IWR
Interdisciplinary Center
for Scientific Computing

UNIVERSITÄT
HEIDELBERG
ZUKUNFT
SEIT 1386

# Interdisciplinary Center for Scientific Computing (IWR)

# REPORT 2009 – 2014

Interdisciplinary Center for Scientific Computing (IWR)

# REPORT 2009–2014

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## Executive Summary

Scientific computing has become one of the so-called "key enabling technologies" for coping with scientific and technological challenges. Nowadays, it is already seen as the third methodological pillar of research complementing theory and experiment. Since its foundation in 1987, the Interdisciplinary Center for Scientific Computing (IWR) focuses on and drives the development of new innovative mathematical and computational methods for science, engineering and recently also humanities and medicine. By transporting mathematical and computational methods into different areas of application, the IWR naturally builds bridges across different disciplines and promotes Computational Science. This interdisciplinary tradition is not only restricted to research, but it embraces also the education of the next generation of excellent scientists.

Through the 27 years of its existence, the IWR has grown to a university spanning central institute with 45 faculty members and overall more than 500 researchers from mathematics, informatics, physics, chemistry, earth sciences, biological sciences, medicine and philosophy. It has become an internationally leading place for scientific computing, which is impressively documented by the successful application within the Excellence Initiative for the Heidelberg Graduate School of Mathematical and Computational Methods for the Sciences (HGS MathComp) and nine running ERC grants among the IWR members. In addition, the ten core members of the IWR manage to raise about 6 Million € third-party funds per year, resulting in ~170 externally funded researchers compared to 15 paid by the university, resulting in an incredibly large multiplication factor of eleven.

Despite its great success and enormous growth, the annual budget provided by the Ruprecht-Karls University remained essentially constant over the last ten years. A particular drawback of the financial situation of the IWR is the inherent need for continuous renewal of the local computing facilities to remain in the position to perform cutting-edge research in the field of scientific computing. In the current situation, money for these inevitable investments is withdrawn from the annual budgets of the researchers and the global IWR budget and saved over several years. For the IWR to be competitive in the future, an institutional investment budget of 200.000 € per year, aside from the budgets of the researchers is highly desirable.

In addition, the number of administrative staff members remained constant, leading to a dramatic undersupply in view of the enormous growth of the scientific personnel. Two additional administrative positions (full time equivalent) for secretary and system administration are crucially important to ensure the administrative functionality of the IWR.
From a scientific point of view, the IWR intends also in the future to further strengthen the strengths, i. e. its methodological key competences: mathematical modeling, simulation, optimization and image processing. It is clear that the IWR will continue to follow its mission to promote scientific computing into new areas of science, for which mathematical and computational tools have played only minor roles so far. It is planned to expand the already existing pioneering initiatives in the fields of computational humanities, computational medicine, computational molecular material science as well as computational social and behavioural sciences into larger collaborative research units.

In view of the end of the Excellence Initiative in October 2017, Liebig Centers or DFG Research/Competence Centers are discussed as measures of the federal government to provide sustainable long-term funding to secure the achievements and infrastructure generated. In case of their advertisement, the managing board of the IWR plans to apply as leading, responsible institute for such a center under the notion of "Scientific Computing meets Computational Science". The IWR is the ideal institute to spearhead such an endeavor, since it possesses all necessary prerequisites. The HGS MathComp of the IWR funded by the Excellence Initiative provides a blueprint for a successful interdisciplinary graduate and postgraduate education. The organizational structure of the IWR is inherently interdisciplinary, since it overarches the faculties of Heidelberg University. Ten core faculty members exist already, as well as some administrative and scientific staff. The IWR promoted new forms of private public partnership-based transfer platforms with the Heidelberg Collaboratory for Image Processing (HCI) and the Heidelberg Collaboratory for Industrial Optimization (HCO). All researchers have an outstanding scientific reputation resulting in the exceedingly high overall third-party funding of the IWR. The foundation of a joint "Romberg Center" between the University Computing Center and the IWR would provide a unique research infrastructure in high-performance computing for cutting-edge research. Foremost, however, the IWR is particularly well suited because of its internationally highly visible research topics in method development and its challenging applications in all areas of computational science.

Hans Georg Bock
Andreas Dreuw
Peter Bastian

# 1 The Interdisciplinary Center for Scientific Computing

"Mathematics is the key and door to the sciences."

Galileo Galilei


Prof. Hans Georg Bock welcomes our guests at the 25th anniversary of the IWR.

## The Mission of the IWR

The Interdisciplinary Center for Scientific Computing (IWR) pursues, since more than twenty-five years now, successfully its vision to develop mathematical and computational methods for science, engineering and humanities. By transporting mathematical and computational methods into different areas of application, the IWR naturally builds bridges across different disciplines. This interdisciplinary tradition is not only restricted to research, but it embraces also the education of the next generation of excellent scientists. Since its foundation, the IWR set out to advance international research networks and is still promoting scientific computing all over the world.

## A Brief Historical Overview

The IWR was founded 27 years ago by the state of Baden-Württemberg and the Ruprecht-Karls University of Heidelberg as a central research institute to promote research in the highly interdisciplinary field of scientific computing. Since then the IWR dedicates itself to interdisciplinary research and the promotion of high-performance computing. Also owing to the success of the IWR, scientific computing has developed into one of the key technologies of the 21st century and is nowadays considered an integral part of scientific research, bridging and complementing theory and experiment. Being placed between theory and application, scientific computing is per definition an interdisciplinary research area, since it requires expertise in both areas in addition to computer science and technology. This interdisciplinarity has been realized within the IWR right from its foundation, as it was furnished with scientists originating from three different disciplines: mathematics, physics and chemistry. These scientists worked together within the IWR, however, they were also part of their home faculties ensuring from the start disciplinary excellence together with an interdisciplinary spirit. This structure has proven to be very successful and has thus been maintained until today.

In the eyes of the IWR, scientific computing comprises the development of mathematical methods and efficient software to tackle challenging applications using high-performance computers. This clearly distinguishes the research at the IWR from purely computational science, which refers to the application of existing computer programs to scientific questions. In other words, the research at the IWR drives computational science and is itself driven by the computational needs for efficiency and demands of experimental scientists. Hence, the methodological aspect is important to all members of the IWR and is inspired by challenging scientific applications and most modern computer developments.

## Research Philosophy

The research at the IWR is dedicated to the development of mathematical and computational methods for science, technology and humanities, requiring formal mathematical research as well as the development of efficient, tailored software to utilize high-performance computing. The IWR has built up a unique expertise in all aspects of scientific computing with the core competence in innovative methods for modeling, simulation, optimization, and image processing. Key methodological research fields of the IWR members comprise:

**Multi-Scale Modeling and Simulation:** A great challenge for modeling and simulation is the building of bridges from microscopic structures and models across the disparate scales of space, time and organization to macroscopic systems.

**Optimization and Optimization-Based Simulation**: Optimization-based methods play an ever-increasing role in scientific computing, because most applications require complex optimization problems like parameter estimation, optimum experimental design, and optimal design and control to be solved. Optimization-based methods, nowadays, play a crucial role in modeling processes.

**Model and Mesh Adaptivity:** Discretization of continuum models leads to sequences of nonlinear and then linear systems of algebraic equations. Since the accuracy and computational effort of the solution is directly linked to the discretization level, i. e. the density of the mesh, adaptive discretization leads to efficient and accurate computational methods.

**Multilevel and Parallel Methods:** The simulation of complex multiscale, multiphysics problems including optimization and uncertainties requires enormous computational resources despite all algorithmic improvements. Parallel algorithms once being an esoteric area of research has now become mainstream as even desktop computers only get faster by adding more compute cores.

**Image Processing:** Imaging technologies rapidly advance in areas like medicine and driver assistance systems, for example. The research aims at providing cutting-edge solutions to basic image analysis problems for applications in science, engineering and the humanities.

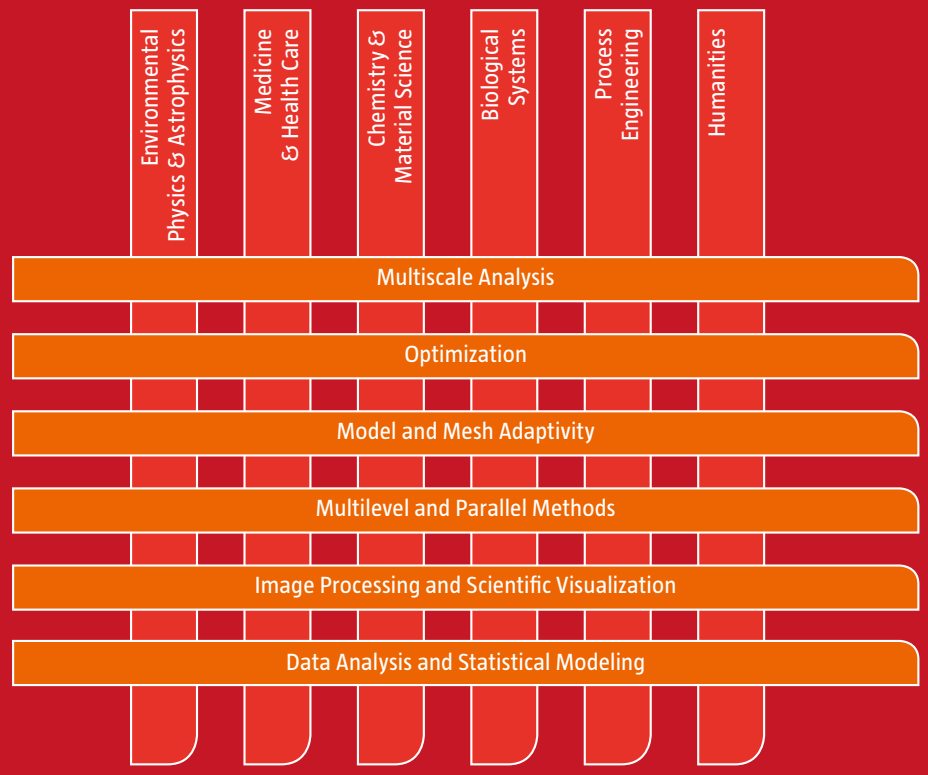


**Fostering Interdisciplinary Cooperations**
The special horizontal structure of the IWR as a central institution of the university connects the vertical structures of the faculties and subjects


**Data Analysis and Statistical Modeling:** Research in statistics and data analysis addresses pressing needs in the analysis and modeling of complex systems, high dimensions and massive data sets. These developments are driven by qualitatively new demands in a very broad range of scientific, business and societal applications.

It is impossible to list the plethora of applications of these developed methodologies of the IWR members here. A more comprehensive list of examples can be found in the compilation of the IWR members. Examples of areas in which challenging problems of scientific computing, which have been successfully addressed through the research at the IWR, demanding optimal computational tools in modeling, simulation and optimization are:

## Research Areas
Linking methods of scientific computing and challenging fields of scientific application




**Computational Chemistry:** Breakthroughs have been achieved in the simulation and modeling of reactive flows, the theoretical description of time-dependent chemical phenomena like the intermolecular coulombic decay and nuclear motion, for which efficient computer programs have been developed and disseminated into the scientific community.

**Computational Physics:** Algorithms and computer programs could be devised to model, for instance, three-dimensional radiation transport in astrophysics and to simulate the fate of pesticides in ground water in collaboration with environmental physicists.



**Industrial Applications of Scientific Computing:** New methods and algorithms have been tailored for real-time optimization and control of industrial processes, for example, reactive distillation columns (BASF) or heavy-duty trucks (Daimler). The Heidelberg Collaboratory for Image Processing (HCI) as a new form of private-public partnerships serves as a role model for "Industry-on-Campus" ventures.

**Computational Biosciences:** Efficient algorithms and methods have been devised to allow for high-performance computer simulations of biological macromolecules, systems biology, cell biology and plant physiology, for example.

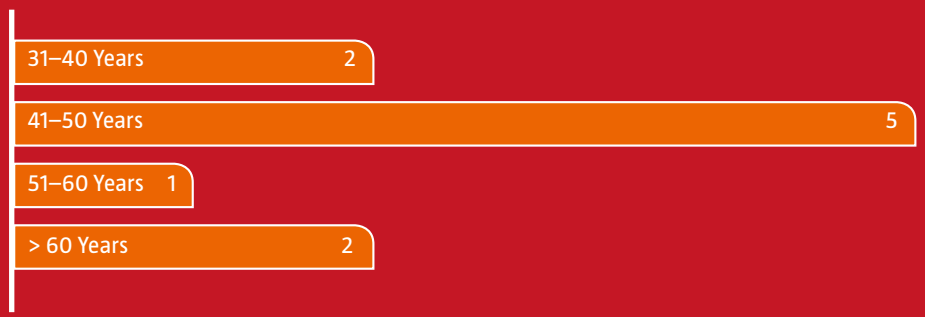
Following its philosophy, the IWR has become one of the most integrative research centers of Heidelberg University with at present 45 active members and twelve junior research group from eight different faculties, i.e. mathematics, informatics, physics, chemistry, earth sciences, biological sciences, medicine, philosophy. As one consequence, scientific computing has become one pillar of the strategy of the Ruprecht-Karls University as a comprehensive university. However, the IWR is not only the key player in scientific computing here in Heidelberg, but served also as blueprint for other national and international institutes and research centers, like the Interdisciplinary Center for Mathematical and Computational Modeling in Warsaw.

## Present Situation

The dual strategy of the IWR to develop new, powerful and innovative methods of scientific computing on the one hand, and to promote their application in computational science on the other, is visibly reflected in the special structure as an interdisciplinary so-called "central research institution" of the university. Today, it integrates 45 senior and 12 junior research groups from the faculties of mathematics and computer science, physics and astronomy, chemistry and geography, bioscience, medicine, philosophy and behavioral and cultural studies. Of these, 14 senior and 9 junior research groups are members of the "core" unit, i.e., they are located on the premises of the IWR and have their budgets there. In addition, another 31 + 3 groups reside at different university institutes but are ("associate") members of equal right and duties.
The Core or "Budgetary" Unit of the IWR is an interdisciplinary, cross-faculty institution with its own budgets, office space, professorships and administrative staff. Its basic infrastructure has the following elements:

- 10 positions for tenured (regular) professorships.
- 4 temporary professorships financed within the Excellence Initiative

## Age Distribution of Tenured Professors




Of the ten tenured positions, six are from mathematics and computer science (Bastian, Bock, Böckle, Heuveline, Kanschat, Ommer), two from chemistry (Dreuw, Gutheil) and two from physics (Hamprecht, Jähne). In principle, with every reappointment, the IWR can decide a new discipline and strategic research area to be filled. According to the university law, all of the IWR professors are also members of one faculty where they fulfill their standard teaching duties.

During the reporting period 2009–2014, five of these ten professorships were reappointed: Gebhard Böckle (2010), Andreas Dreuw (2011), Guido Kanschat (2012), Vincent Heuveline (2013) and Björn Ommer (2013). The age structure of the tenured professors is given in the table. The professorship of Bernd Jähne will be reappointed early, tentative date 2015, the reappointment of the professorship of Hans Georg Bock is planned for 2019.

Heike Leitte (Junior Professorship, 2010–2016), Katja Mombaur (Start-Up Professorship, 2010–2017) and Willi Jäger (Senior Professorship, 2008–2014) hold three of the four temporary professorships. The fourth professorship within the HGS MathComp on "Scientific Visualization" is in the stage of appointment. It is temporary for five years, but intended to be changed into a permanent position depending on sustainable funding. It will be complemented by a second professorship in the field of "Computer Graphics", which will be created by the Heidelberg Institute of Theoretical Studies (HITS), a private research institute of the Klaus-Tschira Stiftung, a German foundation that promotes natural sciences, mathematics and computer sciences.



## Contrasting the Numbers of State- and Third-Party Funded Staff of the Core Unit at the IWR

| RESEARCH GROUP | | STATE FUNDED | THIRD-PARTY FUNDED |
|---|---|---|---|
| **Tenured Professorships** | | | |
| **Bastian** | | 2 | 11 |
| **Bock** | [including JRG Kirches, Körkel, Potschka] | 3 | 28 |
| **Böckle** | | – | 7 |
| **Dreuw** | [including JRG Faraji] | 2 | 11 |
| **Gutheil** | | – | 6 |
| **Hamprecht** | | 1 | 10 |
| **Jähne** | [including JRG Garbe] | 1 | 16 |
| HCI | | – | 14 |
| **Ommer** | | 1 | 6 |
| **Heuveline** | * 2 KTS-funded positions for scientific staff at the HITS | –* | 11 |
| **Kanschat** | | 2 | – |
| **Temporary Professorships and JRG** | | | |
| **Jäger** (Senior Professor, ZuK) | | – | 10 |
| **Leitte** (Junior Professor, GSC 220) | | – | 4 |
| **Mombaur** (Start Up Professor, ZUK) | | – | 9 |
| **N. N.** (Scientific Visualisation, GSC 220) | | 1 | – |
| 4 additional JRG: Chavarría Krauser, Fischer, Hujeirat, Matthäus | | 1 | 10 |
| **Collaborative Projects** | | | |
| **GSC 220 HGS MathComp** | | 2 | 3 |
| **RTG 1653 Spatio-Temporal Graphical Models** | | – | 12 |
| **BIOMS** | | – | 8 |
| **TOTAL** | | **16** | **176** |

**Scientific Staff**: The IWR has 22 state-funded positions for scientific assistants. 16 attributed to research groups and units. Four are members of the so-called "Central Scientific Services" and responsible for the management of compute servers and parallel computers, computer pools, as well as central management and acquisition. Two persons are responsible for the administration of the HGS MathComp.
In addition, 176 scientists, including the doctoral students, are funded by the close to 6 Million € third-party grants of the Core Unit of the IWR, which makes a very remarkable ratio of 1:11 for state vs. third-party funded scientific staff. Together with the administrative staff approximately 240 people form the Core Unit.

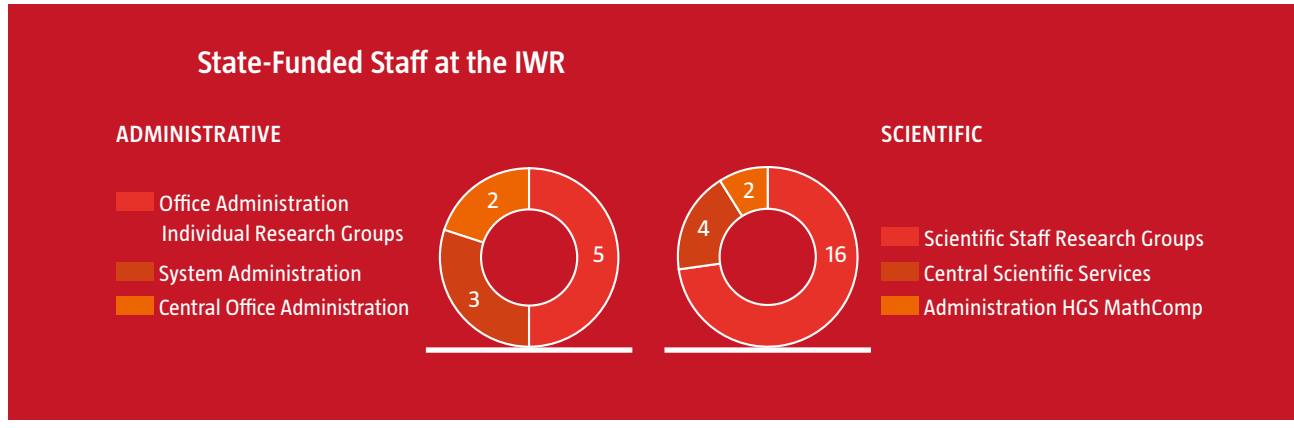
**Administrative Staff:** For the whole Core Unit of fourteen senior and nine junior research groups and over 200 scientists, there are a total of five full-time equivalent (FTE) positions for office administration assistants for the individual research groups. They are responsible for staff, project and time management, third-party projects, bookkeeping and controlling. For system administration purposes there are three FTE positions, which are responsible for hardware and software administration and acquisition. Two FTE positions are responsible for the central office administration of the IWR, which includes major acquisitions, management of the center, support of the managing board of directors and third-party funded large collaborative projects.

Since the administrative resources are too scarce to serve the whole IWR, four half time positions for office administration and three half time positions for system administration are financed from the budget of the IWR, or from third-party grants.

**IWR Budget:** The IWR has its own annual financial funds. Its basic resources are an annual amount of about 290.000 € for common interests, and another 258.000 € for the individual demands of the research groups of the Core Unit as negotiated typically upon appointment. However, the IWR is not provided with separate investment funds. Every major investment requires savings of annual personal and institutional budgets.

IWR has presently approximately 2.387 sqm of office space at two different locations to its disposal, on the campus Neuenheimer Feld plus an additional 2.166 sqm rented office space in a separate building at Speyerer Straße. We are eagerly looking forward to move to our new residence, the Mathematikon, in early 2016.






**IWR Governance Structure:** The IWR management and decision-making structures have three levels:

A **Managing Director** (presently Hans Georg Bock) is responsible for the management and official representation of the IWR. The managing director reports directly to the rector of the Ruprecht-Karls University.

The managing director is a member of the **Managing Board of Directors** which is responsible for all ongoing decisions and meets approximately every month. It has presently five members: Peter Bastian, Hans Georg Bock, Peter Comba, Andreas Dreuw and Bernd Jähne. The managing director and the members of the board are appointed by the rector of the university for a term of three years, based on a proposal by the extended board of directors of the IWR.

**The Extended Board of Directors** consists of all 47 professors, who are members of the IWR also appointed by the rector. The extended board of directors is responsible for all strategic decisions. Their vote overrules decisions of the two other levels.

**Computational Infrastructure:** Obviously, an excellent computational infrastructure on several levels is mandatory for excellent research at the IWR. Of course every scientist is equipped with an appropriate workplace for software development and test-runs, as well as office needs. For the special needs of certain demanding problem classes, which require higher computing performance or very large memory, the center provides to all members eleven compute servers, the most powerful of which is equipped with 4x15 cores and 2 Terabyte of memory.

## Distribution of Co-Authors of IWR Publications


Ever since its foundation, the IWR has invested into massively parallel computers, not for production runs, but rather for research and development of innovative parallel algorithms and experimental test systems. With the first system of 1989 being a 128 processors transputer system, our present system is a 640 cores AMD-Myrinet unit that was installed in 2007. The IWR has invested about 1 Million € of its own budget into the new research system to be installed in the beginning of 2015. This system will have over 5000 Xeon Haswell cores with an expected total performance of about 200 Teraflop/s and will be integrated in the parallel environment of the University Computing Center. Nevertheless, it is necessary to have shorter replacement cycles than eight years in order to stay scientifically competitive, and we hope that the situation will improve in the future.

The IWR also maintains a graphics laboratory with 3D equipment and a robotics lab, which is used for practical courses for our students as well as for research experiments.

## Success Stories

**Research:** The exact total number of original research papers of all IWR members is not determinable. However, randomly sampling the number of publications of ten members gives on average ten publications per year per researcher. Neglecting the 12 junior research groups, the IWR has published ~2250 research papers during the last five years, and most likely even more.
The developed mathematical tools are collected in software packages, which are disseminated into the scientific community, usually for free. Among these packages are, for example:

**Deal II:** A C++ software library supporting the creation of finite element codes and an open community of users and developers.

**Dune:** The "Distributed and Unified Numerics Environment" software is a modular toolbox for solving partial differential equations (PDEs) with grid-based methods.



## IWR in the Media

| | |
|---|---|
| **2010** | Important that we are in the top of the global league – Rector Eitel sees the IWR and HCI as spearheads of the application-oriented basic research at the Ruprecht-Karls University • **RHEIN-NECKAR-ZEITUNG (RNZ)** |
| | Chiseled secrets: Researchers decipher Jewish grave inscriptions • **SPIEGEL ONLINE** |
| **2011** | How Myosin functions • **DEUTSCHES ÄRZTEBLATT** |
| **2012** | Raiders of the lost data • **C'T** |
| | What social network operators may know about non-members **NDR RADIO, SPIEGEL ONLINE, DRADIO, NEW SCIENTIST MAGAZINE, DER STANDARD** |
| **2013** | Evidence for Low-Temperature Melting of Mercury owing to Relativity **DIE WELT, DER STANDARD, SPEKTRUM DER WISSENSCHAFT** |
| | Brilliant Minds: HGS MathComp Fellow Emöke-Ágnes Horvát **DEUTSCHE WELLE TV (DW-TV)** |
| | Discover Angkor – Scientists explore the history of Angkor Wat • **ARTE TV** |
| **2014** | Robots – walking like a human being • **BAYERISCHER RUNDFUNK** |

**Gascoigne:** This finite-element simulation toolkit is developed for incompressible, compressible, non-reacting and reacting flows in two and three dimensions based

**MUSCOD-II:** A software package for numerical solution of optimal control problems involving differential-algebraic equations

**Q-Chem:** A comprehensive software package for quantum-chemical calculations

**VIGRA:** It's an image processing and analysis library with main emphasis on customizable algorithms and data structures.

During the last five years, the results produced at the IWR frequently also triggered news in public media like newspapers, radio and television highlighting their immediate public relevance.

## Selected Third-Party Funded Research Projects

**2007–2010** Numerical optimization methods for parameter estimation and design of optimal experiments considering uncertainties in model validation of technical processes in chemistry and biotechnology (NOVOEXP) • Prof. H. G. Bock
**850.000,00 €** • German Federal Ministry of Education and Research (BMBF)

**2007–2012** Graduate College 850/3 "Modeling of Molecular Properties" • Prof. P. Comba
**1.966.484,00 €** • German Research Foundation (DFG)

**2009–2014** BIOMS (Center for Modeling and Simulation in Biosciences) • Prof. W. Jäger
**9.000.000,00 €** • Klaus Tschira Foundation, Federal State of Baden-Württemberg

**2009–2014** Principles of development and pattern formation in biology
Prof. A. Marciniak-Czochra
**1.054.000,00 €** • Heidelberg Academy of Sciences and Humanities

**2010–2015** Emmy Noether research group "Mathematical modelling of transport processes in plant tissues" • Dr. A. Chavarría Krauser
**750.000,00 €** • DFG

**2010–2015** VirtualLiver • Prof. U. Kummer
**2.100.000,00 €** • BMBF

**2010–2015** ICGC: The Genomes of Early Onset Prostate Cancers – Data Management & Bioinformatics • Prof. R. Eils
**1.700.580,00 €** • BMBF

**2010–2019** Research Training Group 1653 "Spatio/Temporal Probabilistic Graphical Models and Applications in Image Analysis" • Prof. C. Schnörr
**9.979.764,00 €** • DFG

**2012–2017** Heidelberg Collaboratory for Image Processing (HCI) • Prof. B. Jähne, Prof. F. Hamprecht, Prof. B. Ommer, Prof. C. Schnörr
**8.093.000,00 €** • Industry/DFG

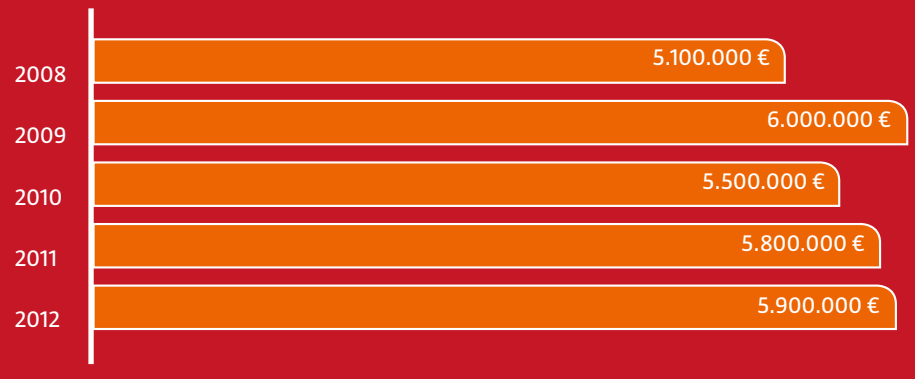
**2012–2017** Heidelberg Graduate School of Mathematical and Computational Methods for the Sciences (HGS MathComp) • Prof. P. Bastian
**6.000.000,00 €** • DFG

**Funding and Grants:** One measure of success of a research institute is the amount of third-party funding raised by its members. In this respect, the IWR was extremely successful. The researchers applied for all kinds of grants comprising numerous individual project proposals with varying funding periods and financial volumes as well as grants for huge research consortia. The number is too large to list here each of these proposals of all IWR members within the last five years, instead, a small selection of important grants is presented.

These grants have been selected, since they represent together the typical distribution of grants within the IWR. Of course, particularly important are the large collaborative grants, the Graduate College (GRK) 1653 "Spatio/Temporal Probabilistic Graphical Models and Applications in Image Analysis" funded by the DFG, the Heidelberg Collaboratory for Image Processing (HCI), which is funded within the Excellence Initiative and with substantial support by seven industry partners, the Center for Modeling and Simulation in Biosciences (BIOMS) funded largely by the Klaus-Tschira Stiftung and the Heidelberg Graduate School for Mathematical and Computational Methods in the Sciences (HGS MathComp) funded by the DFG in the framework of the Excellence Initiative. Most impressive is the total amount of third-party funding by the ten core members of the IWR only. This amounts to about 6 Million € per year since 2009.

Grants of the European Research Council (ERC) are particularly prestigious. At present nine members of the IWR hold such ERC grants.

### Total Third-Party Funding of the 10 Core Members of the IWR



**Honors and Awards:** The scientists of the IWR have received several honors and awards during the last five years. The best-paper awards and poster prizes are numerous, and shall not be listed here. Again, only a small fraction of selected awards can be presented. However, the IWR is particularly proud of its distinguished scientists, who have received honorary degrees from various renowned international universities.

