents to rise in the sky without flapping their wings, and then glide or swoop down. They then repeat this cycle of ascent and descent for hours, or even for weeks if they are migratory birds. They're able to do this because birds are very effective at extract-

Antonio Celani



Antonio Celani

ing energy from the atmosphere to turn it into potential energy, even though the atmospheric flow is turbulent, hence very dynamic and unpredictable.

In those works, we showed that we could use reinforcement learning to train virtual birds and also real toy gliders to soar. That got us wondering whether this same approach could be exported to AWE.

When we started looking at the literature, we saw that in most cases, the goal was to control the kite to follow a predetermined path, irrespective of the changing wind conditions. These cases typically used only simple models of atmospheric flow, and almost invariably ignored turbulence.

This is very different from what we see in birds, which adapt their trajectories on the fly depending on the strength and direction of the fluctuating wind they experience. This led us to ask: can a reinforcement learning (RL) algorithm discover efficient, adaptive ways of controlling a kite in a turbulent environment to extract energy for human consumption?

Lorenzo Basile



Lorenzo Basile

What is the most important advance in the paper?

We offer a proof of principle that it is indeed possible to do this using a minimal set of sensor inputs and control variables, plus an appropriately designed reward/punishment structure that guides trial-and-error learning. The algorithm we deploy finds a way to manoeuvre the kite such that it generates net energy over one cycle of operation. Most importantly, this strategy autonomously adapts to the ever-fluctuating conditions induced by turbulence.

The main point of RL is that it can learn to control a system just by interacting with the environment, without requiring any a priori knowledge of the dynamical laws that rule its behaviour. This is extremely useful when the systems are very complex, like the turbulent atmosphere and the aerodynamics of a kite.

What are the barriers to implementing RL in real AWE kites, and how might these barriers be overcome?

The virtual environment that we use in our paper to train the kite controller is very simplified, and in general the gap between simulations and reality is wide. We therefore regard the present work mostly as a stimulus for the AWE community to look deeper into alternatives to model-predictive control, like RL.

On the physics side, we found that some phases of an AWE generating cycle are very difficult for our system to learn, and they require a painful fine-tuning of the reward structure. This is especially true when the kite is close to the ground, where winds are weaker and errors are the most punishing. In those cases, it might be a wise choice to use other heuristic, hard-wired control strategies rather than RL.

Finally, in a virtual environment like the one we used to do the RL training in this work, it is possible to perform many trials. In real power kites, this approach is not feasible – it would take too long. However, techniques like offline RL might resolve this issue by interleaving a few field experiments where data are collected with extensive off-line optimization of the strategy. We successfully used this approach in our previous work to train real gliders for soaring.

We asked: can a reinforcement learning (RL) algorithm discover efficient, adaptive ways of controlling a kite in a turbulent environment to extract energy for human consumption?

What do you plan to do next?

We would like to explore the use of offline RL to optimize energy production for a small, real AWE system. In our opinion, the application to low-power systems is particularly relevant in contexts where access to the power grid is limited or uncertain. A lightweight, easily portable device that can produce even small amounts of energy might make a big difference in the everyday life of remote, rural communities, and more generally in the global south.

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Droplet scientists push the boundary between living and non-living matter

In this episode of the *Physics World Weekly* podcast, we hear from a trio of scientists with a common interest in the physics of droplets

Joe Forth, Rob Malinowski and Giorgio Volpe share a fascination with droplets that are "animate" – that is, capable of responding to their surroundings in ways that resemble the behaviour of living organisms.

As they explain in the podcast, systems must tick three boxes to qualify as animate. First, they must be active, able to use energy from their environment to do work and perform tasks. Second, they must be adaptive, able to move between different dynamical states in response to changes to their environment or their own internal states. Finally, they must be autonomous, able to process multiple inputs and choose how to respond to them without intervention from the outside world.

Incorporating all these behaviours into a droplet – or a system of many droplets – is challenging. The boundary between autonomous and non-autonomous systems is proving especially hard to overcome, and Volpe, Malinowski and Forth have a friendly disagreement over whether any droplet-based system has managed it yet.

