EUROPHYSICSNEWS

The magazine of the European Physical Society

physics and **transportation**

EPS Young Minds
PONYS

Herwig Schopper
a century in physics

Zoom in on
Brownian motion

edp sciences

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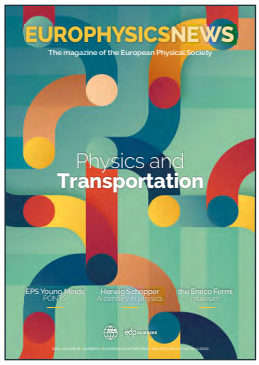

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Cover picture: Artist's impression of transportation. © iStockPhoto.

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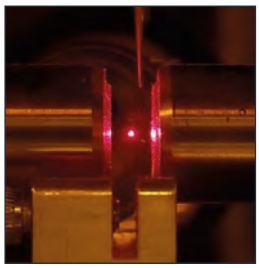
Physicist's approach to public transportation networks



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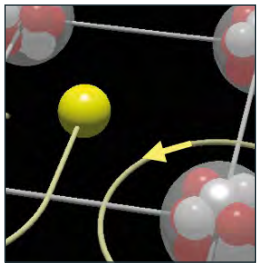
Zooming in on Brownian motion with optical trapping microscopy



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Non-equilibrium orbital angular momentum for orbitronics

EPS EDITORIAL

YOUNG MINDS

EPS NEWS

IN THE SPOTLIGHTS

FEATURES

Towards a muon collider

A muon collider could be a tool for a big jump ahead in the exploration of fundamental particles and interactions [1]. Muons can be made to collide in a relatively compact ring (figure), without limitations from synchrotron radiation. A muon collider is more effective than a proton collider with comparable energy and luminosity, because the nominal centre of mass collision energy is entirely available to produce high-energy reactions. However, the main challenge of a muon collider is the fact that muons are unstable particles making. A soon as muon bunches circulate in the accelerator complex, the products of the in-flight decays of the muons and the results of their interactions with beam line material, or the detectors themselves, will pollute the collision environment. In a meeting on 11-12 March 2024 at CERN [2] the International Muon Collider Collaboration [3] discussed the progress of R&D for a muon collider with 10 TeV energy or more in the centre of mass. ■

References

[1] C. Accettura, D. Adams, R. Agarwal *et al.*, *Eur. Phys. J. C* **83**, 864 (2023). https://doi.org/10.1140/epjc/s10052-023-11889-x

[2] https://indico.cern.ch/event/1353612/overview

[3] https://muoncollider.web.cern.ch/

Sagittarius A*

In March 2024, astronomers of the Event Horizon Telescope unveil strong magnetic fields spiraling at the edge of the central black hole of our Milky Way. ■
https://eventhorizontelescope.org/

[EPS EDITORIAL]

EPS going forward

I am honoured to have been entrusted with the Presidency of the European Physical Society for the next two years and I will do my best to contribute to its legacy.

First, I would like to pay tribute to my predecessor, Luc Bergé, for his abiding commitment to the EPS during the last three years.

During the EPS Council meeting in Porto last year, I presented my dreams for the role of EPS within Europe and the world. With the confidence of the EPS Council, these dreams should now become reality with the support of the Executive Committee and the vital collaboration of all EPS members.

During my mandate, our main objectives will be the following:

Strengthen the position of Europe

The world is facing crucial issues, for which science can help with making the right choices. Among the most urgent ones are the environmental sustainability and economic independence of Europe (*e.g.*, sources of energy, technological advances in electronics, biophysics and medical applications, quantum technologies, …). Reinforcing the collaboration with national scientific societies and maintaining a dialogue with our international partners, we will build working groups to address these crucial issues. We aim at producing detailed documents and subsequently propose to advise decision makers at the European level. Apart from the scientific, economic and social dimensions of this goal, EPS will play an important role in uniting European scientists, in a world where divisions explode.

Orient scientific policy in Europe

The scientific community in Europe, under the umbrella of EPS, should play a decisive role in European scientific policy (decisions at the level of European Commission/Parliament or national governments in Europe). We will collaborate with scientific institutions and funding bodies in Europe, reinforce the role of EPS in the European Commission, and create a database of scientific experts made available to funding bodies and agencies.

Adapt higher education to fast changing professional demands

There are fast changing professional needs due to demand for technological and soft skills in the era of artificial intelligence, combined with the constantly increasing professional mobility. The higher education degrees offered by our universities must be adapted to the current job market. In close collaboration with national societies and partners, we will document the foreseen demands and subsequently suggest suitable degree programmes to the competent authorities.

Maintain and reinforce the role of EPS in Europe and beyond

Despite efforts, the European physics community still faces a certain degree of fragmentation and EPS can help to achieve European integration. We will reinforce the existing EPS activities to support and promote actions focusing on Central, Eastern and Southern Europe. In collaboration with our international partners, we will maintain actions to provide career-enhancing opportunities for active early career scientists from developing countries across the world. In addition, we plan to strengthen regional collaboration. The "International Decade of Sciences for Sustainable Development 2024-2033" has now started, and EPS will play an active role in this United Nations programme.

Make science attractive without barriers

We will stimulate the imagination of kids, girls and boys, from a very young age, beginning at primary school. Various events are organised across all Europe and EPS can be a valuable partner.

We will support diversity, focusing on increasing the visibility of women in physics and achieving equal opportunities in the professional world.

To achieve these objectives, we need to ensure high level scientific education and secure the participation of scientists across Europe with no restriction on background, origin or gender. In addition, as EPS shares common goals with other societies, for instance in North America or Asia, we will maintain a constant dialogue with them.

I am aware that the Presidency of the European Physical Society is a demanding task with significant responsibilities. I will devote my energy and enthusiasm, as well as the time needed to turn these ambitious goals into reality. Moving ahead with new demanding challenges has been always my driving force and I am confident that, with the support of all EPS members, we will succeed. ■

■ **Mairi Sakellariadou,**
EPS President

Thirsty for science?
The Young Minds PONYS are here to "Parla Potabile"!

Serina Almassu and Paolo Di Meo – DOI: https://doi.org/10.1051/epn/2024201

The Young Minds program has public-outreach of physics and science as one of its major goals as a global connecting hub for students and early- career physicists. Every year, many of our student-run chapters (sections) surprise us with astonishing new ideas for reaching out to people and specially school students, with a range of enjoyable, inspirational, and educational activities. In this issue we are proud to spotlight this unique grand science festival organized by the Physics and Optics Naples Young Students (PONYS) in its second edition.

For the second year in a row, PONYS topped-up our expectations with the "Parla Potabile: La Scienza Per Tutt3" event which took place this time in the middle of Naples-Italy at the cultural center "Scugnizzo Liberato". As the name refers ("Speaking drinkable" as a metaphor for "make it easy"), the event aimed to offer the people of Naples and many groups of school students and kids, an extraordinary experience with scientific experiments, exhibits, shows, and games making physics as easy as never before. The scientific festival served also as a platform to bring together various associations, professors, and researchers, who were invited to showcase their own engaging outreach activities.

During the two-days festival (18-19th of April 2023), visitors got the chance to expand their knowledge of physics and science with the many interactive live-experiments organized in more than twenty captivating STEM-themed stands. The heart of the festival laid in these stands where a lot of exciting talks also took place. The stands prepared by PONYS in particular focused in the themes on Optics, Mechanics, Microwaves, and Fire; providing a series of simple experiments which aim to explain some basic concepts of physics and to spark the curiosity of the audience. Additionally, 20 collaborating associations from Federico II University presented a plethora of activities, like interactive stands, board games and talks; covering a wide spectrum of themes, such as particle physics,

mathematics, biology, and geology. This diverse array of exhibits ensured that attendees can explore and appreciate the fascinating realms of different scientific disciplines.

In a much developed design than the first edition, Parla Potabile (2022), the scientific escape room was again a hit with themed riddles in additional new rooms and stories where people had to use what they learned in all stands and their intuition to save the world! The challenges in the rooms this time were designed to be played in 5-6 people groups offering a unique adventure, fostering teamwork and critical thinking skills.

Did you think the PONYS where done with the fun? Then wait to hear about the "Quantum Game"(1) . Developed by the IBM researchers, the game Entanglion continued to steal people's attention in this edition as well. It is a cooperative board game based on quantum computation. It offers an interactive and educational experience, bridging the gap between theoretical concepts and practical applications. They were not finished here, because this year's special new game "AEON – The Emergence of life"(2) took the players to think at a whole different level. It was developed by scientists in the framework of the CRC 235 "Emergence of Life" funded by the Deutsche Forschungsgemeinschaft (DFG) and published by the Deutsches Museum. It's a board game about the origin of life on early Earth, and for such topic the joining associations specialized in biology helped explain the fundamentals of life, while our PONYS members dealt with the importance of energy and reaction in the story.

The limits of "interactive" festival did not stop here. The electronics lab was a great addition that gave people the true hands-on experience with basic concepts of electromagnetism and circuits. They got the chance as well to build their own small electroscope which they kept as a memory of the day.

Last but not least, and since children and school student are the team's focus to inspire and spark science in their little hearts and minds, the PONYS members volunteered to present a thirty minutes show, in which they read fairy tails punctuated by little experiments of acoustic and optics to discover the 3D world and dimensionality. The tales were made for the children to extrapolate the scientific concept, which is further explained and deepened with a conjugate experiment.

The first day could not end for PONYS and attendees without dancing, and catching up on the music of the Scalzbanda band whose members are oriented to promote inclusion and social integration through music.

The event was concluded in the second day with the rhythms of the the Scugnizzo Liberato's music band "Basaglia" while enjoying an exhibition which created a moment of connection between the audience, all the present volunteers and professors.

We cannot be more proud of and thankful for PONYS and all other collaborating associations for this truly unforgettable science festival that must have watered the visitors' thirst for science and discoveries. We look eagerly to the third edition of Parla Potabile, and for the great science to be presented. ■

References

[1] https://entanglion.github.io/

(2) https://aeon-game.eu/about/

First impressions of the EPS Forum and Council meeting

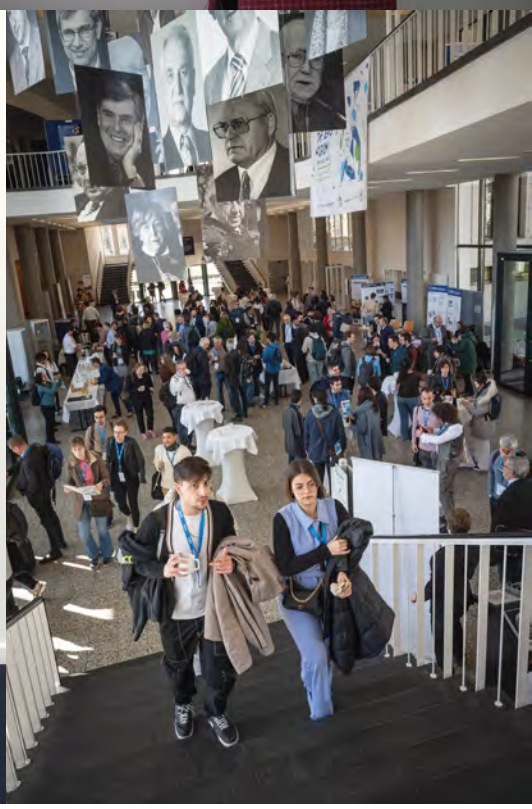
The EPS Forum and Council meeting were held at the Freie Universität Berlin 25th to 27th of March. This lively event brought together physicists from 35 separate countries and involved over 200 students in a series of conference sessions, round tables and formal and informal networking.

▼ Prof. Klaus von Klitzing (Nobel Laureate) discusses with student attendees.

▼ Prof. Anne L'Huillier (Nobel Laureate) presenting her Nobel Prize research.

▲ Prof. Stefan Hell (Nobel Laurea te) presents his latest work.

▲ Luc Bergé hands over the EPS presidency to Mairi Sakellariadou.



▲ Networking during the coffee breaks.

Photos Bernd Wannenmacher and Gina Gunaratnam

A century in physics

– DOI: 10.1051/epn/2024203

Herwig Schopper, EPS President from 1995 to 1997, recently celebrated his 100th birthday.

Herwig Schopper was born on 28 February 1924 in Lanškroun (Landskron), in a German-speaking region of what is now the Czech Republic. After an idyllic childhood, he found himself in turbulent times: in 1938 his hometown was annexed by Germany following the Munich Agreement, and in 1942 he was drafted into the German military. Fortunately, his technical talent was already evident, and he was able to work on telecommunications and radar, which saved him from being deployed to the front lines. Shortly after the end of World War II, Herwig began studying physics at the University of Hamburg. After receiving his PhD in 1951, he spent a period as research assistant with Lise Meitner in Stockholm. In 1956-57, he worked with Otto Frisch in Cambridge, and he obtained his "Habilitation" at the University of Erlangen in 1957.

Most of Herwig's early work was devoted to experimental nuclear physics, where he made landmark contributions to the understanding of parity violation in weak interactions. He developed the first polarized proton source and, with the help of circularly polarized gamma rays, demonstrated the opposite helicities of neutrinos and antineutrinos. A year with Robert R. Wilson at Cornell in 1960-61 marked his first encounter with particle physics. In his professorships in Mainz, Karlsruhe, and later Hamburg, he made a lasting impact on shaping the German research landscape. Particularly productive were his years Karlsruhe, where he initiated a vigorous R&D program on superconducting RF cavities, essential today for the construction of large particle accelerators, and during a stay at CERN, he developed the first hadron calorimeter – still an integral part of most particle physics experiments today.

Herwig Schopper's talent and success as a science administrator did not go unnoticed internationally. In 1970, he was appointed Leader of the CERN Nuclear Physics Division and in 1973, chairman of the DESY directorate. His DESY years were marked by the construction of the PETRA electron-positron storage ring, which led to the discovery of the gluon, and by DESY's diversification into synchrotron radiation science with HASYLAB. In 1981, he became Director-General of CERN, a position he held until 1988. His foresight in insisting on a 27 rather than a 22 km tunnel for the LEP electron-positron collider paved the way for the Large Hadron Collider (LHC), which was later installed in the same tunnel. After his term of office at CERN and retirement from the University of Hamburg, Herwig did not rest on his laurels but embarked on a new career as science diplomat that keeps him active until this day. From 1992-94, he was president of the German Physical Society and managed the integration of the Physical Society of the former German Democratic Republic, the first merger of two major scientific societies following the reunification of Germany. In 1995-97, Herwig served as president of the EPS, where we remember him mostly as the president who steered our society calmly through a tumultuous period when the seat and the secretariat were moved from Geneva to Mulhouse, saving the EPS from a severe political and financial crisis and building a new basis for the universal representation of European physicists.