Another marker for the success of the research groups at the IWR and the quality of the promoted scientific education is the success of our young academics. Within the last five years 17 of our young academics were appointed to professorships at various universities in Germany or their home countries. This remarkable rate certifies the high qualification of the graduates of the IWR.

## European Research Council (ERC) Grants

| | |
|---|---|
| 2008 | Intermolecular Coulombic Decay • Chemistry, Advanced Grant • **PROF. L. S. CEDERBAUM** |
| | BioStruct: Multiscale Mathematical Modelling of Dynamics of Structure Formation in Cell Systems • Mathematics, Starting Grant • **PROF. A. MARCINIAK-CZOCHRA** |
| 2010 | Self-Amplifying Stereodynamic Catalysts in Enantioselective Catalysis AMPCAT • Chemistry, Starting Grant • **PROF. O. TRAPP** |
| 2012 | Model-Based Optimizing Control – from a Vision to Industrial Reality • Mathematics, Advanced Grant • **PROF. H. G. BOCK** |
| | The Science of Forecasting: Probabilistic Foundations, Statistical Methodology and Applications • Mathematics, Advanced Grant • **PROF. T. GNEITING** |
| | Hydrodynamical Simulations of Galaxy Formation at the Peta- and Exascale • Physics, Starting Grant • **PROF. V. SPRINGEL** |
| 2013 | STARLIGHT: Formation of the First Stars • Physics, Advanced Grant • **PROF. R. S. KLESSEN** |
| | Light Field Imaging and Analysis • Mathematics, Starting Grant • **DR. B. GOLDLÜCKE** |
| 2014 | Deformation Spaces of Geometric Structures • Mathematics, Consolidator Grant • **PROF. A. WIENHARD** |

## Selection of Honors and Awards

| | |
|---|---|
| 2009 | Best Business Idea Award, Innovation Forum 2009 of Baden-Württemberg **PROF. C. CREMER** |
| | Honorary doctoral degree, Sofia University • **PROF. L.S. CEDERBAUM** |
| | The Outstanding Young German Scientist Award of the Lise Meitner-Minerva Center of Computational Quantum Chemistry • **PROF. A. DREUW** |
| | Honorary doctoral degree, University of Erlangen-Nuremberg • **PROF. R. RANNACHER** |
| | Award of the German Society for Radiooncology (DEGRO) • **PROF. J. HESSER** |
| 2010 | Roberts Price • **PROF. J. HESSER** |
| | Honorary doctoral degree, Vietnamese Academy of Science and Technology **PROF. W. JÄGER** |
| 2011 | Klaus Tschira Award for Achievements in Public Understanding of Science **DR. C. KIRCHES** |
| 2012 | Honorary doctoral degree, Russian Academiy of Sciences • **PROF. H. G. BOCK** |
| | Klaus Tschira Award for Achievements in Public Understanding of Science **DR. A. POTSCHKA** |
| 2013 | Grand Prize Winner, international Genetically Engineered Machine (iGEM) Competition, MIT • **PROF. R. EILS** |
| | Honorary Professorship (Physics), Johannes Gutenberg University Mainz **PROF. C. CREMER** |
| | Award of the German Society for Pattern Recognition (DAGM) • **PROF. F. HAMPRECHT** |
| 2014 | Honorary doctoral degree, Peoples Friendship University of Russia • **PROF. W. JÄGER** |

## Initial Appointments of Researchers from the IWR

| | |
|---|---|
| **2010** | Junior Professor (W2) • University of Münster • **DR. CHRISTIAN ENGWER** |
| | Junior Professor • Insitute for Applied Mathematics, Heidelberg University **DR. THOMAS RICHTER** |
| | "Junior Research Group Leader (W2; Associate Professor)" • Max-Planck-Institute for Dynamics of Complex Technical Systems, Magdeburg • **DR. MATTHIAS STEIN** |
| **2011** | Junior Professor • Department of Mathematics, Hamburg University **DR. WINNIFRIED WOLLNER** |
| | Professor • University of Applied Sciences Albstadt-Sigmaringen • **DR. RALPH GAUGES** |
| | Lecturer (now Dean) • Royal University of Phnom Penh • **DR. PHEAKDEY NGUONPHAN** |
| | Independent Research Group Leader • Robert Koch Institute • **DR. BERNHARD RENARD** |
| **2012** | Professor (W3) • Otto von Guericke University Magdeburg • **DR. SEBASTIAN SAGER** |
| **2013** | Professor (W2) • University of Konstanz • **DR. BASTIAN GOLDLÜCKE** |
| | Professor (W3) • Medical Faculty, Heidelberg University • **DR. BENEDIKT BRORS** |
| | Professor (W2) • Jena University Hospital • **DR. RAINER KÖNIG** |
| | Junior Professor • University of Mannheim • **DR. SIMONE PAOLO PONZETTO** |
| **2014** | Professor (W2) • Clausthal University of Technology • **DR. OLAF IPPISCH** |
| | Associate Professor • School of Atmospheric Physics, Nanjing University of Information Science and Technology, China • **DR. CAO LE** |
| | Professor • Department of Mechanical Engineering, Universidad Técnica Federico Santa María, Chile • **DR. HERNÁN A. OLGUÍN ASTUDILLO** |
| | Assistant Professor • TU München • **DR. BJÖRN MENZE** |
| | Assistant Professor (tenure track) • The University of Texas at El Paso, USA **DR. NATASHA SHARMA** |



## International Relations

Owing to the international standing of the scientists working at the IWR and the international orientation of the HGS MathComp, a manifold of close individual personal contacts of our members to international partners all over the world exist. These are by far too many to be listed in detail, however, these form the basis for the international spirit of the IWR and its collaborations and research activities.

As one outcome of these first individual collaborations, formal institutional agreements are set up. This has happened in the past several times. As representative examples, institutional collaborations between Heidelberg University and Shanghai Jiao Tong University have initially been driven by the IWR, as well as with Columbia University. In both cases a Memorandum of Understanding (MoU) has been signed. It is important to note that the MoUs are not just declarations of intend but contain clear plans about how the scientific and educational collaborations are going to proceed.

The next level of international collaborations occurs when joint projects of the institutions are planned together and joint grant proposals are submitted. For such extended collaborations, two examples are the long-standing collaboration of the IWR with the Royal University Phnom Penh and the International Graduate College 710 "Complex Processes: Modeling, Simulation and Optimization International Graduate" together with the Interdisciplinary Center for Mathematical and Computational Modeling of the University of Warsaw.

A somewhat unusual aspect of our international activities is the focus on supporting research in the developing countries of Southeast Asia, e.g. Cambodia, Thailand, Vietnam, Myanmar and Laos. The intention of the IWR in these countries is mainly to promote scientific computing by joint research projects, organizing conferences on topical issues, and promoting scientific exchange in an Erasmus Mundus program. Indeed, former doctoral students of the IWR now hold important position in these countries.

The IWR profits also substantially from the high international visibility and the networking of the Ruprecht-Karls University. A most recent example is a beginning international collaboration with Kyoto University, which was initiated via the German-Japanese Universities Alliance (HeKKSaGOn) network.

## International Partner Network


1 IWR, Heidelberg University
2 ICM, University of Warsaw
3 University of Milan
4 Charles University in Prague
5 ETH Zürich
6 RICAM Linz
7 University of Oxford
8 University of Cambridge
9 DTU Lyngby
10 University of Helsinki
11 University of Jyväskylä
12 University of Valencia
13 AIMS African of Mathematical Sciences
14 Princeton University
15 NYU/Columbia University
16 MIT
17 McMaster University
18 Carnegie Mellon University
19 Ohio State
20 Northwestern University
21 Argonne National Lab
22 University of Minnesota
23 University of British Columbia/ Simon Fraser University
24 Stanford University
25 University of Texas at Austin
26 Lomonosow University Moscow/ People's Friendship University Moscow/ Russian Academy of Sciences
27 St. Petersburg State University
28 CAS/Tsinghua University Peking
29 Seoul NU
30 Fudan University Shanghai/ Shanghai Jiao Tong University
31 Vietnam Academy of Sciences/ Ho Chi Minh City University of Technology
32 National University of Laos
33 Royal University of Phnom Penh
34 Chulalongkorn University
35 Walailak University
36 NU Singapore
37 Hong Kong University of Science and Technology
38 Yangon University
39 University of Dhaka
40 Jadavpur University
41 COMSATS Institute of Information Technology
42 ANU Canberra




## Collaborative Projects and Knowledge Transfer with Industry

Scientific computing has developed into a key enabling technology in many branches of the industry, also triggered by the research successes of the IWR. From the start, our research groups have produced many highly technologically relevant research results that have boosted many individual as well as collaborative projects with the industry, from global players to small or medium-sized enterprises.

The collaborations typically start with smaller joint research projects, which are profitable also for fundamental research, since complex industrial problems that require the know-how of IWR research usually provide excellent challenges for methodological research. Based on the grown faith of the industry in the potential of scientific computing to help solving their technological problems, new forms of intensified collaborations, i.e. of private public partnerships (PPP), between industry and the IWR have emerged.

The most prominent and extremely successful example of the IWR is the "Industry-on-Campus" venture Heidelberg Collaboratory for Image Processing (HCI), which is largely financed by companies like Bosch, Zeiss, Sony and smaller enterprises. In addition, Heidelberg University supports the HCI via funds of the Excellence Initiative. From its foundation, the HCI has grown to a remarkable research unit with altogether about 80 scientists with more than 1,5 Million € third-party funding per year. The HCI is the lighthouse collaboration with industrial partners and serves as role model for other PPPs.

Inspired by the HCI, the IWR is presently founding the Heidelberg Collaboratory for Industrial Optimization (HCO) with partners like BASF, Daimler, ESA, Lufthansa and others. A forerunner of the HCO, is the BASF funded research group "Optimum Experimental Design", which has received about 250,000 € per year over the last six years for basic research.

The strategic Committee for Mathematical Modeling, Simulation and Optimization (KoMSO) located at the IWR and funded by the BMBF plays an essential role for intensifying national and international networking of the Ruprecht-Karls University with industrial partners. It also serves as the German node in the European Network for Industrial Mathematics (EU-MATHS-IN).



"I never think of the future. It comes soon enough."
Albert Einstein

## The Future of the IWR

At present, no technology is advancing faster than information technology, comprising communication networks, software and computer architecture and performance. Ever bigger and faster computers, in particular in the area of high-performance computing, result in enormously growing expectations for mathematical and computational methods. For example, data deluge from new imaging techniques in the biosciences or medicine as well as the needs from emerging field of computational humanities must be met with innovative methodological research. In contrast to Albert Einstein, we have thought about the future development of the IWR, since fast developing research fields require substantial pre-thinking to provide the necessary environment and equipment to enable innovative, cutting-edge research. On the next few pages, the future perspectives for structure, organization and research plans of the IWR will be described.


**Moving to a New Home in 2016 – the Mathematikon:** Owing to the success of the IWR and the enormous growth of the number of participating scientists, the home building INF 368 has quickly become too small to harbor all core members. As a consequence, they are distributed all over the campus and even beyond with the HCI and two IWR groups in rented rooms at Speyerer Straße 6.
This situation is going to change in the near future in spring 2016, when all members will move into our new building the "Mathematikon", which is a donation of the Klaus Tschira Stiftung, a German foundation that promotes natural sciences, mathematics and computer sciences, to the Ruprecht-Karls University. Bringing all IWR members spatially even closer together will further spark interdisciplinary research between the individual groups and may lead to new innovative collaborations.

**Appointments & Hiring Policy:** During the last years, five of the ten core W3-professorships have been appointed with young colleagues, almost concluding the generational change within the IWR. However, two further appointments are ongoing:

- W3-Professorship on "Scientific Visualization" of the HGS MathComp
- W3-Professorship on "Digital Image Processing in Environmental Science" (Early successor of Bernd Jähne) within the HCI



Since the core members of the IWR are attached to individual faculties as well, it is common practice that the appointment committees are composed of IWR members as well as members of the faculty with equal weight. This procedure ensures the scientific quality of the selected candidates as well as the desired interdisciplinary spirit.

## "Tackling Future Research Challenges"

**Strengthening the Strengths:** The interdisciplinary approach of application-driven development of new mathematical methods and computational tools is unique to the IWR from a national as well as international point of view. It is clear that further strengthening the existing expertise is a key ingredient for an ongoing success. These areas comprise:

- Multiscale, multiphysics, multidimensional modeling
- Adaptive numerical simulations
- Model-based optimization and optimal control
- Image processing and static analyses, big data
- Cutting-edge software development and high-performance computing

In addition to the already ongoing and very successful research directions at the IWR, it is planned to reinvigorate application fields, which had already been very actively pursued. These fields are in particular:

- Computational astrophysics
- Computational environmental physics

Through the generational change among the researchers at the IWR and the respective institutes new scientific interaction points have become apparent, which will be promoted in the near future.

**Developing New Fields:** Most important for a striving institute like the IWR, however, is the discovery and exploration of totally new areas of application for scientific computing. Emerging from the research of the last years and in line with the institutional strategy of Heidelberg University, the IWR has, does and intends to further build bridges between research areas by promoting mathematical and computational methods to scientific areas, in which computation plays no or only a minor role so far. It is important to stress that the researchers of the IWR will focus on methodological developments thereby promoting the computational science in the corresponding individual fields, which are in particular:

**Computational Humanities:** Several interdisciplinary, already running projects are a unique selling point of the IWR. The appointment of a W3-Professor (Björn Ommer) for "Scientific Computing in the Humanities" and the establishment of the junior research group "Forensic Computational Geometry Laboratory" (Hubert Mara) are first successes.

**Computational Molecular Material Science:** The scientific orientation of the science campus of Heidelberg University moved recently towards organic electronics, with a special emphasis on fundamental research. Together with the great expertise of the IWR in modeling, simulation and optimization of complex processes, this impetus led to the successful application for the Center of Advanced Materials (CAM), which will be harbored in an own building on the Neuenheimer Feld science campus. The appointment of a W3-Professor for "Theoretical and Computational Chemistry" (Andreas Dreuw) was a first step into this direction.

**Computational Social and Behavioral Sciences:** Several ongoing Ph.D. projects in this new area are already running, mostly funded through the HGS MathComp. In these highly interdisciplinary projects, problems arising in vision, cognition and psychology, for example, are tackled.

**Computational Medicine and Health Care:** In this highly innovative and widely unexplored branch of computational science, first interdisciplinary projects are successfully running addressing problems in cardiology, sepsis, epidemiology and tumor recognition, to name just a few.

The means by which the IWR strengthens these research areas follow its interdisciplinary, open-minded philosophy. "Challenge Workshops" and mini-symposia will be organized, to which leading experts as well as promising junior researchers in the field of application are invited, and hot problems calling for computational support are to be identified. These interactions usually readily lead to intial grant proposals of individual researchers of the IWR together with the partner of the other discipline, as they are currently already under way. Another promising model for the establishment of a research field within the IWR is to implement junior research groups, as it has already been successfully done in the past for computational humanities. Fostering these initial steps and expansion to related problems lead to smaller and larger collaborative centers, as for example, graduate colleges, collaborative research centers, like the HGS MathComp and the HCI.

**Bringing up the Next Generation Scientists:** Within the HGS MathComp, a unique interdisciplinary approach to graduate education has already been successfully implemented. In addition, the IWR initiated and led the establishment of the master program "Scientific Computing" at Ruprecht-Karls University, which has a curriculum covering computer science, informatics and mathematics. In the future, the IWR plans to further integrate their researchers into this curriculum highlighting computational challenges in the sciences. To recruit the best students for the future, we integrate young students early into ongoing research projects.

**Gender Equality:** The IWR is aware that female scientists are underrepresented in natural science and mathematics, and so also in scientific computing. Within the fellowship program of the HGS MathComp many young female scientists could already be recruited during the last years, which led to an increased number (30 %) of female Ph.D. students, for example, compared to the average in natural sciences (25 %) at Heidelberg University in 2011. However, the immense potential of gifted young women is still clearly underexploited. As part of Heidelberg University, the IWR follows the cascade model, and feels strongly committed to further promote gender balance at all levels of education by all possible means. Here, the measures taken up by the HGS MathComp will serve as blueprint for further actions.

**Public Outreach and Visibility:** At the IWR, there are several activities already going on, in which individual members are involved, who, for example, deliver talks at student information days or give presentations to a general audience on the boat "MS Wissenschaft" on scientific computing. Also, public lectures are frequently held, and the "Long Night of Robotics" has been established. In the future, the IWR plans to focus more on joint public events and to further intensify our activities in promoting scientific computing to the general public





Selection of public lectures organized by the IWR and its affiliates.



and school education. These activities are also part of the strategy of the IWR to increase its visibility in the university, scientific landscape and society. This report is also intended as a first step in this direction.

## “Our Vision – Creating Sustainable Structures Beyond the Excellence Initiative”

Motivated and enthused by the growth and its national and international success of the IWR during the last 27 years, for example, in the application for the HGS MathComp within the Excellence Initiative, the managing board intends to establish long-term administrative and organizational structures.

**“Romberg Center for High Performance Computing”** is a suggested name for a joint organizational structure between the IWR and the University Computing Center which manages projects and acquisition in the field of high-performance computing, scientific visualization, and data management and storage. Such a focused high-performance computing center will allow Heidelberg University to aim higher than the current classification level Tier 3.

**Liebig Centers, DFG Research/Competence Centers:** These are the anticipated measures of the federal government to provide sustainable funding beyond the Excellence Initiative. In case of their advertisement, the IWR plans to apply as leading, responsible institute for such a center under the notion of “Scientific Computing meets Computational Science”. The IWR is the ideal institute to spearhead such an endeavor, since it possesses all necessary prerequisites:

- with the graduate school HGS MathComp funded by the Excellence Initiative providing an interdisciplinary curriculum,
- with its faculties overarching structure,
- with its own faculty members and existing administrative and scientific stuff,
- with its private public partnership-based transfer platforms HCI and HCO,
- with its scientific standing and its exceedingly high third-party funding,
- with a “Romberg Center” as research infrastructure in high-performance computing for cutting-edge research,
- and foremost with its internationally visible research topics in method development and its challenging applications in all areas of computational science.

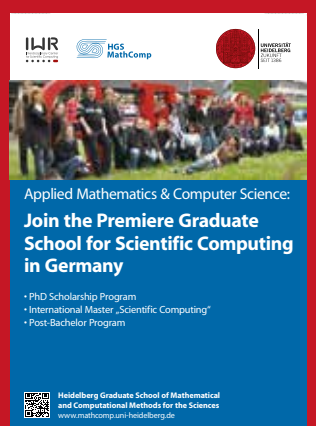
# 2 The Heidelberg Graduate School of Mathematical and Computational Methods for the Sciences

"Investment in knowledge pays the best interest"

Benjamin Franklin

## The HGS MathComp and its Environment

Mathematical modeling, simulation and optimization, in short scientific computing, have developed into one of the key technologies of the 21st century. This generically interdisciplinary approach is widely considered to be the third pillar of scientific research, bridging and complementing theory and experiment. Fast growing expectations from mathematical and computational methods, the data deluge from new imaging techniques in the biosciences or the needs from the emerging field of computational humanities represent challenges that must be met with innovative methodological research. Located at the Interdisciplinary Center for Scientific Computing (IWR) the Heidelberg Graduate School of Mathematical and Computational Methods for the Sciences (HGS MathComp) is the core research training facility for the doctoral researchers of the IWR. The graduate school was established in the first round of the Excellence Initiative in 2007 and was renewed for another five years in 2012.

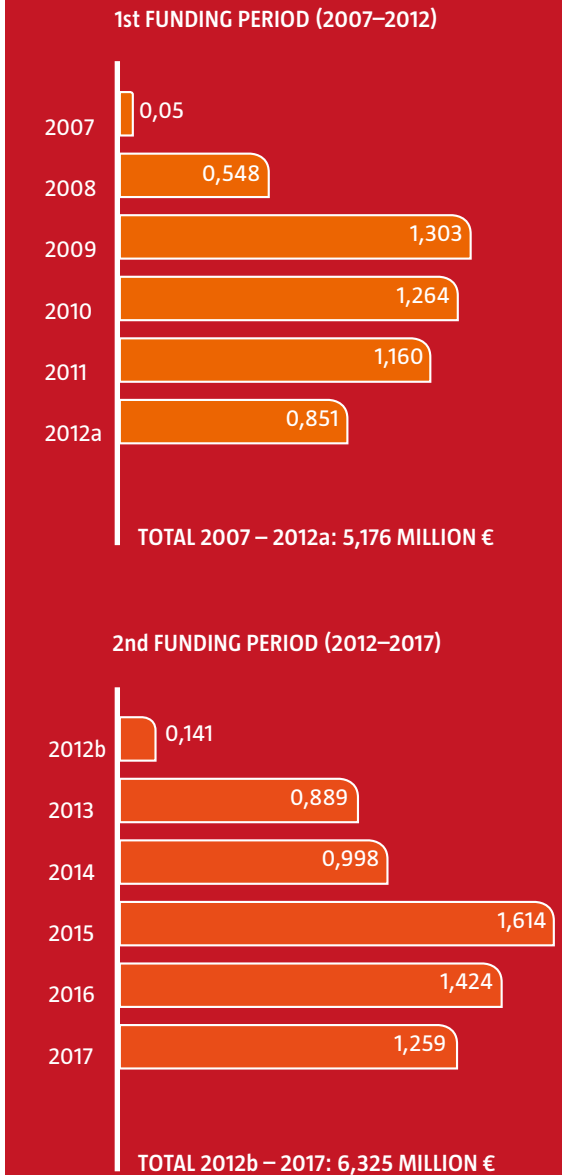



The infrastructure of the HGS MathComp, its research program and doctoral training profit enormously from its scientifically strong research environment at the IWR and around. Based on the expertise of its members and their home faculties, all ranked as top-level research faculties on the national level, it benefits from the interdisciplinary tradition and international visibility of its host institution and strong university and non-university research partners in the region. The collaboration with German Cancer Research Center (DKFZ) and the Center for Modelling and Simulation in the Biosciences (BIOMS) gave a big push to mathematical modeling, simulation and optimization of experiments in structural and systems biology and provided fascinating projects and funding for many doctoral students through collaborative research projects. The Heidelberg Institute of Theoretical Studies (HITS) and the Klaus-Tschira Stiftung make significant contributions to the scientific expertise of the graduate school. Five research group leaders of the HITS are members of the graduate school, which has thus access to the facilities of the HITS. The graduate school is also supported by strong industrial partners. BASF finances one of its junior research groups in optimum experimental design. Bosch and Sony, among others, support the Heidelberg Collaboratory for Image Processing (HCI). Others, like Daimler or the European Space Agency (ESA), have individual research collaborations with members of the graduate school. For Germany, which lacks a sponsoring tradition, it is a novel experience that industrial companies make significant investments into fundamental research in mathematics and computational science – certainly one of the added values produced by the graduate school and its funding through the highly competitive Excellence Initiative.

Developing innovative and powerful mathematical and computational methods for the challenges in various properly selected areas of applications is a truly interdisciplinary endeavor, which requires tight interaction between the researchers from the application area (computational science) and the scientists specializing in sophisticated solution methods, their theory and their implementation (scientific computing). The members of the graduate school and its host institution IWR have a proven record of many successful interdisciplinary collaborative projects. Examples are their research training groups, initiation of and participation in SFBs and DFG priority programs or large BMBF programs such as Mathematics in

### The HGS MathComp in Numbers

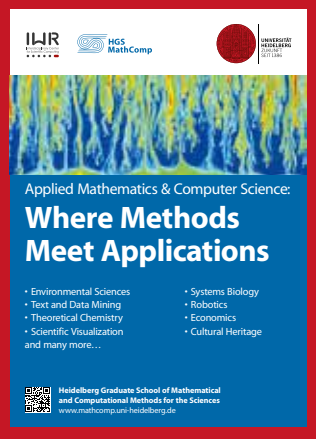
[Funding in Million €]



Industry, the top-level cluster Forum Organic Electronics, the systems biology program ViroQuant or the Bernstein Center for Computational Neuroscience Heidelberg-Mannheim (BCCN). Interdisciplinary doctoral projects of the graduate school play also an important role in university centers such as the Center for Advanced Materials (CAM), BioQuant and the The Heidelberg Center for the Environment (HCE) as well as in the clusters of excellence Cellular Networks and Asia & Europe.

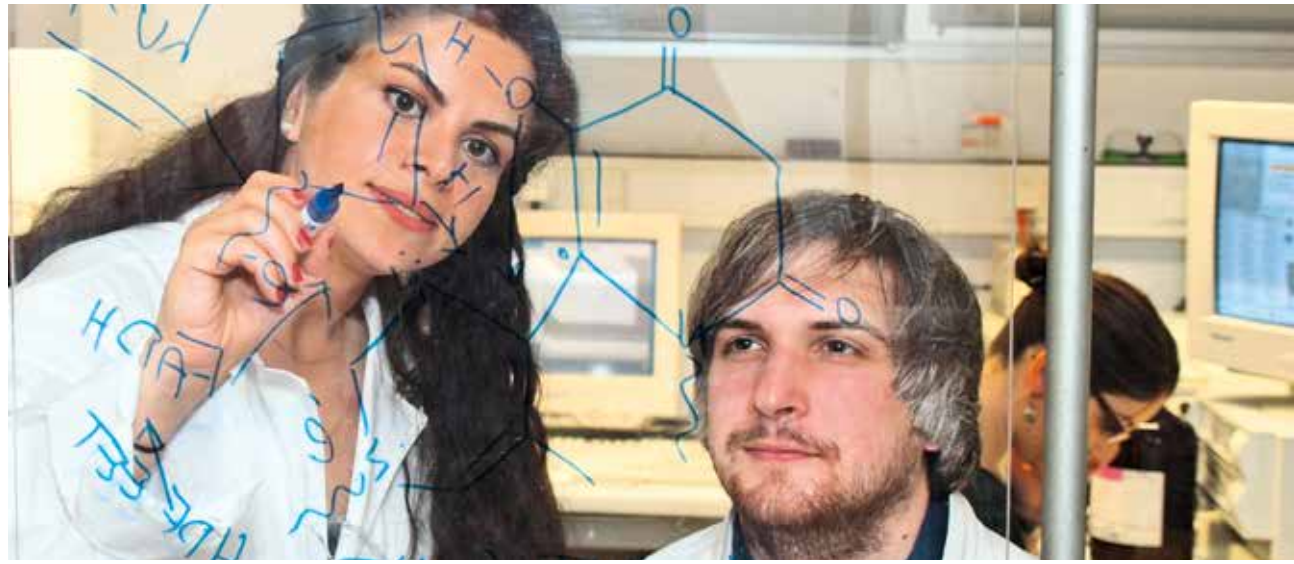
## Scientific Fields

The work of the doctoral students and research groups of the graduate school is in analogy to the research philosophy of the IWR centered around the development of novel computational methods for modeling, simulation and optimization of complex processes and the application of such methods in challenging areas. On the one hand, the complexity of the problems to be treated may result from properties of the underlying processes, such as multiple scales, phases, geometries, or multiple physics, as for example the combination of fluid dynamics, structural mechanics and heat transfer. On the other hand, it may result from the requirement to combine and dovetail techniques from various methodological areas such as optimization, numerical PDEs, statistics and image processing to form new intelligent and hybrid mathematical and computational methods. Mastering the complexity strongly depends on key computer-science methodologies such as software development, parallelization and visualization. The groups participating in the HGS MathComp represent a high-quality research program with the following major methodological approaches:




- Multiscale analysis in modeling and simulation,
- All-at-once methods in model-based optimization,
- Adaptive numerical methods and high-performance computing,
- Simulation software and scientific visualization,
- Model-based image processing, and
- Data analysis and statistical modeling.

While the core of the HGS MathComp lies in methodology, its interdisciplinary approach is inseparably connected with application fields. The list below represents areas where strong expertise is available in the scientific environment



of the school. They are not understood to be covered comprehensively but provide examples of challenging doctoral research problems. Other, more detailed examples can be found in the list of the IWR members.

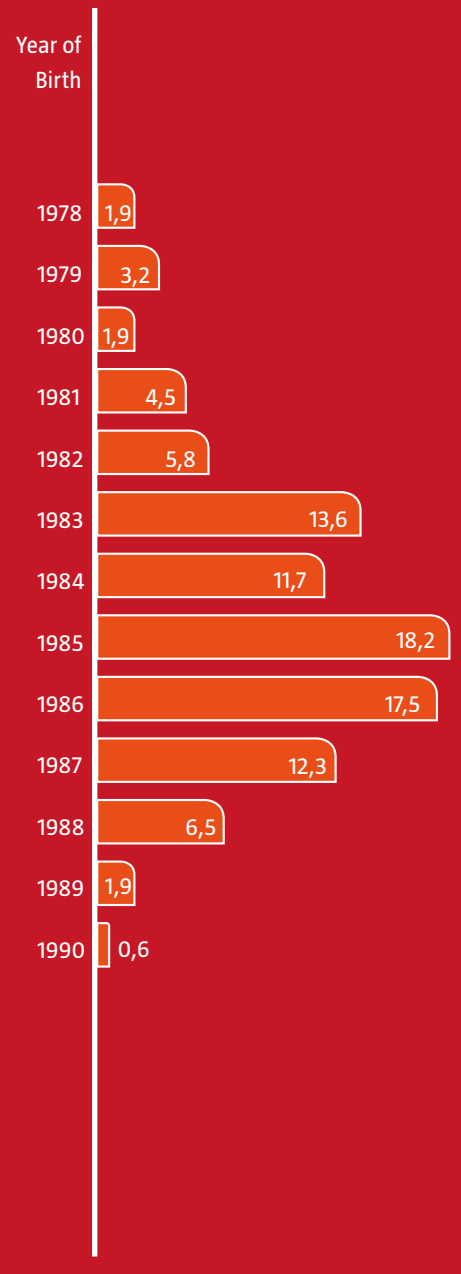
- Porous media and environmental physics
- Computational medicine – developing tools for diagnosis and therapy
- Biomolecular simulation
- Systems biology
- Optimization in process engineering
- Computational physical chemistry and advanced materials
- Scientific computing in the humanities

## Research Training

The foremost aim of HGS MathComp is to attract excellent students from all over the world to pursue an interdisciplinary doctoral degree in one of the research groups of the IWR. To cope with the formidable challenge of interdisciplinary doctoral degrees requiring competence in two different fields we devised the “Heidelberg Way” of structured doctoral training based on the following four pillars:

- Research is carried out in **twin-projects**, a doctoral student is advised by two supervisors and two mentors forming the thesis advisory committee (TAC).

