STRUCTURES | NEWS

STRUCTURES CLUSTER OF EXCELLENCE

UNIVERSITÄT HEIDELBERG ZUKUNFT SEIT 1386

May 2025

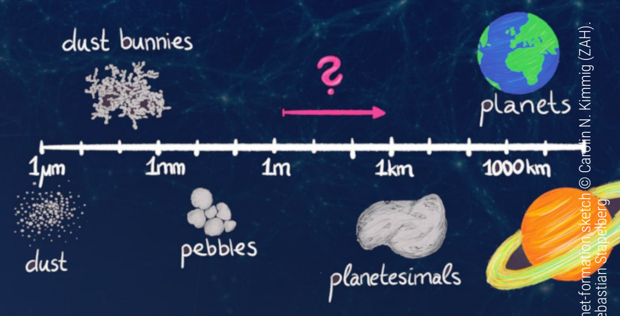

Image Credits: Handdrawn planet-formation sketch © Carolin N. Kimmig (ZAH). Surrounding composition by Sebastian Stapelberg

FROM SMALL TO LARGE – FROM SIMPLE TO COMPLEX

On the occasion of the 20th edition, this newsletter appears as a special 12-page issue including interdisciplinary research topics, community news and announcements.

Contents

Upcoming

- **May 23:** Internal Get-Together (EINC)
- **May 28:** Persistent Seminar
- **June 24:** AI and Ethics Talk Series
- **July 14-18:** Workshop: Billiards and Quantitative Symplectic Geometry
- **Aug. 26-29:** Schöntal Workshop on Inverse Problems
- **Sept. 1-5:** ENUMATH Conference

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RESEARCH

Analytic Theory Reveals Clues of Universal Clumping in Planet Formation

Planet formation begins when micrometre-sized dust particles in a protoplanetary disk collide and stick together, gradually growing into larger aggregates or "pebbles". The solar system's meteoritic record suggests that turbulent concentrations of these pebbles are continuously converted into planetesimals – a process lasting at least a few million years. While most planetesimals eventually form planets, a small fraction survives as asteroids and comets.

However, core questions remain unresolved: When and where do these planetesimals form? What was their initial size distribution and how much mass did they contain? The answers lie in the properties of turbulent solar nebula. Simulations show that certain turbulent conditions foster planetesimal formation, while others suppress it or fragment pebbles in collisions. Critically, both turbulence strength and particle concentration depend on the initial particle size distribution; and simulating varying sizes is computationally expensive. This has inspired semi-analytic methods, yet a comprehensive theoretical framework is still lacking.

A novel analytic approach to explore planet formation is *Kinetic Field Theory* (KFT) – a statistical description of classical particle ensembles in or out of equilibrium, which was recently successfully applied to large-scale structure formation in the cosmos. Unlike numerical simulations, KFT is not limited by spatial resolution, and its equations of motion are fully deterministic.

In their new study, STRUCTURES scientists from theoretical physics, astronomy and astrophysics presented the first application of KFT to planetesimal formation. Using a simplified model of freely streaming dust particles with initial *phase-space* data from simulations, they demonstrated the feasibility of this approach and found that the non-linearly evolved *density power spectrum* of dust particles develops a universal slope at small scales, independent of the initial spectrum – suggesting *scale-invariant* structure formation at small scales.

These findings, obtained within the project *CP2: From Dust to Planets*, establish a foundation for future research incorporating more complex physics within KFT.

Original Publication

J. Shi, M. Bartelmann, H. Klahr, C. P. Dullemond, Kinetic field theory applied to planetesimal formation I: freely streaming dust particles, Mon. Not. R. Astron. Soc. 536.2 (2025): 1625-1644.

AWARDS

Wolfram Pernice Receives the Gottfried Wilhelm Leibniz Prize

We are delighted to announce that our member Wolfram Pernice has been awarded the prestigious *Gottfried Wilhelm Leibniz Prize* of the German Research Foundation (DFG). The award honours his groundbreaking pioneering work on neuromorphic photonic computing, a transformative field at the intersection of physics, computer science, and engineering.

Prof. Wolfram Pernice is heading the research group *Neuromorphic Quantum Photonics* at *Kirchhoff Institute for Physics* (KIP). The goal of his research in the field of integrated photonics is to develop new methods for information processing and rapid computation using light. The DFG underlines that his interdisciplinary research crosses traditional boundaries – impacting natural, engineering and computer sciences.

The *Gottfried Wilhelm Leibniz Prize* is considered the most important research award in Germany, and has been awarded annually by the DFG since 1986. Up to ten prizes can be awarded each year with prize money of 2.5 million euros each. An award also goes to mathematician Prof. Angkana Rüland (Bonn), a former STRUCTURES member who did research on applied mathematics in Heidelberg from 2020 to 2023.

Wolfram Pernice, Professor at KIP.
(Image Credit: Tobias Schwerdt)

STRUCTURES COMMUNITY

Dominika Wylezalek Promoted to Full Professor (Extragalactic Astrophysics)

We are delighted to announce that STRUCTURES member Dominika Wylezalek has been appointed as a Full Professor for *Extragalactic Astrophysics* at the Centre for Astronomy at Heidelberg University (ZAH); and Director at the *Astronomisches Rechen-Institut (ARI)*.

Prof. Wylezalek is heading the research group *"Galaxy Evolution and AGN (GALENA)."* Her research employs multi-wavelength observations to investigate how supermassive black holes influence their host galaxies across different cosmic epochs. Recently, her team has been granted observing time with the *James Webb Space Telescope* and discovered an extremely red quasar in a galaxy cluster, which was active about ten billion years ago. Wylezalek's observations help in understanding how galaxies in the early universe evolved into the *cosmic web* we see today. For her significant contributions to the field, she has received various awards, including the *MERAC prize* of the *European Astronomical Society* and the German Research Foundation's *Heinz Maier-Leibnitz Prize*.