▲ Herwig Schopper in 1982, during his term as Director-General of CERN in front of a map of the LEP tunnel, which today houses the Large Hadron Collider.

In the following years, Herwig held several important positions at UNESCO, including chairing the advisory committee for the International Basic Science Programme (2003-2009). Guided by his strong personal vision of "science for peace", he embarked on his most ambitious science diplomacy project: the SESAME light source in the middle east under the auspices of UNESCO and built on the CERN model of international cooperation and governance. SESAME, which includes Israel and Palestine amongst its members, was established in Jordan and formally inaugurated in 2017. It continues to deliver world-class results, notwithstanding the current political turmoil in the region.

On 1 March 2024, Herwig's unique personality and countless achievements were celebrated at CERN with a festive symposium, "A century in physics", by a prestigious line-up of speakers who had witnessed different stages of his life and career. His daughter Doris, herself a physician, disclosed Herwig's secrets for reaching the age of 100: the right genes (his mother reached the age of 98!), a healthy lifestyle, a passion for science and music, and – most important – lifelong curiosity. Herwig himself announced his next target: reaching the age of 105. The EPS congratulates and wishes him good luck on the journey to this next milestone – and beyond! ■

James Gillies, Rolf Heuer and Rüdiger Voss *(CERN)*

Reference

[1] Herwig Schopper and James Gillies: *Herwig Schopper – Scientist and Diplomat in a Changing World*, Springer 2024: https://link.springer.com/book/10.1007/978-3-031-51042-7 (Open Access).

[1] https://indico.cern.ch/event/1366175/timetable

Past, present and future of the Enrico Fermi museum

– DOI: 10.1051/epn/2024202

The Enrico Fermi Museum[1] is a journey in the life and scientific discoveries of Enrico Fermi, defined as 'a giant' of the physics of the 20th century. It is an emotional journey in which the visitors can immerse themself to discover and understand how the explorations of the matter were intertwined with the historical events of that period.

The research and experiments carried out within the walls of Panisperna cannot be disjointed from the events that characterized the 20th century. Born as a moving exhibition, first exposed in Genoa in 2015, and then set up in Bologna the following year, in 2019 the Museum found its permanent home in Rome. The building of via Panisperna was the seat of the Royal Institute of Physics of the University of Rome, inaugurated in the 1880s under the direction of the physics Pietro Blaserna. It represented the first Italian "practical school" of physics, with a revolutionary teaching idea: the laboratory becomes the protagonist. No longer 'ex-cathedra' lessons were carried on, but students could independently use scientific tools and carry out research activities. Half a century later, Enrico Fermi and his collaborators conducted here the famous experiments on radioactivity induced by neutrons. These fundamental experiments allowed to understand the structure of the atomic nucleus which earned Fermi the Nobel Prize for Physics in 1938.

Today the building, returned after a long and philological restoration at the end of 2018, houses the 'Enrico Fermi' Study and Research Center (CREF) in addition to the Museum. A young institution with a dual mission: on the one hand, in the spirit that characterized Enrico Fermi's activities, it aims at developing original and interdisciplinary lines of research; on the other hand, thanks to the Museum and strong outreach activity, it intends to offer wide dissemination and communication of Enrico Fermi's life and discoveries, and, in general, of the historical and scientific events that took place here, in a period in which Italian physics was at the center of the international science panoramaThrough the identification of a dozen steps, combining traditional objects and panels with modern multimedia technologies, the most significant stages of Fermi's life and discoveries are presented.

▲ Enrico Fermi Museum, entrance.

At the end of 2022, the Museum also acquired, through a private donation, two autograph letters by Enrico Fermi, dated 1947 and 1954, sent, the first from Chicago, the second from Como to his elementary school teacher. In the autumn of 2023, the entrance was redesigned, and a timeline was installed in Italian and English with the most important stages in the history of via Panisperna.

Located in the internal courtyard of the complex, as an integral part of the Museum itinerary, there is the 'Goldfish Fountain', the first Italian historical site of the European Physical Society inaugurated in 2012. Of particular interest is the access staircase, immortalized in an iconic image from 1931 taken at the first International Congress of Nuclear Physics organized by Fermi, with Guglielmo Marconi as honorary president and Orso Mario Corbino as effective president. That was the opportunity for the 'Panisperna's boys' to appear on the international scene for the first time.

Reopened in March 2022, in the aftermath of the COVID-19 pandemic, today the Enrico Fermi Museum is experiencing exceptional success and notoriety. In March 2022, a technical-scientific committee was officially established made up of researchers from CREF that deals with the organization and management of the Museum. Today, we aim at placing teaching at the center of our activities, in a continuous dialogue with the history and diffusion of scientific culture. The focus of the proposals and projects involving the Museum are the themes of communication, accessibility, and inclusiveness, with the fundamental issues of research and conservation. We therefore support stimulating and engaging learning paths; we certainly share the model of "open education", through an integrated and multidisciplinary approach that can improve the learning experiences of everyone, starting from students. Museum experiences are extraordinarily memorable and remain imprinted in the memory for a long time, thus becoming a driving force for learning.

We aim at creating itineraries for the Museum, which is a place of historical memory, as a unique experience, in a continuous dialogue between history, and

[1] www.museum.cref.it

dissemination of science.

Schools are the Enrico Fermi Museum's target audience, but the exhibition is open to all.

In 2023, over 3500 visitors attendes the Musem, of which schools represented over 75%. These data are extremely significant: the Museum is open to schools one morning a week and welcomes the public once a month, on special Open Days. These results are made possible by the continuous and passionate work of the CREF research staff who are making the Enrico Fermi Museum possible for ever larger groups of visitors, guiding them in the Museum.

The future goal is to welcome an ever-increasing number of visitors with an adequate training offer of high educational value. We aim at making the Museum a place of dialogue and exchange, where different but complementary skills and professionalism can meet and collaborate to create learning paths. We are starting to create a network of contacts and collaborations to increasingly insert the Museum within a network for the diffusion of scientific museology and to create connections with the institutions and interested operators, through an exchange of opinions and news.

Since October 2023, the Museum has been officially a member of the National Association of Scientific Museums (ANMS). A dialogue in which the Museum's visitors are the protagonists, often represented by young students who are organizing and planning their own choices to fit into society. Future citizens must increasingly be able to approach science critically and consciously to orient themselves in our knowledge society. An awareness that brings with it curiosity, open-mindedness, and a critical spirit. ■

Miriam Focaccia
Museo Storico della Fisica e Centro Studi e Ricerche 'Enrico Fermi'

▼ Enrico Fermi Museum's interactive fountain.

Access to burgeoning quantum technology field could be widened by open master educational model

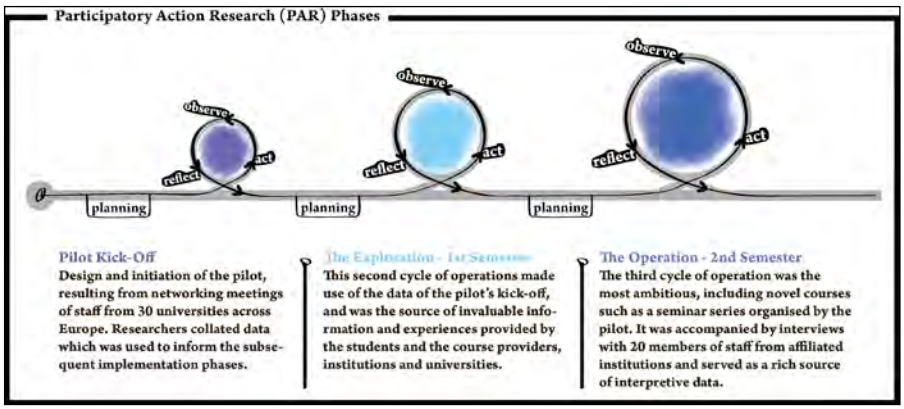
– DOI: 10.1051/epn/2024203

Quantum technology offers major societal benefits, but its growth depends on the supply of a qualified workforce.

Quantum Technology is based on the engineering of devices that make use of the quantum properties of matter. One of the most prominent avenues of this technology is quantum computing, which may be able to leverage quantum bits (qubits) to perform calculations more efficiently than classical computers. Technology with this "quantum advantage" will also operate in the background of our lives, providing ultra-secure communications and high-precision sensors and clocks. The applications of quantum technology have led to a boom in investment worldwide; with this technology expected to have a huge societal impact. But to maintain this burgeoning industry, it is crucial that graduates with training in quantum technology enter the workforce. Plus, for the European Union to stay ahead in the quantum tech race, the workforce must assemble on a much shorter timescale than the 3 to 5 years (or more) of a PhD program.

In a new paper in *EPJ Quantum Technology*, author Simon Goorney, from Aarhus University, Denmark, and his co-authors describe the development of Open Master, a new form of transnational education, that could serve as a means of enhancing accessibility to specialist expertise in quantum technology. The ultimate goal of the pilot scheme, which operated over the academic year of 2021 to 2022, was to use the experience to conceptualise a model for the future of quantum technology education.

Through research conducted during the setup and operation of a pan-European pilot project dubbed the QTEdu Open Master (QTOM), the team examined the viability of this educational model and its capacity to offer flexible learning opportunities to STEM Master's students through the setup and year-long operation of an online course exchange platform. "QTOM was an experimental pilot project of the Quantum Flagship's education community. It was run by a group of volunteers from universities across Europe, with the goal being to explore and develop a model for the future of higher education in Quantum Technology," Goorney said. "QTOM was a great success, as the model, the *open master*, has formed the basis of a 17.6 million Euro project in which many new Master's programs are being developed." Goorney explained that the open master model is characterised by an ecosystem of courses shared across borders, accessible for students of any STEM (or even non-STEM) degree program to study for credit. "It is the 'for credit' part which was the greatest challenge for QTOM because the majority of students were taking courses from outside of their university, even their country," he continued. "They then had to go back to their local representative, who had to find a way to grant them credits for studying in this format. We call that process *local accreditation*, referring to the process of generating credit for external courses."



▲ The operation of the Open Master pilot scheme. Credit: S. Goorney *et al.*, *EPJ Quantum Technology*, (2024)

According to Goorney, the creativity of institutions and teaching staff in creating these local accreditation models came as a big surprise, demonstrating how large of a factor in the success of QTOM was the degree of support provided to the partners by their departments and administration. The authors say that the central message of the QTOM pilot is that the very process of engaging with such an international experiment generates value independent purely of its degree of success. In their case, it may have helped in some way towards building the European quantum industry. ■

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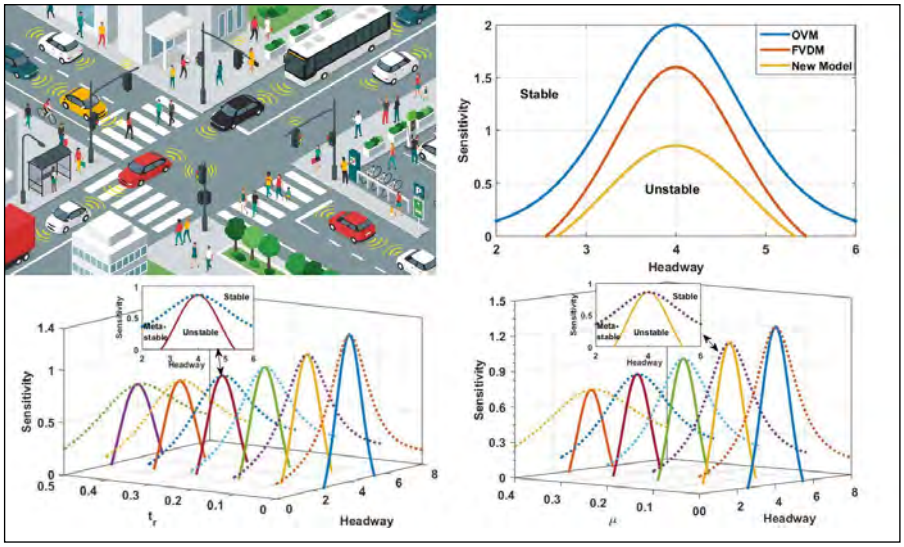
Modeling traffic flow thanks to real time communication between vehicles

– DOI: 10.1051/epn/2024204

Since quite few years, automotive manufacturers have implemented vehicular communication systems such as V2X technology enabling communication from the vehicle-to-many entities such as infrastructures, networks, other vehicles, pedestrians or devices.

As such, V2X technology plays a pivotal role in intelligent transportation systems by providing real-time updates on nearby vehicle movements, helping drivers in maintaining traffic flow difference between actual and anticipated traffic information. Moreover, drivers in the traffic system manage vehicles and need some time to judge and decide the driving state of the vehicles in front of them. Then, V2X systems provide information to the driver with real-time status of the traffic flow and an advance reaction time before the vehicle in front starts moving. Also, the optimal velocity in real traffic reflects the driver's expectations about traffic behavior, which obviously has a significant influence on traffic flow.



▲ Top left: V2X environment with vehicle-to-many communication in yellow; Top right: Comparison between the new model with existing models; Bottom: headway phase diagrams in model parameters space with t_r the driver's advanced reaction time and μ the response coefficient corresponding to optimal velocity deviation.