## Age Distribution of HGS MathComp Fellows

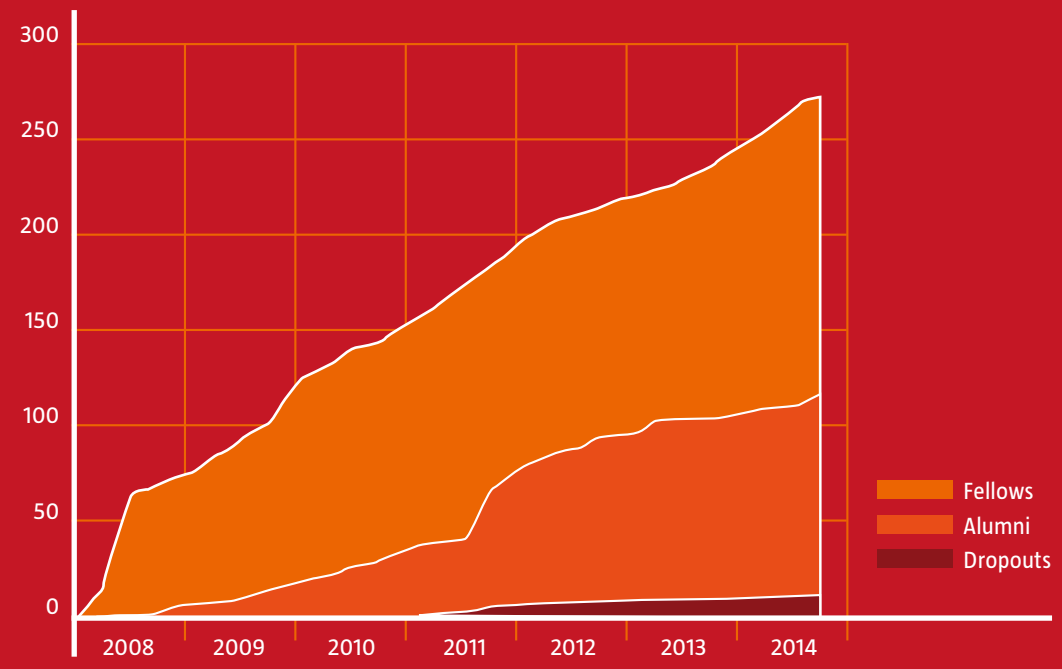



- The research project is always rooted in one discipline to ensure disciplinary excellence, a setup that we call **"asymmetric interdisciplinarity"**.
- Each student follows an **individualized research training program** compiled jointly with the TAC in order to master the challenges of interdisciplinarity.
- **Early scientific independence** is promoted to produce creative and self-reliant young scientists.

The "Heidelberg Way" transformed the research culture at the IWR considerably by forming a community of doctoral researchers. The students do not only exchange ideas during the regular students' colloquium and annual meeting. They also organize sport events (football, half marathon) and meet at the "Fireside Chat", where the students interview successful leaders coming from academia and industry in a cozy atmosphere.

The responsibility of HGS MathComp is not restricted to the three year Ph.D. period. In the second funding period the research-oriented master track was established to allow excellent students the integration of the second master year with the Ph.D. phase. This is especially attractive for the students of the new international master program in scientific computing that was established by the Faculty of Mathematics and Computer Science in 2013 upon initiative by the graduate school. This master program is tailored to the needs of the graduate school and is expected to provide a pool of talented future HGS MathComp fellows. For completing publications or finalizing software releases the HGS MathComp offers up to three postdoctoral positions for up to one year.

## PhD Fellows, Alumni and Dropouts of HGS MathComp




**Attracting the Best Brains:** The first requirement of a successful research project is to find an excellent doctoral student. The HGS MathComp supports the match-making between supervisors and doctoral students in the setup phase of a project through various measures ranging from three month recruiting stipends to presence at recruitment fairs up to organizing international advertisement and selection workshops. In addition the graduate school administration is able to help with visa applications and supports the foreign students when they arrive in Heidelberg.

The 24 stipends of HGS MathComp are strategically used to drive interdisciplinary research at the IWR to new directions, such as computational humanities, computational medicine and advanced materials or to strengthen collaborations among IWR members.

## Improving Gender Balance

It is an undeniable fact that the enormous potential of gifted women for the progress of science is an asset not properly realized. Although the graduate school has reached a relatively good standing compared to other research institutions in comparable fields, we are continuing and strengthening an array of measures and incentives and support young women to pursue a career in research, which start from high school activities (Girls'Day, MINTmachen, MatheStar, ...) and reach far into the postdoctoral and habilitation phase through the Olympia-Morata program. As a new initiative the "Upstream" mentoring program was established in 2013 with external funding. It provides a dynamic network for young female mathematicians from high school to professor level and is managed by HGS MathComp.

All fellows of HGS MathComp can profit from a one year additional stipend in case of becoming a parent, the child care capacity provided by the university, support with home working equipment or general counseling in family affairs.

With respect to the filling of positions offered by the graduate school the goal of filling half of the positions with women has been announced and the achieved numbers are made transparent. Especially with regard to filling of stipend positions the graduate school ensures that half of the positions are filled with women and has achieved this goal since seven years without compromising quality.



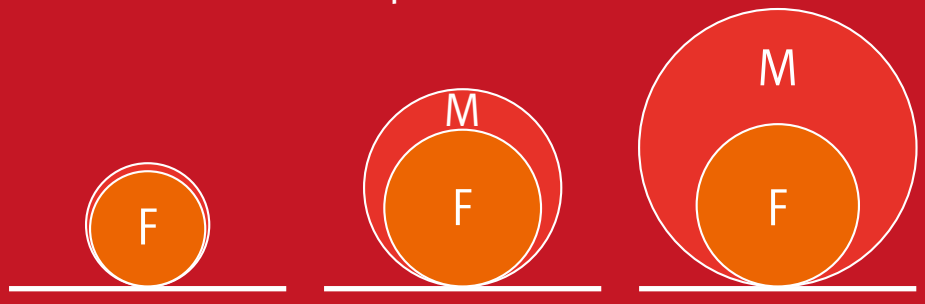
## Learn What You Need – Individualized Research Training

An important added value of interdisciplinary doctoral projects is that the combination of scientific approaches from different disciplines may create enormous synergy. Chances for true research breakthroughs in the one or the other – and optimally in both – are high. However, the demands from doctoral students are also much higher in interdisciplinary research. The challenge is to develop a consistent and convincing research training program for a group of over 150 doctoral students with very different background, yet working with common methodologies. Based on its experience, the HGS MathComp meets this challenge by the following measures: a study and training program individually tailored to the needs of the particular group of doctoral students and individual counseling and feedback by a thesis advisory committee consisting of two supervisors and two mentors from the relevant disciplines.

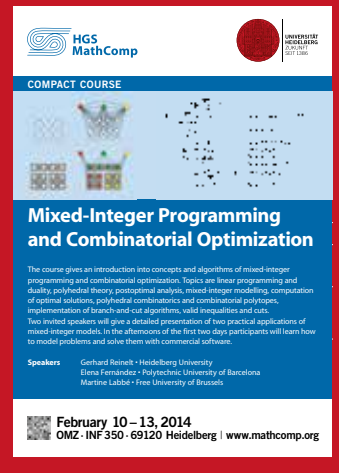
The graduate school offers each semester about ten compact courses, which typically last a week and fall into the four categories:

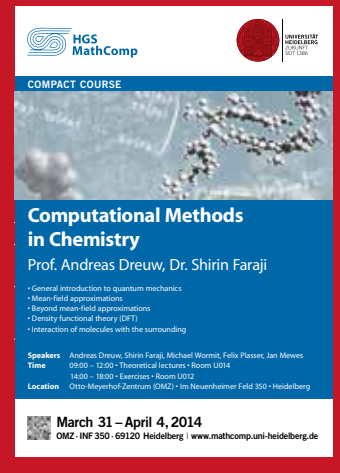
- Introductory courses in methodological or application areas
- Cutting-edge courses leading to the fore-front of research often also including external speakers
- Software training courses teaching the use of particular software developed at the IWR

### Gender Balance HGS MathComp




| HGS MathComp core stipends | All stipends administrated by HGS Mathcomp | Doctoral fellows total since 2008 |
|---|---|---|
| Male: 16 | Male: 38 | Male: 188 |
| Female: 14 | Female: 24 | Female: 71 |




- Key competence courses providing extracurricular skills, which are often organized in collaboration with the Heidelberg Graduate Academy

The TAC together with the doctoral student selects from this offer courses that are appropriate for the research project. In the course of the project each student is required to achieve 18 credit points in total, a number that was chosen deliberately to reserve enough time for the research work. Naturally, the students can influence the course program of the school by suggesting subjects for courses that are in demand.

**Quality Control:** In our interdisciplinary research training concept each student is supervised by two supervisors who are ideally coming from two different faculties. Two mentors, who are typically advanced postdoctoral research fellows, give additional advice, e.g. in the use of software or lab procedures. Together with the supervisors they form the thesis advisory committee, which accompanies the student during the Ph.D.. The annual milestone presentation in front of the TAC assesses the state of the Ph.D. and guides the next steps in the research work. The rights and duties of all parties are fixed by a supervision agreement, which is now mandatory by law in the state of Baden-Württemberg.

## Workshops and International Networking

**Workshops:** As an integral part of the research training concept more than ten workshops have been co-financed by HGS MathComp and organized by the PIs, since the beginning of the second funding period. Among them were:

- Solid State Electrochemistry for Energy Storage and Conversion (2012)
- Multiple Shooting and Time Domain Decomposition Methods (2013)
- Modeling and Simulation of the Cardiovascular System (2014)
- Formal Models of (Dis)Ordered Cognition (2014)
- PDE Software Frameworks (2014)

**International Networking:** To ensure the early integration of the fellows into the international scientific community, international networking is an essential pillar of our doctoral training program. To facilitate this the HGS MathComp supports its doctoral students with the ability:

- To visit national and international conferences to present scientific results and interact with other scientists. In the first year a conference can be visited without an own contribution, in year two and three a poster/oral presen-



## Romberg Guest Professors & Visiting Scholars

**We are particularly proud of our Romberg guest professors and visiting scholars:**

| | |
|---|---|
| 2008 | HOANG XUAN PHU • Vietnam Academy of Science and Technology |
| 2010 | GEORGE PAPANICOLAOU • Stanford University |
| 2011 | ANDRO MIKELIC • Université de Lyon |
| 2012 | MITCH LUSKIN • University of Minnesota |
| 2013 | RICHARD LONGMAN • Columbia University |
| | BLANCA AYUSO • King Abdullah University of Science and Technology |
| 2014 | DONALD RICHARDS • Pennsylvania State University |
| | ROBERT SCHEICHL • University of Bath |

**Forthcoming Romberg Guest professors are:**

| | |
|---|---|
| 2015 | VIVETTE GIRAULT • Pierre-and-Marie-Curie University |
| 2016 | MICHAEL UNSER • Swiss Federal Institute of Technology in Lausanne |



tation is mandatory. Each student is supported with up to 3000 € for the duration of the Ph.D..

- To invite international visitors to Heidelberg, who report about their work and interact ideally with more than one student.
- To organize or help organize international workshops and summer schools in Heidelberg and elsewhere. We believe that the school itself is the best training ground. Help in the organization of a workshop or summer school lets the fellows acquire practical competences expected from future leading scientists.

The HGS MathComp also offers the opportunity to invite internationally renowned scientists who work on a subject that is of general interest for several students and research groups as long-term guests as part of the Romberg guest professorship program. In the second funding period we extended this program by the Romberg visiting scholar, which permits younger scientists a longer stay in Heidelberg and allows them to bring along their doctoral students to conduct joint research with the groups in Heidelberg.

**Internationalization:** The graduate school is utilizing the manifold international interactions of its members and the IWR, even at an institutional level, to intensify and consolidate its international network in scientific computing. The organization of conferences and summer schools by the graduate school, in Heidelberg and abroad, its international visitors' program and the doctoral students' mobility and exchange program are important cornerstones in this strategy. One of our target areas is China, where already several summer schools were organized. For the scientific exchange with the developing countries of South-East Asia, we were able to raise significant funding from the European Union. As an effect the number of doctoral students from Asia is the same as those from Europe outside Germany. The ultimate aims of international networking are threefold:

- Attracting the best students from all over the world,
- Stimulating research collaborations with renowned international partners,
- And last, but not least supporting the individual international networking strategies of our doctoral students.

## Shaping the Profile of the University

The Ruprecht-Karls University realized very early the transformative power of scientific computing on research in all disciplines by founding the Interdisciplinary Center for Scientific Computing already in 1987. It also gives the HGS MathComp and the IWR a pivotal role in its Institutional Strategy with the motto “realizing the potential of a comprehensive university”. Substantial funding is allocated to promote interdisciplinary collaboration in scientific computing in the future concept of the university in the Excellence Initiative. The graduate school also plays an important role in promoting elements of research-oriented teaching and learning in the curricula of the university, e.g. with the new research-oriented master track and by contributing to a new international master program in scientific computing at the Faculty of Mathematics and Computer Science.

Naturally, other contributions of the school to the profile of the university are to bring about excellent doctoral students in support of its strategy to promote young researchers and to contribute to its international visibility and reputation. In addition, the HGS MathComp plays a leading role in promoting structured doctoral programs and interdisciplinary doctoral projects in close alliance with the Heidelberg Graduate Academy and the rectorate.



**Benefits from the Excellence Initiative:** The establishment of the HGS MathComp funded through the Excellence Initiative has allowed for building up an infrastructure and a momentum for fascinating interdisciplinary research and training that has created an added value far beyond expectation. The graduate school has developed into an internationally visible point of attraction for a large number of excellent doctoral candidates from which we can choose those with the best qualifications and the right enthusiasm for interdisciplinary research.

During the seven years since its foundation many new interdisciplinary collaborations were created. Some are in research areas now in full flow, such as modeling, simulation and optimization in the biosciences. Others, such as the new field of computational humanities have had a flying start and are becoming a major internationally visible landmark of the university. Finally, the existence of the HGS MathComp is attracting very substantial support and extra funding from industry companies and private institutions, which want to actively participate in basic research into one of the future key technologies.

**Sustainability:** The IWR and the university understand the HGS MathComp as a permanent institution, since research training in mathematical and computational methods and in cutting-edge modeling, simulation, optimization and control as well as image and data analysis are expected to have a strongly growing importance in more and more disciplines in the foreseeable future. The commitments of the state of Baden-Württemberg, the university and the IWR ensure that in case of a positive evaluation in 2017, the graduate school can be continued – at least in a reduced form on a budget of one third of the granted funding. However, it is hoped that the federal government also comes to the conclusion that the introduction of graduate schools is an important strategic element to strengthen the international competitiveness of German universities, and therefore continues its funding for successful graduate schools.

# 3 Research Groups at the IWR

# Overview of Research Groups

| GROUP LEADER | GROUP NAME | ADDITIONAL AFFILIATION | TYPE |
|---|---|---|---|
| Prof. Dr. A. Andrzejak | Parallel and Distributed Systems | Institute for Informatics | MRG |
| Prof. P. Bastian | Parallel Computing | Institute for Informatics | MRG |
| Prof. H. G. Bock | Simulation and Optimization | Institute for Informatics | MRG |
| Prof. G. Böckle | Computational Arithmetic Geometry | Mathematical Institute | MRG |
| Prof. L. S. Cederbaum | Theoretical Chemistry | Institute of Physical Chemistry | MRG |
| Dr. A. Chavarría Krauser | Mathematical Models of Transport in Plants | Institute of Applied Mathematics | JRG |
| Prof. P. Comba | Transition Metal Coordination and Computational Chemistry | Institute of Inorganic Chemistry | MRG |
| Prof. C. Cremer | Biophotonics and Information Processing | Kirchhoff-Institute for Physics | MRG |
| Prof. R. Dahlhaus | Statistics Group | Institute of Applied Mathematics | MRG |
| Prof. A. Dreuw | Theoretical and Computational Chemistry | Institute of Physical Chemistry | MRG |
| Prof. R. Eils | Integrative Bioinformatics and Systems Biology | DKFZ, Faculty of Biosciences | MRG |
| Dr. S. Faraji | Theoretical Simulation of Time-Resolved Spectroscopy | Institute of Physical Chemistry | JRG |
| Dr. S. Fischer | Computational Biochemistry | Faculty of Biosciences | IRG |
| Prof. A. Frank | Computational Linguistics | Institute for Computational Linguistics | MRG |
| Prof. J. Funke | Cognitive Psychology: Mind in Action Lab | Institute of Psychology | MRG |
| PD Dr. C. Garbe | Image Processing and Modeling | Department of Physics and Astronomy | JRG |
| Prof. M. Gertz | Database Systems | Institute for Informatics | MRG |
| Prof. F. Gräter | Molecular Biomechanics | HITS, Faculty of Biosciences | MRG |
| Dr. F. Graw | Mathematical Immunology | Faculty of Biosciences | JRG |
| Prof. E. Gutheil | Multiphase Flows and Combustion | Institute of Physical Chemistry | MRG |
| Prof. F. Hamprecht | Multidimensional Image Processing | Department of Physics and Astronomy | MRG |
| Prof. D. W. Heermann | Statistical Physics and Theoretical Biophysics Group | Institute for Theoretical Physics | MRG |
| Prof. J. Hesser | Experimental Radiation Oncology | Department of Radiation Oncology | MRG |
| Prof. V. Heuveline | Engineering Mathematics and Computing Lab | HITS, Computing Centre of Heidelberg University | MRG |
| PD Dr. A. Hujeirat | Computational Astrophysics & Algorithmic Design | Institute for Astronomy | IRG |
| Prof. W. Jäger | Applied Analysis | Institute of Applied Mathematics | MRG |
| Prof. B. Jähne | Digital Image Processing | Institute of Environmental Physics | MRG |
| Prof. G. Kanschat | Mathematical Methods of Computation | Institute of Applied Mathematics | MRG |
| Dr. C. Kirches | Optimization of Uncertain Systems | Institute for Informatics | JRG |
| Prof. R. Klessen | Star Formation Group | Center for Astrophysics Heidelberg (ZAH) | MRG |
| Prof. H. Knüpfer | Applied Analysis: Calculus of Variations and PDE | Institute of Applied Mathematics | MRG |
| Dr. S. Körkel | Optimum Experimental Design | Institute for Informatics | JRG |
| Dr. S. Krömker | Visualization and Numerical Geometry | Institute for Informatics | MRG |
| Prof. U. Kummer | Modeling of Biological Processes | Centre for Organismal Studies Heidelberg (COS) | MRG |
| Prof. J. Langowski | Biophysics of Macromolecules | DKFZ, Faculty of Biosciences | MRG |
| Prof. H. Leitte | Computer Graphics and Visualization | Institute for Informatics | MRG |
| Dr. H. Mara | Forensic Computational Geometry Laboratory | Institute for Informatics | JRG |
| Prof. A. Marciniak-Czochra | Applied Analysis and Modeling in Biosciences | Institute of Applied Mathematics | MRG |
| Dr. F. Matthäus | Complex Biological Systems | Faculty of Biosciences | JRG |
| Prof. K. Mombaur | Optimization in Robotics & Biomechanics | Institute for Informatics | MRG |
| Prof. B. Ommer | Computer Vision | Institute for Informatics | MRG |
| Prof. B. Paech | Software Engineering | Institute for Informatics | MRG |
| PD Dr. M. Pernpointner | Theoretical and Quantum Chemistry | Institute of Physical Chemistry | IRG |
| Prof. U. Platt | Environmental Physics | Institute of Environmental Physics | MRG |
| Dr. A. Potschka | Model-Based Optimizing Control | Institute for Informatics | JRG |
| Prof. R. Rannacher | Numerical Methods | Institute of Applied Mathematics | MRG |
| Prof. G. Reinelt | Discrete and Combinatorial Optimization | Institute for Informatics | MRG |
| Prof. Dr.-Ing. A. Reuter | Dependable Systems | HITS, Institute for Informatics | MRG |
| Prof. T. Richter | Numerical Methods for Partial Differential Equations | Institute of Applied Mathematics | MRG |
| Prof. S. Riezler | Statistical Natural Language Processing | Institute for Computational Linguistics | MRG |
| Prof. K. Roth | Terrestrial Systems | Institute of Environmental Physics | MRG |
| Prof. C. Schnörr | Image and Pattern Analysis | Institute of Applied Mathematics | MRG |
| Prof. U. Schwarz | Theoretical Physics of Complex Biosystems | Institute for Theoretical Physics | MRG |
| Prof. V. Springel | Theoretical Astrophysics | HITS, Center for Astrophysics Heidelberg (ZAH) | MRG |
| Prof. O. Trapp | Physical Organic Chemistry | Institute of Organic Chemistry | MRG |
| Prof. R. Wade | Molecular and Cellular Modeling | HITS, Center for Molecular Biology (ZMBH) | MRG |
| Prof. A. Wienhard | Differential Geometry | Mathematical Institute | MRG |
| Prof. J. Wolfrum | Physical Chemistry | Institute of Physical Chemistry | MRG |
| Prof. A. Zipf | GIScience Research Group | Institute for Geography | MRG |

MRG = Main Research Group | IRG = Independent Research Group | JRG = Junior Research Group

# Parallel and Distributed Systems


## PROF. DR. ARTUR ANDRZEJAK

**Artur Andrzejak received a PhD degree in computer science from ETH Zurich and a habilitation degree from FU Berlin. He worked as a post-doc at HP Labs Palo Alto in 2001–2002 and at ZIB Berlin in 2003–2009. In 2010 he was co-leading Data Mining Department at I2R Singapore. Since 2010 he holds the Chair for Parallel and Distributed Systems at IWR.**

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Software systems are progressively permeating all areas of our live, from mobile devices to modern cars to large-scale scientific simulations. With growing demand for software the challenge of its efficient development and testing becomes more important than ever. On the other hand, increasing levels of parallelism and distribution of applications makes their programming and debugging more involved and error-prone.

Our research is aimed at facilitating development, testing and debugging of complex software systems, predominantly parallel and distributed applications. We combine methods from systems research with statistical modeling and data mining to achieve efficient solutions.

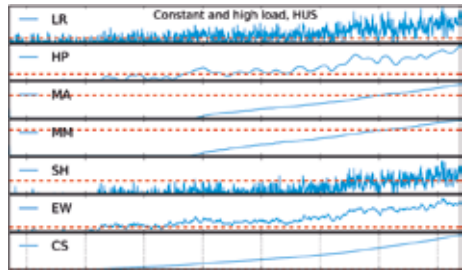
An exemplary collaboration project with industry (SAP AG and NEC Labs Japan) and university partners is devoted to identification and isolation of so-called software aging bugs (see description of the PhD project). Such defects are hard to detect during software development as they usually become visible only after hours of program execution. By using statistical analysis and advanced program instrumentation we are able to accelerate the detection of these costly defects.

In the domain of testing we work together with SAP AG on improving efficiency and accuracy of testing within very large software projects (SAP HANA). We exploit large data sets from historical runs to train machine learning models in order to select significant tests and prioritize their execution.

Analysis of large data sets requires today complex software tools (e.g. Apache Hadoop) which are tedious to program and to debug. Here we support analysts by automating common tasks via program synthesis and methods from machine learning. In this project we cooperate with a major business consultancy on developing approaches for automated preprocessing and cleaning of large data sets.

**LEARN MORE**

**Key Publication** Rivalino Matias, Artur Andrzejak, Fumio Machida, Diego Elias, and Kishor Trivedi: A Systematic Approach for Low-Latency and Robust Detection of Software Aging, 33rd IEEE Symposium on Reliable Distributed Systems (SRDS 2014), Nara, Japan, October 6–9, 2014.




## Early Detection of Software Aging

PhD thesis of Mohammadreza Ghanavati
Project partners: Fumio Machida (NEC Labs Japan); Rivalino Matias Jr. (UFU Brazil); Kishor Trivedi (Duke University)

**Distributed and industrial software systems running continuously for a long time often confront software aging: a phenomenon of progressive performance degradation caused by latent software faults. Discovery and removal of such faults early – preferably in the development phase – prevents costly workarounds in production scenarios. A known major obstacle is typically the large latency until software aging manifests during the execution.**

**In his thesis (in part funded by DFG grant AN 405/2-1, end in 2014) Mr. Ghanavati is developing methods for rapid detection of software aging by exploiting traditional software tests. The most promising approaches are based on comparative analysis of subsequent development versions of an application. Figure shows which anomaly detection methods (e.g. Cumulative Sum CS) applied to significant system metrics (here Heap Usage HUS) are able to detect aging issues in the latest software version in short time (blue line above red threshold indicates defects).**


## Debugging Configuration Errors in Complex Applications

Zhen Dong, Artur Andrzejak

**Defects in configuration settings of complex software are responsible for a substantial part of today's system failures, leading to about one-quarter of all customer-reported issues. Finding their root causes can be costly in terms of time and human resources. We have developed an approach to automatically pinpoint such errors by tracing the dependence between the failures and potential causes in the code.**

**Our technique is inspired by the way how developers typically debug such problems with the help of error stack trace (figure). It also considers various coding styles (in regard to processing of configuration options) which we observed in our real-world test applications. We are able to diagnose a large variety of applications with high accuracy. In an evaluation on 24 configuration errors in 3 large applications (Hadoop, JChord, and Randoop) the average position of the true defect in a ranked list of suspects was very close to the ideal "1.0": 1.6, 1.0, and 1.1, respectively.**

# Parallel Computing


## PROF. DR. PETER BASTIAN

**Peter Bastian studied computer science at the University of Erlangen-Nürnberg and got his doctoral degree in Mathematics at Heidelberg University. He obtained professor positions in Heidelberg and Stuttgart and currently is the speaker of the Heidelberg Graduate School of Mathematical and Computational Methods for the Sciences.**

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Partial differential equations are abundant in science and technology describing e.g. fluid flow, deformation of solid materials and wave propagation. With ever increasing computer power and constantly improving numerical methods more and more complex problems can be solved, with the trend going to incorporate multiple physical processes, small scale effects, identifiying parameters and quantifying the uncertainty of the results.

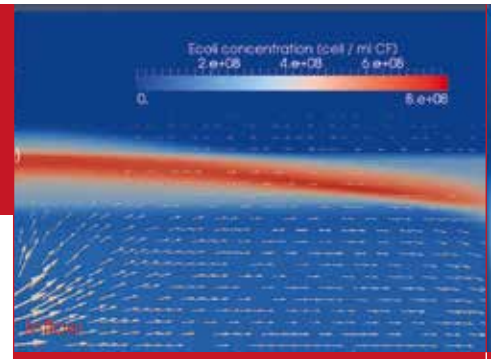
In this field the group develops accurate discretization schemes based on conservative methods, i.e finite volume and discontinuous Galerkin schemes in various applications such as two-phase Navier-Stokes flow, flows in porous media or electromagnetic wave propagation. The solution of the arising extremely large and sparse linear systems requires the use of efficient iterative solvers. Here the group has developed parallel agglomeration based algebraic multigrid algorithms for many years.

State-of-the-art numerical PDE solvers require a major effort in software development that cannot be accomplished by a single individual or a small group. Therefore the group develops together with other groups the open source software framework DUNE (www.dune-project.org) that provides a flexible but yet efficient and scalable foundation for the numerical solution of many different PDE systems with a wide variety of methods. The iterative linear solver package of DUNE scales efficiently to almost a million threads on Germanys largest supercomputer and is a member of the High-Q-club at Jülich supercomputer center. The software is currently adapted to the requirements of future exascale computing systems.

The group concentrates on applications in flow and transport in porous media and has worked on problems arising in the safety assessment of nuclear waste repositories, $CO_2$ sequestration, geostatistical inversion and multiphase reactive flow including microbial growth.

**LEARN MORE**

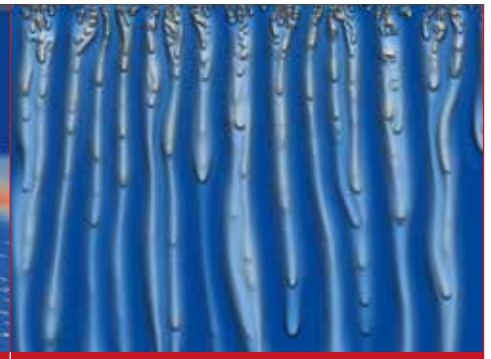
**Key Publication** Peter Bastian, A fully-coupled discontinuous Galerkin method for two-phase flow in porous media with discontinuous capillary pressures. Computational Geosciences, Springer-Verlag, http://dx.doi.org/10.1007/s10596-014-9426-y, accepted 2014.