Crosses disciplinary borders

Part of the challenge, they say, is that the field crosses disciplinary borders. Although Volpe thinks the community of droplet researchers is getting better at finding a common vocabulary for discussions, Forth jokes that it is still the case that "the chemists are scared of physics, the physicists are scared of chemists, everyone is scared of biology". The potential rewards of overcoming these fears are great, however, with possible future applications of animate droplets ranging from consumer products such as deodorant to oil spill clean-up.

This discussion is based on a Perspective article that Volpe (a professor of soft matter in the chemistry department at University College London, UK), Malinowski (a research fellow in soft matter physics in the same department) and Forth (a colloid scientist and lecturer in the chemistry department at the University of Liverpool, UK) wrote for the journal *EPL*, which sponsors this episode of the podcast.

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New model of ocean waves sheds fresh light on the spread of microplastic pollution

Nature is always more complicated than the models we use to describe it. Ocean waves, for example, are constantly evolving. They grow when wind transfers kinetic energy to the water's surface. They interact with each other in highly nonlinear ways. And once the wind dies down, their internal viscosity makes them dissipate away to nothing, leaving behind a surface as flat as glass

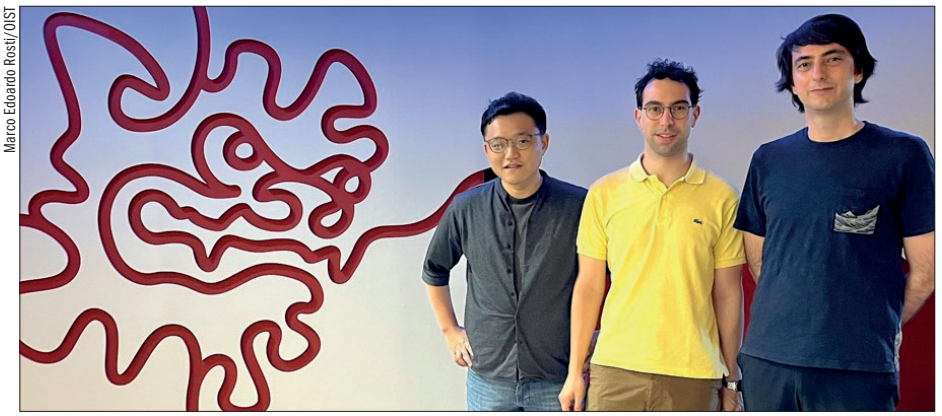


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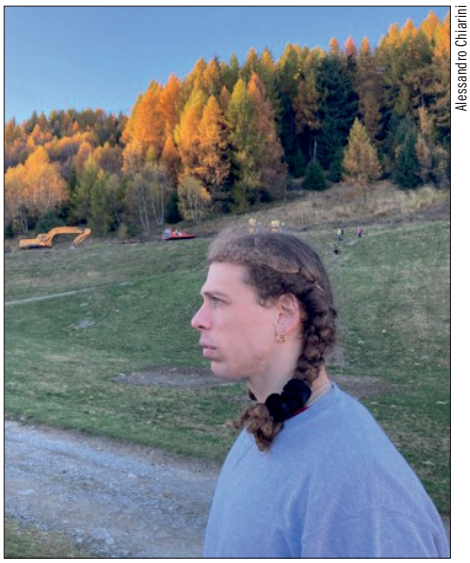
This process is familiar to anyone who's ever been to the seaside, yet physicists' go-to models of water moving through the ocean essentially ignore it. Instead, the standard theory of wave transport, known as classical Stokes drift theory, concentrates on describing the flow of steady waves with finite amplitude. And while extensions of the theory incorporate complications such as nonlinear wave shapes, uneven seabeds and the inertia of particles carried along by the waves, they don't account for waves that grow and fade over time.

For Marco Edoardo Rosti, a physicist at Japan's Okinawa Institute of Science and Technology (OIST), this shortcoming has real-world consequences. "There is increasing interest in understanding near-surface transport processes because they are directly connected to problems such as pollutant dispersion, microplastic accumulation, sediment transport, and air-sea exchange," he explains. "Since these processes depend sensitively on particle trajectories, even subtle modifications of the drift mechanism may become important over long times."