Although it has not been examined in earlier car-following models, there is always some difference between the stable optimal speed and the driver's optimal speed which is referred to as the optimal velocity deviation effect. Drivers may not consistently maintain their ideal speeds because of several factors, including traffic, erratic weather and personal preferences. The driver's optimal speed refers to the optimal speed chosen drivers based on their perception of the headway distance to the vehicle in front and it is often influenced by factors such as safety, comfort and the desire to maintain a reasonable distance from the lead vehicle. This speed is subjective and can vary from one driver to another. On the other hand, the stable optimal speed represents the speed that would lead to a stable traffic flow and minimise congestion when all drivers in the traffic stream follow the same car-following model and react similarly to the traffic conditions. Thus, drivers typically observe and respond to the behaviour of vehicles ahead, thereby influencing traffic dynamics. With the aim of optimising traffic flow in a general set-up and better understanding the effect of these two parameters, we propose a car-following model which makes use of this observation by considering the driver's advanced reaction time and optimal deviation within a V2X setting (Figure 1, top left).

The integration of driver reaction time and optimal velocity deviation has proven to be crucial for predicting traffic variations and making timely speed adjustments, resulting in a smoother traffic flow with fewer unexpected interruptions. Indeed, this approach promotes safe driving conditions by allowing vehicles to anticipate potential risks and optimize their path accordingly. Our study[1] focuses on the driver's perception of running speed influenced by the optimal velocity deviation effect and introduces a novel car-following model that incorporates the driver's advance reaction time in both optimal and local velocity variations within a V2X environment. By comparing this model with conventional OV [2] and FVD[3] models, the research highlights a significant enhancement in traffic flow stability. Linear and nonlinear stability analyses are conducted to determine the neutral and coexisting curves and the stability condition of the model. Results indicate that increased optimal velocity deviation and advance reaction time contribute to improve traffic stability leading to a notable reduction in congestion, as demonstrated in numerical simulations, which align closely with theoretical predictions (Figure 1).

Ultimately, this research contributes to advancing intelligent transportation systems, offering insights into optimizing traffic flow dynamics and mitigating congestion challenges. ■

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The physics of complex systems: from traffic jams to nanoscale transport phenomena

by Christophe Rossel
EPS TIG Chair – DOI: 10.1051/epn/2024205

Understanding transport phenomena is essential in various fields of physics and engineering including thermodynamics, fluid dynamics, material science, optics, *etc.* By studying how quantities such as mass, charge, energy, momentum or angular momentum are transported in various systems, scientists can develop mathematical models to predict, simulate and control specific processes. Particularly interesting is the concept of conduction that refers to the transfer of energy through the movement of particles in a medium or in vacuum. Three different types of classical behaviour, depending on the type of energy being transferred are heat or thermal conduction, electrical conduction and acoustic conduction. The Boltzmann transport theory and statistical physics allow us to develop microscopic models for macroscopic quantities such as mobility, diffusion coefficient, and conductivity in materials. Of course, today the field of transport is much more complex if one considers quantum mechanics with the quantisation of physical properties, relativity and space-time concept, quantum entanglement, uncertainty principle and wave-particle duality that apply in quantum chemistry, quantum field theory, quantum technology, and quantum information science.

In this EPN issue large scale transportation such as the movement of humans, goods, vehicles on land as well as motion of particles at the nanometric scale are presented.

In *Traffic flow from a physics perspective,* A. Schadschneider describes collective phenomena in nonequilibrium systems such as traffic jams and pedestrian dynamics. It is a very interesting topic because most likely we all experience nerve-breaking long lanes on the road and the stress in crowd streams.

In his contribution, *A physicist's approach to public transportation networks*, Y. Holovatch shows how statistical analysis and data processing work when dealing with a complex system of many interacting agents "non-physical" in nature.

V. Rodriguez-Franco *et al.* bring us to the molecular level by describing the *Controlled transport by molecular machines: exploring biological motors and their physics.* Biological machines are fascinating objects that play a crucial role in a variety of cellular processes. It is exciting to read how it is possible to manipulate and monitor the motion of molecular motors that are a paradigm for mass, energy, and information transport processes in the cell.

Certainly, most of us have performed once in our studies a Browian motion experiment. In *Zooming in on Brownian motion with optical trapping microscopy*, M. G. Raizen and colleagues explain how ultra-precise measurements of Brownian motion in various fluids can be done and how picosecond pulsed lasers can be used to measure the effects of flow compressibility on Brownian particles.

With N*on-equilibrium orbital angular momentum for orbitronics*, D. Go *et al.* brings us to the manipulation of magnetisation by electrical current in spintronics and the description of devices such as the spintronic memory based on the giant and tunneling magnetoresistance effects in heterostructures. Spintronics research has focused primarily on the spin degree of freedom, but the authors show that in non-equilibrium the orbital angular momentum of electrons can play an important role, leading to a new interdisciplinary field of research called "orbitronics".

I wish you an interesting reading experience. ■

TRAFFIC FLOW FROM A PHYSICS PERSPECTIVE

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DOI: https://doi.org/10.1051/epn/2024206

Physicists have been interested in traffic for a long time for various reasons. On the one hand, we all participate in traffic as pedestrians or drivers. On the other hand, traffic systems exhibit interesting, and sometimes counter-intuitive, collective phenomena. They are examples for nonequilibrium systems which allows to apply and test methods developed in statistical physics.

Meanwhile they are an important facet of active matter systems, notably because they are macroscopic systems for which extensive data is available. On the practical side there is hope that efficiency and safety in traffic can be improved when underlying mechanisms are better understood.

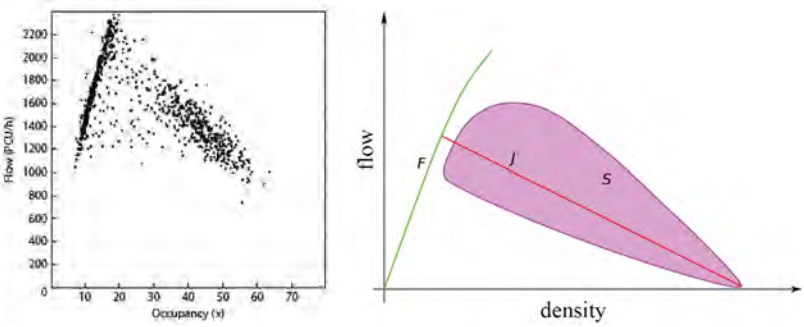
The interest of physicists in traffic goes back to the 1950ies. Well-known researchers like R.B. Potts have made important contributions and I. Prigogine even wrote a book ("Kinetic Theory of Vehicular Traffic" with R.C. Herman) about the application of statistical mechanics to traffic. Currently pedestrian and crowd dynamics has become the focus of attention, not at least due to several crowd disasters reported in the media. Pedestrian dynamics is more challenging than vehicular traffic where the behavior is strongly restricted by traffic rules (lanes!) and physics (inertia!) and can mostly be considered as (quasi-)one-dimensional. In pedestrian motion, agents move in different directions, *i.e.*, the motion is generically two-dimensional, while at the same time direction of motion and speed can change almost instantaneously.

Vehicular traffic

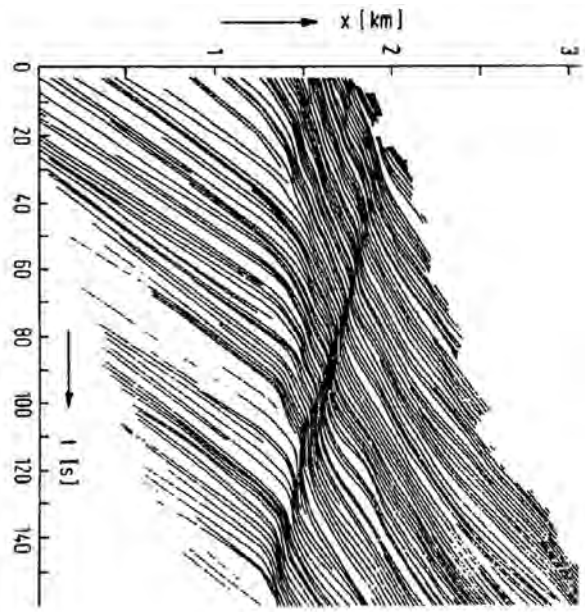
The arguably most important quantity in every traffic system is the fundamental diagram. It depicts the dependence of traffic flow (or current, in physics terminology) on vehicle density. The typical form is shown in Fig. 1. Two different regimes can be distinguished. For small densities the flow increases linearly with density. The slope in this free flow regime is given by the desired velocities of the drivers, *e.g.*, a speed limit. All cars can move at maximal allowed velocity and interactions are rare. For higher densities the flow decreases with increasing density. In this jammed (or congested) regime interactions become relevant and lead to the formation of jams. The dominating driver behavior here is the avoidance of accidents.

The fundamental diagram exhibits a fundamental dilemma. Drivers prefer small densities where one can drive as fast as possible. However, traffic engineers want to optimize flow, but the largest flow (typically larger than 2000 vehicles/h) is reached typically at some finite density ρ_c = 25-30 vehicles/km.

A familiar collective phenomenon are "phantom traffic jams" (Fig. 2). They appear to have no obvious reason like accidents, road construction or lane reduction. Therefore, they should not exist since all drivers try to move as fast as possible! What is their origin then? The consensus is that these jams are caused by a chain reaction triggered by driving imperfections. A fast driver approaching a slower car brakes to avoid an accident, thereby reducing velocity more than necessary. This triggers further braking maneuvers of following cars. If the density is sufficiently high a chain reaction ensues which finally can force ● ● ●



▲ **FIG. 1: Left:** Empirical fundamental of a Canadian highway. Each point corresponds to an average over 5 minutes. At small densities, the flow increases linearly (free flow) whereas at higher densities it decreases with increasing density. **Right:** Schematic fundamental diagram. The free flow, jammed and synchronized phases are indicated by "F", "J" and "S", respectively.



▸ **FIG. 2:** Empirical trajectories showing formation of a phantom traffic jam. The jam front moves at constant velocity oppositely to the driving direction.

a car to stop. Ironically the driver responsible for the formation of this jam will not even notice! Therefore, there is no incentive to change behavior. This mechanism has been not only been observed on real highways (Fig. 2), but also in controlled experiments.

Although spontaneous traffic jams have been observed in many different systems, there is one notable exception, namely ant trails. Using pheromones, many ant species create a road network that has strong similarities with human-build highways. However, they are able to avoid spontaneous jam formation even at extremely high densities.

A closer look exhibits additional features of the fundamental diagram. In a density interval near ρ_c the flow may not be uniquely determined by the density. The states with higher flow are not stable and can decay into jammed states under perturbations. For densities beyond ρ_c the measurement data show a strong scattering (Fig. 1). This has been associated with a new phase, termed somewhat misleadingly "synchronized traffic". Here the desire for driving comfort determines the behavior, *e.g.*, avoiding abrupt changes in speed, which leads to the formation of platoons of cars moving at similar velocities. Depending on the structure of the platoons and their speed, different flows can be realized and no functional relationship between flow and densities exists.

What can we do?

Will new technology help to reduce traffic problems? Historically, the main cure for traffic congestion was building new roads or expanding existing ones. This is usually not very effective in the long-term, which is known as *Paradox of Traffic or Downs-Thomson Paradox*. New or expanded roads are attractive at first because congestion and travel times are reduced. This creates new demand. Using the car becomes more attractive and eventually the increased demand will lead to similar congestion levels than before.

Braess Paradox describes the counter-intuitive situation when improving the capacity of a network by new fast roads leads to an overall increase of travel times. Since drivers try to minimize their travel time this quickly leads to congestion of the new road. This is different from the Downs-Thomson Paradox which is based on the increase of the overall demand whereas in Braess Paradox the demand is only redistributed. Braess' Paradox also occurs in other transportation networks, like power grids, and physical systems such as mechanical or electrical networks.

Meanwhile modern cars are equipped with many sensors and driver-assistance systems, like *Adaptive Cruise Control* (ACC). ACC systems can adjust the velocity automatically according to the traffic situation, *e.g.*, based on the distance to the car ahead. This not only improves safety, but helps to avoid chain reactions leading to jams as ACC systems are able to adjust speed much more precisely than a human driver. Thus, it will help to reduce the number of jams, even if not all vehicles are equipped with ACC. Already a market penetration of 20% will reduce the number of jams and accidents substantially.

Such systems are even more effective when combined with *Car-To-X communication* which connects cars with other cars and infrastructure like traffic signals. Then information about the traffic situation ahead can be transmitted by cars moving in the opposite direction. Up-to-date information is already provided on webpages based on data from counting loops and computer simulations to interpolate the state at locations without detectors. www.verkehr.nrw displays the current state of the Autobahn network of North Rhine-Westphalia where the simulations also provide predictions for the evolution of the state within the next hour.

In contrast to weather forecasts, traffic forecasts become invalid when made publicly available. Users might change their travel decision, *e.g.*, by choosing a different route or starting time, or even use a different mode of transport. This is currently the main obstacle for reliable traffic forecasts! One has to understand in more detail how users react to predictions.

Pedestrian and crowd dynamics

Nowadays the physics of vehicular traffic seems well understood and besides some details there is consensus about the relevant mechanisms even on a quantitative level. This is rather different for the dynamics of pedestrian crowds which have become a focus of attention. Pedestrian dynamics is more complex than vehicular traffic for several reasons. The motion is genuinely two-dimensional with agents moving in different directions. Additionally, it is not strongly restricted by traffic rules, but conventions and habits which might

depend on cultural background *etc.* This makes the description of crowds more challenging, but also more interesting. It leads to several new collective phenomena not observed in vehicular traffic, *e.g.*, the dynamic formation of lanes in pedestrian streams that move in opposite directions (Fig. 3).

Several crowd disasters in recent years have shown that a better understanding of pedestrian dynamics is needed. It will help to improve not only safety in public areas or large-scale event, like music festivals or sports events, but also comfort. In order to develop models for planning of events, optimization of evacuation strategies reliable quantitative data is needed. In contrast to the situation in vehicular traffic, where accurate data can be obtained *e.g.*, using counting loops, field observations of pedestrian motion are much more difficult. Therefore, laboratory experiments have become an important tool. Experiments with up to 1000 test persons have been performed in simple, but characteristic scenarios, *e.g.*, corridors, bottlenecks *etc.* (Fig. 3). The data is used to validate and calibrate models which than allows to make quantitative predictions even in more complex scenarios based on computer simulations. This close interplay between experiment and theory has been established not least due to the influence of physicists active in the field.