"I am thrilled to continue my work at ZAH in this new position and look forward to advancing our understanding of galaxy evolution," says Dominika Wylezalek. *"The resources and collaborative environment here provide an excellent foundation for groundbreaking research."* In this newsletter we interviewed Dominika Wylezalek for our format *"STRUCTURES Asks"* on page 7.

Dominika Wylezalek, Professor at ZAH/ARI.
(Image Credit: Tobias Schwerdt)

RESEARCH-ORIENTED TEACHING

New Master's Degree Programme: Mathematics of Machine Learning & Data Science

Machine learning and data science are currently revolutionizing research across disciplines. Recognizing this transformative power, Heidelberg University is set to launch a new four-semester master's programme, *Mathematics of Machine Learning and Data Science*, starting in the winter semester 2025/26. This research-oriented course aims to equip students with the essential mathematical and methodological groundwork to advance the frontiers of machine learning and scientific data analysis.

"Compared to the regular mathematics master's, this programme is rather interdisciplinary in approach. We see this, for example, in the lecture series for the first semester, which gives a broad overview of core fields of mathematics," says Prof. Christoph Schnörr from the *Institute for Mathematics*. The new curriculum imparts an advanced understanding of how pure and applied mathematics intersect to expand on the methodology of machine learning and scientific data analysis. Students gain practical experience and core competences in analytical & structural thinking, and interdisciplinary problem-solving. The option to spend a semester abroad offers valuable opportunities for international teamwork and collaboration with leading researchers worldwide.

RESEARCH / AWARDS & HONOURS

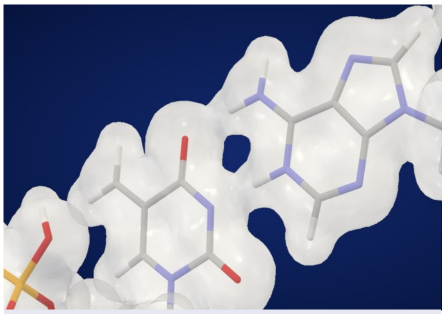
Predicting the Kinetic Energy of Molecular Quantum Systems Using AI

Traditionally, calculating the kinetic energy of electrons in molecules relies on a complex description using wave functions, which depend on the coordinates of all electrons at the same time. A simple proof by Walter Kohn, honoured with the Nobel Prize in 1998, demonstrated that this energy can also be derived from the much simpler electron density. Unfortunately, however, an explicit formula linking electron density to kinetic energy has remained elusive – posing a fundamental challenge for quantum chemistry and physics.

Learning this relationship with artificial intelligence (AI) has become a new research line within STRUCTURES – first successfully pioneered in the exploratory project *Machine Learning in Density Functional Theory*, leading to the development of a novel comprehensive project CPμ *(Molecules: Conformational and electronic structure)* – thus becoming part of STRUCTURES' proposal for a second funding period. In addition, STRUCTURES members Prof. Fred Hamprecht, Prof. Andreas Dreuw and Prof. Maurits W. Haverkort have secured a *CZS Wildcard* grant by the prestigious *Carl Zeiss foundation* in order to probe “quantum chemistry without orbitals”. By bypassing the need for complicated wave functions, the new research could enable quantum-mechanical analysis of vastly more complex systems than currently possible – with potential benefits for pharmacology, photovoltaics, battery technology and chemical catalysis.

The interdisciplinary team brings complementary expertise to the project:

- Fred Hamprecht *(Interdisciplinary Center for Scientific Computing, IWR)* explores artificial intelligence methods for the natural sciences, currently focusing on quantum chemistry.
- Andreas Dreuw (*IWR*) investigates chemical and physical questions with the aid of modern computational and quantum chemistry methods.
- Maurits W. Haverkort’s *(Institute for Theoretical Physics, ITP)* research aims to predict the properties of complex quantum systems and quantum materials on the basis of novel theoretical methods and models.


Electron density isocontour of a DNA base pair.
(Image credit: Tobias Kaczun & Roman Remme. Adapted.)

The Carl Zeiss foundation has allocated more than 745,000€ to fund the research work for a period of two years. Its *Wildcard* programme fosters unconventional, early-stage research of interdisciplinary consortia involving at least three scientists.

EVENTS

Recap: STRUCTURES + IsoQuant Film Screening on International Women's Day

On March 8, the STRUCTURES Cluster of Excellence and the *CRC 1225 IsoQuant* welcomed over 100 participants at *Kamera Kino* Heidelberg to celebrate International Women's Day with a special screening of *Marguerite's Theorem* – a movie about ambition, resilience, and women in science.

During the post screening discussion led by Lisa Ringena, our guests Ana Chavez and Yara Elshiaty shared learnings from their career in Mathematics, a field where women are still underrepresented. The movie sparked an exchange about self-doubt and resilience, reflecting on the idea that individuals, often women, might perceive challenges as personal shortcomings, whereas others might view them as obstacles to overcome. We thank everyone who joined and shared their perspectives!


Kamera Kino Heidelberg


The event welcomed over 100 visitors.


A big thanks to all the people who helped organizing the event!

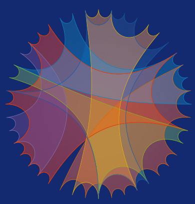

Discussion Panel: Lisa Ringena, Ana Chavez, Yara Elshiaty

Photos kindly provided by IsoQuant

STRUCTURES COMMUNITY

We Are STRUCTURES

In every newsletter issue, we present short interviews with randomly picked members of the STRUCTURES *Young Researchers Convent (YRC)*. The YRC is a subgroup of STRUCTURES that brings together early-career researchers of our scientific community. It represents BSc, MSc, PhD students and postdocs; and aims to give early-career scientists the necessary support to realize their own projects. This ranges from travel funds to the organization of seminars, talks and workshops. The YRC also takes part in the STEPS mentoring programme, designed to promote the exchange between scientists at different stages – especially at the beginning – of their career. Learn more about the YRC in "About the YRC" on page 5.

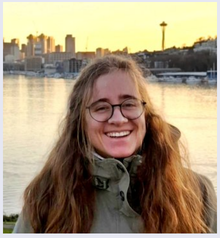


INTERESTED IN JOINING THE YRC?