## Microbacterial growth in the capillary fringe

PhD thesis of Pavel Hron
Project partners: Olaf Ippisch (TU Clausthal); Daniel Jost, Josef Winter, Claudia Gallert (KIT Karlsruhe); Peter Bastian (Heidelberg University)

**The capillary fringe is the part of the subsurface directly above the water table where both water and air is abundant. The hypothesis of the DFG Research group 831 "Dynamic Capillary Fringes" (end in 2014) was that microorganisms strive in this region as the carbon source is disolved in the water phase while oxygen is mostly provided in the air phase. In his thesis Pavel Hron developed a mathematical model that is able to describe all relevant processes including immiscible flow of air and water, transport and phase exchange of disolved components and their consumption, growth of microorganisms as well as their attachment and detachment to and from the porous matrix. Parameters of the model have been derived through inverse modelling of a large number of experiments carried out by our collaborators at the Karlsruhe Institute of Technology. The image shows the concentration of the microorganisms in a Hele-Shaw cell.**



## EXA-DUNE: Flexible PDE Solvers, Numerical Methods and Applications

Olaf Ippisch (TU Clausthal); Christian Engwer, Mario Ohlberger (Münster University); Dominik Göddeke, Stefan Turek (TU Dortmund); Oleg Iliev (ITWM, Kaiserslautern); Peter Bastian, Steffen Müthing (Heidelberg University)

**Next generation supercomputers capable of exascale performance will be characterised by billionfold parallelism at rather slow execution speed, deep memory hierarchies, hybrid many-core architectures comprising message passing and shared memory, as well as wide vector instructions possibly on specialized co-processors. In this project funded within the DFG special programme 1648 "Software for Exascale Computing" we adapt, together with our partners, the software framework DUNE, which specializes on the numerical solution of partial differential equations, to cope with these challenges. The Heidelberg contribution consists of the hybrid parallelization of DUNE's iterative solvers, in particular the algebraic multigrid preconditioner, the efficient implementation of high-order discontinuous Galerkin (DG) methods and the integration of components into a porous media flow simulator. The image shows the solution of density-driven flow with a high-order DG scheme.**

# Simulation and Optimization

**PROF. DR. HANS GEORG BOCK**

**Hans Georg Bock studied Mathematics at Cologne and Bonn, where he obtained his doctoral degree. After a visiting professorship in Heidelberg he became full professor for Applied Mathematics in Augsburg. Since 1991 he is full professor at IWR, Heidelberg. He is active as initiator, project leader and consultant of several research programs.**

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The work concentrates on numerical methods for simulation and optimization of complex dynamic processes described by nonlinear differential algebraic, delay or partial differential equations, and on applications in the sciences, humanities and engineering. Typical problems are large scale, highly nonlinear, contain integer decision variables and require the fulfillment of all kind of restrictions. The methods range from the solution of initial and boundary value problems including sensitivity analysis over parameter estimation and optimum experimental design to off-line and online process optimization.

Problem classes include mixed-integer dynamics in hybrid multiple scale models, multi-level dynamic optimization, real-time system identification and constrained optimization for optimal feedback control and robust optimization.

Emphasis is put on the development of efficient algorithms, especially on structure exploiting parallel methods based on the "optimization boundary value problem approach" that was developed in our group and is now generally considered as standard for DE constrained optimization.

New methods for the direct treatment of state-constrained optimal control problems in the determination of robust nonlinear optimum experimental designs, real-time mixed-integer optimizing control methods and direct structure exploiting methods for inverse constrained optimal control problems are developed.

Challenging application areas have been successfully treated in interdisciplinary collaboration, e.g. biomechanics and gait analysis, energy optimal cruise control of trucks or robotics, catalytic reaction systems, metabolic networks or chemical process engineering.

The research is mostly third-party funded and performed also in the associated junior research groups "Optimization of Uncertain Systems", "Optimum Experimental Design" and "Model-Based Optimizing Control".

**LEARN MORE**

**Key Publication** Kirches, C., Sager, S., Bock, H. G., and Schlöder, J. P., Time-optimal control of automobile test drives with gear shifts, Optimal Control Applications and Methods, 31(2), 137–153, 2010.

## Numerical methods for inverse optimal control in gait modelling

Phd thesis of Kathrin Hatz
Project Partners: Hans Georg Bock, Katja Mombaur, Johannes P. Schlöder, Sebastian Wolf

**The observed behaviour of certain processes, e.g. human locomotion, can be considered as the solution of a parameter-dependent optimal control problem. Parameters show up in the dynamic model and in particular in the objective function, which combines criteria like duration, energy consumption or stability. The determination of such parameters from observed data leads to challenging hierarchical optimization problems. For this class of problems efficient numerical methods were developed. They are based on the direct optimization boundary value problem approach and exploit the specific problem structures.**

**In interdisciplinary cooperation with the Heidelberg MotionLab gaits of able-bodied subjects and cerebral palsy patients were modelled using real-world motion capture data evaluated in the MotionLab. The results show excellent agreement of observed and simulated behaviour.**

**The new gait models may be used in decision support for operative interventions or for assessment of their results.**

## Mixed-integer real-time optimal control methods for energy optimal truck rides

Hans Georg Bock, Christian Kirches, Johannes P. Schlöder

**Energy optimal cruise control for heavy duty trucks is a very promising method towards green traffic. Since heavy duty trucks have up to 16 gears that can frequently be switched and possess different braking systems, an energy optimal ride requires solutions of a mixed-integer state-constrained optimal control problem in real-time, since a changing environment has to be taken into account.**

**For this demanding task in cooperation with Daimler new real-time algorithms have been developed that are based on convexified relaxed formulations, functional analytic investigations of the properties of the relaxed solution, embedding techniques and integer approximations with error control.**

# Computational Arithmetic Geometry


## PROF. DR. GEBHARD BÖCKLE

**Gebhard Böckle received his PhD at the University of Illinois at Urbana-Champaign, USA. After post-doctoral positions in Strasbourg, Essen and Mannheim he obtained his habilitation at the ETH Zürich, Switzerland. In 2003 he became professor of Mathematics at the University of Duisburg-Essen. In 2010 he was appointed at Heidelberg University.**

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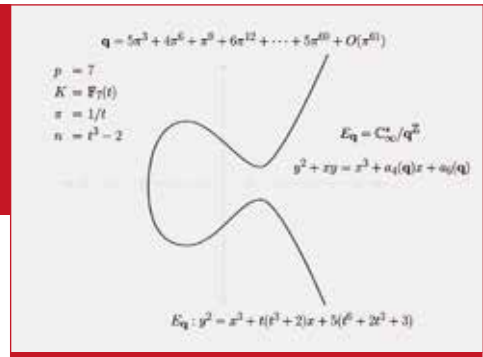
Number theory based on Arithmetic and Algebraic Geometry is a core theme in modern mathematics. The interests of the members of my group range from geometry in positive characteristic via arithmetic questions over global function fields to Galois representations and deformation theory of Galois representations over number fields. In many of these themes computational and algorithmic questions are important since often only via such methods one can make new theoretical predictions or test known conjectures and variants thereof. For instance in deformation theory one can in small dimensions compute universal rings and thereby verify expected ring-theoretic properties. A central computational theme of my research group is the algorithmic of Bruhat-Tits trees, or more generally buildings, and their quotients by arithmetic groups. These are combinatorially defined topological spaces that carry a natural action of a p-adic group. They have abundant applications to many computational questions: the computation of Hecke eigensystems of Drinfeld modular forms of arbitrary weight, the computation of complex or p-adic automorphic forms over global fields for groups that are compact over the Archimedean places, the presentation of arithmetic groups in the sense of group theory and the solution of the word problem in such groups etc. Several of the above applications were realized by members or by former members of my research group in the 1-dimensional tree case. A long-term project is the generalization to higher-dimensional buildings.

**LEARN MORE**

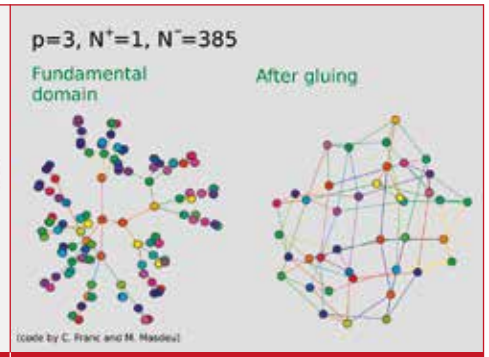
**Key Publication** Gebhard Böckle, Ralf Butenuth, On computing quaternion quotient graphs for function fields, J. Théor. Nombres Bordeaux 24 (2012), no. 1, 73–99.




## Efficient computation of elliptic curves of small conductor over function fields

PhD thesis of Yamidt Bermudez Tobon (DAAD funding)
Project partners: Gebhard Böckle, Juan Cerviño (Heidelberg University)

Elliptic curves are among the most central themes in number theory. Major recent breakthroughs are Wiles' proof of Fermat's last theorem and the proof of the Sato-Tate conjecture. Nevertheless, the abundance of still open conjectures, for instance that of Birch and Swinnerton-Dyer, demands further tools for experimental exploration. Important questions are the (conjectural) construction of points on elliptic curves over global fields and of their field of definition. In recent work, Yamidt Bermudez implements a highly non-trivial algorithm based on joint theoretical work that constructs in polynomial time elliptic curves over function fields of small conductor. This solves a question that has been open for two decades. The algorithm applies analytic tools to find algebraic equations. The implementation will allow in the near future the investigation of number-theoretic properties of so-called Heegner and Darmon points on the so-constructed curves.




## Computational aspects of modular forms and p-adic Galois representations
(DFG project with the SPP 1489)

Panagiotis Tsaknias, Gabor Wiese (Université du Luxembourg); Ian Kiming (University of Copenhagen); Gebhard Böckle, Tommaso Centeleghe, Peter Gräf, Christian Theisen (Heidelberg University)

Recent advances in Arithmetic Geometry and various conjectures in the spirit of the Langlands program establish and postulate deep correspondences between geometric and number-theoretic objects: modular forms and Galois representations. The geometric side is often amenable to calculations. By the explicit nature of the correspondences also number theoretic objects become computationally accessible. The project investigates these objects either directly or through the correspondence. It also develops and implements new algorithms based on existing computer algebra systems. One task is the computation of integral invariants of modular p-adic Galois representations. In an intermediate step, we extend existing algorithms to find endomorphism rings of abelian surfaces over finite fields. Another task inspired by a question of Buzzard is the study of p-adic coefficient fields of newforms. To explore this experimentally, we generate new data of coefficient fields of so-called L-invariants.

# Theoretical Chemistry


## PROF. DR. LORENZ S. CEDERBAUM

**Lorenz Cederbaum studied Physics at the University of Munich and obtained his doctoral degree in Chemistry and habilitation in Physics from the Technical University of Munich. He was professor of Physics in Freiburg and since 1979 he holds the Chair for Theoretical Chemistry at Heidelberg University. He has two honorary doctoral degrees.**

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The research carried out in the group incorporates a rather broad palette of subjects. It is characteristic to the group to derive the basic theory relevant to the subject of research as well as to develop and/or contribute to the numerical algorithms and methods needed to efficiently implement the theory (often in collaboration within the IWR), and to apply the outcome to interesting realistic problems.

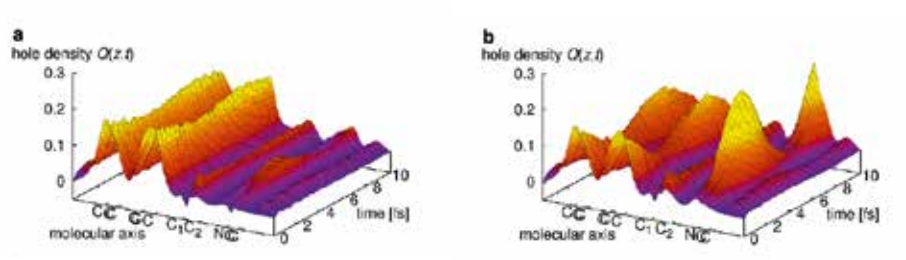
A particularly successful example is the derivation and development of the so called MCTDH (multiconfigurational time dependent Hartree) method which has found ample application in the literature to describe non-adiabatic nuclear motion in molecular systems and which has been extended to successfully treat fermions and bosons where it is named MCTDHF and MCTDHB.

Using the developed methodologies, quite a number of physical phenomena have been predicted theoretically which have subsequently been verified experimentally. Certainly worth mentioning is the ICD (intermolecular Coulombic decay) which has developed to become a rather popular new field of research and charge migration driven by electron correlation, a phenomenon of central relevance to the emerging field of electron dynamics and attosecond physics and chemistry.

**LEARN MORE**


**Key Publication** K. Gokhberg, P. Kolorenc, A. I. Kuleff and L. S. Cederbaum, Site- and energy-selective slow-electron production through intermolecular Coulombic decay, Nature 505 (2014), 661




## Ultrafast hole migration and conical intersections


Alexander Kuleff (Heidelberg University); Ágnes Vibók, Gábor Halász (University of Debrecen); Stephen R. Leone, Daniel M. Neumark (University of California, Berkeley); Zenghu Chang (University of Central Florida); Arvinder Sandhu (University of Arizona); C. William McCurdy (University of California, Davis); Paul B. Corkum (University of Ottawa)


**Exposing molecules to short light pulses populates several and in some cases even many electronic states. In the case of ionization, it has been shown theoretically that there is a universal response of the electrons remaining in the ion to the removal of an electron.**
**This response is less than 50 as and rather independent of the system. At later times the hole created in the system may migrate further, but this migration is then typical for the system under investigation. Only attosecond pulse methods can have the chance to investigate the attosecond response of the electrons. Theory predicts that ultrafast migration of a hole can be driven by electron correlation which has been termed charge migration. This contrasts strongly the standard electron (or hole) transfer which is driven by nuclear motion and is hence much slower.**

**Even if we are interested primarily in the ensuing electron dynamics, like we have often done in the study of ultrafast charge migration, the impact of nuclear dynamics cannot be neglected. In particular, the impact of natural conical intersections (CIs) and of a new kind of such intersections induced by light (LICIs) will be investigated.**

# Mathematical Models of Transport in Plants

**DR. ANDRÉS CHAVARRÍA KRAUSER**

**Andrés Chavarría Krauser studied physics and obtained his doctoral degree in Mathematics at the Heidelberg University in collaboration with the Research Center Jülich. He was a post-doc at the Center for Modelling and Simulation in the Biosciences and has been a member of the IWR since 2006. The German Research Foundation awarded him the Emmy Noether price in 2010.**

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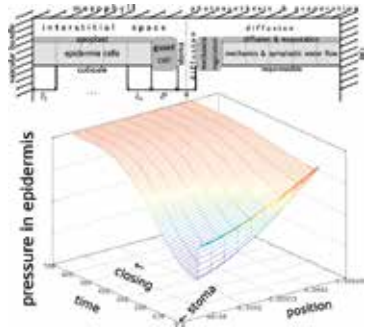
Plants interact with their environment through transport, and hence, adaptation to a changing environment is often accomplished by regulation of transport processes. The relation between tissue structure, regulatory mechanisms and physical processes is understood only very poorly in plants. Thus, our research focuses on mathematical modelling and simulation of such transport processes. We are mainly interested in uptake and transport of solutes by roots and gas fluxes in leaves. Our approach is based on applying conservation equations, which model the fluxes of material and momentum with partial differential equations, and combine these with ordinary differential equations modelling regulatory pathways. This demands a highly interdisciplinary approach between physics, mathematics and biology. For example, the models need to account for biological and physiological facts, as well as to stay rigorous enough for mathematical analysis. We develop the models based on experimental data, such as expression levels and patterns of transporters/channels, and use parameter estimation to parameterize these realistically. From an analytical point of view, we apply techniques, such as homogenization to reduce the complexity and conduct stability analysis of stationary solutions. Further, we develop simulation techniques to guarantee an ideal interaction with biologists, we test and pose new biological hypotheses and contribute this way to elucidation of how plants regulate essential fluxes.

**LEARN MORE**

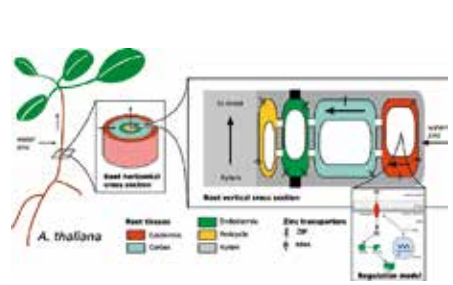
**Key Publication** Claus J, Bohmann A, Chavarría Krauser A (2012) Zinc Uptake and Radial Transport in Roots of Arabidopsis thaliana: A Modelling Approach to Understand Accumulation. Annals of Botany, 112: 369–380.




## Leaf gas exchange and stomatal control

PhD thesis of Ansgar Bohmann

Leaf gas exchange exhibits surprising and seemingly emergent behavior such as patchy oscillations of stomata and inverse behavior. We are building a model of leaf gas exchange from a first principle physical basis. Attention is paid to underlying thermodynamics, mechanics, and transport processes including wind effects. By this, we want to gain insight to physiological control under changing environmental conditions like light flecks on time scales of minutes to hours. Many model parameters are material properties or geometrical data that can be obtained from plant sciences literature. The ongoing work is focused to a PDE model describing the coupling between diffusion, bulk flow, evaporation from cell walls, mechanics, photosynthesis, and stomatal control. Linking together all building blocks would give an intractably complex model. We are working towards a homogenized model to reduce complexity in a mathematically controlled way and allow for analytical and numerical treatment.




## Zinc uptake and transport in plant roots

Ansgar Bohmann, Juliane Claus, Andrés Chavarría Krauser (Heidelberg University)
Project partners: Ute Krämer (University of Bochum); Mariya Ptashnyk (University of Dundee)

Zinc transport in plants has been studied for some time, because it is an essential micronutrient but toxic at high concentrations. Specialized hyperaccumulator plants can tolerate high zinc doses and are of interest for their potential use in phytoremediation and development of functional crops. The ions are taken up from the soil along with water and are transported across different root tissues towards the central vascular bundle, from where they are distributed to the rest of the plant. We developed a model that considers the different tissues of a root and couples water flow to regulated membrane transport of zinc. The central idea was to decompose the root into interacting cells, in which the extent of transporters to be expressed is decided on the local status, and to combine these with a reaction-diffusion-advection equation for transport. Though developed for the heavy metal zinc, the model is general and can be applied to other solutes taken up by plants.

# Transition Metal Coordination and Computational Chemistry

**PROF. DR. PETER COMBA**

**Peter Comba has a diploma from ETH Zürich. After his PhD (Neuchâtel) and before starting at Heidelberg in 1992, he had junior positions in Australia (ANU) and Switzerland. He chaired the DFG graduate college ""Molecular Modeling" and is a member of the Helmholtz Virtual Institute NanoTracking. He is one of the directors of IWR and director of IWH.**

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Coordination chemistry (ligand design and synthesis, preparative coordination chemistry, complex stability, stereochemistry, electrochemistry, electron transfer, activation of small molecules, electronic structures, magnetism, theory and modeling)

The main research areas at present include:

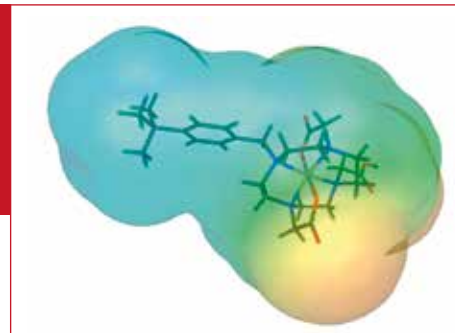
- ligand control of complex formation and stability, in particular for copper(II) and gallium(III) in the context of in vivo imaging of cancer tissues
- bioinorganic model chemistry, in particular nonheme iron oxidation, oxygenation, halogenation and water oxidation; copper-dioxygen chemistry; purple acid phosphatase; copper(II) chemistry of cyclic peptides
- oxidation catalysis by high-valent nonheme iron model compounds
- molecular magnetism
- classical coordination chemistry, in particular ligand-enforced coordination geometries, correlation of electronic with structural properties, reaction mechanisms
- development and application of theoretical and computational methods, in particular ligand field theory, force field calculations, spectra simulation and quantum-chemistry-based methods (only involving applications in the latter area)

Apart from preparative chemistry and routine spectroscopy, used for the characterization of the ligands and complexes prepared in the group, methods often used include: UV-vis-NIR, CD, EPR, magnetism, resonance Raman, MCD and Mössbauer in collaboration, electrochemistry, stopped-flow kinetics, potentiometric and spectrophotometric titrations, force-field, ligand-field and quantum-chemical calculations.

**LEARN MORE**

**Key Publication** Atanasov, M.; Busche, C.; Comba, P.; El Hallak, F.; Martin, B.; Rajaraman, G.; van Slageren, J.; Wadepohl, H., Inorg. Chem. 2008, 47, 8112. Trinuclear $\{M^1\}CN\{M^2\}_2$ complexes ($M^1 = Cr^{III}$, $Fe^{III}$, $Co^{III}$; $M^2 = Cu^{II}$, $Ni^{II}$, $Mn^{II}$). Are single molecule magnets predictable?





## QSAR for hydrophobicities and biodistributions

PhD thesis of Avik Sanyal

Project partners: Holger Stephan (Helmholtz-Zentrum Dresden-Rossendorf); Ashutosh Gupta (Udai Pradap Autonomous College, Varanasi, India); Bodo Martin (Heidelberg University)

There are various techniques to compute charge distributions. The model developed recently in our group is parametrical to produce ab-initio derived charges via an efficient two-parameter model of the chemical potential. This allows for a fast computation of fluxional (i.e. geometry-depended) charges, and parameterizations have been developed for organic molecules and a number of transition metal compounds. Based on the computed partial charges and shape parameters a QSAR model has been developed for the efficient and accurate prediction of hydrophobicities, and this is now the basis for the development of a QSAR for the prediction of biodistributions. This will help to reduce animal experiments, e.g. in the area of multimodal tumor imaging, which is a very active area of research, in which we are also involved as experimentalists.

## Efficient copper-based carbonic anhydrase model systems

PhD thesis of Nina Dovalil, Michael Westphal (Heidelberg University); Project partners: Lawrence R. Gahan, Graeme R. Hanson (University of Queensland, Australia); Marcel Maeder (University of Newcastle, Australia)

Patellamide- and ascidiacylamide-type peptides were discovered and isolated two decades ago but their biological function is still unknown. It is generally assumed that their $Cu^{II}$ complexes are biologically important, and we have extensively studied equilibria as well as geometric and electronic structures of relevant model compounds in solution with combinations of various spectroscopies and computational chemistry. Importantly, we have been able to show that these dicopper(II) complexes are very efficient carbonic anhydrase enzyme models. This is exciting, because these are the most efficient synthetic carbonic anhydrase catalysts ($10^5$ times faster than the uncatalyzed reaction and only $10^2$ times slower that the enzyme) and, if carbonic anhydrase reactivity would be the natural function, these would be the first copper-based carbonic anhydrases. A full computational analysis of the mechanism (DFT and MD calculations) is in progress and detailed biological studies are planned.

# Statistics Group

**PROF. DR. RAINER DAHLHAUS**

**Rainer Dahlhaus is an elected fellow of the Institute of Mathematical Statistics. He has been serving on the editorial board of many international journals such as the Annals of Statistics and on the scientific board at the mathematical research institute at Oberwolfach.**

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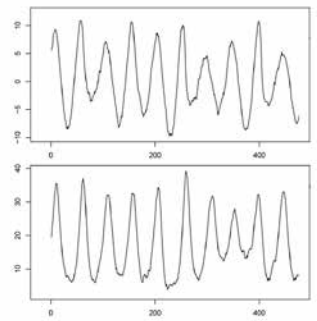
The focus of the Statistics Group is on various aspects of time series analysis and point processes. This includes signal modeling using locally stationary processes, graphical models for time series, phase synchronisation, inference for queuing systems, and recursive Monte Carlo methods. Methods developed in the group have been used for various applications including the identification of synaptic connections in neuron networks, for therapy process research in psychosomatic medicine and in financial econometrics. We have introduced the theory of locally stationary processes which allows for better modeling of nonstationary signals. The theory leads to methods for time varying spectra and to time series models with parameter curves in time. The parameter curves can be estimated by nonparametric methods such as local likelihood or wavelet methods. For phase synchronisation models with time varying phases are investigated. Here different methods of phase estimation have been derived like modified periodogram methods, modifications of the Hilbert transform, and filter techniques in nonlinear state space models. For multivariate processes phase synchronization is modeled by using the theory of cointegration fort he phase processes. For queueing systems different nonparametric methods such as cross-spectral analysis methods for point processes are used to construct estimators of the service time distributions at the nodes as well as estimators for the routing probabilities. Another focus of research are graphical models for dynamic sytems such as time series and point processes. This allows for discriminating between direct dependencies reflected by an edge in the graph or indirect dependencies reflected by a path via several edges in the graph. The graphical models of this type are used for example for the identification of synaptic connections in neural networks.

**LEARN MORE**

**Key Publication** Dahlhaus, R. (1997). Fitting time series models to nonstationary processes. Annals of Statistics 25, 1–37



## Phase synchronisation in neural networks

Rainer Dahlhaus, Stefan Richter, Britta Velten

**In a neural network the relationship between the phase variables of oscillators in different cortical areas may indicate common input sources or task-based cortico-cortical communication. Thus investigation of synchronisation of oscillations is essential for the understanding of functional coupling of different brain regions. Since phase variables are circular data we study the statistical inference for multivariate circular distributions such as the multivariate wrapped normal and the von Mises distribution. Since the maximum likelihood estimator of these distributions can hardly be calculated we use the recently developped score matching method. The structure of the network shall be explored by a graphical model with nodes representing phase variables of different brain regions from which oscillation is recorded and edges representing direct coupling. The techniques shall we extended to multivariate dynamic models which are more realistic for modelling phase synchronisation in neural networks.**

## Bridging the theory of phase synchronization and the theory of cointegration

Rainer Dahlhaus, Jan C. Neddermeyer

**The theory of cointegration has been the leading theory in econometrics with powerful applications to macroeconomics during the last decades, while the theory of phase synchronization for weakly coupled oscillators has been one of the leading theories in physics with many in science. For example in neuroscience phase synchronization is regarded as essential for functional coupling of different brain regions. In this research we explain why there exists a close connection between both theories. We show that there exists a system of stochastic difference equations which can be viewed as close to the Kuramoto equations, whose solution is a cointegrated system. As a consequence the rich theory on cointegrated systems can be applied for statistical inference on phase synchronization. This includes tests for synchronization, unidirectional coupling and the identification of the. For example an unidirectionally coupled Rössler-Lorenz system can be identified with the methods from cointegration.**

# Theoretical and Computational Chemistry


## PROF. DR. ANDREAS DREUW

**Andreas Dreuw obtained his PhD from Heidelberg University. After two years at the UC Berkeley, and eight years as Emmy-Noether and Heisenberg fellow at Goethe-University Frankfurt, he holds the Chair for Theoretical and Computational Chemistry at the IWR since 2011. At present, he is one of the deputy directors of the IWR.**

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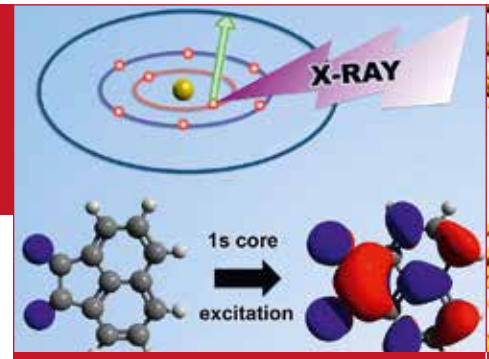
Light triggered processes are ubiquitous in nature and technology, and their fundamental understanding is the key to new and improved existing technologies like organic photovoltaics. In general, this requires modeling and simulation of photo-initiated processes on a sub-atomic level, which requires quantum mechanical methods. However, the theoretical description of the involved excited electronic states is one of the biggest challenges of contemporary Theoretical Chemistry.

Our research is dedicated to the development of computational methods for the description of excited states of large molecules and to their efficient implementation into a generally usable computer program. The focus lies here on perturbation theoretical approaches, in particular in the development of the algebraic-diagrammatic construction (ADC) schemes for the polarization propagator, which represent an elegant route to excitation energies and excited-state properties. The results of these calculations allow for the simulation of various linear and non-linear optical spectroscopies. We are particularly interested in the development of suitable models for molecular environments in ADC calculations. Here, our efforts include the development of ADC methods in connection with polarizable continuum models, effective fragment potentials and density embedding. The developed methods are employed to study photo-biological processes like, for example, light-induced DNA photo-damage repair by photolyases, or optical properties of functional materials for organic electronics. In general, our applications are characterized by close collaborations with experimental groups.

We have recently started a few exploratory research projects comprising the combination of mechanical force with optical spectroscopy and the development of a quantum mechanical force analysis tool, as well as the use of finite elements in correlated quantum chemical methods.

**LEARN MORE**


**Key Publication** M. Wormit, Dirk R. Rehn, Philipp H. P. Harbach, Jan Wenzel, Caroline M. Krauter, Evgeny Epifanovsky and A. Dreuw, Investigating Excited Electronic States using the Algebraic Diagrammatic Construction (ADC) Approach of the Polarisation Propagator, Mol. Phys., 2014, 112, 774

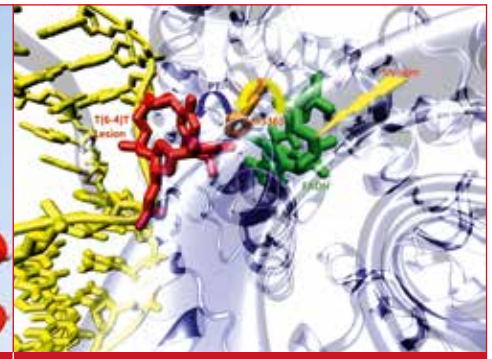




## Nature of core-excited electronic states

PhD thesis of Jan Wenzel
Project partners: Patrick Norman (University of Linkøping); Alexander Trofimov (University of Irkutsk); Jochen Schirmer, Marcus Pernpointner (Heidelberg University)

X-ray absorption spectroscopies (XAS) have become important in analyses of molecular composition of surfaces and the investigation of the electronic structure of large molecules. Jan Wenzel is developing efficient methods for the calculation of core-excited electronic states based on the algebraic-diagrammatic construction scheme for the polarization propagator, which allow for the quantitative simulation of (XAS) spectra. In detail Jan implements the so-called core-valence-separation (CVS) approximation for second and third-order ADC schemes, which des not only provide energies but moreover also densities and excited-state properties, which paves the road to an unprecedented understanding of this class of electronic states.