Laboratory experiments help to improve legal guidelines for mass events. For quite some time even simple scenarios were not fully understood, *e.g.*, how the flow through a corridor varies with its width. Two competing results were both used as basis for guidelines in different countries. One assumed a linear increase of flow with width whereas the other predicted, based on lane formation, a stepwise increase. Experiments showed that the flow indeed increases continuously which is now used *e.g.* in all German guidelines.

For the fundamental diagram there is still no consensus on a quantitative level. Experiments show large differences *e.g.*, in the maximal flow or the critical density. Several influencing factors have been identified (density definition, cultural background of test group, psychological effects,...), but a full understanding is still missing.

As an application, so-called evacuation assistants are developed, *e.g.*, for evacuations of sports arenas. Empirical data for the distribution of spectators in the stadium and information about the availability of exit routes are used to perform faster-than-real-time computer simulations of an evacuation in these circumstances. This information is provided to the decision makers (safety personal, fire fighters,...) allowing them to redirect pedestrian streams to avoid crowding at critical points which is a considerable safety risk.

Outlook

The physics of vehicular traffic is rather well understood. Currently models are used to investigate the effects of CAV, Car2X communication *etc.* which (hopefully) not too far in the future will lead to a substantial reduction of congestion and accidents. For pedestrian dynamics, there are still several open problems. This is partially related to the problems in acquiring accurate empirical data, but also due to the relevance of psychological aspects as pedestrian motion is much less determined by physics than vehicular motion (small inertia effects).

Besides human traffic, other biological traffic-like systems show interesting new features. Ants are able to avoid spontaneous jams, but also intracellular transport by molecular motors has attracted a lot of interest, not at least through possible connections with diseases like Alzheimer's or ALS. Therefore, there is still a lot to do in this fascinating field. ■

About the Author

Andreas Schadschneider has obtained his Ph.D. in 1991 working in theoretical solid state physics. He is professor at the Institute for Theoretical Physics and the Institute for Physics Education of the University of Cologne. His main research interests are related to the fundamental physics underlying all kinds of traffic systems (vehicles, pedestrians, biological systems,...)

▾ **FIG. 3:** Pedestrian experiments: **Left:** flow through a bottleneck; **Right:** lane formation in counterflow. The white hats are needed for automated tracking of the pedestrians when extracting the trajectories from video.

A PHYSICIST'S APPROACH TO PUBLIC TRANSPORTATION NETWORKS

Yurij Holovatch – DOI: https://doi.org/10.1051/epn/2024207

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The above picture shows public transportation on the Halyts'ka Square in my home city of Lviv, Ukraine. One can date the photo simply by having a closer look at the trams with the knowledge that the electric tram appeared in Lviv during 1894 and the horse tram ceased to exist by 1908.

▲ FIG. 1: Public transportation hub of two tram lines in Lviv at the turn of century: too early for complex networks.

If physicists contributed to public transportation in those days, it was only as passengers or directly or indirectly related to the design of electric or mechanical parts of the transport vehicles. Daily use of public transport is an old practice that has shifted today from the cabriolets and horse-drawn trams to subways, buses, modern trolleybuses, trams, *etc.* As such the contribution of physics and physicists has changed to analyzing inherent statistical features and collective processes in public transportation networks and this new phenomenon will be discussed in this article.

Complex systems and complex networks

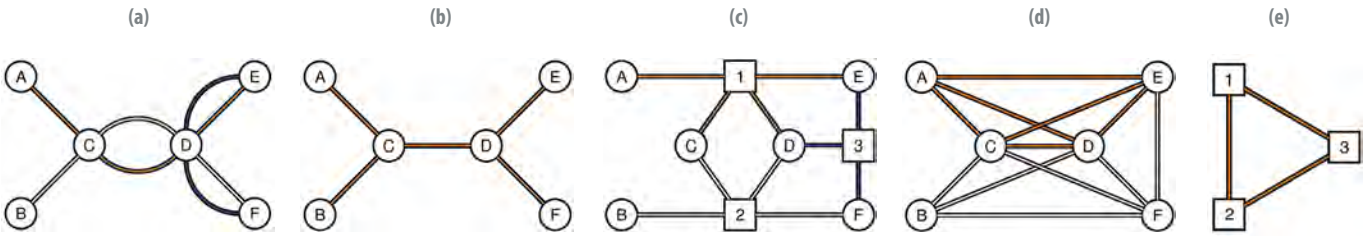
The research we will talk about is entirely due to the intensification of our daily lives and new technologies. Evidence of this is not only the object of analysis itself - the emergence of large public transportation networks (PTNs) - but also the creation of computer technologies, which, on the one hand, allow collecting and storing data about these networks, and, on the other hand, enable big data analysis. Typical analysis of a large amount of data results in measuring statistical properties of a PTN as a whole as well as in quantitative characterization of various processes going on such networks. Very soon it became clear that PTN collective properties do not follow trivially from the behaviors of the network constituents. In turn, it called for theoretical insights aimed at explaining emergent properties of complex transportation networks. In this sense, the study of the properties of large PTNs is a part of a larger process taking place in modern science and, more generally, in modern culture - awareness and conceptualization of the notion of complexity and attempts at its quantitative analysis [1].

Just as mathematics is the language of physics as well as of many other natural sciences (and now, increasingly, of social sciences and even of the humanities), the lingua franca of complexity science is an emerging science of complex networks, *i.e.* of graphs with non-trivial topological features [2]. In the formal description of a complex system of interacting agents, each agent is assigned a vertex (node) of such a graph-network, while the edges (links) of the graph reflect different types of interactions between the agents. It would seem obvious that when constructing such a complex network to describe the PTN, its nodes should be matched with PTN stations, and links between nodes-stations would mean the availability of transport connections between them. Such links can be multiple, if the stations are connected by several routes, or directed, indicating the direction of movement. However, such an interpretation of a PTN in the form of a so-called L-space graph [3] is not the only possible one. Fig. 2 shows several other possible graph interpretations of a PTN. Obviously, only the graphs of Figs. 2a, 2b are embedded in a 2D space, the rest do not share properties of the spatial networks [4]. Moreover, sometimes weight is introduced to network edges (*e.g.* to express the traffic load) or multilayer network interpretations are used to describe situations when it is important to discriminate between different types of transportation. All in all, the journey that began with the application of complex-network tools to analyze the Boston subway and Vienna U-Bahn with $N = 124$ and N=76 stations [5], continues today, when entire megalopolis public transportation systems are considered (see Fig. 3b) and it becomes difficult to find a city on the world map where such tools have not yet been applied to analyze its PTN. Leaving aside the purely technological and applied aspects of such research, let's focus on the application of the methods and concepts of physics here.

Statistical physics

Whereas complex network science serves as an universal language that allows for the description of various complex systems, PTNs being one of them, the methodological and conceptual framework of such analysis originates from many traditional disciplines, statistical physics being probably one of the most important ingredients. It equips such analysis with an arsenal of tools and concepts traditionally used in physics to describe collective phenomena. Below we will aim to show how the physical perspective enriches statistical analysis and data processing when dealing with a complex system of many interacting agents "non-physical" in nature. Among many examples, let us concentrate on universality and scaling, robustness and percolation, fractality and self-avoiding walk statistics as PTN inherent features.

Traditionally, the physical approach consists in distinguishing certain universal features, common governing laws, among the diversity of surrounding phenomena. Quests for such universal characteristics of PTNs for cities that differ in their history, geographical location, culture, and economy has been carried out too. It has become clear that despite the obvious diversity of such networks, being characterized as a whole they share a number of common features. In particular, it concerns their node degree distributions $P(k)$ - this function gives the probability that an arbitrary chosen node of the network has k links. It turns out that not only do such distributions have a common shape, but also in certain intervals they are characterized by a power-law decay. Due to obvious ● ● ●



▼ **FIG. 2:** **(a)** a simple public transport map. Stations A-F are serviced by routes No 1 (orange), No 2 (white), and No 3 (blue). **(b)** L-space graph. **(c)** B-space bipartite graph. Route nodes are shown as squares. **(d)** P-space graph, the complete subgraph corresponding to route No 1 is highlighted (shaded orange). **(e)** C-space graph of routes [3].

spatial constraints, power-law behavior can be observed in the L-space (see Fig. 2b) for rather low values of k. In other representations (*e.g.* in P-space, where all stations that belong to a given route are represented by a complete graph, Fig. 2d, or in the coarse-grained L-space representation) the construction of a network enables much higher node degrees and the power-law dependency has been observed for a wider region of k. Complex networks that obey power-law $P(k)$ dependency are *scale-free* [2], they characterize the structure of many natural and man-made systems and have a number of unusual properties. In particular, they are robust to accidental (random) damage to their structure but are vulnerable to targeted attacks.

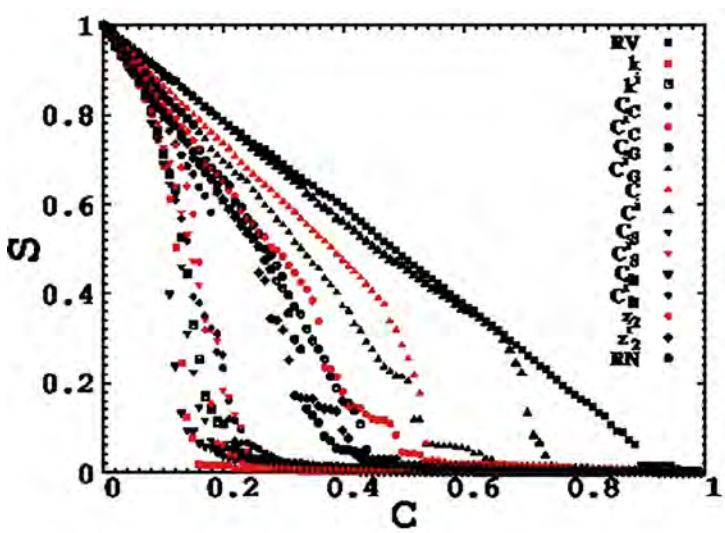
Speaking about PTN reaction on random failures and targeted attacks it is to place mention of the percolation phenomenon, as far as both phenomena have a lot in common. In the problem of (lattice) percolation one considers the possibility of the existence of a spanning percolation cluster, provided that lattice components, nodes or links, are occupied with a certain probability. When parts of the network, such as its nodes or links, cease to function, an analogue of the spanning cluster is network Giant Connected Component (GCC). For networks of finite size, such as PTNs, the role of a GCC is played by the network largest connected part. Unlike a uniform lattice, usually PTNs are inhomogeneous, some of their constituents are more important than others, therefore there are many ways to model removal of network constituents. Such removals, usually called attacks, simulate node malfunction and can be caused by various factors.

Fig. 3a shows how the size of the largest connected component of the PTN of Paris S changes when the share of its station nodes c are removed following different scenarios (both values are normalized so that the values S=1, c=0 correspond to the entire network). The uppermost curve in Fig. 3a shows the change in S when nodes are removed randomly, this simulates random failures in the functioning of stations. As one can see from the plot, Paris PTN remains robust to such attacks: the size of its largest connected component decreases smoothly with c. However, the behavior of S changes when the attacks become directed at the most important nodes of the network. The most important nodes do not necessarily have to be hubs with the largest node degree k. Curves of Fig. 3a corresponds to various attack scenarios, when the importance of a node was determined not only by its degree, but also by its other characteristics such as the so-called centralities, number of next nearest neighbors, clustering, *etc.* The value of S drops sharply at some limiting c, that depends on the attack scenario. This resembles the behavior in the vicinity of the percolation threshold and indicates *collective effects* in the structure of the PTN. Analytical methods allow *a priori* identification of such Achilles' heels in the network structure and comparison of different PTNs of different cities resistance to random failures and targeted attacks.

Although PTNs are embedded in 2D space, empirical analysis shows that very often the whole networks as well as their components are characterized by fractal behavior. One of the examples is shown in Fig. 3b by the PTN network in Greater London. While the central part of the network is densely filled and the number of stations increases with radius as $N \sim R^2$, with further growth of $R > R_c$ the dependence changes to $N \sim N^{df}$ with the fractal dimension $d_f < 2$. Fractal behavior is often also characteristic of the PTN constituents. So, the distance r between initial and final stations for a passenger's journey traveling for l stops on a single route scales as $r \sim l^{\nu}$ with an exponent ν that is rather close 3/4, which is the well known self-avoiding walk exponent in two dimensions [3]. There are ongoing attempts to describe emerging PTN structure in terms of evolutionary growth models and to describe their

▼ **FIG. 3:** **(a)** Largest component size of the PTN of Paris as function of the fraction of removed station nodes for different attack scenarios. Each curve corresponds to a different scenario as indicated in the legend [6]. **(b)** Public transportation network of Greater London. Each of 16397 stations is represented as a network node. The radius R_c ~15.4 km corresponds to the transition from the compact central area to the rarefied space with $d_f < 2$ [7].

(a)



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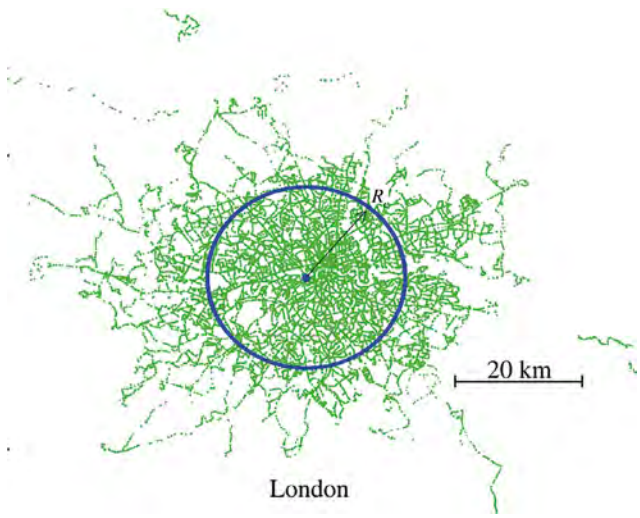

evolution using the statistics of *interacting self-avoiding walks* in two dimensions. In turn, the observation of fractal structures evokes an analogy with the physical models of the fractal growths at diffusion limited aggregation or at percolation.