Any student (BSc, MSc, PhD) or postdoc whose work fits into the concept of STRUCTURES can apply for a YRC membership. If your supervisor is a STRUCTURES member *or* your work is funded by STRUCTURES, you are *directly eligible* for membership in the YRC. Feel free to reach out anytime at: *structuresyrc(at)thphys.uni-heidelberg.de*. For more details, *visit www.structures.uni-heidelberg.de/YRC.php*.

Interviews

For this newsletter issue, we interviewed Katrin Lehle, Julian Nürk, Arthur Limoge and Tobias Witt:



Katrin Lehle
PhD student,
Nelson group (Computational Galaxy Formation and Evolution), ZAH

Interview with Katrin Lehle:

► What are you working on?

I study the gas in the centre of galaxy clusters using cosmological magnetohydrodynamical simulations. In my current project I want to understand the properties of the gas, how the gas evolves over cosmic time, and what processes shape this evolution.

► What fascinates you about your research?

It is fascinating to understand and disentangle all the rich and complex physics shaping the gas in galaxy clusters. Also, creating images and plots that tell a clear story while looking amazing is great fun.

► What motivated you to enter science?

I have always been curious about how things work in the world around me especially about astronomy. This curiosity led me to study physics with a focus on theoretical astrophysics.

► How does one recognize you?

The best way to recognize me is that I am always on the go with a knitting or crocheting project or I am wearing something I have made myself.

Julian Nürk
PhD student,
Scheichl group (Numerical Analysis and Uncertainty Quantification), IWR,
and BOSCH Research

Interview with Julian Nürk:

► What are you working on?

I am working on reliable surrogate models for multi-scale problems. The main problem of interest is modelling and quantifying uncertainties in the simulation chain of short fibre reinforced polymers, where the prediction of structural behaviour is particularly hard due to random and unknown fibre alignment.

► What fascinates you about your research?

Developing mathematical methods to help engineers solve hard problems really fascinates me. Especially, the interplay of mathematical theory and real-world problems for solving them faster and more accurately is a really cool thing.

► What motivated you to enter science?

I always enjoyed the fact that you can grab pen and paper and start working on math, and that everything is built and explained from scratch. That really motivated me in studying and working in the field of mathematics.

► How does one recognize you?

Always just wearing a T-shirt, sometimes with a bike, riding up and down the Königstuhl after work.

Institute abbreviations used on these pages:
ZAH = *Centre for Astronomy Heidelberg* *IWR* = *Interdisciplinary Center for Scientific Computing* *ITP* = *Institute for Theoretical Physics* *IMa* = *Institute for Mathematics*

Arthur Limoge
PhD student,
Moreno Group (Symplectic Geometry), IMa

Interview with Arthur Limoge:

► What are you working on?

I am currently finishing my PhD on methods at the intersection of geometry and astrodynamics. In particular, my supervisor and I have been looking for ways to apply modern tools from symplectic geometry to the Three-Body Problem; to prove existence theorems for specific trajectories, or construct methods for engineers.

► What fascinates you about your research?

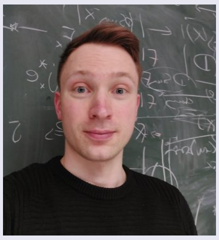
I have a formation in pure maths, and a long-standing physics interest, but never merged the two until I came across the Three-Body Problem. What fascinated me from the get-go is how it requires us to develop specific state-of-the-art geometry and algebraic topology, with physics inspiring new maths.

► What motivated you to enter science?

That's not an easy question to answer, without being very generic. I think what drew me to mathematics is how it lies at the intersection of science and literature – one is trying to understand the world through equations, while the other is about putting to paper abstract concepts. Being a mathematician requires both skills in somewhat equal measures; and I think that is why I like mathematics so much.

► How does one recognize you?

I guess the best bet is trying to locate the French guy talking about space at a geometry conference, or geometry at a space conference.



Tobias Witt
PhD student,
Albers Group (Symplectic Geometry), IMa

Interview with Tobias Witt:

►What are you working on?

I study the existence and multiplicity of periodic orbits on arbitrarily shaped, non-convex billiard tables by importing results from the theory of holomorphic curves.

► What fascinates you about your research?

The interplay between abstract theory and a concrete setup that allows you to calculate quantities like the Conley-Zehnder index explicitly. Also studying the various limiting processes involves a bit of analysis, which is fun in itself.

► What motivated you to enter science?

The dopamine release when you think about math.

► How does one recognize you?

If you collide with someone running downhill in the forest while humming some 80s tune, it might (or might not) be me.

STRUCTURES COMMUNITY

About the YRC: A Short Overview

The YRC brings together early-career researchers of our scientific community. Any early-career researcher who is working in a field that fits into the concept of STRUCTURES can apply for a YRC membership. If your supervisor is a STRUCTURES member, you are directly eligible.

What does the YRC do?

We give young, motivated scientists the necessary support to realize their own projects – from travel funds for conferences and workshops around the globe to the organization of seminars and talks; or support to help members organize their own events.

Regular Events

► *YRC STRUCTURES Days*
Cluster-wide conference for networking.

► *Schöntal Discussion Workshop*
Early-career researchers from different scientific areas engage in discussions over topics beyond the standard curriculum – this year: "Inverse Problems" (August 26-29).

► *Workshops and Talks*
E.g. Active Bystander Trainings, talks within the Physics Graduate Days, special seminars, proposal of Jour Fixe talks.

► *Assemblies & Discussions*
YRC General Assembly and Brainstorming sessions.

Trust Professors

The YRC designates Trust Professors who offer their support, guidance, and mediation for early-career researchers.

YRC Representatives

Every year, the YRC community elects their representatives. The current ones are Freya Jensen (IWR), Marvin Sipp (ITP), and Ricardo Waibel (ITP).

Steering Board

The YRC has three seats in the Extended Steering Board of the STRUCTURES cluster.