Jan's computer program is generally applicable to all kinds of molecules and will be a unique, easy-to-use tool to simulate XAS spectra of large molecules and even small molecular aggregates.



## Photo-initiated processes in DNA Photolyases: upon UV light absorption and electron (e-) and a proton (PT) is transferred triggering DNA repair.3

Shirin Faraji, Lukas Wirz, Philipp H. P. Harbach, Matthias Schneider (Heidelberg University); Dongping Zhong (Ohio State University)

(6-4) Photolyases are fascinating enzymes that utilize UV light to repair DNA (6-4) photo-damages. The absorbed photon energy is transferred from an 9-HDF antenna molecule to a neighboring electron donating FADH-molecule. Using the transferred excitation energy, an electron is transferred to the DNA damage, which eventually catalyzes the repair of the DNA photo-damage restoring the origingal DNA bases. Using state-of-the-art quantum chemical and combined quantum mechanical/molecular mechanical (QM/MM) methods, we could show that the initial photo-initiated electron transfer processes corresponds to an Intermolecular Coulomb Decay (ICD) process, which is the first example of ICD in a biological system. Moreover, we could identify all subsequent repair steps, which comprise a coupled electron and proton transfer as well as a concerted repair step via an oxetane-like transition state. Our proposed mechanism is in agreement with experimental findings and is quoted as "the most reasonable mechanism in the literature".

# eilslabs: Integrative Bioinformatics and Systems Biology

**PROF. DR. ROLAND EILS**

**Roland Eils has a joint affiliation as full professor at Heidelberg University and as division head at the German Cancer Research Center (DKFZ). His research focuses on the integration of tools from mathematical modeling, image analysis and informatics into life science research, delivering contributions to the fields of systems biology and bioinformatics.**

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Using current next generation DNA sequencing methods, it is nowadays feasible to sequence and map an individual human genome (e.g. the genome sequence of a patient-derived tumor) in a single day. This enables the identification of individual cancer-relevant mutations, holding great potential for precise diagnostics leading to a more targeted and personalized treatment. Other complementary technologies, such as epigenome, transcriptome, proteome or metabolome analysis, deliver additional data for diagnostic and research purposes. Given the enormous technological advances in data generation in recent years, the integration of these data in order to generate new insights into complex biological functions is still a major challenge and can only be achieved with interdisciplinary approaches.

Our division is developing computer-assisted methods for interpreting complex genomic and other biological data, as well as methods for modeling and simulation of biological processes. Major activities include the development of integrated bioinformatics approaches for the interpretation and management of cancer genome and accompanying clinical data, the application of state-of-the-art technologies in automated live-cell imaging and image analysis, experimental and theoretical systems biology approaches addressing key cellular mechanisms and their distortions in cancer cells, as well as the development of new synthetic biology tools to manipulate cellular processes. For this purpose, the division is integrating and developing new methods from systems biology and systems medicine, automated image processing, state of the art light-microscopy, cell biology and bioinformatics.

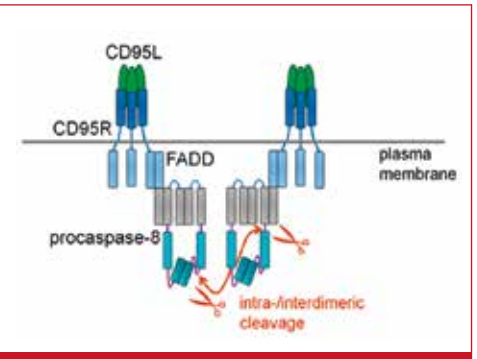
**LEARN MORE**

**Key Publication** Jäger, N., Schlesner, M., Jones, David T.W.,(...) and Eils, R.@ (2013). Hypermutation of the Inactive X Chromosome Is a Frequent Event in Cancer. Cell 155, 1-15. doi: 10.1016/j.cell.2013.09.042

## X-Chromosome Hypermutation:
### A new biological phenomenon observed by pan-cancer analysis of whole human genomes

Natalie Jäger, Matthias Schlesner, Benedikt Brors, Tobias Bauer, Roland Eils

Bioinformatic analysis of whole human genomes delivers exciting new insights into mutational processes during the development of cancer. Using a cross-cancer comparison of mutational patterns across 402 whole human genomes, comprising a diverse set of childhood and adult tumors, we have found that the inactive X chromosome of many cancer genomes of female patients accumulates up to four times as many somatic mutations per megabase when compared to the individual autosomes. Whole genome sequencing of clonally expanded non-tumorigenic human cells revealed no X chromosome hypermutation. Our data suggest that hypermutation of the inactive X chromosome results from DNA replication stress in aberrantly proliferating cells, and is an early and frequent feature of tumorigenesis. This finding has important implications for our understanding of how tumor cells, and in particular the DNA repair machinery, respond to early oncogenic stresses and how mutations evolve in the tumor.




## Mathematical Modeling of Cellular Death Pathways

Stefan Kallenberger, Joel Beaudouin, Roland Eils

The regulation and deregulation of cellular death pathways such as apoptosis is of great importance for several human diseases including cancer. To unravel the molecular mechanisms behind the activation of these processes, we are combining mathematical modeling with quantitative experimental approaches. For the latter we have developed specific molecular probes, which allow observation of the intracellular compartmentalization of key molecules (Beaudouin et al., 2013, Cell Death and Differentiation). In our recent publication (Kallenberger et al., 2014, Science Signaling) we introduce a new modeling approach to simultaneously describe single cell and population data in a cell ensemble model. Using this approach we unraveled how the mechanism of caspase-8 auto-cleavage, after activation of CD95 death receptors, ensures a precise control of apoptosis at various ligand concentrations.

# Theoretical time-resolved spectroscopy

**DR. SHIRIN FARAJI**

**Shirin Faraji received her Ph.D. in chemistry from Heidelberg University. After one year at University of Frankfurt, she was awarded the funding of "Elitepostdoc Baden-Württemberg Stiftung" to start her Habilitation at Heidelberg University. Since 2012 she is a junior research group leader at IWR. At present, she is visiting University of Southern California as a DAAD fellow.**

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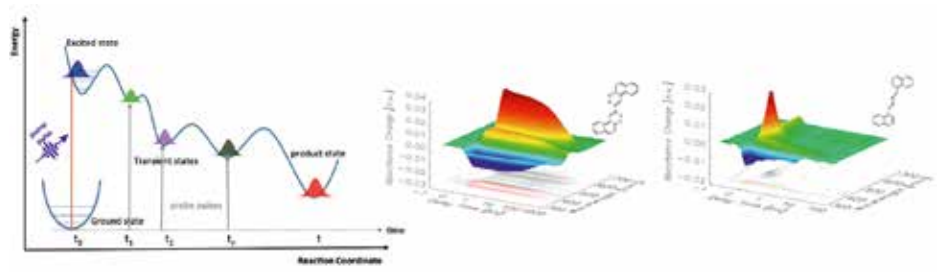
www.iwr.uni-heidelberg.de/groups/theospec/theoretical_time-resolved_spectroscopy/home.html

Time-resolved spectroscopy offers a new twist to traditional spectroscopy and opens up a wide range of application areas, including organic electronics, biology, and material science. In particular, the development of femtosecond-pulsed lasers and pulse shaping techniques, among other innovations, made the development of sophisticated ultrafast time-resolved spectroscopies possible allowing for real-time observation of chemical processes like breaking and forming of chemical bonds. In contrast, theoretical approaches to simulate time-resolved spectra for direct comparison with experiment are lagging behind, as they require a thorough treatment of the electronic structure, the nuclear dynamics and the influence of the solvent at a quantum mechanical level. Our research aims at closing this gap between experiment and theory. Since most systems of interest to biology and chemistry are in condensed phases, our focus here is developing and providing a theoretical methodology that allows for simulation of time-resolved spectra of molecular systems with up to 50 atoms in a molecular environment. Our approach is based on quantum dynamical simulations on quantum chemically computed potential energy surfaces. To this end, we rely on the multi-configurational time-dependent Hartree (MCTDH) method employing the multi-mode multi-state vibronic coupling (MMVC) model, using surfaces based on electronic structure data within "system-environment" framework. We are particularly interested in observables closely related to laser induced dynamics to simulate time-resolved pump-probe spectra, combining the components of ground state bleaching, excited state absorption and stimulated emission. The developed methods are prerequisite for understanding of photochemical reactions in biology, chemistry and material science and pave the road for design of devices like organic photovoltaic or organic light emitting diodes.

**LEARN MORE**

**Key Publication** Book Chapter: "Multi-state vibronic dynamics and multiple conical intersections" S. Faraji, S. Gomez-Carrasco and H. Köppel, in Conical Intersections: Theory, Computation and Experiment, Word Scientific, Singapore, 2011.






## Ultrafast photo-induced dynamics of Pigment Yellow 101 (PY101)

Katharyn Fletcher, Andreas Dreuw (Heidelberg University); Anna Krylov (University of Southern California)

**PY101 exhibits a rich photochemistry in its first excited state S1, and corresponding experimental time-resolved spectra indicate that 5 time constants are required to describe the decay of S1. Quantum chemical results for PY101 so far are based on qualitative descriptions of the excited state dynamics by interpreting the potential energy surfaces (PESs) along specific coordinates. However, for a quantitative comparison with experimental results, time-dependent quantum dynamical simulations are imperative to obtain various spectra, lifetime, quantum yield, and rate constants of radiation-induced processes. To this end, we aimed to go beyond the reaction coordinate analysis and perform quantum dynamical calculations on PY101.**

**A way to reduce the computational effort for the quantum dynamical description of large molecules and to overcome the notorious bottleneck of accurate PESs is to construct an appropriate reduced dimensionality Hamiltonian that still describes the process accurately. Although the inclusion of all relevant modes is important, at ultra-short timescales not all modes play a significant role in the dynamics and do not need to be described at high level of accuracy. This can be realized by partitioned-dimensionality ansätze establishing a system-environment framework. Following this strategy, PESs along relevant system coordinates, as well as model potentials employing MMVC scheme for the remaining coordinates, have been calculated, which is recently published. Reduced-dimensional quantum dynamical simulations have been started, and intermediate results seems very promising.**

**Our next focus will be on extension of the derived methodology to photo-active molecular systems of comparable complexity and size, testing the newly developed ideas for further theoretical developments in the field, such as description of spontaneous emission, four-wave mixing, and, finally, toward multi-dimensional spectroscopy.**

# Computational Biochemistry

**DR. STEFAN FISCHER**

**Stefan Fischer received his Ph.D. in Biophysics from Harvard University (USA). After 3 years post-doctoral research in theoretical chemistry at Harvard and 3 years as a Principal Scientist at Hoffmann-La Roche (Switzerland), since 1999 he leads the Computational Biochemistry group at the Interdisciplinary Center for Scientific Computing (IWR).**

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Proteins are the little "machines" that perform all the tasks in living systems. To understand in a quantitative way how they function at the atomic level of detail, it is necessary to use computer simulations, because there are no experimental techniques that would allow to observe all the atoms of a protein on the ultra-fast time-scale of their motion (which is on the order of $10^{-15}$ seconds). Our main research focus has been on protein nanomachines, such as molecular motors, trans-membrane pumps and channels and catalytic enzymes.

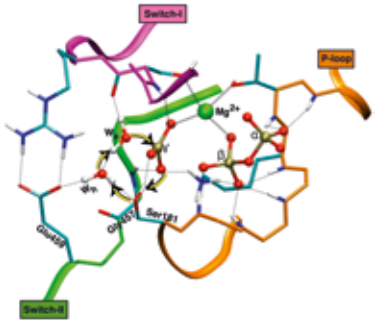
Aside from using the now standard Molecular Dynamics methods (for which the Nobel prize in chemistry was awarded in 2013), we develop algorithms for finding reaction paths and transition states in high-dimensional systems. This enables us to study complex biomolecular processes that occur on time-scales beyond the scope of standard molecular dynamics (i.e., slower than micro-seconds), such as the motions of molecular motors in muscles. We also use combined quantum/classical mechanics (QM/MM), which allow to accurately study chemical reactions inside proteins, such as occurring in enzymatic catalysis. Complex conformational changes in proteins are tackled by using transition network analysis and Markov-models.

We have elucidated the mechanisms of the chemo-mechanical coupling in the myosin muscle motor, the conversion of energy in the light-driven proton pump bacteriorhodopsin, the mechanism of a molecular valve in the light-driven chlorid pump halorhodopsin, the catalytic mechanism of ATP hydrolysis in enzymes and the DNA-cleaving enzyme EcoRV, and the function of tropomyosin during the regulation of muscle contraction. The resulting knowledge serves to optimize processes in biochemical engineering, to inspire developments in the nanotechnologies, and to help pharma and biotechnological research.

**LEARN MORE**

**Key Publication** F. Kiani and S. Fischer. The catalytic strategy used by the myosin motor to hydrolyze ATP. Proc. Natl. Acad. Sci. U. S. A. 2014, DOI: 10.1073/pnas.1401862111

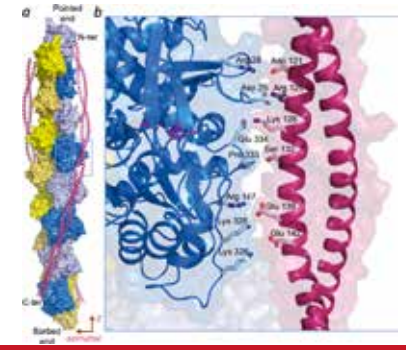





## Catalytic mechanism of the ATPase function in the molecular motor myosin

Farooq Kiani

**Biomolecular motor proteins like myosin generate mechanical force from the chemical energy of ATP. Like gas engines, they have different parts (protein domains) that run through a well-defined cycle of motions, consuming one ATP per cycle. Because ATP is very stable, they must catalyze its breakdown (hydrolysis). The catalytic mechanism is at the core of understanding how these motors work, because the activation of the catalytic ATPase-function coordinates the motion of the different domains. Using combined quantum/classical molecular mechanics (QM/MM), we did a full exploration of the possible catalytic pathways, and found a catalytic mechanism that is consistent with all experiments. We could identify which protein groups are essential for catalysis, which allows to understand how the precise coupling between ATPase activation and mechanical motion is achieved. ATPases are involved in most biochemical process, and can be expected to use a very similar catalytic strategy.**



## Tropomyosin movement on F-actin during muscle activation explained by energy landscapes

Marek Orzechowski, Edward Li, William Lehman (Boston University)

**Muscle contraction is regulated by tropomyosin movement across the actin filament surface, which exposes or blocks myosin-binding sites on actin. Recent atomic structures have yielded different positions of tropomyosin on actin. We examined the repositioning of tropomyosin between these locations by optimizing the energy of the complex for a wide range of tropomyosin positions. The resulting energy landscape provides a full-map of the actin surface, explaining why tropomyosin shifts between the various positions, and indicates that spontaneous movement of tropomyosin away from the energetic "ground-state" is unlikely. Myosin-binding must drive tropomyosin toward the state that activates muscle contraction. Additional energy landscapes were computed for disease-causing actin mutants that distort the topology of the actin-tropomyosin energy landscape, explaining their phenotypes.**

# Computational Linguistics


## PROF. DR. ANETTE FRANK

**Anette Frank holds a PhD in Computational Linguistics from Stuttgart University. After research positions held at XRCE Grenoble and DFKI Saarbrücken she was appointed professor for Computational Linguistics at Heidelberg University. Her research focuses on computational semantics with applications in Information Extraction and Digital Humanities.**

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The field of Computational Linguistics (CL) has undergone a strong development towards statistical and machine learning methods. Recent work makes use of web-scale resources ("the web as corpus") for resource acquisition and model induction using unsupervised or weakly supervised learning techniques. The CL group at the Institute for Computational Linguistics specializes in weakly supervised methods for the corpus-based induction of linguistic – especially semantic – knowledge and its use in advanced semantic applications, including Information Extraction, Natural Language Understanding and Digital Humanities.

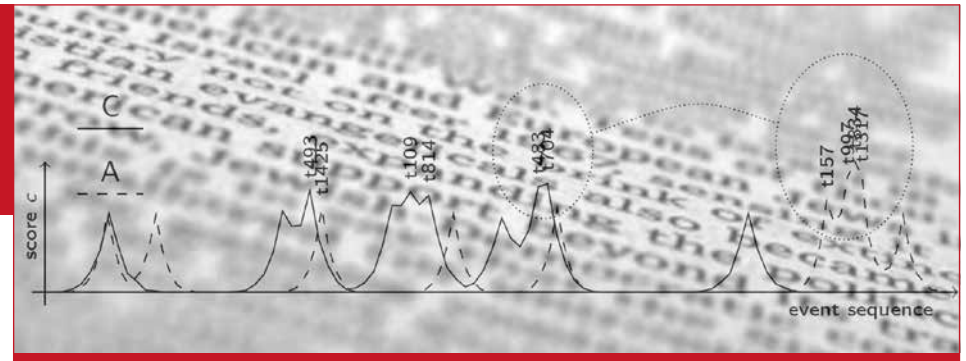
Recent research themes include distributional models for uncovering hidden meanings in compositional semantics, the automated discourse-semantic analysis of narratives, broad-coverage corpus-based methods for weakly supervised induction of linguistic knowledge and the unsupervised induction of discourse coherence models for argument structure realization.

The group has developed a scalable NLP architecture for full computational text analysis that is adaptable to novel domains, as well as parallel processing techniques for building distributional semantic models from web-scale corpora.

The group has significant expertise in applying core NLP technology in Digital Humanities projects, such as the computational analysis of narratives (within the SFB 619 "Ritual Dynamics") or probabilistic inference techniques for citation segmentation of OCRed multilingual bibliographies (within the Center of Excellence "Asia and Europe"). Prof. Frank is involved in the CLARIN-D initiative, where she leads the working group "Computational Linguistics and Applied Linguistics". In this context, she investigates novel research methods for empirical research in linguistics and advanced applications in Digital Humanities contexts.

**LEARN MORE**

**Key Publication** Nils Reiter, Anette Frank and Oliver Hellwig (2014): An NLP-based Cross-Document Approach to Narrative Structure Discovery. To appear in: Literary and Linguistic Computing, Special Issue on Computational Models of Narrative, Oxford Journals.




## Discovering Structural Similarities in Narrative Texts using Event Alignment Algorithms

PhD thesis of Nils Reiter

Project partners: (all Heidelberg University, SFB 619 "Ritual Dynamics") Nils Reiter (Institute of Computational Linguistics), Dr. Oliver Hellwig (South Asia Institute), Prof. Anette Frank (Institute of Computational Linguistics), Prof. Axel Michaels (South Asia Institute)

Project web page: http://www.cl.uni-heidelberg.de/clgroupaf/projects/ritualStructure.mhtml

**Structural similarities across narratives play an important role in many areas of Humanities research. This research project and the accompanying dissertation developed and implemented computational methods for uncovering such similarities automatically in two application scenarios. In both scenarios, folktale and ritual studies, existing research in the Humanities examines similarities of narratives on a structural level and discusses structural principles that govern the combination of individual events to compose tales or rituals. We present a largely unsupervised alignment-based approach for the detection of structural similarities of narratives that realizes a fully automatic data-driven approach for the study of narrative structure.**

**The contributions of this research are threefold. (1) We develop a full-fledged computational linguistic processing architecture that is applied to narrative texts to automatically create an integrated semantic representation of events, participants and their relations in the development of a narrative. The architecture allows straightforward integration of domain adaptation techniques to enhance the analysis of 'non-standard' language varieties and offers visualizations of detected events and their participants. (2) We present three different types of unsupervised semantics-driven cross-document alignment algorithms that determine (sequences of) events shared between narratives, to support the search for recurrent elements in their structure. The alignment algorithms are comparatively evaluated in two experiments for each domain. (3) We develop tools for exploration and interpretation that we offer to Humanities researchers for investigation of the analyzed data. These include search facilities, visualizations, statistical overviews and a graph-based algorithm that identifies densely aligned regions across documents.**

# Cognitive Psychology: Mind in Action Lab


## PROF. DR. JOACHIM FUNKE

**Joachim Funke is full professor for cognitive and experimental psychology at the Department of Psychology at Heidelberg University. His primarily interests are issues within creativity, problem solving, thinking and acting. He is one of the promoters of the European approach of Complex Problem Solving.**

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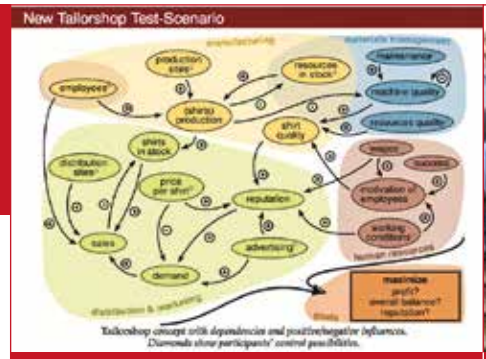
"Mind in Action": The human mind is still one of the open riddles in modern science. How is it possible that myriads of simple neurons produce this wonderful phenomenon called consciousness that allows for motivated action? It is impressing how the human mind organizes all the different psychic functions like perception, learning and memory, motor control, etc. for a proper regulation of action - but even more impressive seems to us the ability to overcome obstacles that block the immediate reach of a goal. This highest form of human action regulation requires the orchestration of all the single competencies and functions in the pursuit of one goal: to make reality what has been anticipated by our imagination and what might not be reachable immediately. During evolution, living organisms developed different mechanisms to adapt to changing environments. Some of these mechanisms have only limited range, others deal with larger changes. The specific human ability to adapt to even drastic changes in our ecosphere (and – if necessary – to change our ecosphere according to our needs) is called problem-solving and makes us to the smart organisms that we are. It is the ability to find creative solutions to given problems, to overcome obstacles on our way to a goal, and to deal with complexity and uncertainty.

Understanding human mind in action: This statement describes our research mission on a broad level. On a more precise level, we are interested in action theory, creativity, thinking and problem solving, dealing with uncertainty, understanding of dynamic processes, regulation of motivation and emotion – to mention some of the topics we are dealing with. For all of these phenomena, we are searching for formal models to better describe, understand, and predict them. This is our psychological way of doing "digital humanities".

**LEARN MORE**

**Key Publication** Funke, J. (2010). Complex problem solving: A case for complex cognition? Cognitive Processing, 11, 133–142.




## A decomposition approach for a new test-scenario in complex problem solving

Michael Engelhart, Joachim Funke, Sebastian Sager

**Psychological research has increasingly used computer-supported tests, especially in the analysis of complex human decision making. The approach is to use computer-based test scenarios and to evaluate the performance of participants. However, two important questions can only be answered with the help of modern optimization methodology. The first one considers an analysis of the exact situations and decisions that led to a bad or good overall performance of test persons. The second important question concerns performance, as the choices made by humans can only be compared to one another, but not to the optimal solution, as it is unknown in general.**

**We use mathematical optimization methodology not only as an analysis and training tool, but also in the design stage of the complex problem scenario. We have developed a novel test scenario, the IWR Tailorshop, together with a tailored decomposition approach to solve the resulting mixed-integer nonlinear programs with nonconvex relaxations.**

## FOMOCOG '14 – Challenge Workshop on Formal Models of (Dis-)Ordered Cognition

Michael Engelhart, Daniel Holt, Christian Kirches, Stefan Körkel, Nadia Said

**In March 2014, 35 researchers (including doctoral and graduate students) from different disciplines and countries met for three days at the IWH to discuss issues of formal models for cognition. Keynote speakers from different disciplines set the stage. Computational modeling and simulation of human cognition is an emergent multidisciplinary field of research promising breakthroughs for both basic research and applications. However, many psychiatric and neurological disorders involve characteristic cognitive deficits that still are poorly understood. Quantitative cognitive process models promise to contribute towards filling this explanatory gap. A successful implementation, however, requires a broad range of skills and knowledge. The workshop was a highlight insofar as the connection between psychology and mathematics was intensified. Understanding of the different approaches increased and new ideas for projects emerged.**

**FomoCog '14 on the web:**
**http://hgs.iwr.uni-heidelberg.de/fomocog14**

# Image Processing and Modeling

**PD DR. CHRISTOPH S. GARBE**

**Following his studies of physics at the Universities of Hamburg and Heidelberg, Christoph Garbe received his PhD and habilitation degree from the University of Heidelberg. He was guest investigator at the Scripps Institution of Oceanography, UCSD, and at the Woods Hole Oceanographic Institution, and a PI at the Intel Visual Computing Institute.**

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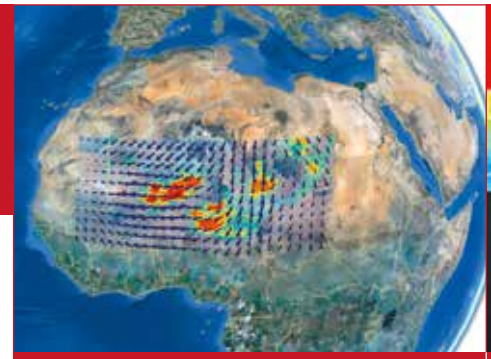
This Junior Research Group focuses on quantitative imaging in conjunction with modeling of complex processes. Quantitative imaging as a measurement technique is an emerging field in the natural and engineering sciences. On a wide range of spatial and temporal scales, imaging is used for gaining insights into complex systems, ranging from satellite remote sensing to Fluorescence Correlation Spectroscopy in confocal or two photon microscopy. Extensive information from this image data can only be extracted in linking advances image processing techniques in conjunction with mathematical models of the underlying measurement technique and physical or chemical processes.

We are interested in all aspects of the analysis of complex systems using quantitative imaging. This includes developing mathematical approaches for image processing in conjunction with physical and chemical modeling as well as devising measurement techniques. Approaches developed are based on solving inverse problems. Models are formulated continuously applying variational principles or discretely using statistical methods. Our work is concentrated on model development, parameter estimation, solving partial differential equations, model selection, confidence measures and physically based interpolation.

Principal applications are Light Field Imaging, measuring and modeling transport processes of complex systems in environmental and life sciences, as well as in engineering. In fluid dynamical applications we have developed new techniques for flow visualization relying on thermography, Light Induced Fluorescence (LIF), molecular tagging, Light Field Imaging or particulate techniques such as Particle Tracking Velocimetry (PTV). A strong focus exists in quantifying transport of reactive atmospheric trace gases from satellite remote sensing, atmosphere-ocean interactions, 3D scanning, as well as physiology.

**LEARN MORE**

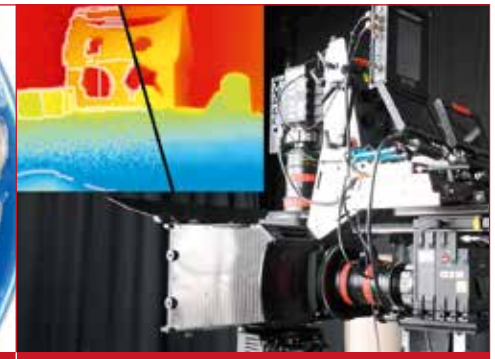
**Key Publication** NEEM community members, “Eemian interglacial reconstructed from a Greenland folded ice core”, Nature, (2013), 493, pp. 489–494. DOI: 10.1038/nature11789



## Physically based models for remote sensing of the dynamics of atmosperhic aerosols

Christoph Garbe, Fabian Bachl, Matthias Klinger, Tilmann Gneiting, Rolf Rannacher

**Dust storms in the earth’s major desert regions significantly influence microphysical weather processes, the CO2-cycle and the global climate in general. Increases in the spatio-temporal resolution of satellite instruments have created new opportunities to understand these phenomena. However, both big data scales and inherent stochasticity of the process pose significant challenges. In this interdisciplinary project, we develop a statistical model of atmospheric transport that relies on latent Gaussian Markov random fields for inference. We link optical flow methods and the formulation of the transport process as a latent field in a generalized linear model using the integrated nested Laplace approximation for inference. This framework is specified such that it satisfies physical constraint equations. Our methodology is able to both accurately and coherently detect sources of dust and it’s temporal evolution. For the first time we are able to solve these critical problems in this field.**



## Algorithmic enhancements of novel depth sensors

Christoph Garbe, Henrik Schäfer, Jens-Malte Gottfried, Stephan Meister, Rahul Nair, Daniel Kondermann, Frank Lenzen

**Very cheap single view depth imaging cameras, i.e. Time of Fight cameras (ToF) or Microsoft’s Kinect system, are entering the mass consumer market. While there has been a steadily increasing number of publications and startup companies which address the hardware design of such systems, currently only a few approaches are tackling the challenges of enhancement and analysis of the obtained 2.5D depth data. In general, the acquired images have a low spatial resolution and suffer from noise as well as technology specific artifacts. The goal of this project is to provide algorithmic solutions to the entire depth imaging pipeline, ranging from preprocessing to depth image analysis. The aim of the this project is to provide holistic algorithmic solutions to improve and enhance these sensors. In general, we assume that most “real world” application scenarios of depth systems require a real time processing as well as high depth measurement accuracies. Hence, we provide algorithms to meet these goals.**

# Database Systems


## PROF. DR. MICHAEL GERTZ

**Michael Gertz studied Computer Science at the University of Dortmund and obtained his doctoral degree in Computer Science at the University of Hannover. In 1997 he moved to the University of California at Davis where he worked as a professor. Since 2008 he is leading the Database Systems Research Group at Heidelberg University.**

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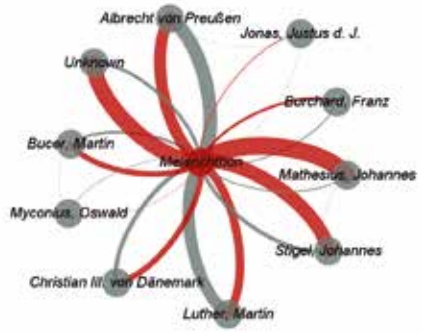
Spatio-temporal data are ubiquitous. They occur in scientific data obtained through observations and simulations as well as in the form of spatial and temporal information embedded in textual documents. Certain combinations of spatial and temporal data form events that exhibit patterns and correlations to other events. We consider events and relationships among events as a key means to abstract from and aggregate complex data sources.