Physics is what physicists do

I gave only a few examples of the application of physical concepts in the analysis of PTNs. Many other examples and even whole areas such as dynamics, cascading failures or traffic jams were left out. Going back to the title of this article, it is a good place to cite Giorgio Parisi who started one of his articles (entitled "Complex systems: a physicist's viewpoint" [8]) with the words: "In recent years physicists have been deeply interested in studying the behavior of complex systems. The result of this effort has been a conceptual revolution, a paradigmatic shift that has far reaching consequences for the very definition of physics.". Of course, if physics is defined as the science of four fundamental interactions, the science of matter and energy, it has nothing to do with public transportation in the sense discussed. However, a physical conceptual framework, physicist's approach to PTN analysis serves in favour of another opinion [9]. ■

About the Author

Yurij Holovatch is a chief researcher at the Institute for Condensed Matter Physics of the National Academy of Sciences of Ukraine and a full member of the Academy. He is a co-founder and a co-director of the L4 Collaboration and International Doctoral College "Statistical Physics of Complex Systems". He is also an external faculty member at the Complexity Science Hub Vienna (Austria) and a visiting professor in Coventry university (UK). His principal research fields are phase transitions and critical phenomena, complex systems, and the history of science.

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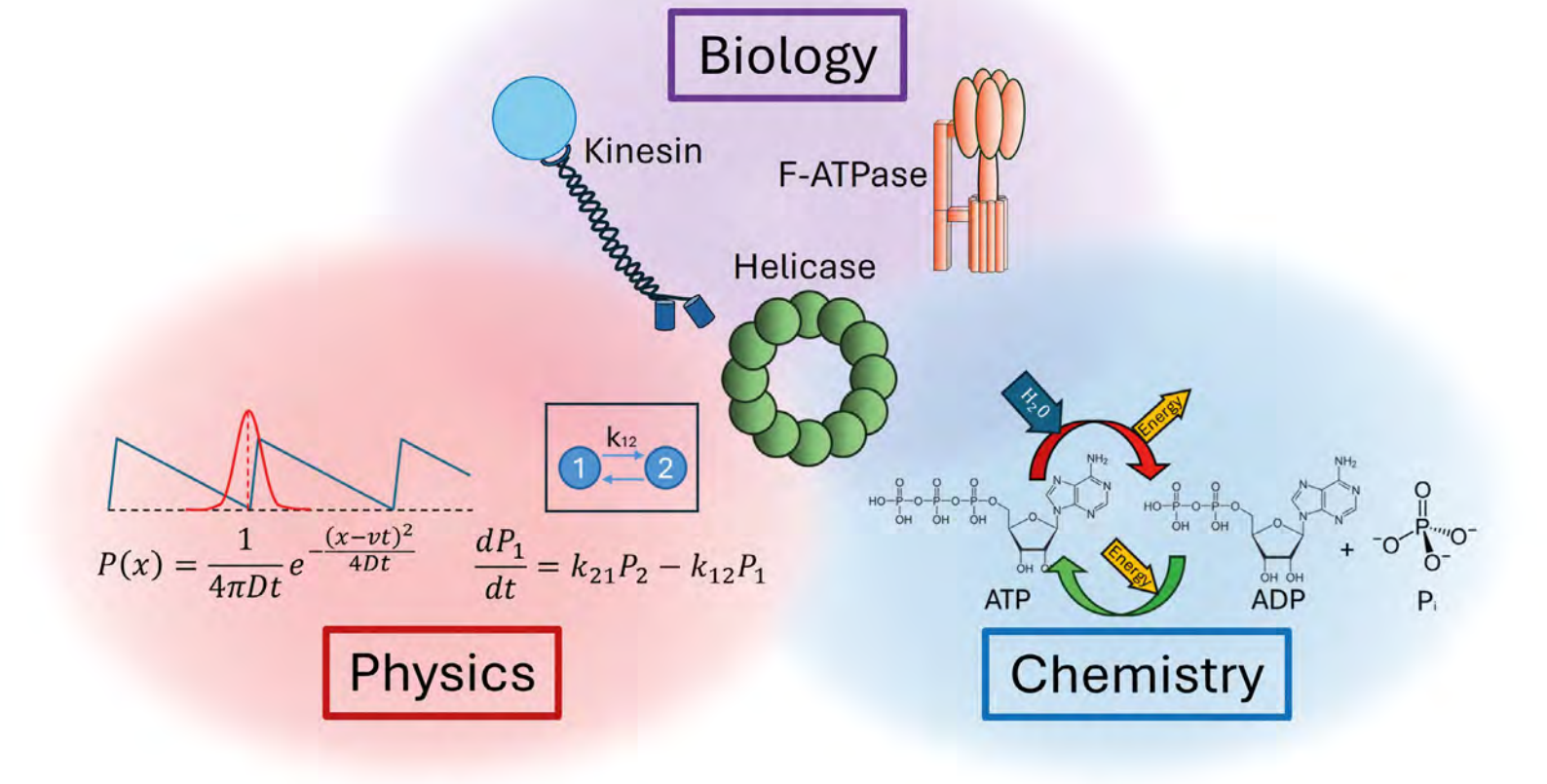

CONTROLLED TRANSPORT BY MOLECULAR MACHINES: EXPLORING BIOLOGICAL MOTORS AND THEIR PHYSICS

V. Rodriguez-Franco, M. Mañosas and F. Ritort – DOI: https://doi.org/10.1051/epn/2024208
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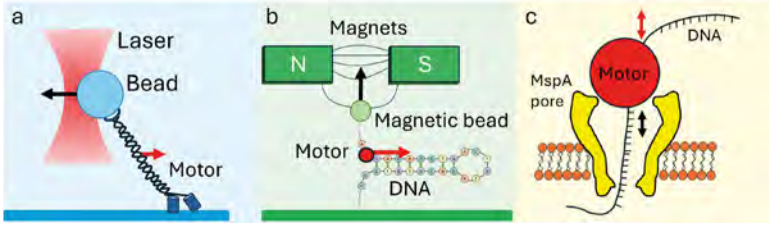
Molecular motors are fascinating biological machines that play a crucial role in a variety of cellular processes, including mass transport, muscle contraction, DNA replication, transcription and repair, and RNA translation. These structures convert chemical energy from adenosine triphosphate (ATP) hydrolysis into mechanical work.

ATP serves as the primary currency in the chemical reactions occurring in biological systems. ATP hydrolysis involves the breaking of a high-energy phosphate bond within ATP, resulting in the formation of ADP (adenosine diphosphate) and inorganic phosphate (Pi). This process releases energy on the order of 10-20 kBT (where kB is the Boltzmann constant and T is the temperature). At room temperature, the thermal agitation energy equals $1 \cdot k_B T = 4 \cdot 10^{-21}$J=4pN·nm (1pN=1picoNewton=10^{-12}N and 1nm=1nanometer=10^{-9}m). Molecular motors operate at the nanoscale in highly noisy and viscous environments against forces in the pN scale.

Despite these conditions, some molecular motors exhibit surprisingly high efficiencies. Particularly interesting is the case of F1-ATPase, an enzyme responsible for generating ATP from ADP and inorganic phosphate, which operates with efficiency close to 100%. Researchers have long been intrigued by the question of how biological molecular motors can function so effectively in highly noisy environments [1].

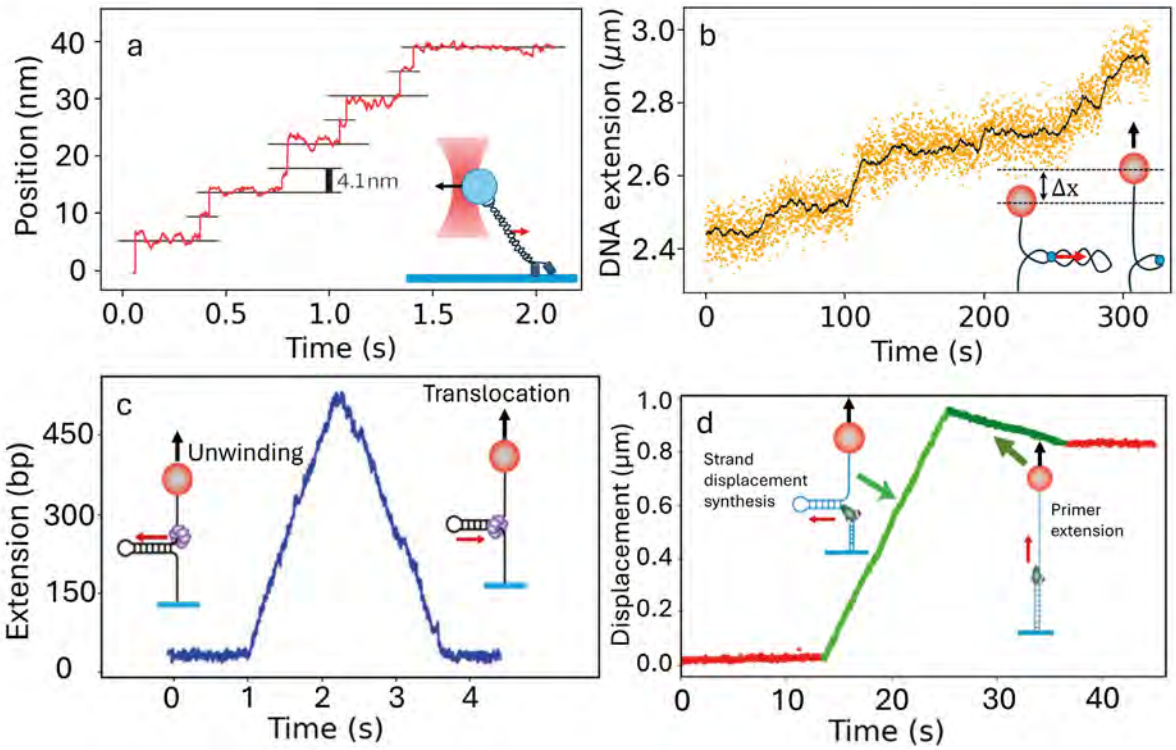
Traditionally, molecular motors have been studied using standard biochemical ensemble assays that measure the average behaviour of a large ensemble of molecules. Average measurements provide limited information about rare events and heterogeneous dynamics. Single-molecule techniques have remodelled the field of molecular biophysics, permitting access to monitoring individual reaction coordinates informative of molecular physico-chemical properties such as conformation, orientation, and position [2,3].



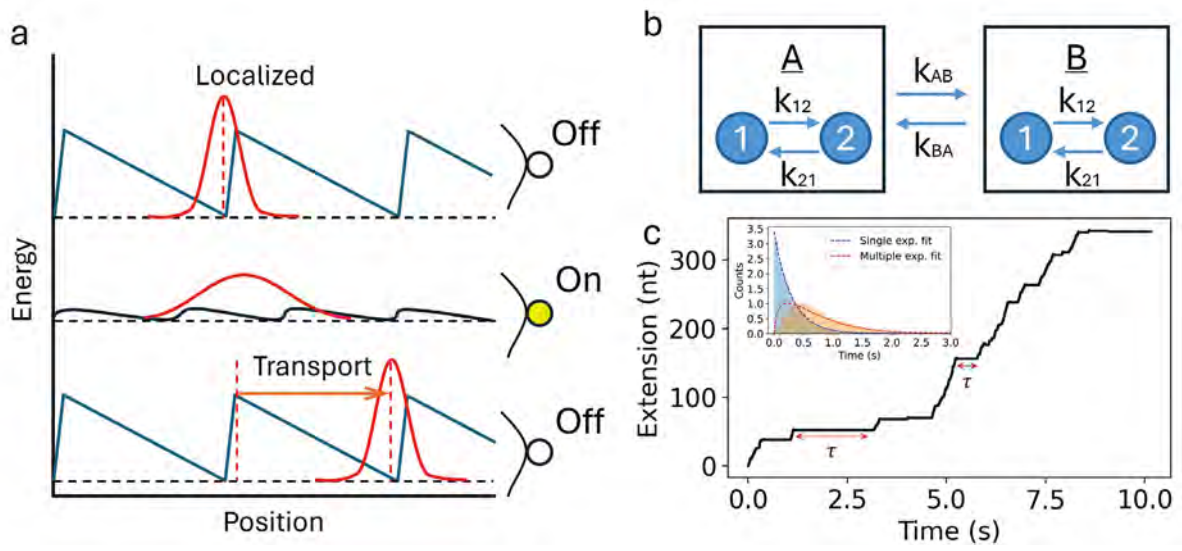
▲ **FIG. 1:** Schematic representation of SME. a) LOT experiment showing an optically trapped bead tethered to a kinesin motor. b) MT experiments showing the magnets pulling on a DNA hairpin to study a DNA translocating motor (red circle). c) SNPRT experiment showing a biological nanopore inserted in a lipid bilayer and a DNA molecule whose translocation is controlled by a motor. Force is controlled by applying a voltage difference across the membrane. Black and red arrows indicate the direction of applied force and the motor direction respectively.

Techniques

Structural information about these motors emerges through various microscopy and spectroscopy techniques. Examples are X-ray crystallography which uses the unique pattern of scattered X-rays by the crystallized sample, or cryo-electron microscopy which studies biological samples by rapidly freezing them to preserve their natural state. Structural techniques are complemented by single-molecule experiments (SME) that monitor the dynamic behaviour of individual motors with high spatial and temporal resolution. SME include fluorescence and force spectroscopy. They have been combined in the lab, and in commercial instruments making SME accessible to biology research groups worldwide. Fluorescence techniques are total internal reflection fluorescence (TIRF) for single-molecule localization and Förster resonance energy transfer (FRET) for conformational dynamics, among others [4]. Force spectroscopy techniques permit the direct manipulation by exerting forces on single molecules [5]. Examples are atomic force microscope (AFM), laser optical tweezers (LOT), magnetic tweezers (MT), and acoustic force-spectroscopy (AFS), among others. Mechanical manipulation is achieved by tethering a single molecule between a surface and a force probe (cantilever tip or optically/magnetically trapped bead). With them, we can controllably exert mechanical forces and torques while measuring the molecular extension. AFM and LOT are suitable to study cellular and molecular interactions by exerting forces in the pN to nN range (1nN=1nanoNewton=10-9N) with sub-nanometer spatial resolution over timescales limited by the corner frequency of the probe, typically in the range 1-100kHz. MT can detect forces ranging from fN (1fN=1femtoNewton=10^{-15}N) to ~100 pN, with a temporal resolution limited by the imaging frequency acquisition. Compared to AFM, LOT and MTs can exert torque, proving them very useful in studying topoisomerases, which are responsible for relieving torsional stress created in DNA during polymerase transcription and replication. Furthermore, MTs are a ●●●



◀ **FIG. 2:** SME traces for different motors. **a)** Kinesin walking on a microtubule studied with LOT. **b)** Topoisomerase unwinding a DNA hairpin using MT. **c)** Helicase unwinding a DNA hairpin using MT, the rising edge corresponds to the DNA unwinding catalysed by the helicase, whereas the falling edge corresponds to the helicase translocation while the DNA reforms in its wake. **d)** Polymerase copying a DNA hairpin using MT, while it opens the DNA. Black and red arrows indicate the direction of the applied force and the motor direction respectively.