STRUCTURES COMMUNITY

The Young African Mathematicians Programme 2024 and 2025

With its participation in the *Young African Mathematicians (YAM)* Programme, the STRUCTURES Cluster of Excellence aims to promote equal access and diverse international collaborations with early-career researchers from the Global South.

YAM is a cooperation between the five centres of the *African Institute for Mathematical Science (AIMS)* and four German clusters of excellence (Münster, Berlin, Bonn, Heidelberg). The programme enables outstanding graduates of the AIMS Master Programme to spend an academic year at a German cluster of excellence.

During their fellowships, the YAM students participate in a rich and dynamic course and seminar programme, and are able to conduct their own independent research. More than just a fellowship programme, YAM is building up an international community by organizing regular meetings connecting all its participating institutions, allowing the YAM fellows to enhance their academic and professional network. The next such meeting will be hosted by STRUCTURES in Heidelberg on June 30 and July 01, and we look forward to lively exchanges and vibrant interactions.

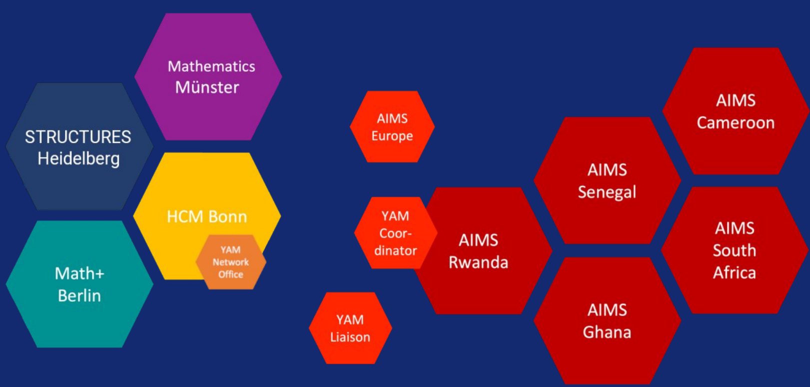
The YAM Fellows 2024/25 together with some of the supervisors, supporters and organizers. Top left: Mina Chavelle Tchoua Tchoua and Mickaya Aimé Razanaparany (AIMS). Top right: Eunisse Nzetchuen Mangaptche (AIMS) and Fabio Schlindwein (STRUCTURES YRC). Bottom left: Group photo of YAM students together with Josephine Westermann, Jakob Zech, Fabio Schlindwein, Maximilian Siebel, Christoph Schnörr, Hans Knüpfer. Bottom right: Mickaya Aimé Razanaparany together with Christoph Schnörr and colleagues.

In 2024, STRUCTURES welcomed Mina Chavelle Tchoua Tchoua, Mickaya Aimé Razanaparany, and Eunisse Nzetchuen Mangaptche from AIMS. Supervised by Jakob Zech, Christoph Schnörr, Jan Pawlowski, and Johannes Walcher, they carried out own research, engaged in many activities and established new contacts. Additional support was provided by early-career researchers Josephine Westermann, Maximilian Siebel and Fabio Schlindwein.

The YAM research stay has been co-organized by Hans Knüpfer, May-Britt Becker and the STRUCTURES office team.

YAM NETWORK

YAM is a joint initiative between the five AIMS centres in Cameroon, Senegal, Rwanda, Ghana and South Africa, and four notable German clusters of excellence (Hausdorff Center Bonn, Mathematics Münster, MATH+ Berlin, STRUCTURES Heidelberg).



Graphic © Magdalena Balcerak Jackson, adapted

Each German participant institution hosts two to four YAM fellows per year, chosen by a collaborative selection process. The partners take turns in organizing networking events during which YAM fellows from all partner institutions can meet, talk about their research, and create a community by sharing their experiences. This enables the fellows to expand their academic and professional network, and all of us to build a stronger community.

STRUCTURES COMMUNITY

STRUCTURES Asks: Dominika Wylezalek (Extragalactic Astrophysics)

For this edition of "STRUCTURES Asks," we interviewed Dominika Wylezalek, a professor at Heidelberg University's *Centre for Astronomy* (ZAH) and the director of the *Astronomisches Recheninstitut (ARI)*. Since 2020, she has been leading the research group GALENA (*Galaxy Evolution and AGN*), after having worked as a postdoctoral fellow at *Johns Hopkins University* and *European Southern Observatory* (ESO). Her award-winning research in observational astronomy focuses on the interplay of supermassive black holes and galaxy evolution. In 2024, she became a member of STRUCTURES. We thank her for taking the time for our interview:

Interview with Dominika Wylezalek

What are the main research themes of your group GALENA?

In our research group GALENA, we study how active supermassive black holes, also referred to as active galactic nuclei or AGN, influence galaxy evolution, focusing on how their energy output during accretion affects star formation and gas dynamics. Our themes include black hole growth, AGN feedback, and galaxy–AGN co-evolution.

What are the main challenges in observing the signatures of AGN feedback?

AGN feedback operates across vast scales– from black hole accretion disks, galaxy-wide outflows out to affecting the circumgalactic medium – making it hard to trace a clear causal link. Observationally, disentangling feedback signatures from other galactic processes is especially challenging due to limited spatial and temporal resolution.

Working with data from instruments like the James Webb Space Telescope (JWST) must be thrilling – how does it impact your research?

JWST provides unprecedented infrared sensitivity and resolution, allowing us to probe dust-obscured regions, spatially resolved gas and stellar kinematics and early galaxy evolution in detail. Its data are revolutionizing our understanding of black hole activity in the early universe.

What sparked your initial interest in becoming a scientist?

I was always fascinated by the night sky, but it was the curiosity about how the universe works – and the desire to ask big, fundamental questions – that drew me to science.

In early March, you were part of a delegation that visited endangered telescope sites in Chile together with President Frank-Walter Steinmeier. What was this about?

I received a surprise invitation from the Federal President's Office to join President Steinmeier's delegation on a visit to the ESO sites in Chile. The purpose of the trip was to assess the vital astronomical research conducted in the Atacama Desert, one of the most important astronomical research sites worldwide. The region is known for its exceptionally clear, dark night skies. However, an industrial project threatens to significantly increase light pollution. My ESO experience provided the delegation with insights into the facilities. President Steinmeier himself was very impressed by the sites – calling the Paranal Observatory a 'magical place' – and in his press statement stressed their importance for scientific cooperation.