In this field the research group develops novel techniques to extract spatio-temporal information from textual sources such as social media and news documents. Of particular interest are (1) probabilistic models to determine both the regional (geographic) and temporal (duration) aspect of events, and (2) techniques to discover dependencies among detected events. For this, the research combines techniques from text mining, data mining, machine learning, and computational linguistics. Recently, the detection of events in real-time has become a major research focus where events, including their regional aspects, are detected and extracted from streaming textual data common in social media and news articles. Detected events can be used, for example, to enrich recommender systems and to provide monitoring capabilities in mission critical applications. An essential component for the extraction of temporal information from textual data is the temporal tagger HeidelTime (https://code.google.com/p/heideltime/), a system that detects and extracts temporal expressions from text data. HeidelTime is used by many research groups worldwide for various types of textual data sources, including social media, narrative texts, and news articles. With respect to applications, the group concentrates on applications in the humanities and social sciences where events with their spatio-temporal properties are a key means for data exploration and analysis.

**LEARN MORE**

**Key Publication** Jannik Strötgen, Michael Gertz: Multilingual and cross-domain temporal tagging. Language Resources and Evaluation 47(2): 269-298 (2013)


## Social network extraction from historic letters

PhD thesis of Hui Li (Computer Science)
Project partners: Christoph Strohm (Theology, Heidelberg University), Stefan Riezler (Computational Linguistic, Heidelberg University)

**Driven by major advancements in digitalization projects, large amounts of historic documents become readily accessible to researchers in many areas of the humanities, including history, theology, and arts, to name but a few. The focus of this project is on extracting information from letters (correspondences) written in the first half of the 16th century. The historic context of the correspondences is the German reformation with a focus on correspondences between key figures such as Philipp Melanchthon and Martin Bucer.**

**A key challenge is to extract information about sender and receiver(s) as well as temporal and geographic information from such letters, which are written in Latin and various dialects of Early New High German. While also in this context events play a crucial role, the main focus currently is on extracting a social network structure based on the mentioning of persons in the letters (beyond sender and receiver). The objective is to determine key figures over time, the evolution of communities as well as the topics addressed in correspondences over time. To address the challenges, named entity recognition techniques are modified to suitably deal with the various dialects in which correspondences are written. With eventually more than 10,000 correspondences, we expect that social network structures (as they are known for today's social media) and the evolution of these structures provide scientists new insights into an important phase of German history. The models and techniques that are being developed in this project will provide an important basis for related projects in the humanities, thus contributing to the important branch of Computational Humanities at the IWR.**

# Molecular Biomechanics


## PROF. DR. FRAUKE GRÄTER

**Frauke Gräter is group leader at the Heidelberg Institute for Theoretical Studies since 2009, and joined IWR as full professor in 2014. She previously worked at the CAS-MPG Partner Institute for Computational Biology in Shanghai as a junior group leader. Her scientific interests range from protein dynamics and mechanics to biomaterials.**

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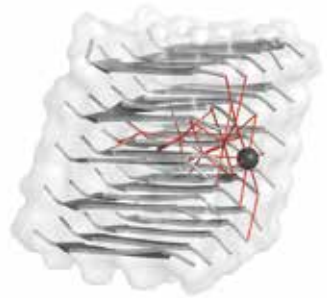
Mechanical force recently emerges also as a critical quantity in biology. Cellular functions such as growth, motility, and signaling are closely coupled to stretching or shearing forces. Proteins play a pivotal role in such mechanically guided processes, acting as robust elements bearing cellular stress or as mechano-sensors transducing the mechanical signal into a biochemical response.

The work of the Molecular Biomechanics group is designed to elucidate the interaction between mechanical force and the structure and function of biomolecules. We use and develop a number of simulation techniques to study how complex structures such as proteins, protein complexes, or protein-based materials respond to external forces and in turn exert an influence on a biological cell or organism. The group works as a multidisciplinary team at the interface between biology, physics and computational sciences. Molecular Dynamics simulations, Finite Element Methods, and bioinformatics tools are applied to biological systems at varying scales.

A major aim is the discovery of new mechano-sensors, more specifically proteins, which deform or unfold under mechanical forces and thereby change their function. Such proteins might be situated at cellular adhesion sites, in muscle, or in flowing blood – environments, which involve high mechanical stresses. To this end, we have developed and are expanding our in-house developed method to detect forces within protein structures, termed Force Distribution Analysis (FDA). Using FDA, we are able to monitor how force propagates through complex structures such as proteins or protein complexes, in order to predict sites of high stress concentration and rupture. In the long-term, we envision to tackle the question of how mechanical signals are integrated into signaling circuits of cells by altering the structure and dynamics of protein assemblies.

**LEARN MORE**

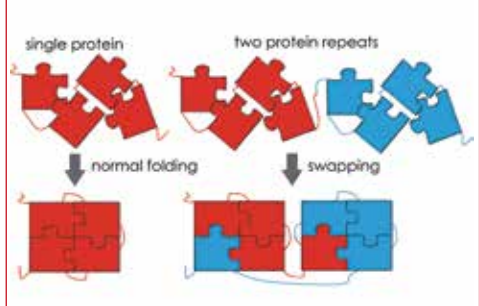

**Key Publication** Costescu BI, Gräter F., Time-resolved force distribution analysis. BMC Biophys. 2013 May 1;6(1):5.

## A bottom-up computational approach to understand spider silk fibers


Senbo Xiao, Murat Cetinkaya, Sandeep Patil, Eduardo Cruz-Chu


**Silk fibers constitute an intriguing class of natural materials. Through a flawless assembly of strong and soft building blocks, they exhibit astonishing mechanical properties, with a strength comparable to steel. Our aim was to understand the origins of the mechanical properties of spider silk fibers and further predict fiber mechanics under different structural variations by using a bottom-up computational approach. Our approach combines the accuracy of atomistic Molecular Dynamics simulations with the practicality of Finite Element models in order to predict the macroscopic properties of spider silk fibers that are the results of molecular interactions. This interdisciplinary approach, bringing together biophysicists, mechanical engineers, and material scientists, revealed that Nature makes a trade-off between elasticity and strength in spider silk fibers, thereby optimizing their toughness, by choosing a moderate crystallinity level of 10–25 %.**




## Protein origami: Quick folders are the best


Fei Xia, Cedric Debes


**Proteins are elementary building blocks of life. In order to become active, proteins have to fold into three-dimensional structures. Mechanical force can guide their folding, unfolding, and misfolding. The latter leads to diseases such as Alzheimer's, but is only partly understood.**

**Together with colleagues at the Universities of Illinois and Maryland, we used computer analyses to examine the folding speed of all currently known proteins. For most of protein evolution, namely nearly 4 billion years, the folding speed increased, from archaea to multicellular organisms. Thus, over time, Nature improved protein folding so that eventually, more complex structures of spezialized functions were able to develop, while faster folding makes proteins less susceptible to misfolding. According to our simulations, poly-proteins, comprising several identical repeats, are particularly prone to misfold, as they can undergo domain swapping, i.e. exchange identical building blocks between neighbors.**

# Mathematical Immunology


## DR. FREDERIK GRAW

**Frederik Graw studied Mathematics at the Universities of Siegen and Freiburg. After obtaining his doctoral degree in Theoretical Immunology from the ETH Zurich in 2010, he did a post-doc at the Los Alamos National Laboratory. In 2012, he became a group leader at the Center for Modeling and Simulation in the Biosciences/IWR at Heidelberg University.**

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www.bioquant.uni-heidelberg.de/research/junior-research-groups/bioms-mathematical-immunology.html

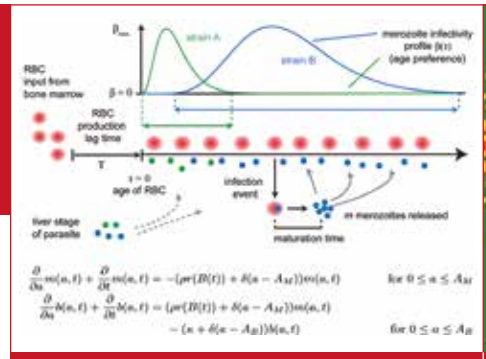

Infectious diseases represent a major public health concern, and are the second leading cause of death worldwide. Viruses, such as the human immunodeficiency virus (HIV), bacteria (e.g. Tuberculosis), or other parasites are still a global threat that is constantly rising in importance. The spread of an infection through a population and within a host represents a complex biological and dynamical system covering multiple scales in space and time.

In our group, we develop mathematical models and combine them with experimental data to understand fundamental immunological and virological processes that occur within a host in response to infection. Technically, we use systems of ordinary and partial differential equations describing the interaction of pathogens, host cells and immune responses, as well as methods from spatial statistics and sophisticated computational simulations. In particular, we develop multiscale models that cover the dynamics ranging from the intracellular level within single cells, addressing pathogen replication and the inhibiting effect of immune responses, up to cell population behavior inside and between specific organs. Thereby, we combine observations from cell culture experiments and biopsy sections considering genetic data, bulk cell measurements and microscopy images.

We work in close collaboration with experimental and clinical groups to obtain a quantitative and qualitative understanding of the underlying processes that shape infection and immune dynamics for various pathogens. Our specific focus is on chronic infections, with projects addressing different aspects of infections by HIV, hepatitis C virus and within Malaria. Besides analyzing disease development, we also determine and predict the effect of therapeutic interventions, aiming to design optimal treatment regimes.

**LEARN MORE**

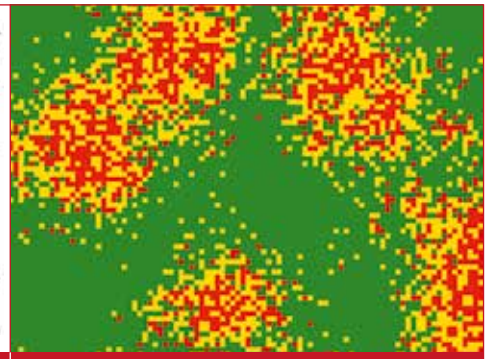
**Key Publication** Graw F, Regoes RR "Influence of the fibroblastic reticular network on cell-cell interactions in lymphoid organs", PLoS Computational Biology 2012, 8(3):e1002436




## Specific blood cell invasion and Malaria pathogenesis

PhD thesis of Neha Thakre
Project partners: Priyanka Fernandes, Ann-Kristin Mueller (Heidelberg University Hospital); Frederik Graw (Heidelberg University)

**Malaria is one of the most serious tropical diseases with an estimated 210 million cases and ~660,000 deaths in 2010. Some strains of malarial parasites are known to cause more serious disease outcomes than other strains, i.e., leading to cerebral malaria and death. Thereby, parasite specificity for particular red blood cells (RBC) seems to play a key role in disease development. In this interdisciplinary PhD project, Neha develops a mathematical model for blood stage malaria infection and immune dynamics, thereby accounting for RBC age structure and disease induced anaemia. Combining the model with experimental data of different murine malaria strains, we provide a systematic and quantitative analysis of how parasite specificity for RBC influences the spread of infection and disease development. The results are an important prerequisite for determining the precise mechanisms that lead to the observed neuropathology within the brain during malaria infection.**



## Spread of Hepatitis C virus in the liver

Peter Kumberger, Frederik Graw (Heidelberg University); Ashwin Balagopal, Stuart Ray, Abraham Kandathil (Johns Hopkins University); Ruy M. Ribeiro, Alan S. Perelson (Los Alamos National Laboratory)

**Several aspects of the Hepatitis C virus (HCV) infection dynamics within the human liver during chronic infection are still unknown. For example, does the virus propagate by cell-to-cell transmission or mostly via diffusion of viral particles? And how many cells are infected? In this long-term project, we are using mathematical methods to determine how viral replication and transmission dynamics, as well as local immune responses shape the spatial distribution of infected cells. Analyzing liver biopsy samples of chronically infected patients by clustering algorithms we found that infected cells tend to occur in clusters. Combining the observed patterns of intracellular viral load with mathematical models on viral replication and spread, we were able to infer aspects of the infection dynamics from these static in vivo data. We now develop specific computational simulation environments inferred by clinical and experimental data to reveal the influence of immune responses on HCV spread.**

# Multiphase Flows and Combustion


## PROF. DR. EVA GUTHEIL

**Eva Gutheil studied Mathematics at TU Darmstadt, where she also obtained her doctoral degree in Chemical Engineering. She completed her habilitation at Stuttgart University. After post-doctorial years at UC San Diego and UC Irvine, at Stuttgart University and at the German Aerospace Center, she got a professor position at Heidelberg University.**

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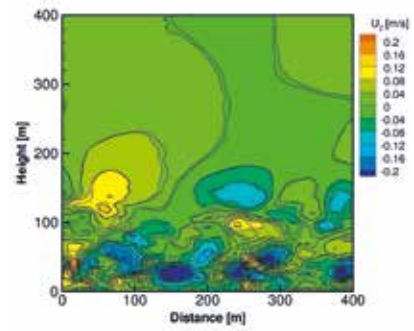
Multiphase flows are relevant in many application including spray drying, technical combustion processes, life sciences, and in environmental physics. Numerical tools are essential for the prediction, understanding, and improvement of these processes. The research aims to develop mathematical models for the simulation of both non-reacting and reacting multiphase flows to gain an improved knowledge of the underlying processes. In particular, detailed processes of the physical-chemical processes are studied, and the developed models are integrated into integral simulations, which account for the entire process. Methods include transported joint probability density methods for the modeling of turbulent flows, where phase transition, i.e. evaporation, is considered. Direct quadrature methods of moments (DQMOM) may be used for the description of the dispersed phase, where detailed models for evaporation and droplet interactions are taken into account. A novel spray flamelet model is developed to account for the evaporation process in spray combustion. The research includes advancement of solution methods of the above equations including DQMOM, Monte Carlo methods, particle-source-in-cell methods as well as solvers for partial differential equations coupled with these for Lagrangian particle methods.

The applications studied include the spray drying of PVP/water and mannitol/water solutions, the ozone depletion in polar spring, spray combustion processes, particle dispersion and deposition in the upper human respiratory system, and the medical implant treatment of cerebral aneurysms.

Model evaluation is achieved through co-operations with other research groups in the Heidelberg Medical School and the Institute of Environmental Physics, with colleagues from TU Graz, Delft University, TU Dortmund and Hamburg University, just to name some major collaborating groups.

**LEARN MORE**

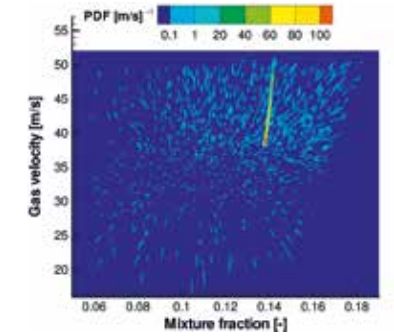

**Key Publication** H. Olguin, E. Gutheil, Influence of Evaporation on Spray Flamelet Structures, Combustion and Flame, 161(4): 987–996, 2014. http://dx.doi.org/10.1016/j.combustflame.2013.10.010


## Mechanisms of Ozone Depletion and Halogen Release in the Polar Troposphere


Le Cao (Heidelberg University); Holger Sihler (Max-Planck Institute of Physics, Mainz); Ulrich Platt (Institute for Environmental Physics, Heidelberg); Eva Gutheil (Heidelberg University)


The role of halogen species (e.g. Br, Cl) in the troposphere of polar region has been investigated since the discovery of their importance for boundary layer ozone destruction in the polar spring. Halogen species take part in an autocatalytic chemical reaction cycle, which releases $Br_2$ and BrCl from the sea salt aerosols, fresh sea ice or snow pack, leading to ozone depletion. Three different chemical reaction schemes are investigated: a bromine only reaction scheme, which then is subsequently extended to include nitrogen containing compounds and chlorine species and corresponding chemical reactions. The importance of specific reactions and their rate constants is identified by a sensitivity analysis. The heterogeneous reaction rates are parameterized considering the aerodynamic resistance, a reactive surface ratio, i.e. the ratio of reactive surface area and the total ground surface area, and the boundary layer height. The figure shows the vertical wind velocity.




## Transported Joint PDF Modeling for Turbulent Evaporating Spray Flows


Yong Hu (Heidelberg University); Hai-Wen Ge (Ford Motor Company, Detroit, MI, USA); Eva Gutheil (Heidelberg University)


Transported probability density function (pdf) modeling is an excellent method for the investigation of the shape of a pdf and for the development of presumed pdfs for use in the simulation of both turbulent spray flows and flames. Joint pdfs of more than one variable are suitable to study the validity of the assumption of the statistical independence of the dependent variables of the joint pdf, which is typically assumed in approaches to model turbulent non-reacting and reacting flows. The figure shows a joint pdf of the gas velocity and the mixture fraction in a turbulent, non-reacting acetone/air spray flow. It is seen that there is a small range in which linear dependence of the variables exists, whereas there is no regime where statistical independence prevails. The transported pdf approach is used to describe the evolution of the mixture fraction in the turbulent spray, and a novel four-parameter ß-function is developed to account for the deviation of the standard two-parameter function due to spray evaporation.

# Multidimensional Image Processing


## PROF. DR. FRED HAMPRECHT

**Fred Hamprecht studied at ETH Zurich and has been a Professor in Heidelberg since 2001. He hosts visiting projects at HHMI Janelia Farm Research Campus, and in 2014/15 is a Weston Visiting Professor in the Dept. of Comp. Sci. and Appl. Math. at the Weizmann Institute. He is a co-founder of the Heidelberg Collaboratory for Image Processing (HCI).**

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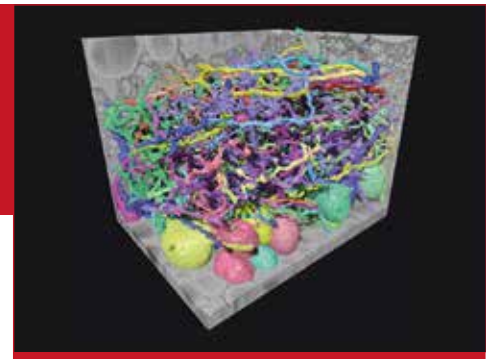
We develop, apply and deploy image analysis methods based on machine learning. Our primary applications come from the life sciences. Our ambition is to let the user indicate, in the simplest possible fashion, what parts of an image are of interest. The computer should learn to emulate the human expert from such minimal annotation, and then process automatically very large or very many images. In general, we encounter a tradeoff between the required level of detail of the human expert annotations on the one side; and the computational effort required to learn from annotations on the other side.

Recurrent themes in our work are i) learning from weak supervision (active learning, multiple instance learning, learning with latent variables), ii) structured learning problems and iii) heuristics for approximate inference in NP-hard problems.

Our work lies at the interface of Machine Learning, Image Processing, Optimization and, because we seek to widely disseminate the most successful methods, Software Development. The latter allows us to package machine learning methods in a user-friendly form that is accessible to domain experts with no prior experience in machine learning or image analysis.

**LEARN MORE**

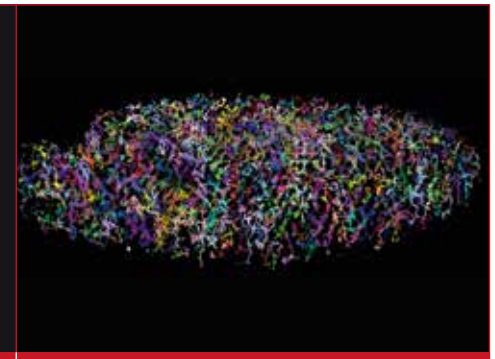

**Key Publication** Active Structured Learning for Cell Tracking: Algorithm, Framework and Usability, X. Lou, M. Schiegg, F. A. Hamprecht, IEEE Transactions on Medical Imaging, (2014) 33 (4), 849–860

## Connectomics

Anna Kreshuk, Thorsten Beier (Heidelberg University); Graham Knott (EPFL); Davi Bock, Albert Cardona, Steve Plaza (HHMI); Winfried Denk (MPI)

**The tenet of connectomics is that knowledge of the wiring diagram of a brain is prerequisite for an understanding of its function. Electron microscopy now yields brilliant volume images that allow human experts to accurately follow all neural processes in tiny parts of a brain. The race is on for microscopic volume imaging of an entire mammalian brain, and the target is likely to be reached in the foreseeable future. However, human tracing would literally take centuries on such exceedingly large volumes. Besides the actual image acquisition, the automated reconstruction of brain circuits is thus becoming the major bottleneck. We are working on such automated reconstruction, and have presented the first fully automated methods ever for the reliable detection of synapses in both isotropic and non-isotropic volume images. Our formulation of the segmentation itself revolves around the NP-hard multicut formulation for which we are developing efficient approximate and distributed solvers.**



## Tracking

Lars Hufnagel (EMBL); Martin Schiegg, Carsten Haubold, Christoph Decker, Jochen Wittbrodt, Hannah Monyer, Andreas Draguhn, Hans-Georg Kräusslich (Heidelberg University)

**The tracking of an unknown number of divisible cells, or of mutually occluding animals, is an intriguing problem with important applications in developmental biology, ethology and beyond. We have formulated structured learning approaches for tracking-by-assignment. The latter cannot correct any errors made in the foregoing detection / segmentation stage. To overcome these limitations, we are developing i) formulations that explicitly allow for undersegmentation ("conservation tracking", ICCV 2013); ii) generalized multi-commodity flow formulations (CVPR 2014) and iii) joint segmentation and data association (in progress). The resulting large-scale optimization problems call for efficient distributed optimization. Ongoing work also explores how to compute uncertainty measures to allow for guided proofreading.**

# Statistical Physics and Theoretical Biophysics Group


## PROF. DR. DIETER W. HEERMANN

**Dieter Heermann studied Informatics, Mathematics and Physics and was awarded a PhD from Boston University (USA). At Heidelberg University he is heading the research group on complex systems specifically theoretical biophysics. Since 2013 he is Pro Rector of the university.**

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The group pursues research at the forefront of physics and quantitative biology with emphasis on mathematical modelling and analysis of biological data, development of computational methods, systems biology, biophysics, and biomathematics.

We develop and apply predictive models for biological and biophysical systems and their interactions at multiple scales, and create statistical methods for the analysis of the complex correlated data. We are actively engaged in joint projects with experimental biologists and physicists producing such data.

Much of our current research is directed at combining genomic sequence and expression level information with structural information to develop models to predict biological function.

Our efforts have focused on the development and application of biophysical and bioinformatics methods aimed at understanding the structural and energetic origins of chromosome interactions to reveal the underlying physical folding principles. Our work includes fundamental theoretical research and applications to problems of biological importance as well as the development of appropriate software.

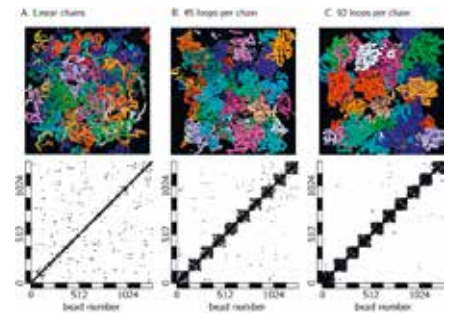
**LEARN MORE**


**Key Publication** Monte Carlo Simulation in Statistical Mechanics: An Introduction, K. Binder and D.W. Heermann, Springer Verlag, Heidelberg, 1988, 4 te Auflage, Springer Verlag, Heidelberg, 2002


## A model of a metaphase chromosome

Yang Zhang

We have introduced a new polymer model for mitotic chromosomes. The key assumption of the model is the ability of the chromatin fibre to crosslink to itself due to binding proteins. These protein-chromatin interactions are included by a probabilistic and dynamic mechanism. The hypothesis is motivated by the observation of high repulsive forces between ring polymers. Our results show that the presence of loops lead to a tight compaction and contribute significantly to the bending rigidity of chromosomes. Moreover, its qualitative prediction of the force elongation behaviour are close to experimental findings. The Dynamic Loop Model presented here indicates a crucial role of loops in mitotic chromosomes and a strong influence of their number and size on the mechanical properties. We suggest that changes of these mechanical characteristics under different conditions can be explained by an altered loop structure.



## The interaction of chromosomes in interphase

J. Mateos-Langerak, M. Bohn, W. de Leeuw, O. Giromus, E.M. Manders, P.J. Verschure, M.H. Indemans, H.J. Gierman, D.W. Heermann, R. van Driel, S. Goetze.

Genome function in higher eukaryotes involves major changes in the spatial organization of the chromatin fiber. Nevertheless, our understanding of chromatin folding is remarkably limited. Polymer models have been used to describe chromatin folding. However, none of the proposed models gives a satisfactory explanation of experimental data. In particularly, they ignore that each chromosome occupies a confined space, i.e., the chromosome territory. We have developed a polymer model that is able to describe key properties of chromatin over length scales ranging from 0.5 to 75 Mb. The model is based on the creation and destruction of loops. The model predictions can be compared with systematic measurements of chromatin folding of the q-arms of chromosomes 1 and 11. It can explain observed data and suggests that on the tens-of-megabases 10-30 loops per 100 Mb exit. This is sufficient to enforce folding inside the confined space of a chromosome territory.

# Experimental Radiation Oncology


## PROF. DR. JÜRGEN HESSER

**Jürgen Hesser studied Physics at Heidelberg University. He habilitated at the University of Mannheim in Computer Engineering. He was Professor at the University of Mannheim in Medical Technology before he joined Heidelberg University as professor for experimental radiation oncology at the Medical Faculty Mannheim.**

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Many questions in science, imaging, and simulation require solving ill-posed inverse problems. Typical examples are image segmentation, image registration, image reconstruction, and parameter fitting. Standard strategies like Tikhonov regularization are in widespread use but suffer from principle limitations.

Further developments are non-linear regularization techniques like total variation that represent sparse solutions. In particular, in many application areas like tomography, these regularizers are meanwhile standard.

Further improvements, especially concerning the resolution of the result, can be achieved by dedicated anisotropic versions where our research group had recently many contributions and where we are currently a center of expertise in computer tomography in our faculty.

Further recent developments concern higher order moments for denoising, a new method for noise parameter estimation, new compressed sensing based techniques for solving inverse planning problems in radiotherapy, and new instrumentation for patch-based organ function measurements including new artifact detection and elimination strategies.

**LEARN MORE**

**Key Publication** Pyatykh, S.; Hesser, J., "Image Sensor Noise Parameter Estimation by Variance Stabilization and Normality Assessment," Image Processing, IEEE Transactions on, vol.PP, no.99, pp.1,1

## Organ Function Measurement

Norbert Gretz, Sabine Neudecker, Daniel Schock-Kusch, Stefania Geraci, Jochen Friedemann (ZMF, Heidelberg University); Yuri Shulhevich, Anatoli Shmarlouski, Jürgen Hesser (IWR, Heidelberg University)

**The focus on this project is the percutaneous measurement of organ function. We developed an instrumentation that registers the fluorescent photons of a marker that is eliminated exclusively by the organ under investigation (in our case the kidney). The physiological system is described by a multi-compartment model and its parameters are estimated by a robust fitting technique. The main problem in case of awake animals is motion artifacts. A new strategy has been developed by the group that allows classifying the presence of artifacts and then a model-based method has been developed to correct for them. Two measurement techniques have been developed. An intelligent patch of a thumbnail size is intended for a low-cost measurement system while a single photon life time system has been developed that uses the fluorescence life time to differentiate between foreground and background and hence achieves a three orders higher sensitivity.**

## Noise parameter estimation using principal components

Stanislav Pyatykh, Lei Zheng, Jürgen Hesser

**Noise parameters are essential elements for solving inverse problems on one hand side and for denoising images on the other hand side. Most techniques for noise parameter estimation require homogeneous areas in the image. However, in many images, this condition is not fulfilled. In this project, a new strategy is developed that uses sparsity in the principal component (PC) space. We assume that noise-free images can be well represented with a sparse number of PC-coefficients while noise cannot be bounded, i.e. is presented in the low-amplitude coefficients. By investigating the statistical behavior of additive Gaussian noise for the latter amplitudes, one can estimate their variance. In case of other noise models, variance stabilization can be used to convert them into additive Gaussian noise.**
**The advantage of the approach is that it can be applied for all textured image patches and evidence on large image databases show that it clearly outperforms all competing approaches.**

# Engineering Mathematics and Computing Lab (EMCL)

**PROF. DR. VINCENT HEUVELINE**

**Vincent Heuveline is leading the EMCL. He is Director of the Computing Centre of Heidelberg University and group leader at the Heidelberg Institute for Theoretical Studies. His research interests include numerical simulation, high-performance computing, data mining with main application in medical engineering and environmental science.**

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The Engineering Mathematics and Computing Lab (EMCL), directed by Prof. Dr. Vincent Heuveline, is a research group at the Interdisciplinary Center for Scientific Computing (IWR), dedicated to creating a stimulating and supportive environment for innovative research. EMCL is particularly noted for its openness to multidisciplinary research in the field of engineering and scientific computing. At EMCL, interdisciplinarity characterizes both daily activities and the long-range direction of research. Our challenge is to enable scientific research by employing leading-edge supercomputing technologies.