▲ **FIG. 3: a)** Ratchet model described by an energy landscape that changes depending on the ATP cycle state (On/Off). The ATP hydrolysis changes the energy landscape in a way that favours the movement in a specific direction. **b)** Discrete model including two main states (A and B) with different sub-states (1 and 2), whose transitions are characterized by kinetic rates **c)** Simulated trace of a molecular motor following the scheme depicted in panel (b). Two lifetime events are shown in red arrows as an example. Inset: Comparison between lifetime distributions for a single-step reaction (single exponential) and multiple-step reaction (multiple exponential).

high-throughput technique with the capability of parallel measurements by the simultaneous tracking of multiple molecular tethers in a single experiment.

Recent methods include electrical measurements of single motor enzymes translocating nucleic acids through solid-state and biological pores. Jens Gundlach and coworkers, from the University of Washington in Seattle, introduced Single-molecule Picometer Resolution Nanopore Tweezers (SPRNT), a technique that provides readout of a DNA sequence moving through an enzyme, allowing to investigate sequence effects on the enzymatic activity with high spatiotemporal resolution [6].

Motors

Kinesin and myosin were the first studied molecular motors using optical traps [7]. Kinesin is a dimeric and processive motor that moves along a microtubule through a coordinated action of its two heads, playing a central role in cellular transport of vesicles. Myosin is a non-processive motor responsible for muscle contraction by pulling on actin filaments. Myosin works cooperatively in concerted action with other myosins. Other examples of processive motors include DNA and RNA translocating motors such as helicases and polymerases [8] which are involved in DNA replication, transcription, recombination, and repair. Helicases promote DNA unwinding, whereas polymerases catalyse new DNA strands.

Theoretical models for processive enzymes

Theoretical modelling aims at capturing the mechanochemical cycle of the enzyme relating ATP hydrolysis to its movement. We can differentiate two types of models: continuum ratchet models and discrete Markov chains [9]. In continuum models the motor diffuses over an asymmetric energy landscape characterized by energy barriers and wells. The jumps over the barriers are thermal activated processes and the ATP hydrolysis can modify the landscape lowering the barriers and promoting the forward motion. The landscape asymmetry favours forward direction (as compared to backward motion) generating directed motion. In discrete models, the motor moves from state A to state B through several biochemical sub-states. In these substates the motor can undergo conformational changes or chemical reactions such as ATP hydrolysis.

A relevant kinetic descriptor is the first passage time or lifetime of the motor defined as the average amount of time spent in each state. If the motor's cycle has a single rate-limiting step, the lifetime distribution is a Poisson process, whereas in the presence of multiple steps, the distribution is more complex. For some kinesins lifetimes are exponentially distributed [7], suggesting that one ATP molecule is hydrolysed at each step. In contrast, some helicases exhibit multi-exponential lifetime distributions indicating the presence of several intermediates, such as backward steps [6]. It is an open question whether such backwards steps consume steps or rather re-synthesize ATP from ADP and Pi.

A fundamental measurement to characterize the relationship between the biochemical and mechanical cycle of the motor is the measurement of the fundamental step. This has been achieved for various motors, such as kinesin with an 8nm step, F1-ATPase with 90° rotation steps and helicases and polymerases with one base pair step (0.34nm). With the development of high-resolution setups, it has been possible to observe that some motors exhibit sub-steps such as kinesin with 4nm sub-steps [10]

and F1-ATP-ase with 30º sub-steps [11]. Finally, even half-base pair sub-steps have been observed for a viral helicase [12].

Molecular motors, the machines of life, are a paradigm for mass, energy, and information transport processes in the cell. The possibility of manipulating and monitoring them with nanometric precision and accuracy permits biologists to investigate such processes with unprecedented detail. At the same time, physicists can investigate and test fundamental theories for the behavior of living matter. ■

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Kinesin trace from: S. Sudhakar, M. K. Abdosamadi, T. J. Jachowski, M. Bugiel, A. Jannasch, and E. Schäffer, *Science* **371(6530)**, eabd9944 (2021).

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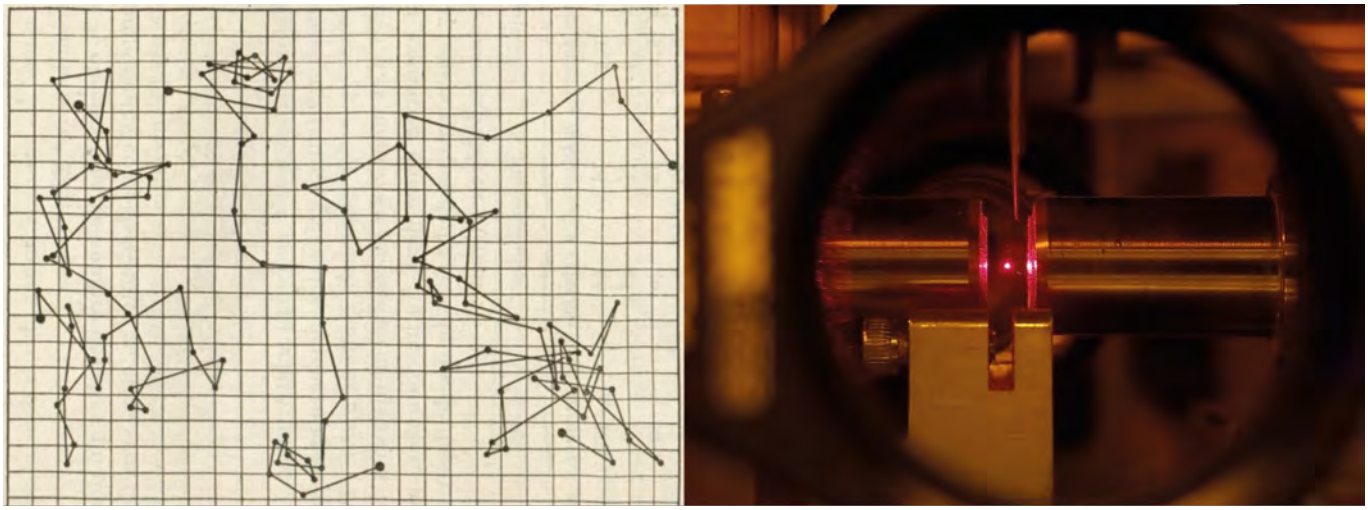

ZOOMING IN ON BROWNIAN MOTION WITH OPTICAL TRAPPING MICROSCOPY

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Optical trapping microscopy unravels open questions in statistical physics by making ultra-precise measurements of Brownian motion in diverse fluid environments. Moreover, the advent of pulsed lasers promises to push the boundaries even further, offering insights on how the compressibility of fluid flow affects Brownian particles at previously unexplored time scales.

Albert Einstein studied diffusion in his PhD thesis with a specific aim to determine then-unknown Avogadro's constant N_A. He derived a value for the translational diffusion coefficient D for a particle of radius a in a fluid of viscosity η

$$D = k_B T/6\pi\eta a, \qquad (1)$$

where k_B is Boltzmann constant ($k_B = R/N_A$, where R is the gas constant) and T is the temperature. For his determination of N_A, he used known values of D and η for sugar dissolved in water. Shortly afterwards, with the same aim of determining N_A, he published a paper [1] where he proposed a formula for the mean square displacement $<(\Delta x)^2>$ of one-dimensional translational Brownian motion

$$<(\Delta x)^2> = 2Dt. \qquad (2)$$

N_A could be estimated by observing micrometer-sized particles diffuse in water, over an observable distance within a minute. The root-mean-squared displacement of a Brownian particle grows with the square-root of time, a defining feature of diffusive motion. However, basic kinematics demands that at any instant t, the particle has a continuous — though fluctuating — instantaneous velocity $v(t)$ with which it moves from one point to the next.

Einstein realized this and published a paper [2] where he estimated a time θ below which Eq. (2) would fail:

$$\theta = m/(\log_{10} e \ 6\pi\eta a), \quad (3)$$

where m is a mass of the Brownian particle. He obtained Eq. (3) by considering how long it takes for a particle's velocity to decrease to one tenth of its initial value due to Stokes friction. In equilibrium, the root-mean-square velocity of a Brownian particle quantifies its typical velocity scale and is given by the variance of the Maxwell-Boltzmann distribution

$$<v^2> = k_B T/m. \quad (4)$$

Soon after Einstein's work, Jean Baptiste Perrin used Eq.(2) to determine the value of N_A using time-lapse microscopy of tree resin particles with varying sizes [3]. A reproduction of his hand-drawn Brownian motion trajectories are shown in the cover image of this article. Over half a century later, Arthur Ashkin invented optical trapping [4] and developed its application to colloidal particles [5]. In the decades since, accompanying detection techniques [6] evolved greater resolution [7] and enabled direct measurement of coloured thermal noise [8]. This form of optical trapping microscopy finally granted access to times below θ, allowing direct measurement of the Maxwell-Boltzmann distribution of Brownian velocities in gases [9] and in liquids [10], though Einstein famously expressed his view that such a precise measurement would be impossible [2].

A probe for non-equilibrium physics

It is clear from Eq. (3) and (4) that by measuring θ one can estimate particle mass or fluid viscosity while by measuring $<v^2>$ one can estimate particle mass or fluid temperature. Rapid measurement of these properties offers a new probe of non-equilibrium systems where thermodynamic quantities are well defined. To convey the concept, consider a micron-sized polystyrene sphere in air, where $\theta = 8$ µs. Position tracking of the particle has to remain accurate at times shorter than θ in order to directly measure the Maxwell-Boltzmann distribution of velocities, see Figure 1 for a demonstration with experimental data. The duration of measurement (integration time) tmax is determined by the acceptable uncertainty in $<v^2>$. In the data shown in Figure 2, an integration time of 1 ms gives an uncertainty of 30%, *i.e.* two independent 1 ms long measurements of $<v^2>$ differ by 30%. A longer integration time of 10 ms reduces this uncertainty to 10%.

In water, θ is much smaller than in air due to the different viscosities of these fluids. Therefore, changes in a system's properties must be tracked more rapidly in liquids. For example, a micron-sized polystyrene sphere has $\theta = 0.14$ µs in water. By measuring θ, the viscosity of various fluids have been measured using only 20 µs of high-resolution data [11]. However, liquids induce hydrodynamic memory effects, so the thermal force is no longer random white noise. It acquires a colour, *i.e.* it is correlated in time and the bare mass m appearing in Eq. (4) is replaced by the added mass $m^* > m$ that includes the inertia of the liquid dragged by the particle.

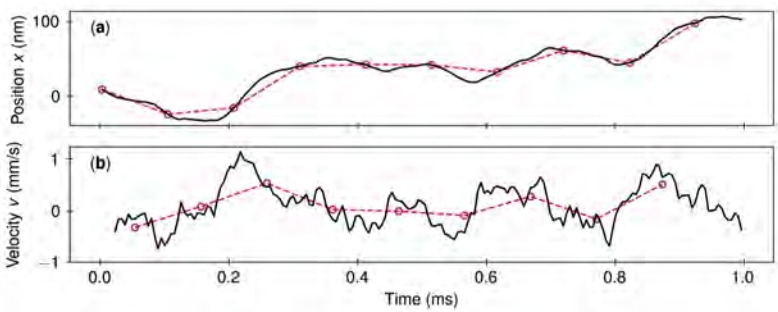
> **The Maxwell-Boltzmann distribution is now routinely measured in the lab using optical trapping microscopy**

These time scales of optical trapping microscopy have to be contrasted with measurements in changes in diffusion coefficient D from Eq. (1), a quantity that is defined for times greater than θ for particles in air. Ability to measure θ instead of D thus introduces a finer time scale to explore a physical system of interest.

These preliminary studies might offer a probe for non-equilibrium systems, but their use in actual systems is at an early stage. The ability to weigh a changing mass is important for studies of nucleation. For example, we lack a complete understanding of how ice is formed in clouds. Controlling nucleation processes is crucial for optimized cloud seeding, a technique used to encourage precipitation.

Applications of optical trapping microscopy

High-precision optical trapping microscopy is primarily used to investigate equilibrium systems. For example, a particle in an incompressible bulk fluid or next to a wall with either stick or slip boundary condition was investigated: $<v^2>$ has been measured directly for particles in both gas and liquid, and it has been shown that the color of thermal noise is suppressed for a particle in liquid next to a wall [12]. Thus, this experimental technique can be used as a probe of *e.g.* temperature, viscosity or even surface wettability. In these applications, integration times can be much longer than in the case of non-equilibrium systems and accuracy can be significantly increased.



▾ **FIG. 1:** Time traces of **(a)** position and **(b)** velocity for a sphere with a diameter of 3 µm optically trapped in air and recorded at two different time resolutions, ~ θ/20 (black) and ~ θ theta (red). Velocity fluctuations can only be resolved for time resolutions below θ.

Future instrumentation with picosecond resolution is expected to tackle phenomena of compressibility in fluid flows.

In a recent example of such an application a microsphere was optically trapped in air and weighed using Eq. (4) [13]. Mass of 24 picograms was measured with uncertainty of 4%. This application is interesting in the context of ground-state cooling and sensitive force-transduction where accurate knowledge of the trapped particle's mass is required.