In a study published in the journal *EPL*, Rosti and his colleagues Alessandro Chiarini, Tatsuo Izawa and Giulio Foggi Rota explored ways of remedying this deficiency. They focused on the simplest type of wave evolution: a freely decaying, single-frequency gravity wave, one where the force of gravity acts to restore equilibrium and smooth out the surface of the water. *Physics World* spoke with the team about the findings.


Marco Edoardo Rosti/OIST

Wave mechanics Team members (l-r) Tatsuo Izawa, Giulio Foggi Rota and Marco Edoardo Rosti.


Alessandro Chiarini

International collaboration Team member Alessandro Chiarini.

What is the most important advance in this work?

Classical Stokes drift theory predicts that on average, particles will get transported through the water horizontally, in the direction of the wave. But by combining fully nonlinear two-phase simulations with a perturbative analytical model, we demonstrate that when you allow those waves to decay, additional transport mechanisms appear.

Specifically, we identified a net vertical particle migration that arises solely from the temporal decay of the wave field, due to the interplay between fluid inertia and viscous dissipation. This migration persists even for fluids with relatively weak viscosity. Also, because the drift velocity depends on depth, even small vertical displacements alter particle trajectories and mixing properties.

More broadly, our results show that unsteadiness in the wave amplitude is not a minor correction to classical Stokes drift. It's something that can qualitatively change how an individual parcel of fluid moves through space and time – what we call Lagrangian transport. This has important implications for understanding how floating and suspended materials, including sediments, aerosols and microplastics, get redistributed near the ocean surface.

Can you say more about those implications?

Because gravity waves at the ocean surface span a broad range of wavelengths, from centimetres to hundreds of meters, even a modest fractional vertical displacement per wave cycle can significantly change the depth of a drifting particle. And because the drift velocity beneath a wave decays exponentially with depth, these small vertical excursions can substantially alter how much horizontal drift a particle accumulates. That could influence whether microplastics remain near the surface (where they are most bioavailable), or whether they instead migrate to greater depths, where different biological and physical processes govern their fate.

Why have previous studies not seen this vertical drift?

The drift mechanism we identify accumulates gradually as the wave field decays. That means it only becomes apparent when "tracer" particles in the water are exposed to the same wave as its amplitude decreases over many periods. Most wave-tank experiments and field measurements instead follow tracers as they are swept through a passing wave packet, which is a fundamentally different configuration.

In open-sea conditions, similar arguments apply, and the presence of currents, wind forcing and turbulence all complicate the picture. These effects mask a signal that only shows up unambiguously in clean, unforced conditions.

What was the most challenging aspect of this work?

The most challenging part was to bridge the limits of classical wave theories with the fully nonlinear, two-phase simulations of an air-water interface. The classical Landau wave-decay theory, for example, assumes an isolated, weakly viscous fluid (water). However, our high-resolution simulations demonstrate (as previously reported in other studies) a deviation from these idealized assumptions. In fact, the dominant viscous energy dissipation occurs in a thin layer of air just above the water surface, rather than in the bulk.

To investigate how continuous wave energy decay affects Lagrangian particle transport, we developed a perturbative analytical model based on the classical Landau framework. This was a difficult step because the framework is inherently blind to the two-phase dissipative system. As a result, its asymptotic predictions progressively diverged from simulated flow fields at long times, likely due to intrinsic limitations of the Landau decay-wave model.

What do you plan to do next?

The drift mechanism we discuss in this study applies to a very idealized form of wave decay. In the future, we would like to test whether and how this mechanism propagates in more complex but realistic wave conditions. In particular, we want to work out how to measure such mechanisms in wave-tank experiments. To do so, we will study a different setup, one in which waves decay spatially instead of temporally, since this is closer to what observed in wave tanks. We would also like to study how our mechanism affects drift in waves that vary over time, with controlled unsteadiness, rather than simply decaying.