Working at EMCL often involves developing innovative mathematical approaches, methodologies and technological tools to reveal new insights into the physical world. EMCL currently pursues 4 major research themes. These fields comprise:

- Computational Mathematics
- Hardware Aware Numerics and High-Performance Computing
- Cloud Computing
- Scientific Visualization

The research group seeks, on the one hand, to develop basic understanding and intellectual means to model complex phenomena and, on the other hand, to create a foundation for building new high-performance technologies. Underlining the importance of application-driven research, part of the activities of EMCL is dedicated to transferring cutting-edge developments to the most daunting challenges with a main emphasis on the following application areas:

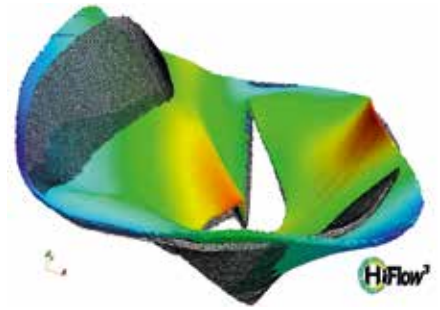
- Medical Engineering
- Meteorology and Environmental Sciences

The researchers at EMCL are a recognized partner in numerous collaborative research and development projects. To encourage students to actively pursue their own research and entrepreneurial ideas, EMCL supports students of Heidelberg University by providing supercomputing technology and scientific support by the EMCL Team.

**LEARN MORE**

**Key Publication** Schick, M., Heuveline, V. & Le Maître, O. P.: A Newton-Galerkin method for fluid flow exhibiting uncertain periodic dynamics, SIAM/ASA J. Uncertainty Quantification, 2(1), 153–173. 2014






Collaborative Research Center (SFB/Transregio 125)

## "Cognition-Guided Surgery" Project I-03: "Functional Modeling"

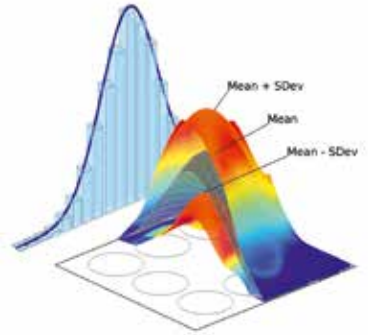
Nicolai Schoch, Jonas Kratzke, Chen Song

**In the framework of the SFB TRR 125 "Cognition-guided Surgery", the EMCL focuses on the numerical simulation of physiological processes of soft tissues in the human body during operations due to surgical manipulation.**

**The simulations are based on the finite element method (FEM), and developed using the open-source C++ FEM software HiFlow3, which makes use of high-performance computing (HPC) methods as well as modern HPC infrastructure, in order to cope with real-time and accuracy requirements in surgery.**

**Current cooperations projects within the SFB framework deal with**

- **the Medical Simulation Markup Language (MSML), which aims at Simplifying the Biomechanical Modeling and Simulation Workflow;**
- **the Integration of a Biomechanical Simulation for Mitral Valve Reconstruction into a Knowledge-based Surgery Assistance System;**
- **the Enhancement of 4D PC-MRI in an Aortic Silicon Phantom by means of Numerical Simulations**
- **Uncertainty Quantification (UQ) for medical engineering.**




## Uncertainty Quantification and High-Performance Computing

Michael Schick

**The increasing demand on the quality and reliability of numerical simulations results in an increasing complexity of mathematical models and methods. Especially, the knowledge for the description and definition of model relevant parameters is often subject to uncertainties, such as for example data generated from inexact measurements.**

**To this end, we develop efficient and fast numerical solution methods for uncertainty propagation problems. Thereby, we focus on the stochastic Galerkin approach, which provides a powerful tool to obtain high accuracies at the price of the curse of dimensionality: the number of degrees of freedom grows exponentially with the number of employed random variables requiring the use of high-performance computing. The challenge we address is to combine fast iterative methods with a parallel and scalable memory distributed computation to tackle the memory requirements of large scale computations with applications in fluid mechanics and medical engineering.**

# Computational Astrophysics & Algorithmic Design (CAAD)

**PD DR. AHMAD A. HUJEIRAT**

**Dr. Hujeirat completed his PhD in applied mathematics/Heidelberg in 1994, his habilitation in Physics in 2006 and in Astronomy in 2011. Since 2011 he is head of the research group on CAAD/ IWR, 2012 adjunct professor at both AUI/Morocco and An-Najah/Palestine, since 2013 he is the founding and EiC of Computational Astrophysics and Cosmology.**

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The CAAD research group consists of the following members:
PD Dr. Hujeirat, Prof. Cammenzind, Dipl.Phys. Sofie Fehlmann, Dipl. Math. Norman Shakir, Fabian Klein, Dipl.Phys. Fawwad Qureshi, Dipl. Phys. Hassan Bourhrous, Kor Sokchea, Zephyr Penoyre and Albert Hofstetter.

• Professor Max Camenzind/ZAH/University of Heidelberg joined the CAAD group as honorary advisor in 2001; two years after his retirement from Landessternwarte-Heidelberg

• Mr. Noman Shakir completed his Master thesis in Mathematics at the COMSATS Institute of Information Technology/Islamabad/Pakistan in 2012 and joined the CAAD group as a PhD in March 2013. He is registered as a PhD-student in applied mathematics and since April 2014 a member of the Heidelberg Graduate School - HGS. The research project of Mr. Shakir is jointly supervised by Dr. Hujeirat and Prof. Guido Kanschat.

• Mrs. Sofie Fehlmann completed her Master in Physics at Basel University under the supervision of Prof. Thielemann in 2012 and since then she is enrolled as a PhD student in the Departement Physik/University of Basel, under the joint supervision of both Dr. Hujeirat and Prof. Thielemann.

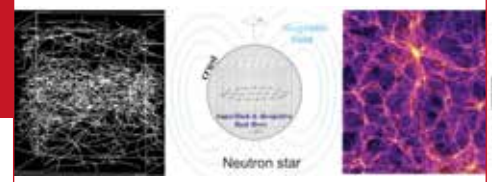
• Mr. Hassan Bourhrous completed his MSc at the University of Cape Town, South Africa in 2012 and started his PhD-studies right thereafter at University of Ifrane/Morocco under the joint supervision of PD Dr. Hujeirat and Prof. Darhmaoui/Ifrane

• Mr. Fabian Klein completed his Bachelor in Physics at Heidelberg University in the year 2013 and entitled to submit his Master thesis in Computational astrophysics (supervised by Dr. Hujeirat) by mid of September 2014

• Dipl.Phys. Albert Hofstetter, Mr. Kor Sokchea and Mr. Zephyr Penoyre are part time employed as scientific assistants.

**LEARN MORE**

**Key Publication** Hujeirat, A., A problem-orientable numerical algorithm for modeling multi-dimensional radiative MHD flows in astrophysics – the hierarchical solution scenario, Computer Physics Communications, Vol. 168, Issue 1, p. 1–24, 2005



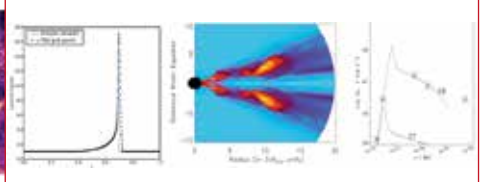

## Normal and superfluid interaction in the cores of neutron stars: a massive-parallel numerical study

Mr. Noman Shakir, Dr. A. A. Hujeirat, Prof. G. Kanschat

Cores of neutron stars are considered to be made of a mixture of normal and superfluids. The post-glitch recoveries of the Crab and Vela pulsars are considered to be observational evidences that superfluidity is the state of matter of the cores of ultra-compact neutron stars.

By means of massive-parallel computations, we intend to investigate the dynamical behavior of a mixture of two-component (normal dissipative and superfluid flows), rotating, weakly-compressible under the effect of strong gravitational fields in three-dimensions and explore the parameter regime in which this flow-mixture turns turbulent.

These studies will shed the light on the cosmological fate of neutron stars, probably elucidating their connection to dark matter, which considered to govern the dynamics of galaxies, as shown in the above figure.



## Numerical studies of the formation, acceleration and propagation of radio jets in active galaxies: from the event horizon up to interstellar scales

Dipl.Phys. Fabian Klein, Prof. Rainer Spurzem, PD Dr. Ahmad Hujeirat

Observations of jets both in X-ray binaries (XRBs) and in active galaxies, AGNs experienced a remarkable progress in recent years, thanks to coordinated multi-wavelength observations.

Modeling of dynamics of such jets consistently require a coupling and simultaneous employment of sophisticated, but rather different solvers. Therefore, in this project, massive parallel calculations based on coupling of the three solvers: GR-I-RMHD, OpenFoam and N-body will be carried.

The flow configurations obtained using GR-I-RMHD will be used to initiate the OpenFoam solver, which, together with the N-Body solver, will be employed to study gravitational and rotational effects resulting from the interaction of the jet-matter with the stars, determine their energetic and conversion into large scale turbulence. In the above figure, the Lorentz factor of a moving 1D shock (left), the jet-disk-black hole interaction (middle) opposed to the radio map of the NGC315 radio jet.

# Applied Analysis


## PROF. DR. WILLI JÄGER

**Willi Jäger studied mathematics and physics in Munich (PhD 1964) He received his habilitation in Göttingen (1969) and was a one-year visiting member of the Courant Institute, NYC. Becoming senior professor at Heidelberg University (1974), he was one of the founders and the first director of IWR (1987) as well as the Mathematics Center Heidelberg (2008).**

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Our team develops mathematical models for many different application areas. We engineer tools to analyse and simulate the arising model systems, which are mainly formulated as deterministic and stochastic nonlinear dynamics, in particular partial differential equations, which are quite often non-standard. In the focus are theory and methods, helping to master complexity, high-dimensionality, nonlinearities, instabilities, multi-scales and randomness.

Methodological core themes are system reduction, model links between different scales and the derivation of macroscopic laws, which preserve substantial information on micro-scales. Further key areas are asymptotic numerical methods to handle processes in porous and complex media and the analysis of multi-phases and interfaces problems

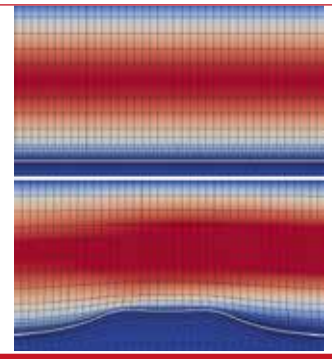
The methods are largely driven by challenging applications in physical, chemical and biological processes. This leads to the development of state-of-the-art methods for flow, diffusion, transport and reactions models as well as multi-scale analysis for surface reactions including effects in transport through membranes or of charged particles. In medical application adhesion processes, blood coagulation, processes of brain infarct, the remodelling of bone and the dynamics of neurotransmitters are current areas of investigation.

Public health poses questions concerned with dynamics of diseases such as Malaria and Dengue, models for drug resistance, the growth of chemical gradients, of biofilms and of plants, inducing developments in both the modelling and the simulation techniques.

The expertise generated in these fields also carried over to models for energy markets and the simulation and optimization of price dynamics for commodities. Scientific visualization finds new targets in image processing and data analysis of historic documents of the Khmer and the Babylonian culture.

**LEARN MORE**

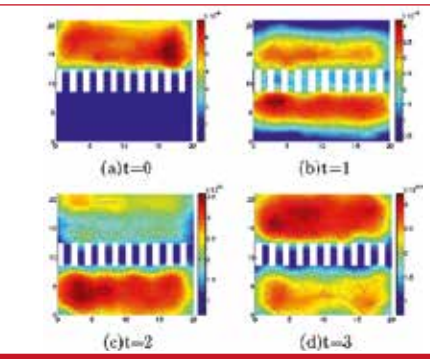
**Key Publication** W. Jäger, A. Mikelic, M. Neuss-Radu: Homogenization Limit of a Model System for Interaction of Flow, Chemical Reactions and Mechanics in Cell Tissues. SIAM J. Math. Anal. 2011



## Modeling, Simulation and Control of Physiological Processes in Ischemic Brain Infarct

PhD topic of Yifan Yang (Jan 2014) and Valeria Malieva (Dec 2014)
Advisors: Willi Jäger, Thomas Richter, Peter Bastian (IWR); Maria Neuss-Radu (Erlangen) and Michael Hennerici (Heidelberg, Neurology)

Brain infarct is a main cause for disabilities and death. It occurs when oxygen supply is restricted by a blockage of a blood vessel. The resulting hypoxia leads to swollen brain tissue and increasingintracranial pressure. The physiological and molecular sub-processes are qualitatively understood. The project aims at a quantitative understanding of crucial sub-processes to support diagnostics and therapy. We developed a system of coupled PDE to model the interaction between blood flow and vessel walls, the growth due to adhesion and penetration of monocytes and the accumulation of foam cells. Finding criteria for ruptures of plaques is crucial for medical interventions. The cellular processes are modeled based on the fact that hypoxia changes the permeability of cell walls. The osmotic pressure is increased, the cell walls expand. The model system includes a Biot-model for the mechanics of the cyto-plasma. The resulting multi-physics problem with free boundary is numerically solved.




## Multiscale Modelling and Simulation of Interacting Fluid and Solid Phases in Complex Media: Coupling Reactive Flows, Transport and Mechanics

W. Jäger, M. Heida, S. Ludwig, Y. Yang, V. Malieva, M. Kihn (IWR); M. Neuss-Radu (Erlangen), A. Mikelic ( Romberg Prof.)

Modelling reactive flows, diffusion, transport and mechanical interactions in media with multiple phases, e.g. a fluid and a solid phase in porous media, is giving rise to many open problems for multi-scale analysis and simulation.

We study the diffusion, transport, and reaction of substances, the mechanical interactions between phases, the change of the mechanical properties by chemical reactions and volume changes of the solid phase. For tissue, a homogenization limit lead to an effective system, containing a pressure gradient, satisfying a Biot law, where the chemical substances satisfy diffusion-transport-reaction equations and influence the mechanical parameters.

Applications are in Biosciences, Medicine and Material Sciences. Atomic and molecular processes have to be included, demanding stochastic and discrete modelling. Treading structured membranes lead to large systems of highly nonlinear PDE and stochastic particle systems, which poses challenges to analysis and numerics.

# Digital Image Processing

**PROF. DR. BERND JÄHNE**

**Bernd Jähne received his doctoral (1980) and habilitation (1985) degrees in Physics from Heidelberg University and a habilitation degree in Applied Computer Science from TUHH (1992). From 1988 to 2003 he held a research professorship at UCSD. Since 1994 he is Professor for Image Processing at IWR and IUP. Since 2008 he is coordinating HCI director and deputy IWR director.**

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The image processing research group was founded in 1986 at the Institute for Environmental Physics (IUP) as a junior research group and integrated at the Interdisciplinary Center for Scientific Computing in 1994. Nowadays, it is one of four research groups of the Heidelberg Collaboratory for Image Processing (HCI). Image processing is the fastest growing research area at the IWR.

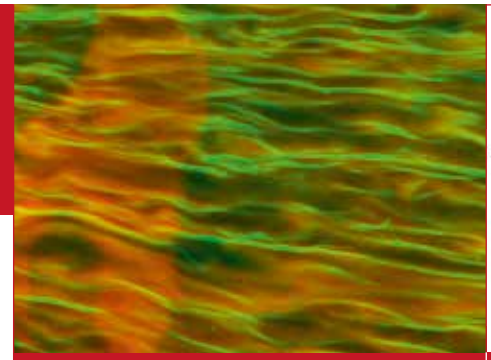
The research group is unique at the IWR in the sense that it both includes experimental environmental research at the IUP as well as image processing. The group has built and is operating a world-wide unique air-sea interaction facility, the Heidelberg Aeolotron. It is optimized to apply imaging techniques in order to study the mechanisms of air-sea gas transfer and the dynamics of short wind waves. Regularly, international and national partners take part in experiments.

Current research topics include novel image acquisition systems including fluorescence, time-of-flight, extended depth-of-focus, and thermal imaging with the long-term goal for high-resolution spatio-temporal imaging of all parameters relevant for small-scale air sea interaction processes including short wind waves, flow fields, concentration fields, bubbles and spray. In image processing, research activities include orientation analysis, motion analysis, ground truth generation, performance metrics, and light fields. Industrial partners are Bosch, Zeiss, Sony Deutschland, Silicon Software, and PCO.

The research group is also pioneering education. The Heidelberg Image Processing Forum (www.bv-forum.de), founded 1995, has become a major forum for continuous education and for fostering contacts between research and industry.

**LEARN MORE**

**Key Publication** S. Wanner, J. Fehr, and B. Jähne, Generating EPI representations of 4D light fields with a single lens focused plenoptic camera, Advances in Visual Computing, Springer, 2011, 90–101



## Fluorescence imaging of the mechanism of air-sea gas exchange in the Heidelberg Aeolotron

Christine Kräuter (member GRK 1114) and Darya Trofimova (member HGS MathComp)

The mechanisms of air-sea gas transfer taking place at more than two-thirds of our planet's surface are still not well understood. This is because it is both very difficult to obtain experimental data as well as to simulate these processes, which are taking place in a thin mass boundary layer (20–200 $\mu$m thickness) on the water side at a shear driven surface undulated by wind waves. In this PhD project a technique was developed, which is a radical departure from all previously used laser induced fluorescence techniques. It includes three disciplines, a) chemistry to set up a proper chemical system to absorb an alkaline volatile chemical species in a slightly acid liquid, b) advanced photonics for fluorescence imaging, and c) image processing techniques. The brightness of the resulting images is proportional to a controllable fraction of the mass boundary layer thickness (figure at top). For the first time, experimental data and numerical simulations can be compared quantitatively.


## Light field-based Image Acquisition and Processing

PD. Dr. Christoph Garbe, Dr. Harlyn Baker, Dr. Sven Wanner, Max Diebold, Alessandro Viannelo and former member with ERC starting grant, Dr. Bastian Goldlücke

There is a well-known saying: "a picture is worth a thousand words". True. However, how much does a single two-dimensional image say about a three-dimensional scene? Not much. Neither the 3-D structure, nor orientation of surfaces, nor the optical properties of the observed objects can be estimated. This limitation can be related to a too sparse sampling of the so-called multidimensional light field, a complete description of the radiation field in a 3-D scene. This the starting point for a general theory of image generation, which includes all known image generation techniques and gives a frame work for the invention of novel imaging modalities. Current research focuses on the local analysis of multiple orientations in the light field in combination with global variational approaches jointly modeling depth, surface orientation, and the reflection properties. First results include depth accuracy even from non-lambertian surfaces, which surpasses current sate-of-the art stereo algorithms.

# Mathematical Methods of Computation


## PROF. DR. GUIDO KANSCHAT

**Guido Kanschat studied mathematics in Bonn. He received his doctoral degree and habilitation in Heidelberg. After appointments in Minnesota and Texas, he joined the IWR in 2012. He and his coauthors received the 2007 Wilkinson Prize for Numerical Software. He founded the Archive of Numerical Software and currently he is Associate Dean for Education.**

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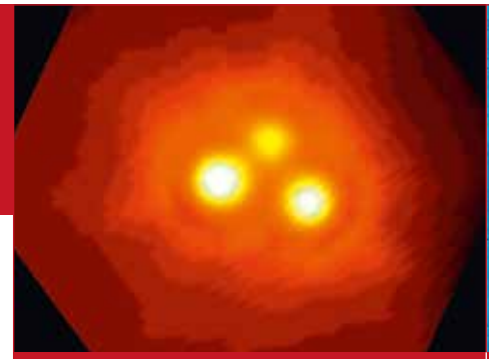
Research in our group is centered around the simulation of problems governed by partial differential from development and analysis of suitable discretizations to the implementation on high performance computers. To this end, we founded the DEAL, later deal.II, software project (http://www.dealii.org), which is now one of the most wide-spread finite element toolboxes in the world and still under active development.

The applications we focus on are coupled flow problems and radiation transport. In the first area, we have developed conservative schemes with balanced approximation properties for the coupling of Stokes and Darcy flow, complemented by a highly efficient multigrid solver. These methods are currently extended to linear and nonlinear models of poroelasticity with applications in medical research. In radiation transport, we focus on discontinuous Galerkin methods with correct asymptotic behavior towards the diffusion limit. Such methods are essential for reliable radiation transport approximations of heterogeneous problems in astrophysics, climate science, and nuclear engineering.

Mathematically, our research has two main focuses. First, the development and analysis of compatible discretization methods for problems with heterogeneities and extreme parameters. Examples for such problems are scattering dominated radiation transport, where the leading term of the equation is almost eclipsed by a 4–6 orders larger scattering operator, or problems like poroelasticity, where multiscale methods or homogenization techniques are necessary. Second, we focus on geometric multigrid methods which are robust in the parameter regimes described above. These methods can be implemented efficiently (matrix-free) on modern computer architectures and are thus particularly suited to the software we develop.

**LEARN MORE**

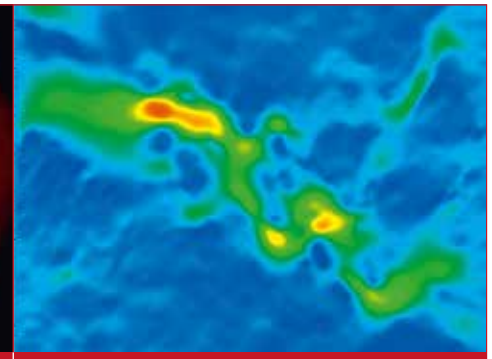

**Key Publication** V. Girault, G. Kanschat, B. Rivière. Error analysis for a monolithic discretization of coupled Darcy and Stokes problems, J. Numer. Math. 22(2), pp. 109–142. 2014

## Multilevel discontinuous Galerkin methods for radiative transfer in local thermodynamic equilibrium

PhD thesis of José Pablo Lucero Lorca
Project partners: Cornelis Dullemond (Heidelberg University); Jean Ragusa (Texas A&M University); Blanca Ayuso de Dios (King Abdullah University of Science and Technology)

**Radiative transfer problems in astrophysical applications, for instance in circumstellar clouds, are characterized by extreme parameter changes over highly varying scales. Adding to this the 6-dimensional phase space and bad conditioning of the problems, accurate simulation of such problems is highly challenging even on high performance computers. In this project, we focus on radiation fields coupled in a nonlinear way (local thermodynamic equilibrium) to a temperature field. The discretization and solution algorithms are based on recent developments of multilevel discontinuous Galerkin methods for the grey approximation. Since the problem at hand involves serveral hundred coupled unknowns in every point in space, a major aspect of this project is the efficient, matrix-free implementation on high performance computers. Data for circumstellar clouds is used for benchmarking our developments albeit the methods have much wider applicatbility.**



## Cochain discretization and multigrid methods for heterogeneous porous media flow

Natasha Sharma
Raytcho Lazarov, Youli Mao (Texas A&M University)

**We have developed conservative multilevel methods for heterogeneous porous media flow as it appears for instance in vuggy materials used as filters. Here, the characteristics of the governing equations vary on fairly local scales from Stokes via Brinkman to Darcy equations. Interfaces between the substructures are to fine to be resolved by the fine element mesh. Therefore, we chose a cochain-complex based, monolithic discontinuous Galerkin approach, which guarantees mass conservation independent of parameters. The resulting discrete problems are solved by a geometric multigrid method with a cochain-based, additive Schwarz smoother. The method has been tested successfully on more academic Darcy-Stokes coupling problems, where mathematical predictions are still available. It was applied as well as the SPE 10 benchmark for subsurface flow, where it performs very robustly.**

# Optimization of Uncertain Systems


## DR. CHRISTIAN KIRCHES

**Christian Kirches studied mathematics at Heidelberg University and obtained his doctoral degree in 2010. After appointments at Argonne National Laboratory and University of Chicago, he became head of the IWR research group "Optimization of Uncertain Systems" in 2013. Christian has been awarded the 2011 Klaus Tschira Prize and the 2014 Hengstberger Prize.**

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The research group "Optimization of Uncertain Systems" develops new numerical methods for modeling, simulation, and optimization of switched uncertain systems. Research addresses uncertainties in system structure, parameters, and state estimates; simulations to quantify the amount of uncertainty; and optimization reduce sensitivity to quantified uncertainties.

A special focus is put on discrete-continuous systems that typically preclude themselves from an intuitive understanding, are computationally difficult to assess, and show a high potential for optimization. These include integer controls, logical decisions, and non-convex structures.

In cooperation with academic and industrial partners, the group applies mathematical optimization methods to prototypical real-world applications to demonstrate the impact on the state of the art in process control. Three examples include

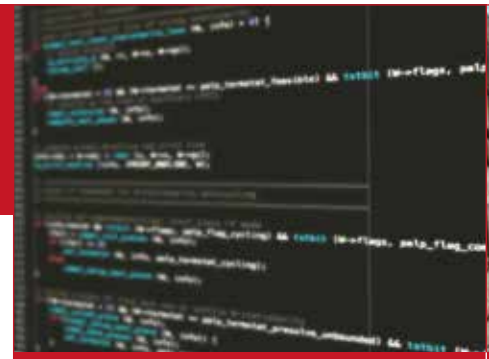
1) Automotive systems, where intelligent driving strategies that take into account time- and energy optimality as well as emission characteristics have to be computed on-line in view of uncertain road and traffic conditions. The group develops methods for optimization under uncertainty of gearbox activity, mode switches in between hybrid drive trains, battery charging, and compartment air conditioning.

2) Thermodynamic systems, where environmentally friendly air conditioning and cooling systems operate under uncertainties in environmental conditions and future load. Airflow reversal phe¬nomena and operation in a cyclic sequence of discrete modes make these systems a challenging target.

3) Chemical processing plants, where startup and shutdown procedures to date have frequently been found by trial and error. The group develops numerical methods for optimal startup and shutdown that account for uncertainties in, e.g., temperature, concentrations, or reaction rates.

**LEARN MORE**

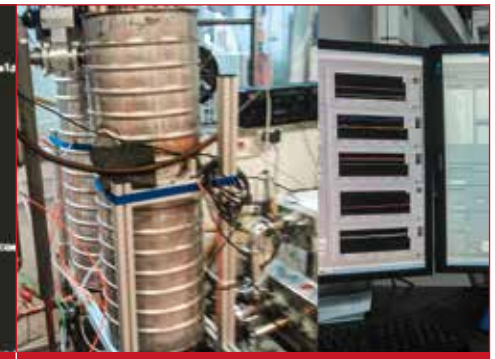
**Key Publication** P. Belotti, C. Kirches, S. Leyffer, J. Linderoth, J. Luedtke, A. Mahajan. Mixed-Integer Nonlinear Optimization. Acta Numerica, 22, pp. 1–131, 2013. Cambridge University Press



## Mixed-integer feedback control for real-time application to heat pumps

PhD thesis of Felix Lenders
Project partners: Wilhelm Tegethoff, Manuel Gräber (TLK-Thermo GmbH and Technical University of Braunschweig); Christian Kirches (Heidelberg University)

**Heat pump systems are a key enabling technology for more sustainable vehicle traffic. In next generation hybrid vehicles, they are seen as a promising alternative to battery power for compartment heating and cooling, and will be instrumental in extending the action radius of electrical vehicles. Their thermodynamic behavior is characterized by strong nonlinearities, by state- dependent discontinuities, switched controls, and uncertainty in process models and data. Realizing their full potential hence requires advanced optimization-based predictive control algorithms. In his PhD project, Felix Lenders develops mathematical formulations and implements numerical algorithms for real-time capable optimization based control of switched dynamic processes subject to uncertainties. Felix closely cooperates with academic and industrial partners to deploy his mathematical technology to lab-scale test rigs. The image gives you a glimpse of the new mathematical optimization codes Felix develops.**



## Nonlinear mixed-integer optimization and optimal control of strongly coupled industrial processes

Hans Georg Bock, Andreas Potschka, Christian Kirches (Heidelberg University); Sebastian Sager (University of Magdeburg); Ekaterina Kostina (University of Marburg)

**With regard to climate, energy, and future mobility challenges, harnessing the potential for optimization of increasing complex and strongly coupled industrial processes requires the development of new mathematical methods for nonlinear dynamic mixed-integer optimization and optimal control. Applications include startup and shutdown of plants with switched inputs and dynamic configuration changes, operation of hybrid vehicles with thermodynamic coupling, and next generation heat pumps. Challenges like strong nonlinearities, discrete decisions, and uncertainties in process data and model ask for state estimation and optimal control in real time. The project implements new optimization methods and involves major industrial players Daimler and BASF to demonstrate the impact of mathematical modeling, simulation, and optimization on industrial process control. The image shows a laboratory test rig for optimization-based control of a heat pump with cooling and heating circuits.**

# Star Formation Group


## PROF. DR. RALF S. KLESSEN

**Ralf S. Klessen is professor for theoretical astrophysics at the Center for Astronomy at Heidelberg University. He has served as director of the Institute for Theoretical Astrophysics and as Dean of Study in the Faculty of Physics and Astronomy. He has recently received an ERC Advanced Research Grant to study the formation of the first stars.**

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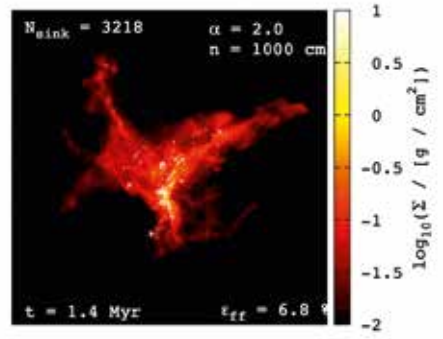
Understanding the formation of stars together with their subsequent evolution and identifying the physical processes that govern the dynamics of the interstellar medium are central research themes in astronomy and astrophysics. Knowledge of stellar birth is a prerequisite for insights into the assembly of planets and planetary systems and for the search of our own origins. Stars and star clusters are fundamental dynamical building blocks of the galaxies we observe. Understanding the formation and evolution of galaxies, their chemical enrichment history, and their observational properties throughout the cosmic ages therefore requires information about the physical processes that govern stellar birth at present days as well as in the primordial universe.