In addition to thermal fluctuations, a trapped particle may also be driven by the flow of surrounding fluid. Flow oscillations with up to a few hundred Hz have been measured with video microscopy. High-resolution optical trapping microscopy in air has recently extended this bandwidth to nearly 1 MHz, enabling measurement of flows associated with acoustic radiation [14]. This technique can be compared to other, more established acoustic sensors, such as a microphone.

Figure 3 compares a high-bandwidth microphone to an optically trapped particle when exposed to an impulsive sound generated by laser ablation of an aluminum target. Compared to the microphone, optical trapping microscopy offers a superior measurement bandwidth that is capable of resolving a steeper rising edge and a higher peak pressure. Interestingly, accurate calibration of optical trapping microscopy for high bandwidth acoustic sensing must account for hydrodynamic memory effects, even in air. Even though this example is limited to particles in air, it can easily be extended to liquid environments.

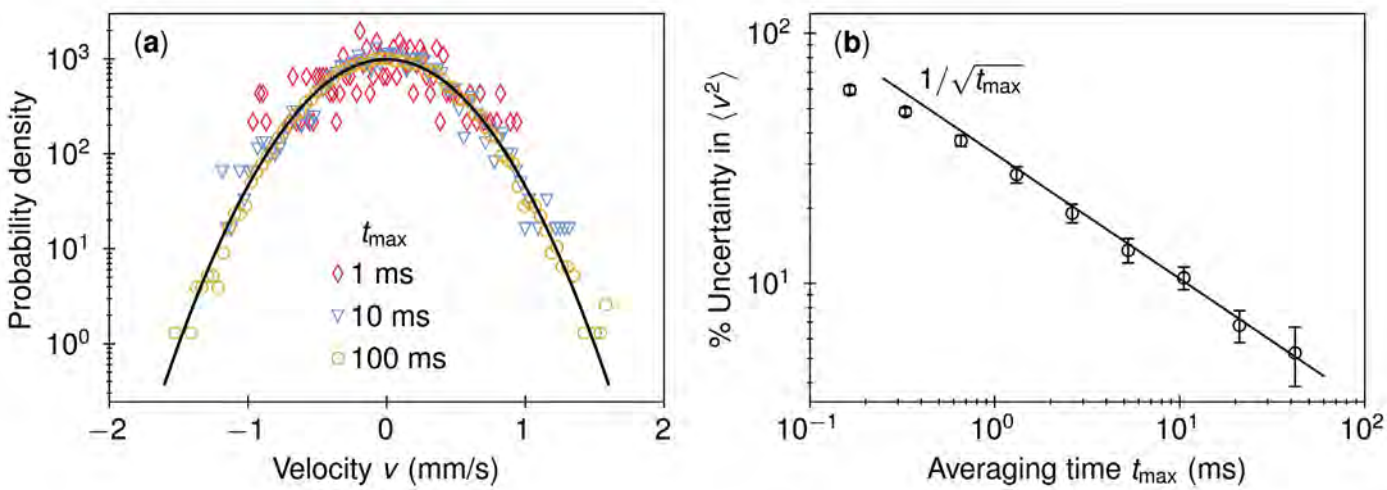
Future instrumentation and experiments

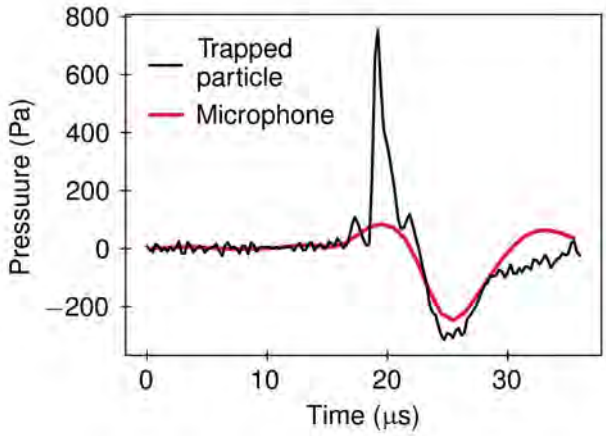
A next step in instrumentation development is the use of pulsed lasers for the position detection [12]. It is expected that the temporal resolution will reach the picosecond regime. Accessing these short time scales will, for the first time, reveal the effects of flow compressibility for a Brownian particle, *e.g.* the onset of viscosity and the bare mass of the Brownian particle in liquid.

Compressibility effects are expected to be especially pronounced in confined fluids, a regular situation in microfluidics. Numerical simulations [15] predict correlations between molecular collisions arising from density fluctuations in confined fluids, unlike those arising from hydrodynamic memory effects in bulk fluids, observed by optical trapping microscopy two decades ago [7]. A convincing experimental confirmation of these correlations in confined fluids is still lacking and there is a hope that optical trapping microscopy might provide it.

In conclusion, we turn our gaze towards the 19th century when the atomic hypothesis found utility in kinetic-molecular theory. Boltzmann proposed that collisions between these discrete microscopic entities are entirely random. This led Maxwell to propose the first distribution for a physical phenomenon. Einstein's and Perrin's work was a culmination of the centennial effort to determine Avogadro's constant, *i.e.* the physical size of these entities. The Maxwell-Boltzmann distribution is now routinely measured in the lab using optical trapping microscopy and it is authors' hope that the text here showed that the simple noise produced by atomic motions is far from being a conceptually closed subject. ■

▾ **FIG. 2: (a)** Maxwell-Boltzmann distribution of velocity traces recorded for different integration times tmax, give a different uncertainty in $<v^2>$ which is inversely proportional with root of tmax. The black line is theoretical expectation of the distribution. **(b)** The uncertainty in $<v^2>$ decreases as tmax-1/2.





▲ **FIG. 3:** Detecting the sound induced by laser ablation of an aluminum target. The trapped particle reacts quicker to an acoustic perturbation than a high-bandwidth microphone and better resolves the peak of a sound wave.

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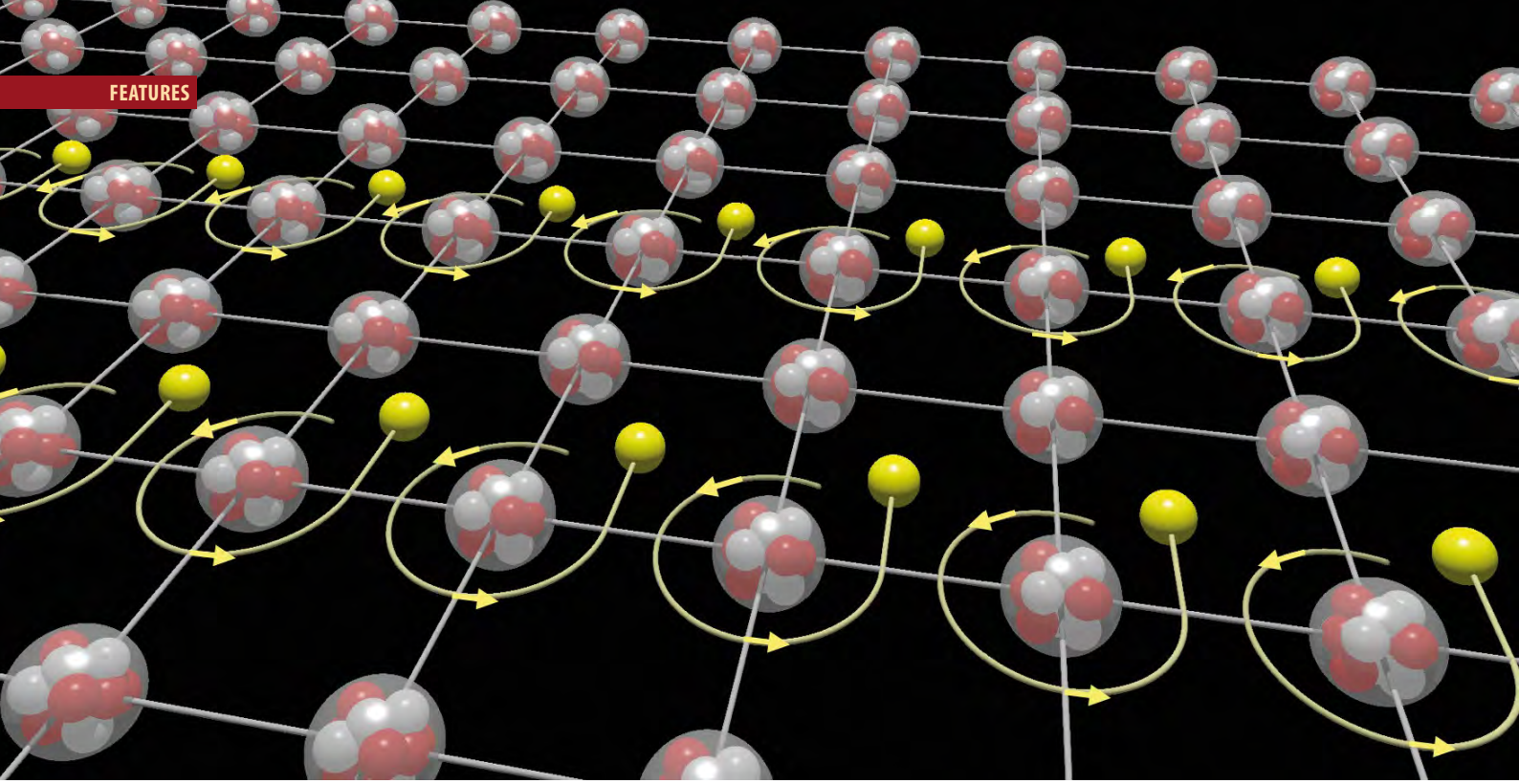

NON-EQUILIBRIUM ORBITAL ANGULAR MOMENTUM FOR ORBITRONICS

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Efficient manipulation of magnetization by electrical current is a key aim in spintronics. The state-of-the-art theories and experiments in spintronics show that harnessing non-equilibrium orbital angular momentum can significantly enhance the efficiency due to novel torques. Devices are based on environment-friendly materials, which has been difficult to achieve by the mechanisms based on spin only, and this has also kickstarted a new emerging field of research: orbitronics.

Physical principles of spintronic memory

In spintronics memory devices, a bit of information is encoded in the configuration of magnetization, *e.g.* "0" and "1" for the states with magnetization up and down, respectively. Reading the magnetic bit has become possible thanks to the discovery of giant magnetoresistance (GMR) and tunneling magnetoresistance (TMR), in which the electrical resistance of a ferromagnet/nonmagnet/ferromagnet (FM/NM/FM) heterostructure varies significantly depending on whether the two FMs have parallel or antiparallel magnetization configurations [1]. As shown in Figs. 1a and 1b, the physical principle of for instance the GMR effect is analogous to an optical polarizer. When electrical current flows across the FM/NM/FM junction, the first FM acts as a spin polarizer which filters only the electrons whose spin direction is the same as that of the FM. If the magnetization direction in the second FM is parallel to that of the first FM, the electrons can easily pass through (Fig. 1a). In the anti-parallel configuration, on the other hand, the spin-polarized electrons by the first FM are blocked by the second FM (Fig. 1b).

An obvious way to "write" the magnetic bit of information is to use a magnetic field, but this method exhibits poor scaling. Also, generating a magnetic field requires

an additional conductor in which electrical current flows. The idea of manipulating the magnetization by electrical current was proposed in 2000's, by injecting spin-polarized electrons into a FM (Fig. 1c) [2]. The injected spins interact with the magnetization, and eventually, the outgoing electrons will acquire the spin polarization of the FM. Since the total angular momentum is conserved, the difference of the spins of the in and out states implies that the magnetization must experience a torque as a back action. The corresponding process is called the spin torque, and it enables efficient manipulation of magnetization by electrical current. The GMR and spin torque are the key mechanisms behind spintronic memory devices such as magnetic random-access memory (MRAM), which can serve as a robust hardware for in-memory and neuromorphic computing devices as well as for storage-class memories.

Generating non-equilibrium spin

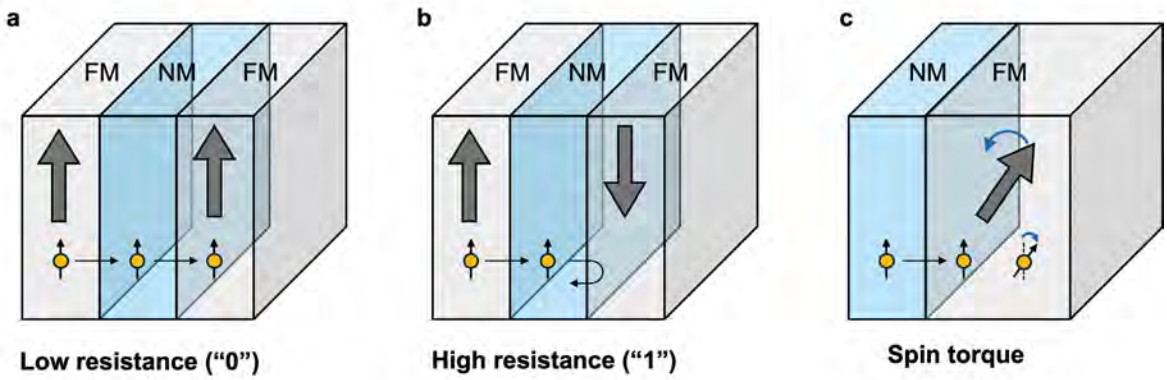
Although a FM may be used as a spin polarizer, other mechanisms exist for generating non-equilibrium spin even in NMs by utilizing relativistic spin-orbit coupling (SOC). Two well-known mechanisms are the spin Hall effect (SHE) and spin Edelstein effect (SEE), in which an external electric field induces non-equilibrium spin current and density, respectively (Figs. 2a and 2b) [3]. These have become of major interest in spintronics research for more than ten years, as magnetization switching by the electrically generated non-equilibrium spin was experimentally demonstrated [4]. This was surprising because the SOC effects have been so far regarded weak, giving mostly perturbative corrections to other strong effects that do not require the SOC. In fact, it has been found that the efficiencies of the SHE and SEE can be large in materials with heavy elements whose SOC is sizable. Since then, researchers have proposed various novel material systems that may enhance the relativistic effects by, *e.g.*, Rashba-type interfacial states, Dirac surface states of topological insulators, oxide heterostructures, metal alloys, *etc.* Despite noticeable progress within more than a decade, the efficiency of SHE and SEE could not be improved significantly beyond a certain limit. Also, many studies focused on materials including heavy elements (Ta, Pt, Au, Bi) and even rare-earth elements (Gd, Tb, Dy, Ho) owing to their large SOC. However, dependence on heavy and/or rare-earth elements has raised a concern in spintronic device applications because they are not only scarce and costly but also environmentally harmful. In fact, many of them are included in the EU's List of Critical Raw Materials [5].