Dominika Wylezalek, Professor for Extragalactic Astrophysics at ZAH / ARI

What advice would you give to young girls or women who are curious or passionate about becoming a scientist?

Follow your curiosity relentlessly, don't be afraid to take up space, and remember that science needs diverse perspectives – your questions and ideas matter.

What are hobbies or interests that you pursue aside from astronomy?

I enjoy doing home workouts, hiking, gardening, spending time with my family and friends and interior design – activities that offer a balance to my research.

Visit of the light-pollution endangered ESO sites in Chile together with the German Federal President's delegation. The region is "one of the last truly dark places on the planet", stresses Dominika Wylezalek.

Image source: Bundesregierung/ Steffen Kugler

BACKGROUNDS & METHODS

From Ordinary Differential Equations to Measure-Valued Structured Population Models

By Carolin Lindow (IMa)

In mathematics, we often seek to understand how certain quantities evolve over time. We might consider questions such as *"Where will a moving object be in an hour?"* or *"How many cells of a certain type will be in the human body at a certain age?"* Questions like these can be studied using *differential equations*, which describe how a quantity changes over time.

Ordinary Differential Equations

We begin with *ordinary differential equations (ODEs)*, where the rate of change (given by the time derivative) depends only on time and on the current value of the quantity. For example, the future position of a vehicle can be predicted if we know its current position, and the speed and direction of the vehicle.

Another possible example is the number of animals in a habitat. For a single species, a simple ODE might look like this:

$$\frac{\mathrm{d}}{\mathrm{d}t}\underbrace{u(t)}_{\text{Number of animals}} = \underbrace{b(t, u(t))\, u(t)}_{\text{Birth rate}} - \underbrace{d(t,u(t))\, u(t)}_{\text{Death rate}},$$

$$u(0) = \underbrace{u_0}_{\text{Initial number of animals}}.$$

Here, $u(t)$ is the number of animals at a given time t, and the rate $b(t, u(t))$ quantifies how many animals give birth to new animals per unit of time. If $b(t, u(t)) = 0.1$ for example, it would mean that 1 out of 10 animals has a baby. Similarly, the death rate $d(t,u(t))$ describes which fraction of the population dies per unit of time.

When Simple Models Are Not Enough

In the above "toy example," birth and death rates depend only on time and on the current number of animals. However, nature is rarely so simple. In the real world, these rates may be influenced by many other factors: Older animals have larger mortality rates, while larger animals are more likely to survive and have offspring. Environmental factors matter as well: Is there enough food and water for the animals? Are there any predators?

We can describe some of these effects by smart choices of rate functions in our equation. For instance, the scarcity of resources could be modelled via a birth rate decreasing when too many animals of the species are present. However, other important factors, such as the influence of an animal's size on its probability of survival cannot be described with ordinary differential equations, as these do not track information about the size of individual members.

In mathematical modelling, we now get to make a choice: Do we wish to stick to ordinary differential equations – which may be easy to solve (at least on a computer) and allow us to extract much information about population averages – or are we interested in details such as the dependencies on the size of animals? The latter requires sophisticated models that include this information. This leads to the concept of *structured population models*.

What Are Structured Population Models?

In many examples inspired by biology, the parameters describing changes in a population do not only depend on time but on other intrinsic variables. We can, for example, imagine that the number of offspring of an individual depends on its size. How can we incorporate such dependencies in our mathematical models?

We do this by identifying a meaningful set of variables that describe the aspects of the population, influencing the parameter functions. These are called *state variables*. An example would be the size of an individual. Other possible variables include the age and physical location of individuals.

The type of equation that we will now use describes how the distribution of individuals in this state variable changes over time. We obtain what we call a *structured population model*, which is a particular type of partial differential equation. Just like ordinary differential equations, partial differential equations describe how something changes. Now, the solution depends on several variables (here time and the state variable). We also have derivatives in several variables, *i.e.* we consider how several aspects of the population change.

Such a structured population model is described by an equation of the following form:

$$\underbrace{\partial_t u(t, x)}_{\text{Change in time}} + \underbrace{\partial_x (cu(t, x))}_{\text{Change in state variable at speed c}} = 0, \qquad (1)$$

$$u(0,x) = u_0, \qquad (2)$$

where $u(t, x)$ is the number of individuals at time t that have a certain characteristic x. ∂_t and ∂_x denote the *partial derivatives* of the function $u(t, x)$ with respect to t and x, respectively.

For simplicity, we assume here that the rate of change c of the state variable x is constant. In this case, we can calculate the solution to the structured population model, which is given by:

$$u(t, x) = u_0(x - ct), \qquad (3)$$

which means that the initial population "moves" through the state space at speed c as time passes. Note that we assumed the initial distribution u_0 to be differentiable.

We can also add an influx function $f(t,x)$ to a structured population model in order to represent external factors that might modify the population. In the animal example, this could be animals entering or leaving the

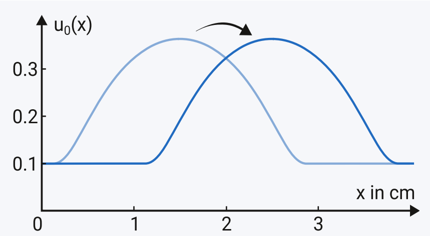


Fig. 1: In the simple case where we consider only growth, the initial distribution of the size of animals (semi-transparent curve) simply moves forward in the state variable over time, to the new position x - ct at time t.

area that we are considering. Our differential equation system will then look like this:

$$\partial_t u(t,x) + \partial_x (cu(t,x)) = f(t,x), \quad (4)$$
$$u(0) = u_0, \quad (5)$$

which means that, additionally to the movement through the state space, the population also increases (or decreases) at the speed $f(t,x)$.
The solution in this case is given by:

$$u(t,x) = u_0(x-ct) + \int_0^t f(s, x+c(s-t))\,\mathrm{d}s \quad (6)$$

for a function f that has continuous derivatives in t and x. Comparing this solution to (3), we can see that in any point x we add the "mass" that was created somewhere in the state space and has moved to x at time t.