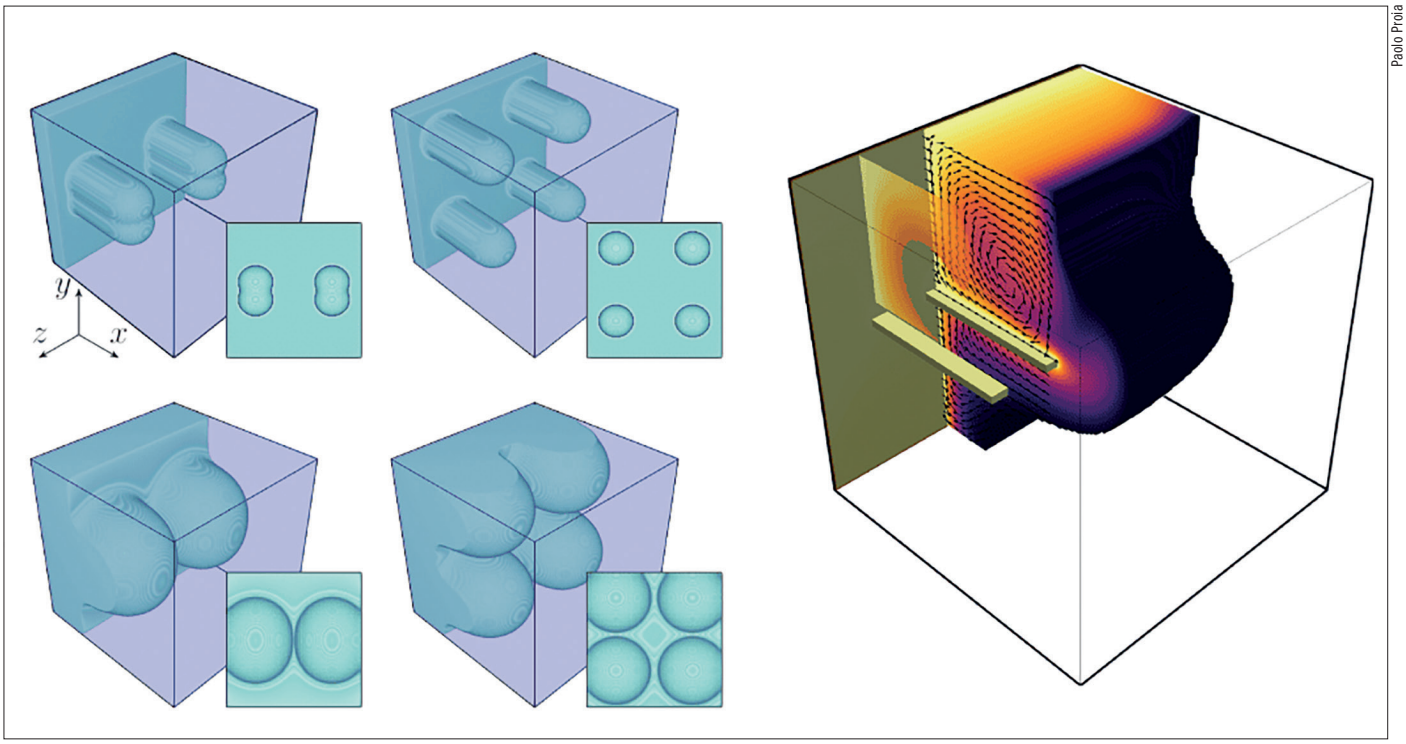
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Heat-transfer fins give phase change materials a boost

If you've ever kept a drink cool on a hot summer day by placing it inside a frozen, gel-filled sleeve, you'll understand the appeal of phase change materials (PCMs)



Paolo Proia

Fin placement (left) Purely conductive simulations of heating in a phase-change material (PCM) via sets of four heat-transfer fins in two different configurations. As time progresses, "interference" creates overlapping regions of melting for the closely-spaced fins (far left), but less so for fins spaced further apart (near left), indicating that the latter configuration is more efficient. (right) A snapshot of a typical convective simulation of a finned PCM showing the characteristic thermal plumes that form in this kind of system.

The reason these sleeves work so well (and so much better than simply putting your drink in a cold bath or cool room) is that the solid inside them has a high latent heat, meaning it can absorb relatively large quantities of energy before melting and beginning to warm up.

But what if surrounding your drink with a frozen PCM isn't enough? What if you want to cool your drink more quickly and evenly? One option would be to create a PCM sleeve with fin-shaped extensions that protrude into your drinking vessel. These fins would cool your drink – or, equivalently, allow your drink to melt the PCM – much more efficiently than a simple sleeve. But what should the fins look like? How far apart should they be? And how many of them do you need?