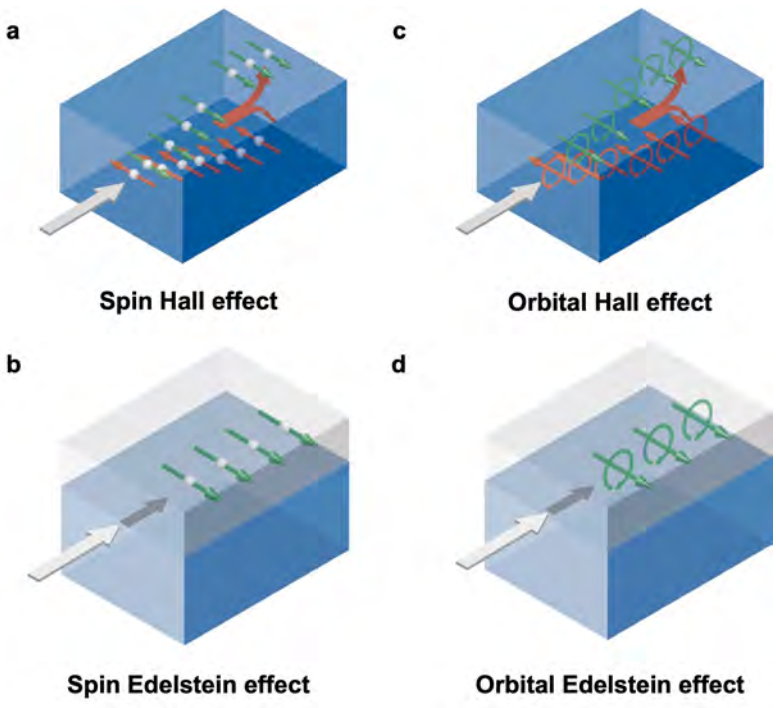
Orbital degree of freedom: Quenched in solids?

As the name of the field suggests, spintronics research has focused primarily on the spin degree of freedom, and the role of other degrees of freedom has been relatively overlooked. However, quantum mechanically, spin is only one part of the electron's angular momentum, with its orbital degree of freedom being a second source. Although this is a well-known statement, the orbital angular momentum (OAM) has been considered unimportant for spintronics because the orbital motion of electrons is suppressed in a crystalline environment. This is known as "orbital quenching" which is discussed in textbooks on solid-state physics.

Nonetheless, the idea of generating current of OAM-polarized electrons was theoretically proposed in 2005 in hole-doped Si [6] and in 2009 in transition metals [7]. These works predicted an orbital analog of the SHE, namely the orbital Hall effect (OHE). Similarly, the orbital Edelstein effect (OEE), which is an orbital analog of the SEE, was also theoretically proposed in 2018 [8]. The OHE and OEE are schematically illustrated in Figs. 2c and 2d, respectively. However, these works did not trigger much interest at the time, probably due to the focus of the community on spin-based effects, such as *e.g.* the discovery of the spin Hall effect in 2004, and their interpretation in terms of spin only. The rich physics of the orbital degree of freedom in transport phenomena started gaining significant attention only since very recently.

▾ **FIG. 1: Physical principles of spintronic memory. (a,b) A magnetic bit of information can be read for instance by the giant magnetoresistance in the FM/NM/FM structure, where the first and second FMs act as a spin polarizer and analyzer, respectively. (c) When the injected spin is not parallel to the magnetization in the FM, magnetization dynamics is induced as a result of the back action of the change of the spins of conduction electrons.**





▲ **FIG. 2:** Schematic illustrations of (a) spin Hall effect, (b) spin Edelstein effect, (c) orbital Hall effect, and (d) orbital Edelstein effect. When an electric field is applied, the spin(orbital) Hall effect generates a transverse spin(orbital) current. In the spin(orbital) Edelstein effect, spin(orbital) is accumulated by an external electric field.

OAM in non-equilibrium

In *equilibrium*, the OAM is strongly suppressed when compared to the spin, with difference that at times reach orders of magnitude. This is because the OAM is induced by SOC as a secondary effect in the presence of the spontaneous ordering of the spin which is more robust. Analogously, it has been commonly assumed that the *non-equilibrium* OAM and its related effects mentioned above must be suppressed in crystalline solids unless the SOC is strong. However, some of us have explicitly demonstrated that the hierarchy between the OAM and spin in non-equilibrium is exactly opposite to that in equilibrium: upon applying an external electric field, non-equilibrium OAM or its current can be generated robustly despite the orbital quenching and even in the absence of the SOC [9]. When sizeable SOC is present, the spin "follows" the OAM. This is because the electric field couples directly to the orbital part of the wave function, *i.e.* a charge distribution, via a dipolar coupling. The work has uncovered an intrinsic magneto-electric mechanism by which the OAM is induced by an external electric field, even if the OAM is completely quenched in equilibrium, demonstrating that the equilibrium and non-equilibrium properties of the OAM are completely different. Consequently, it has been theoretically shown that the OHE can be huge in 3d metals such as V, Cr, and Mn, in which the SOC is weak and thus the SHE is negligibly small [10]. Interestingly, these materials have been traditionally considered not very useful for spintronics. The theoretical prediction of large OHE was experimentally confirmed recently by optically measuring the orbital accumulation driven by the OHE in Ti and Cr thin films [11,12].

Orbital torque for spintronics

Fundamentally, the physical principle of magnetization dynamics is the conservation of total angular momentum, including both the spin and orbital contributions. The well-known mechanism of the spin torque, however, considers only the conservation of the total spin, ignoring the orbital contribution. The possibility of inducing magnetization dynamics by non-equilibrium OAM, which is nowadays called the "orbital torque", has been theoretically proposed in 2020 (Fig. 3a) [13]. In the mechanism of the orbital torque, the SOC is still necessary for the OAM to interact with the magnetization. This might be considered as a bottleneck of the efficiency, but the orbital torque can be comparable or even larger than the spin torque because the efficiency of the electrical generation of non-equilibrium OAM, *e.g.* by the OHE or OEE, is often much higher than that the equivalent effects for the spin.

Numerous experiments have demonstrated high efficiency of current-induced magnetization dynamics even in systems without any heavy element by utilizing the OAM instead of, or, together with the spin. This has attracted significant attention and has become one of the most important topics in spintronics research nowadays because the orbital torque provides a way to avoid using heavy and/or rare-earth elements for device application, thus avoiding the problem of critical raw materials. Spintronics can go green by harnessing non-equilibrium OAM.

A novel strategy to significantly enhance the efficiency of current-induced magnetization dynamics is to convert the OAM into the spin in another layer, which is inserted between the OAM-generation layer and the FM (Fig. 3b) [14]. The insertion layer acts as a highly efficient "orbital-to-spin" converter if the SOC is sufficiently strong such as Pt. For example, this idea has been first demonstrated in FM/Pt/surface-oxidized Cu, where the surface-oxidized Cu exhibits strong OEE and Pt converts the OAM into spin [14]. While even an ultrathin (~ 1 nm) Pt insertion layer is already sufficient to convert the OAM to the spin, it has been shown that also the ferromagnets themselves can convert the OAM into spin (Fig. 3a). Experimental demonstrations include some early work using permalloy [15] and more recently Ni was shown to be very efficient for this conversion [16, 17].

Orbitronics: Beyond spintronics

The traditional solid-state physics has taught us that the OAM is suppressed in equilibrium, but recent works have shown that the OAM manifests crucially in

non-equilibrium, which can also interact with other degrees of freedom such as local moments and be converted into the spin. Because of the possibility of enhancing the efficiency of current-induced magnetization dynamics with abundant and environment-friendly materials, utilizing non-equilibrium OAM has become one of the most important topics in spintronics research. Meanwhile, there are yet numerous unknowns on the fundamental properties of the orbital dynamics and transport, such as orbital relaxation, dephasing, and its lifetime. As a result, an interdisciplinary field of research called "orbitronics" working with generation, detection, transport, and manipulation of the OAM, has emerged [18]. All the time we see more and more exciting results being reported, and new materials and systems are being explored. This strongly suggests that orbitronics has potential to become one of the major topics in condensed matter physics, which can be useful for devices but may also solve grand puzzles in other fields such as superconductivity, multiferroics, and ultrafast phenomena. ■

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Dongwook Go obtained his PhD from POSTECH in South Korea in 2019, where he worked as a postdoc for one year. Since 2020, he joined the group of Yuriy Mokrousov at JGU Mainz as a postdoctoral researcher.

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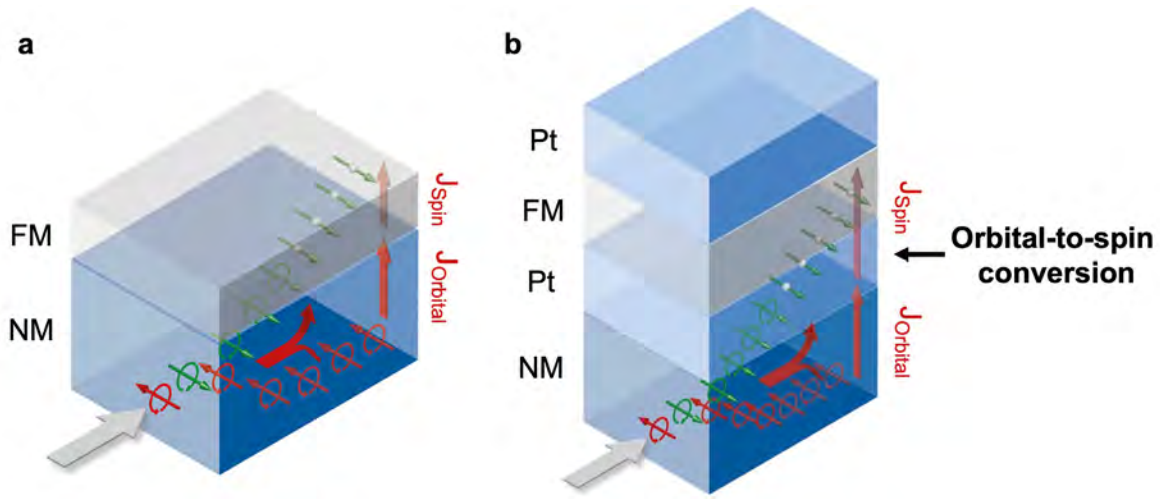
▼ **FIG. 3:** (a) Schematic illustration of the orbital torque, in which magnetization dynamics is induced by the injection of OAM-polarized electrons. (b) The OAM can be converted to the spin in the insertion layer by the SOC, by which the OAM can be harnessed for enhancing the efficiency of the spin torque. For the demonstration of the effect, an additional Pt layer needs to be placed such that the SHEs from the two Pt layers cancel out and only the orbital-to-spin conversion contributes to the torque on the FM.



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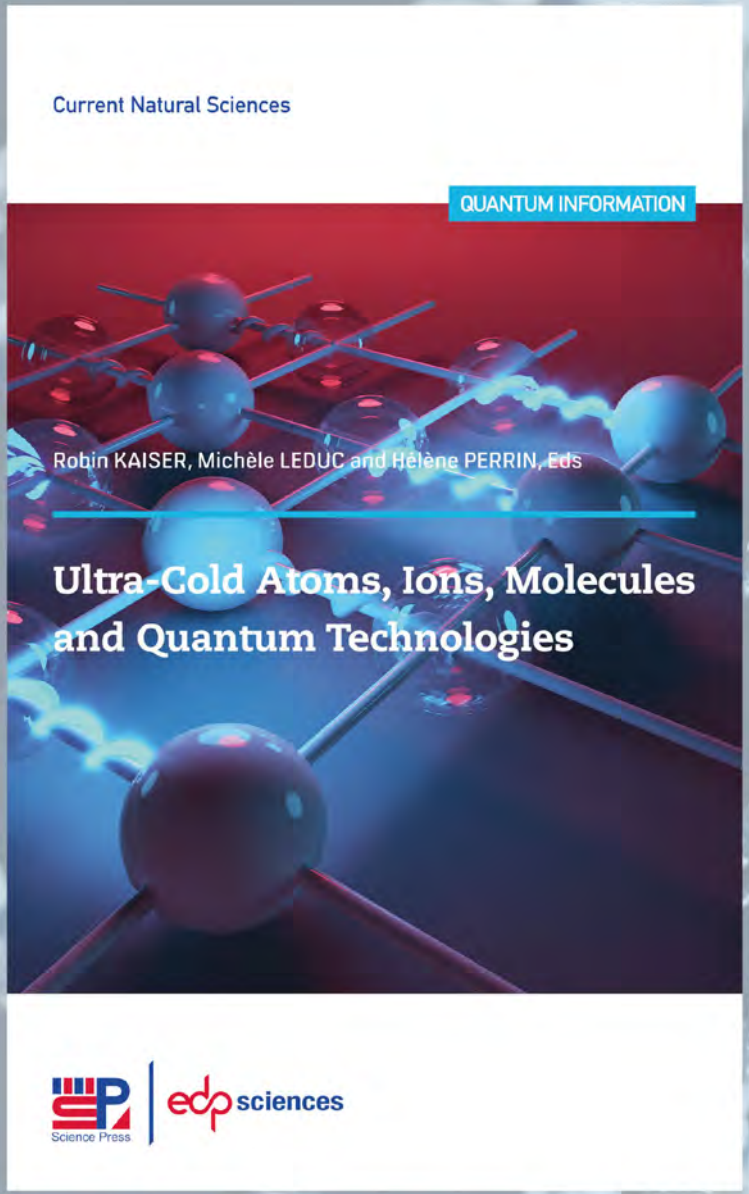

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