Applied Example: Insect Population

Let's look at more examples. Unfortunately, birth processes lead to some more technical delicacies that would make these examples quite complicated. This is why we are considering a population of insects within a year. Let us assume that the species completes its lifetime within one summer. At the onset of spring ($t = 0$), we have an initial population $u_0(x) : (-\infty,\infty) \to [0, \infty)$ of insects, where the value $u_0(x)$ is the number of insects of a given size x.

Throughout summer, the insects grow. At the end of summer the insects would lay eggs that give rise to next years' population. For simplicity, we assume that the insects grow at speed 1. To further simplify the setting, we can imagine an invasive species with no natural predators. Invasive species are often harmful to the environment. Suppose conservation efforts involve selective removal of insects using traps to protect biodiversity. We want to use our influx function $f(t,x)$ from (4) to do this. For simplicity, let's assume that the limiting factor is the capacity of the traps, such that we can use a "catching rate" that is independent of the population size. If the traps catch all of the insects equally at a small rate r, then $f(t,x) = -r$ on the right-hand side of equation (4). This yields the solution:

$$u(t,x) = u_0(x-ct) - \int_0^t r\,\mathrm{d}s$$
$$= u_0(x-ct) - rt. \quad (7)$$

Admittedly, this highly simplified model is of limited use. In reality, insects cannot have negative sizes, and if there are no longer any insects of a certain size x, they can also not enter the trap. Thus the model should be taken with care.

Continuing with the same example, something more interesting happens if we say that only insects of certain sizes, say 0.5 to 1 cm, are caught. The influx function f would be given by:

$$f(t,x) = \begin{cases} -r & \text{if } 0.5 \le x \le 1 \\ 0 & \text{else,} \end{cases} \quad (8)$$

which is not continuously differentiable. Technically, we can no longer apply formula (6) because its proof (that was not given here) requires that we can differentiate the influx function, which is not possible for a function that has jumps like f.

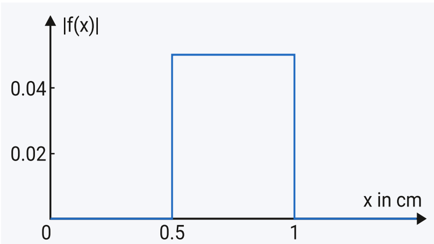


Fig. 2: Influx function f from equation (8). The function f has jumps at $x = 0.5$ and $x = 1$ and is thus not differentiable.

We can, however, still calculate the quantity that is given by formula (6). We can figure out that $x + (s - t) \in [0.5, 1]$ is the same as saying $s \in [0.5 + t - x, 1 + t - x]$, which we can use to calculate that

$$u(t,x) = u_0(x-ct) - \int_{\max(0,\,0.5+t-x)}^{\min(t,\,1+t-x)} r\,\mathrm{d}s$$
$$= u_0(x-ct) - r \cdot (\min(t, 1+t-x) - \max(0, 0.5+t-x)). \quad (9)$$

What happened here? We just applied a formula derived under conditions no longer met, and obtained a reasonable quantity.

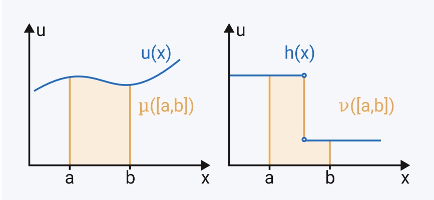


Fig. 3: The area under the curve can be calculated for functions which have jumps. If we only consider those areas instead of the value at each point, we can have many more solutions.

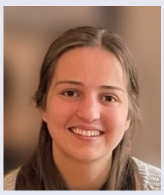
Broadening the Concept of Solutions:

This turns out to be quite common in analysis: when we cannot solve an equation, we broaden the understanding of what we still accept as a solution. While this may sound like "cheating", it is a rigorous process. We identify essential properties satisfied by all "classical" solutions, then define a broader class of functions that maintain these properties. In our example, we've moved from requiring pointwise satisfaction of equation (4) to accepting functions which fulfil the integral formulation (6).

A further generalization we can make in this particular setting is to say that we only care about the values of subsets instead of the value of the solution in every single point. Mathematically, we call such solutions *measures*. These allow us to consider initial values and influx functions that are not continuously differentiable but integrable. Although this restricts what we can calculate to total amounts in subintervals, it turns out highly useful for numerous applications, as it allows us to consider many more functions.

Overall, we have seen how we can use properties of a population to describe its evolution. By broadening what we accept as a solution we can study more situations, even if we might obtain less information about the solution.

About the Author:



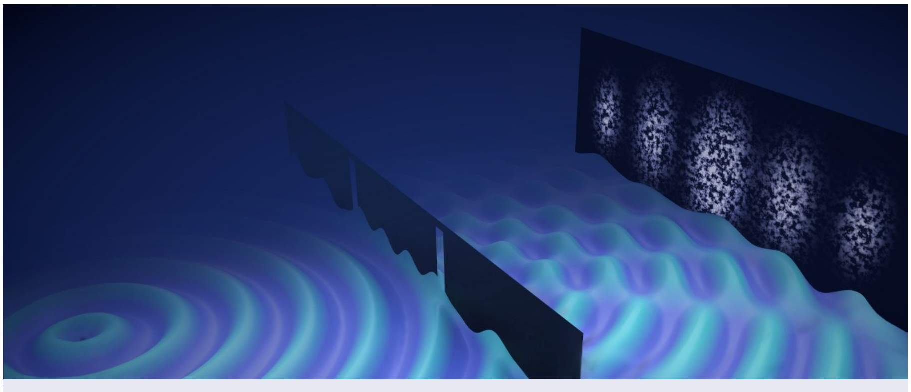
Carolin Lindow is a doctoral student in Prof. Anna Marciniak-Czochra's group at the *Institute for Mathematics (IMa)*. She is working on mathematical models for the dynamics of neural stem cells.