These are the questions that Paolo Proia, Mauro Sbragaglia and Giacomo Falcucci considered in a study published in EPL – though not with the aim of keeping their drinks cold. As researchers at the University Tor Vergata of Rome, Italy, Proia, Sbragaglia and Falcucci are interested in PCMs that store and release heat like a battery. Such materials are useful in fields such as electronics and refrigeration where heat is a common byproduct. Other applications include maintaining the efficiency of solar panels by preventing them from getting too hot and keeping buildings cool in the daytime via insulation.

Physics World spoke with them about their work.

What was your motivation for doing this research?

Our interest in PCMs stems, in part, from our interest in their many applications, especially in the ecological transition to less carbon-intensive fuels. PCMs are particularly good at managing heat in hydrogen storage with metal hydrides, for example, because storing hydrogen in these materials produces heat, while releasing the hydrogen requires it. Using a PCM to store the heat of the adsorption process and give it back during the release means that the produced heat doesn't go to waste. Instead, it improves the efficiency of the process.

We're also fascinated by the complexity of the equations involved. The coupling of fluid and temperature dynamics already

Paolo Proia



Phase change modellers (left-right) Paolo Proia, Mauro Sbragaglia and Giacomo Falcucci.

causes interesting phenomena such as convection. By adding a phase transition to the mix, you introduce a moving boundary that complicates the system even more, both phenomenologically and analytically, since the describing equations must account for it.

We started this paper as a way of extending our previous work on the insertion of fins inside a PCM to three dimensions. PCMs are exceptionally good in latent heat but severely lacking in sensible heat; in other words, they store heat well, but they absorb and release it poorly. Fins are useful in relieving this flaw since they enhance the heat transfer surface and provide a horizontal heat source, which is instrumental for the development of convection, the main driver of heat transfer in this kind of system. By switching to a 3D system, we had more freedom to explore complex layouts of multiple fins and the importance of their relative position.

As researchers at the University Tor Vergata of Rome, Italy, Proia, Sbragaglia and Falcucci are interested in PCMs that store and release heat like a battery

What is the most important advance in the paper?

The most important result is that naively inserting fins too close to each other can cause interference. If there are overlaps in the fins' "influence zone", the system will waste energy by, in effect, trying to melt something that was already molten from heating by a nearby fin. Moreover, by comparing a single fin and multiple fins with the same total surface, we found that the latter configuration benefits from the gaps between the fins. This is because the substance in these gaps melts early and starts acting as an extra heating surface, contributing to the development of bigger convective structures.

Why is it so challenging to model melting in phase change materials in 3D?

Beyond the analytical requirements we already mentioned, the success of this type of modelling depends on having a resolution that is high enough to capture correctly all the phenomena in the system. This means the number of computational sites N must be sufficiently large. In 2D, we "only" have N^2 sites to model, but in 3D, this scales to N^3. That creates a challenge because making N too large would severely slow down the simulation. Moreover, we must be sure to respect the restraints on the physical parameters for which the lattice Boltzmann method is a correct approximation of the equations involved. So, we underwent a thorough validation process to pinpoint the best parameters for the algorithm.

What do you plan to do next?

First, we'd like to further optimize the code. The main bottleneck is the speed of a single iteration. Ideally, we'd like to study a wider range of layouts and physical conditions, but with the code we have now, that would impact heavily on performance. For example, a slower-melting substance requires more iterations to completely melt, which translates into more real-life time to model, sometimes outside the limits of feasibility. This problem would obviously be solved if we can make a single iteration faster.

Metamaterial boosts heat transfer on the nanoscale

Another issue we have is that some ranges of physical parameters can make the simulation unstable. Fortunately, there exist some remedies to this, and we plan to eventually adopt them.

Finally, we would be happy to see other researchers use these findings in their own optimization studies on fin shapes and spatial layouts. It would also be very interesting to see someone study this problem from an analytical angle or to see some experimental validation. In the medium term, we are planning to conduct our own experiments to use as a benchmark for our computational results.

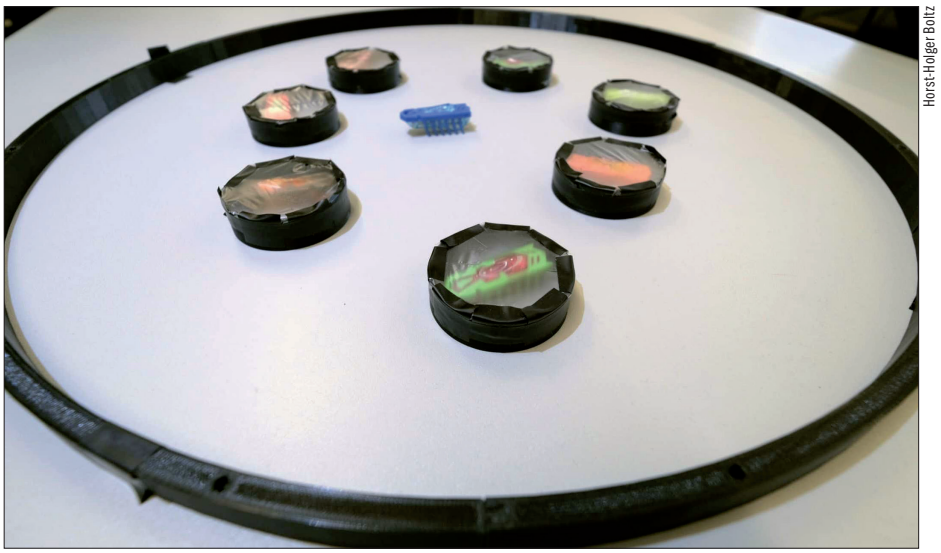
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Chiral bristlebot toys shed light on transport dynamics in active matter systems

Leaning in to the natural "handedness" of vibrating bots revealed "qualitatively new phenomena", say physicists



Horst-Holger Boltz

Bristlebots assemble The "arena" used to study how bristlebots encased in rings and foil interact with each other. An unmodified blue bristlebot is also shown.

Flocks of birds, schools of fish, colonies of swimming bacteria and even crowds of humans have something important in common. Although the details of how they move and interact are very different, they are all examples of what physicists call "active matter" – collections of particles that propel themselves through their environments, consuming energy as they go.

Because real-world active matter systems can be complex and hard to model mathematically, physicists working in this field sometimes study simpler "toy" systems instead. In a study published in *EPL*, Timo Wagner, Michael Himpel, Thomas Ihle and Horst-Holger Boltz took this principle a step further by building an active matter system made from literal toys.

Working at the University of Greifswald, Germany, they developed a model active matter system based on bristlebots, which use the friction and the elasticity of their asymmetric legs (the bristles) to turn vibrations from their small onboard motors into directed motion. The overall effect is similar to a smartphone moving across a table as it vibrates, with one important difference: the Greifswald team's bristlebots incorporate a bias, or chirality, into their movement. *Physics World* spoke to Boltz about the group's work.

Why did you decide to use bristlebots as your model active matter system?

Our research group is developing kinetic theory for active matter systems, and we aim to derive statistical descriptions that start from the equations of motion of individual particles. In active matter, the effective dynamics are more general than truly microscopic equations of motion, which means one can write down a great variety of models. However, not all these models are physically realizable, so we needed an experimental system that would allow us to determine which dynamics actually occur and to infer realistic parameter values.

It turns out that this is surprisingly hard to do in most active matter experiments. In colloidal or biological systems, for example, you typically observe the collective behaviour, but you have limited access to the microscopic parameters that enter the theory. We wanted a model realization of an active gas that we have full control of and insight into.

Bristlebots are an attractive option because they are cheap and operate on length scales that are easy to work with. Although there are limits to how analogous they are to real physical systems (among other shortcomings, bristlebots are dry, frictional, macroscopic objects with no hydrodynamics, no thermal noise in the usual sense, and interactions that depend purely on spatial arrangement), they do allow us to isolate and study specific aspects of the dynamics. In this study, we chose to focus on the interplay of chirality and self-alignment with structured environments, in a setting where we have full experimental access to all the relevant parameters.

Why were you interested in chirality?

From a theoretical perspective, adding chirality is a logical step because it is the simplest form of free dynamics in a system's internal degrees of freedom. Whereas a non-chiral particle will only change its direction due to noise or interactions with other particles, a chiral particle constantly turns on its own with a deterministic drift.