SCIENCE CELEBRATES:

International Year of Quantum Science and Technology 2025

This year marks the centenary of modern quantum mechanics. In 1925, Heisenberg, Born and Jordan developed the first mathematically consistent formulation of quantum mechanics. Already by the early 20th century, first hints had emerged at the failure of classical physics – resulting in attempts to cure theory, as well as in new concepts. Planck's 1900 postulate of discrete energy quanta and Einstein's 1905 explanation of the *photoelectric effect* introduced a notion of discreteness to physics. Bohr and Sommerfeld introduced quantization rules for the atom, which received an intuitive interpretation when de Broglie's 1924 *matter-wave postulate* allowed comparing atomic electrons to standing waves. In 1926, a second formulation of quantum mechanics based on waves was put forward by Schrödinger, and later shown to be equivalent to Heisenberg's formalism.

The ensuing quantum revolution became the basis for all subsequent modern physics – laying the foundation for the standard model of particle physics – and a crucial driver of modern technology, such as electronics devices, computers, lasers or magnetic resonance imaging, to name a few.



The famous **quantum-mechanical double slit experiment** demonstrates fundamental aspects of quantum mechanics, such as wave-particle duality: fundamental entities like photons and electrons can exhibit both wave and particle properties; or the uncertainty principle: position and momentum cannot be simultaneously known with certainty.
Image credit: AdobeStock/User:Ricardo, adapted colours.

Quantum Mechanics in STRUCTURES

Quantum theory and experiments play a huge role in the research of the STRUCTURES Cluster. The unique interdisciplinary environment of STRUCTURES brings together theorists, experimentalists, and computational scientists. Their close interaction fosters an environment where theoretical questions can directly inform experimental designs, and experimental results can guide the refinement of theoretical models.

On the experimental side, the *Heidelberg Quantum Architecture* (HQA), a novel modular and programmable platform for quantum experiments, serves as a versatile tool for testing theoretical ideas and exploring complex quantum phenomena in a controlled laboratory setting.

Beyond fundamental research, the science of STRUCTURES bridges the interface to engineering sciences, for instance with the development of neuromorphic and photonic hardware, harnessing properties of physical structures in order to pioneer new ways of computing.

On the occasion of quantum mechanics' centenary, we asked STRUCTURES members about the role quantum theory plays in their research. On page 11, we present the answers from our community.

Event Tip: Academic Lunch Hour *"Quanten am Mittag – von kleinen Teilchen & großen Ideen"*

We are pleased to announce that this year's *"Akademische Mittagspause" ("Academic Lunch Hour")* will be hosted by *CRC1225 IsoQuant* and the *Max Planck Institute for Nuclear Physics* – and is dedicated to the International Year of Quantum Science.

The Academic Lunch Hour is an annual series of science talks at Heidelberg University. From **May 7 to June 18**, every Monday to Thursday at **12:30 PM**, the Peterskirche in Heidelberg's Old Town will be home to the lecture series *"Quanten am Mittag – von kleinen Teilchen und großen Ideen" ("Quanta at Noon – From Small Particles to Great Ideas.")*

In engaging and accessible 15-minute talks, researchers will share the latest insights into the fascinating world of quantum physics – from fundamental particles of matter to the frontiers of future technology. This is part of the celebration of the *International Year of Quantum Science 2025* marking 100 years since the initial development of quantum mechanics.

Akademische Mittagspause
https://www.uni-heidelberg.de/de/mittagspause

STRUCTURES COMMUNITY & RESEARCH

Quantum Research in STRUCTURES – Bridging Theory, Experiment and Computation

“

Markus Oberthaler (Experimental Physics):

Quantum matter allows us to implement model systems in the lab, which are going beyond mere gases of atoms; and to explore new material properties emerging when driving the system strongly. Thanks to the quantum nature of atoms, we have built a quantum field simulator for studying particle production in time-dependent spacetime.

“

Rüdiger Klingeler (Experimental Physics):

The quantum nature of atoms involving the uncertainty principle yields novel states of matter and spectacular phenomena in actual materials. We exploit quantum effects as a new route towards innovative materials with unprecedented properties.

“

Thomas Pfeifer (Nuclear Physics):

We use quantum mechanics to develop an understanding of how intense flashes of light modify the fundamental physical properties of atoms and molecules. We explore the quantum nature of atoms and molecules to test their suitability for ultrafast and ultrasmall quantum processors, programmed by light, for future computing applications.

“

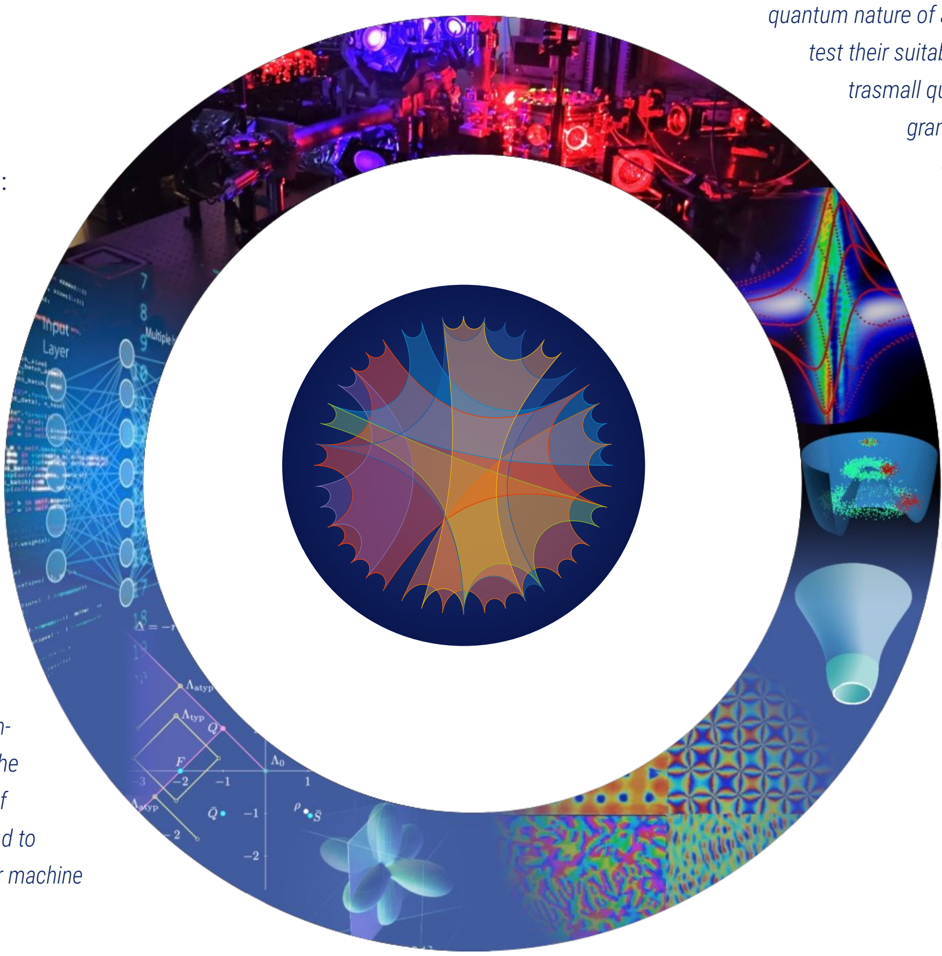
Thomas Gasenzer (Experimental Physics):