Our chiral bristlebot system is based on a commercial toy bot called a Hexbug nano with a motor that is placed off-axis, such that a single bristlebot will always move in a circular pattern. Many previous bristlebot experiments have sought to control this chirality, or to suppress it by adding counterweights, but we leaned into it.

We found that if you design the system to have pronounced chirality, qualitatively new phenomena become accessible. In particular, you start to see interplay between the chirality of the particle and the chirality of the environment, which gives you a form of passive control over collective transport. That was not something we set out to find: it came out of the design process for the particle housings.

What is the most important advance in the paper?

There are several layers to this. On the most practical level, we show how to turn a cheap commercial toy into a self-aligning chiral active particle by enclosing it in a 3D-printed housing with an elastic cover. This is an

Working at the University of Greifswald, Germany, they developed a model active matter system based on bristlebots



Arabinda Bera/U Greifswald

Members of the bristlebot research team (left-right) Horst-Holger Boltz, Thomas Ihle and Timo Wagner. Not pictured: Michael Himpel.

experimental platform that high school students could use: it requires little investment yet still allows for relevant research.

Our central physics result is about how chirality interacts with geometry to control transport. In a circular arena, our "particles" – the chiral bristlebots – form edge currents along the boundary. We show that the stability of these currents depends on the relative handedness: if the chirality of the particle and the direction of the current are mismatched, the particles are constantly pushed into the wall and the current is very stable. In the opposite case, they tend to leave the wall and the current is volatile. This asymmetry is a direct consequence of the self-alignment and would not be present in a standard active particle model based on Brownian motion.

We then exploit this behaviour by placing a chiral obstacle shaped like a nautilus shell in the arena. This creates a bottleneck with effects that depend simultaneously on three different chiralities: the particle's own chirality, the direction of the collective motion, and the handedness of the obstacle. In the best case, transport is essentially unimpeded. In the worst case, you get pronounced jamming. This is a chirality-sensitive ratchet effect, a genuinely non-equilibrium phenomenon that could not occur in a passive system.

If I had to pick just one highlight, though, it would be the demonstration that passive geometric control of active transport is possible and that chirality is the relevant control parameter. This is not an abstract theoretical observation: we show it working in a real system with real particles. I am rather fond of the Nautilus-like geometry that we found to rectify (or at least bias) transport based on handedness. It's somewhat like a diode or a valve, where transport in one direction is strongly favoured over the other direction.

What was the most challenging aspect of this work?

The commercial bristlebots we use tend to jam at walls, so they accumulate into immobile clusters. Enclosing each bot in a circular ring solves this because the particle can now rotate within its housing and reverse direction on the spot; however, we also needed the particles to be fast and to retain their chirality. Many design choices that helped with one aspect hurt the other, and we went through 11 iterations before arriving at a design that uses a thin elastic foil as a cover.

That foil introduced a coupling between propulsion direction and actual velocity, which we had not planned for. So during the design phase, the scope of the project shifted from studying a chiral active gas to studying a chiral self-aligning active gas, which is a richer system but also one for which less theory exists.

A separate challenge is that the data you can get from our system is inherently limited. The bots run on small batteries, so each measurement lasts at most a few minutes before ageing effects become relevant, and we have a finite number of bots. We cannot simply run for longer or add more particles. This meant the analysis had to be designed to extract as much information as possible from relatively short trajectories, which is part of why we developed the adjusted velocity autocorrelation that factors out the deterministic chirality and isolates the noise contribution. There are many ideas that improve on this, but we are primarily a theoretical group and operated on limited resources.

What are your next steps?

We now have a well-characterized experimental system with known parameters, which is exactly the input that kinetic theory needs. We are working on deriving transport coefficients, diffusion constants and flow profiles from the microscopic equations of motion for chiral self-aligning particles. The goal is a quantitative, first-principles prediction that we can then compare to experimental data. That cycle of prediction and experimental test is what we want this platform to enable.

On the experimental side, one natural direction would be to vary the geometry of the rigid constraints, for example changing the shape or size of the linked structures to see how the effective energy landscape and the mode-switching behaviour respond. Another is to implement non-reciprocal interactions, meaning that particles respond differently to a neighbour depending on some internal state. That would be a significant step up in complexity and would connect to a very active theoretical debate.

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