Quantum matter out of equilibrium makes us think how to make cool gases colder.

“

Fred Hamprecht (Scientific Computing):

We use Quantum Mechanics as a framework for the accelerated prediction of molecular properties, and to generate training data for machine learning.



“

Arthur Hebecker (Theoretical Physics):

Our favourite statement would be: “Everything is quantum.”

“

Johannes Walcher (Mathematical Physics):

Insights from quantum field theory have changed the way we think about problems in geometry. Quantum mathematics is a thing. Thinking of geometric and algebraic invariants as quantum mechanical observables continues to provide marvellous insights into fundamental mathematical structures.

“

Viktoria Noel (Theoretical Physics):

We further investigate into quantum theory by uncovering hidden symmetries in the dynamics of quantum matter far from equilibrium. It is well known that one of the most powerful ideas in physics is that of symmetry—the notion that certain properties of a system remain unchanged under specific transformations, like rotations or reflections. In our research, we explore what happens when a quantum system is far away from its balanced, equilibrium state and we’ve developed a method to detect the “hidden” or “emergent” symmetries that appear during such dynamics.

“

Maurits Haverkort (Theoretical Physics):

We use quantum mechanics to develop methods for measuring the local, atom-like electron wave functions in materials. Quantum matter allows us to design better batteries, solar cells, electronic devices, and catalysts. Thanks to the quantum nature of atoms, molecules, and solids, we live in a rich world full of symmetry-breaking structures.

LECTURE NOTES

Electrodynamics eBook by Björn Malte Schäfer

Looking for an interesting read? We are happy to share that Heidelberg University's publishing service *heiUP* recently published lecture notes on electrodynamics by our member Björn Malte Schäfer (professor at ZAH) as a book. It covers the material of a theoretical physics course on electrodynamics, starting from Maxwell's equations, introducing special relativity, and leading the students to relativistic field theory. Embedded links to Wikipedia and 40 colourful figures illustrate the material.

The ebook is downloadable for free on heiUP's website:

Lecture Notes | Heidelberg University Publishing
https://heiup.uni-heidelberg.de/catalog/book/1055

We also invite you to browse and discover further books on the heiUP pages, including lectures on statistical physics, mathematics and much more.

Have fun reading!

LECTURES & COURSES

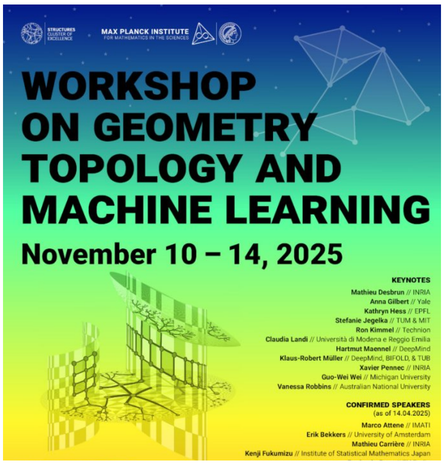
SSC Courses Summer 2025

This semester, the *Scientific Software Center (SSC)* at Heidelberg University offers again a rich programme of compact courses on software engineering best practices and tools – from python packaging to `cmake`, version control with `git` and many more topics. The courses are open to all students and researchers. Learn more at:

Scientific Software Center: Courses
https://www.ssc.uni-heidelberg.de/de/node/248

EVENTS

Workshop on Geometry, Topology & Machine Learning



We are pleased to announce the workshop *Geometry, Topology and Machine Learning (GTML)*, jointly organized by the Max Planck Institute for Mathematics in the Sciences (MPI-MIS) and the STRUCTURES Cluster of Excellence. The event, taking place from November 10 to 14, will bring together two rapidly evolving fields central to modern machine learning: Geometry and topology offer fundamental methods for understanding data structure and provide powerful frameworks for analyzing, unifying, and generalizing machine learning techniques across diverse applications.

The workshop will feature 10 keynote talks and 20 presentations by leading experts. Topics range from mathematical foundations of machine learning to geometric & topological deep learning, as well as multidisciplinary applications of geometry & topology. By merging the previous workshops on *Geometry in Machine Learning (GaML)* and on *Topological Methods in Data Analysis (TMDA),* GTML creates a platform to foster collaboration and to explore the synergistic relationship between geometry, topology, and machine learning.

Further details, including an overview of talks and speakers, can be found at the workshop's webpage:

Workshop GTML 2025: MPI MIS
https://www.mis.mpg.de/events/series/workshop-on-geometry-topology-and-machine-learning-gtml-2025

STRUCTURES ON THE WEB
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