Shedding light on the fundamental physical processes that control the formation and evolution of stars at different cosmic epochs and identifying and characterizing the various feedback loops that link these together are the focal points of the research activities of the star formation group at the Center for Astronomy. Members of the group have been involved in developing a theory of star formation based on the interplay between interstellar turbulence and gravity. This approach is quite successful, has high predictive power, and has become the accepted paradigm for the birth of stars in nearby molecular clouds. Researchers in Heidelberg are extending this theory on large scales to account for the global star-formation relations in disk galaxies, and they are exploring the nature of stellar birth in the early universe and study the transition from primordial star formation to the mode observed today. Fragmentation is a widespread phenomenon in early star formation, and so stellar birth at very high redshift is not as simple as previously thought, but instead faces the same complexities as present-day star formation.

**LEARN MORE**

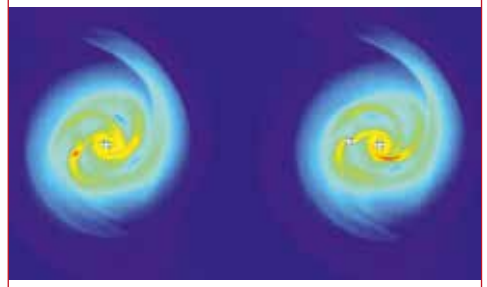

**Key Publication** "The Control of Star Formation by Supersonic Turbulence", Mac Low, M.-M., Klessen, R. S., 2004, Reviews of Modern Physics, 76, 125 –194


## Star Formation in the Galactic Center


Erik Bertram, Paul Clark, Simon Glover, Ralf Klessen


**Our goal is to improve our understanding of the physics of star formation in the Central Molecular Zone (CMZ) of the Milky Way. The Galactic Center is a very extreme environment. Compared to the solar neighborhood it is highly turbulent, threaded by strong magnetic fields, and illuminated both by a strong interstellar radiation field and also by a highly elevated level of cosmic rays and X-rays. Although extreme for the Milky Way, such conditions are similar to those found in starburst galaxies, and likely represent the conditions in which much of the star formation in the Universe has occurred. The influence of this extreme environment on the star formation process is not understood in detail. To help us learn more about how star formation proceeds under these conditions, we perform detailed numerical simulations that follow the chemical, dynamical and thermal evolution of the gas, and use these to make predictions for state-of-the-art observational facilities.**



## Star Formation in the High-Redshift Universe


Christian Baczyinski, Paul Clark, Simon Glover, Ralf Klessen, Jan-Pieter Paardekooper, Mei Sasaki, Anna Schauer, Daniel Whalen, Katharina Wollenberg


**The goal of our research activities in early star formation studies is to bridge the gap between cosmological and stellar scales, and to study the formation and evolution of the first and second generations of stars in our Universe with high detail and accuracy. Following the collapse of gas in high-redshift halos while at the same time resolving the energy production in accretion shocks and the interaction of the released radiation with the infalling material requires us to combine very high-resolution (magneto-)hydrodynamics with radiation transfer and time-dependent chemistry. We perform cosmological simulations and study a large number of individual halos with very high resolution using re-zooming techniques. We begin with dark-matter only simulations, and build up a database of halo characteristics. We then include gas physics and model star formation within a statistically representative subset of these halos.**

# Applied Analysis: Calculus of Variations and PDE

**PROF. DR. HANS KNÜPFER**

**Hans Knüpfer studied Mathematics at the University of Bonn where he obtained his doctoral degree in 2007. In the following three years, he was Courant Instructor at the Courant Institute in New York. From 2010, he worked as a post-doc in Bonn and Bochum. Since 2013, he is professor at the Institute of Applied Mathematics in Heidelberg.**

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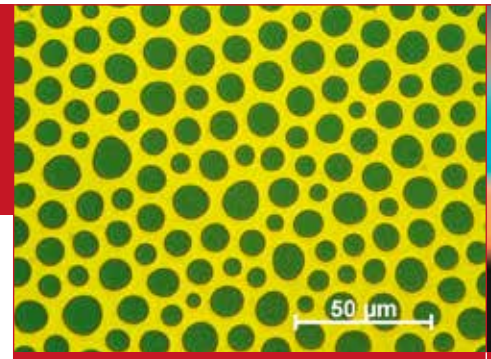
Energy is fundamental in driving dynamics and structure in a large class of models from materials science and fluid mechanics. These dynamics are driven by an interplay between complex energy landscape and dissipation. Examples of such systems include ferromagnets, superconductors, shape-memory alloys, polymer systems and various systems from fluid mechanics. Often the energy exhibits multiple scales, nonlocal interactions and vector valued order parameters; in terms of dynamics, particular difficulties arise in the presence of moving phase boundaries. In our analysis, we investigate the qualitative behaviour of such systems by the rigorous derivation of scaling laws. We also derive reduced models in certain asymptotic regimes. Our aim is to better understand the relevant mechanism that drive the system. The reduced models can also be used to study solutions computationally.

We study pattern formation in different models from materials science. These systems are governed by a underlying non-convex variational energy and include one or many small parameters. In elasticity theory, we address optimal patterns during martensitic phase transformations. In particular, we have been concerned with the energetic costs of interior nucleation of the new phase and its relation to the lattice parameters of the material. We also investigate ferromagnetic materials where we study the formation of optimal domain patterns, structure of transition layers and the strength of hysteresis. In fluid dynamics, we are concerned with well-posedness and regularity of solutions at moving triple lines. In the theory of polymer systems, we study the stability of minimizers as well as the behaviour of solutions in the macroscopic limit. Our methods are based on the underlying energetic and dissipative structure and apply to a wide range of energy-driven systems.

**LEARN MORE**

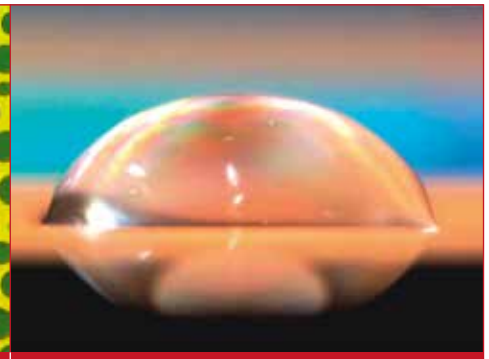
**Key Publication** H.K., N. Masmoudi, Darcy flow on a plate with prescribed contact angle: Well-posedness and lubrication approximation, to appear in Arch.Rat.Mech.Ana.




## Onset of pattern formation in thin ferromagnetic plates under the influence of an applied external field

PhD thesis of Florian Nolte
Project Partners: Radu Ignat (University of Toulouse IV); Cyrill Muratov (New Jersey Tech)

Ferromagnetic materials exhibit a rich variety of spatial patterns. The observed patterns depend on material parameters such as crystalline anisotropy as well as applied field strength and sample geometry. Ferromagnetic materials are used in many applications such as magnetic memory devices. The observed patterns can be understood as minimizers of an underlying free energy. Due to the complexity of the underlying model, one cannot hope to find explicit solutions. Instead, we rigorously identify scaling laws and derive reduced models in the framework of Gamma-convergence in relevant asymptotic parameter regimes. Such reduced models are also useful from the computational perspective to avoid high computational costs. In particular, we consider the onset of pattern formation in ferromagnetic thin-plates with high uni-axial anisotropy normal to the plate under the influence of external magnetic fields. Our goal is to understand the strength of hysteresis and structure of minimizers.



## Contact line regularity in the fluid evolution of multiphase flows

Nader Masmoudi (Courant Institute, New York); Manuel Gnann, Felix Otto (MPI Leipzig); Lorenzo Giacomelli (La Sapienza, Rome)

Multi-phase fluid evolution is ubiquitous in nature. While the analysis of two-phase fluid evolution is well understood, interestingly, only few analytical results exist on fluid evolution with three or more phases, even on basic questions about well-posedness and regularity of solutions. The challenge both analytically and computationally lies in the analysis of the contact line, i.e. the set where three phases meet. We have previously established well-posedness for a spreading droplet on a solid substrate whose evolution is governed by Darcy's Law. Using suitably designed function spaces, we show convergence of the solutions to solutions of a reduced model in the long-wave approximation. The analysis connects theory of elliptic operators on non-smooth domains with techniques for degenerate parabolic operators. New difficulties arise in the analysis of the Stokes flow with Navier slip. We also investigate the justification of macroscopic scaling laws such as the Cox-Voinov Law.

# Optimum Experimental Design

**DR. STEFAN KÖRKEL**

**Stefan Körkel studied Mathematics, Physics and Astronomy at Heidelberg University. He obtained his doctoral degree in Mathematics at Heidelberg University. After post-docs in Heidelberg and at Matheon in Berlin, he became head of the BASF JRG Optimum Experimental Design at the HGS MathComp at IWR, Heidelberg University.**

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Our area of research are numerical methods for optimization-based model validation. We cover the scope from the modeling of processes over the development of mathematical techniques for nonlinear optimization and process simulation and the development of numerical software up to the application of the methods in projects from various fields. Our method development is driven directly by applications from our cooperation partners. They are described mathematically by dynamic process models, typically ODE, DAE or PDE systems, in general high-dimensional, nonlinear and stiff.

The aim of optimum experimental design is to plan experiments in order to yield maximum information from experimental data with minimal experimental effort. For this purpose, cost functionals on the covariance matrix of the underlying parameter estimation problem are minimized under constraints on cost and feasibility. This leads to non-standard optimization problems with an objective implicitly defined on sensitivities of the model states. For the solution, tailored efficient numerical methods are needed.

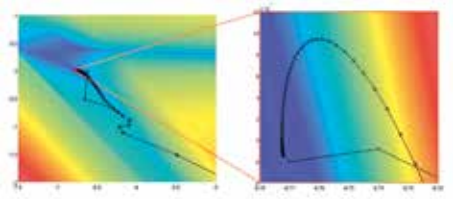
Our approach is to use the principle of boundary value problem methods optimization approach, in which the differential equation system is parametrized by shooting methods and the resulting non-linear optimization problems are solved by Newton-type methods equipped with a tailored derivative evaluation.

Because we are permanently working with industrial partners, we provide the methods in a consistent, flexible and well operable framework, being implemented in our software package VPLAN. Our methods are used for applications in various fields. Examples are chemical reaction kinetics, thermodynamics and catalysis, chemical engineering, organic electronics, biotechnology, epidemiology and economics. Ongoing work is also dealing with applications in systems biology, medicine, psychology and sports science.

**LEARN MORE**

**Key Publication** A. Schmidt, A. Potschka, S. Körkel, and H. G. Bock. Derivative-extended POD for reduced-order modeling for parameter estimation. SIAM Journal on Scientific Computing, 35(6):A2696–A2717, 2013.





## Optimum Experimental Design for the Identification of Gaussian Disorder Mobility Parameters in Charge Transport Models of Organic Semiconductors

Dr. Christoph Weiler, Dr. Stefan Körkel, (IWR); Dr. Alexander Badinski (BASF SE); Mustapha Al Helwi (InnovationLab GmbH)

**This completed doctoral project treated optimum experimental design for the parameter estimation problem of mobility parameters in charge transport models of organic semiconductors. The models consist of the van Roosbroeck system, a quasi-electrochemical potential defining equation, and the Extended Gaussian Disorder Model for the mobility. The problems are very ill-conditioned. The essential results are:**

- **The robust numerical solution of the model equations w.r.t. varying parameters, control parameters, boundary values and initial guesses for iterative methods.**
- **The computation of exact derivatives up to order two, which are necessary for the optimum experimental design problem. This includes derivatives of the model functions and implicitly given derivatives of the solution.**
- **The simulations of the problems are used for the optimum experimental design. for newest organic materials, like NRS-PPV and alpha-NPD. The confidence regions of the parameters are reduced by a factor of 100.**

## VPLAN – A Virtual Laboratory for Dynamic Processes

Dr. Stefan Körkel, Dr. Sebastian Walter, Dr. Christoph Weiler, Andreas Schmidt, Robert Kircheis, Dennis Janka (IWR); Adrian Bürger (Hochschule Karlsruhe); Johannes Willkomm (TU Darmstadt); Joachim Mees (BASF SE)

**We are developing a software package for modeling, simulation, sensitivity analysis, parameter estimation, optimum experimental design and optimal control of dynamic processes described by nonlinear systems of differential equations.**

**The implemented numerical methods are based on the boundary value problem optimization approach combined with structure exploiting Newton-type optimization methods and efficient derivative evaluation by automatic differentiation.**

**The software is equipped with user interfaces as well as APIs for C++, Python and Matlab.**

**VPLAN is being applied in various projects with partners from industry and academia, ranging, e.g., from microbial enhanced oil recovery over biochemical processes and calibration of industrial robots to computational modeling of higher cognition.**

# Visualization and Numerical Geometry

**DR. SUSANNE KRÖMKER**

**Susanne Krömker studied Mathematics at the Universities of Osnabrück and Heidelberg and obtained her PhD at Heidelberg University. She collaborated with the Fritz-Haber-Institute Berlin on surface catalysis. From 1998 to 2004, she was scientific assistant (C1) at IWR, and since then, she is head of the Visualization and Numerical Geometry group.**

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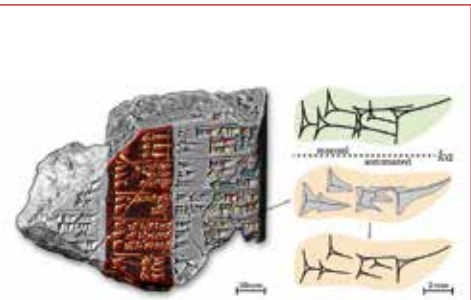
Mid range and close range laser scanning for surveying sites are popular, resulting in extremely large data sets of meshed point clouds. We combine methods from scientific computing with demands of cultural heritage sites to draw the interesting information out of the data. Automated texturing is done as well as level-of-detail mesh simplification for reconstructions of buildings, potsherds and broken fragments. Combing our knowledge on image filtering with 3D surface data results in automated transcriptions of scripts (epigraphy) for ancient documents (Assyrian cuneiform, Hebrew and Greek inscriptions, Chinese sutras) based on multi-scale integral invariants. For example, the today's status of medieval gravestones on the Jewish Cemetery "Heiliger Sand" in Worms is acquired and an ongoing weathering of the sandstone surface is documented. Subsequently the digitized surfaces are analyzed and so far unreadable characters are deciphered. In another project with the École française d'Extrême-Orient and the Royal University of Phnom Penh, we selected fragments of a 6 m high Shiva statue from Koh Ker. The various parts of the puzzle to be scanned are located in the temple on site as well as in the museums in Cambodia and France. Due to the thoroughgoing investigations, the proof could be furnished that the King's temple of Koh Ker had the purpose of intramural burials.

Acceleration of computing time with programmable graphics cards for fast feedback in user interactive data exploration is of great demand. But not every algorithm can benefit from this architecture. Our main focus is the evaluation of algorithms due to their applicability on topics such as particle filtering methods or anisotropic nonlinear diffusion filtering used in medical applications. We are currently investigating the use of parallelization in fluid visualization techniques and topological methods.

**LEARN MORE**

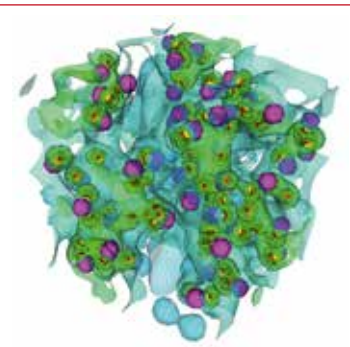
**Key Publication** H. Mara, S. Krömker, S. Jakob and B. Breuckmann: GigaMesh and Gilgamesh - 3D Multiscale Integral Invariant Cuneiform Character Extraction, in: A. Artusi, M. Joly, G. Lucet, D. Pitzalis, and A. Ribes (eds.), Proc. VAST Int. Symposium on Virtual Reality, Archaeology and Cultural Heritage, Palais du Louvre, Paris, France: Eurographics Association, pp. 131–138, 2010



## Multi-Scale Integral Invariants for Robust Character Extraction from Irregular Polygon Mesh Data

PhD thesis of Hubert Mara
Project partners: Stefan Maul, Stefan Jakob (Assyriology, Heidelberg University)

Numerous ancient documents with cuneiform script (handwriting used in the Middle East) are the sources to the origins of civilization. The script's 3D shape results from a stylus pressed in clay. Manually drawing and transcribing these tablets demand the assistance of an automated feature extraction from irregular triangular meshes, acquired by optical 3D scanners. Integral invariant filtering is a robust technique, adapted to precisely determine 3D shapes of characters using algorithms from image processing and pattern recognition. Convolutions and combined metrics are computed on high-dimensional feature spaces due to multiple scales. The results determine connected components via robust curvature measures leading to edge detection and segmentation. A Voronoi method yields a vector representation necessary for character recognition. The proposed methods are implemented in the GigaMesh software framework and tested on hundreds of cuneiform tablets as well as on other objects.



## Visualizing High-Resolution Numerical Data with Isosurfaces using Topological Methods

Lisa Kolb, Elfriede Friedmann, Daniel Gerecht, Anna Marciniak-Czochra (Heidelberg University); Thomas Höfer (German Cancer Research Center); Mariya Ptashnyk (University of Dundee)

Simulations of T-cells in the lymph nodes result in time-dependent 3D scalar concentrations of biochemical substances visualized using isosurfaces. Peculiarities of the given data are that the values range over several orders of magnitude and that the domain has holes. This leads to holes in the isosurfaces. The quality of visualizations using isosurfaces highly depends on the choice and number of the isovalues. In order to choose those values that represent important features of the data, topological information is computed. For this purpose, discrete Morse theory originally applied to grayscale images is modified to use it on biochemical concentrations. The algorithm computes the Morse complex of the data, which can then be utilized to determine the persistent homology classes and corresponding Betti numbers. All the extracted information is used to gain an improved visualization using isosurfaces and varying transparencies for different isovalues.

# Modeling of Biological Processes


## PROF. DR. URSULA KUMMER

**Ursula Kummer studied biochemistry, chemistry and physics at the Universities of Tübingen, Germany and Oregon, Eugene, USA, respectively. She became a group leader at EML Research gGmbH in Heidelberg in 2000. In 2007 she joined Heidelberg University as full professor. Currently, she is a vice-dean of the faculty of biosciences.**

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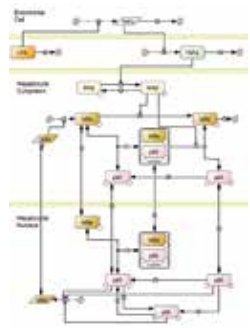
Research in the group focuses on one side on the development of computational methods of methods for the modeling, simulation and analysis of biochemical networks. On the other hand, application projects on relevant biological systems are of major importance for the group. Thus, on the methodological side, during the last five years, algorithms for the complexity reduction of large systems, as well as improved methods for the stochastic simulation of these have been developed and integrated in our software package COPASI. In addition, global sensitivity analysis approaches have been analysed. The software COPASI itself is increasingly used in computational systems biology with current download numbers per release of about 8000. This heavy use also led to the establishment of a user forum which is currently used by ca. 600 registered users.

The group is also heavily involved in the development of standardized data exchange, e.g. in the development of SBML (systems biology markup language). Apart from method development, we have been applying the methods in projects modeling both signalling as well as metabolic networks in different organisms. Thus, understanding information processing in calcium signalling has been one of the major topics. However, also information processing in other signalling pathways like NFkB and IFNa is under investigation. Finally, understanding the determining factors in metabolic networks like the central metabolism in microbial species and the sulfur assimilation pathways in plants is another goal.

**LEARN MORE**

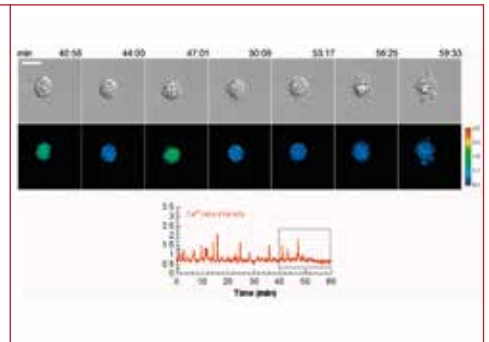

**Key Publication** Stefan Hoops, Sven Sahle, Ralph Gauges, Christine Lee, Jürgen Pahle, Natalia Simus, M Singhal, L Xu, Pedro Mendes, Ursula Kummer, COPASI – a COmplex PAthway SImulator, Bioinformatics, 22:3067–74, 2006

## Modeling cell-cell communication in the liver during inflammation


Katharina Beuke, Ursula Kummer, Sven Sahle
Collaborators: Federico Pinna, Kai Breuhahn, Percy Knolle, Frank Schildberg


**Bacterial infections are a major cause of inflammation in the liver. They produce lipopolysaccharides (LPS) which are potent stimuli for non-parenchymal cells, which secrete a number of cytokines, e.g. TNFα in response. TNFα stimulates hepatocytes and induces NFκB signalling which in turn activates quiescent hepatocytes. It is very difficult to experimentally investigate this kind of cross-talk for a numbers of reasons. The most important one being the non-existence of a cell cultural setup to accurately replicate the physiological tissue embedding of cells. Therefore, we set up a computational model to investigate this cell communication based on a model describing the experimentally determined cytokine expression profile of nonparenchymal liver cells upon LPS stimulation and the cellular hepatocyte response in form of TNFα induced NFκB signalling. The model allows us to assess the respective contribution of the different non-parenchymal cells to liver reponse during inflammation.**



## Calcium dynamics correlates with functional phenotypes in human neutrophils


Katrin Hübner, Ursula Kummer, Irina Surovtsova (now with Prof. Ulrich Schwarz)
Collaborator: Maria Hänsch


**We investigated the mechanisms how information is encoded and decoded in calcium signal transduction in different cell types and species. In human neutrophilc leukocytes, we found a tight coupling between calcium dynamics and function (Hübner et al., 2013). Thus, neutrophils exhibiting specific functional behaviour, e.g. during cell migration, cell adherence or blebbing simultaneously show distinct calcium dynamics. We studied this system by means of multi-variate live cell imaging (performed by our group with support of the Nikon Imaging Center at BIOQUANT) on isolated primary human neutrophils (provided by the group of Maria Hänsch (Medical Faculty). During imaging we followed both the calcium concentration, as well as different morphological parameters that later allowed us to semi-automatically classify different functional states of the cells. We started to establish a model for integrin mediated calcium signalling in this cell type.**

# Biophysics of Macromolecules DKFZ

**PROF. DR. JÖRG LANGOWSKI**

**Biochemistry studies, University of Hannover, 1972–77; Internship, Stanford University, 1977–78; Dr. rer. nat., University of Hannover, 1982; Postdoc, Dept. of Chemistry, University of Washington, 1982–83; Heisenberg fellow, Medizinische Hochschule Hannover and EMBL Grenoble, 1983–84; Group leader, EMBL Grenoble, 1985–94; Head of Division Biophysics of Macromolecules, DKFZ, 1994–present.**

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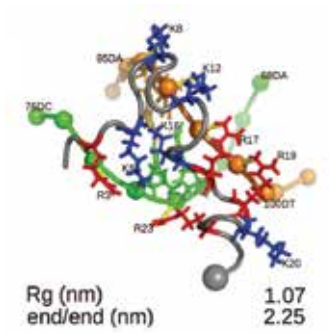
The main goal of our work is to study the three-dimensional structure and dynamics of the genome in normal and tumor cells and to describe it by quantitative models. This will help us understand the connection between genome structure and normal or pathological states of the cell. To this aim, we study long-range interactions in DNA when genes are regulated by transcription factors, the structure of nucleosomes and chromatin fiber, and the organization of chromosome territories. This is done by combining experiments with advanced computer simulation techniques that describe the organization of DNA and chromatin in the cell from all-atom resolution to coarse grained flexible polymer models.

Biophysical methods in our research program include in particular single-molecule techniques (fluorescence correlation spectroscopy, single pair FRET, scanning force microscopy), advanced optical microscopy (light sheet microscopy) but also dynamic light scattering, neutron scattering, analytical ultracentrifugation, absorption and fluorescence spectroscopy, and stopped flow kinetics. We also develop and provide biophysical techniques for the characterization of other systems of biological macromolecules, especially in protein-protein and protein-DNA interaction and intermediate filament proteins.

The simulations encompass classical molecular dynamics simulations of mononucleosomes and histone tails, Langevin and Brownian dynamics simulations of the nucleosome and chromatin fiber, and polymer dynamics of wormlike chains on a three-dimensional grid to study diffusional motion in crowded systems.

**LEARN MORE**

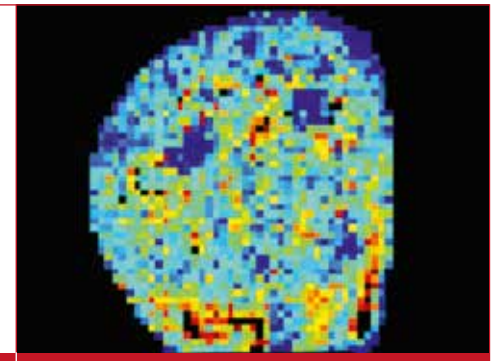
**Key Publication** M. Biswas, K. Voltz, J.C. Smith, J. Langowski: Role of histone tails in nucleosome stability. (2011) PLoS Comp Biol 7(12), e1002279




## Effect of chromatin modifications on nucleosome dynamics

Ruihan Zhang (PhD student), Jörg Langowski (advisor and mentor), Andreas Dreuw (advisor), Shirin Faraji (mentor)

Packaging of DNA into chromatin by histone proteins is centrally important for regulating gene activity. The nucleosome is the fundamental packaging unit and consists of approximately 150 base pairs of DNA wrapped around an octameric histone core, containing two copies each of histone protein H2A, H2B, H3 and H4. The N-terminal tails of these proteins are rich in lysine and arginine, and "intrinsically disordered", i.e., they do not assume a single defined structure. Chromatin compaction is regulated through specific modifications on the histone tails; enzymes that participate in this process have become important targets for anticancer drugs. We could recently show by molecular dynamics modeling (see key reference) that removal of some histone tails leads to an allosteric change in the nucleosome core. In this project we study the effect of histone tail modifications on the dynamics of the nucleosome and could show a disordering of histone tails by the presence of the nucleosome core.



## Characterization of intracellular transport by fast two-dimensional in vivo imaging in a light sheet microscope

Jan Krieger, Jan Buchholz, Agata Pernus, Jörg Langowski

Protein transport in the cell mostly occurs by Brownian motion. Analyzing this motion with appropriate models can help us understand transport mechanisms and the structure of the crowded intracellular environment. Most experiments in this field have been done by fluorescence fluctuation methods (FFMs), observing a single spot in a confocal microscope. However, recording the concentration fluctuations of a macromolecule in an entire two-dimensional plane of a cell can yield much more information. For this purpose we built a single plane illumination microscope (SPIM) and are using it for studying protein transport and interaction in live cells. This requires advanced methods for data analysis, instrument control, and modeling of transport processes. The goal is to develop a "mobility image" of fluorescently labeled proteins in the cell, offering both a new imaging mode and a deeper insight into the transport processes in the dense macromolecular network of the intracellular environment.

# Computer Graphics and Visualization


## JPROF. DR. HEIKE LEITTE

**Heike Leitte studied computer science at Leipzig University where she also obtained her doctoral degree. After post-doc at Swansea University (UK), she became juniorprofessor (assistent professor) at Heidelberg University in 2010.She is member of the extened board of directors of IWR and member of the Research Council of Heidelberg University.**

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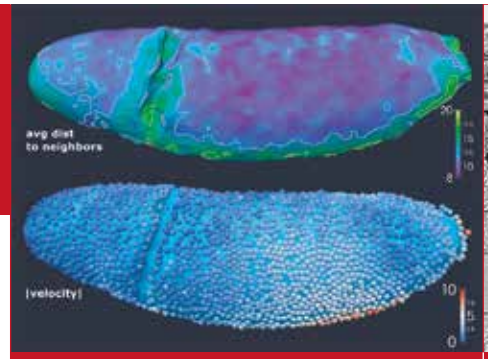
Modern data acquisition devices and simulation codes can capture highly complex and rich in detail data.They record, for example, growing embryos on a cellular basis in 3D+T or simulate the evolution of the universe including the formation of approx. 20 million galaxies. Understanding this kind of data with correlated patterns on multiple scales is extremely challenging. Scientific visualization is a powerful tool to describe, structure, and explore intricate phenomena in such large scale data.

A special focus of the "Computer Graphics and Visualization" group is on multivariate time-dependent data with a spatial context such as 3D videos or spatial simulations. To structure the data and filter the most relevant aspects, all algorithms have a strong mathematical basis using methods from information theory, statistics, and topology. The resulting derived data is encoded visually and interaction mechanisms allow for data exploration. Linked views highlight different extracted aspects of the data and help the users link their input data to derived information spaces. All members of the group contribute to the open-source software Scifer that provides a powerful platform for interactive data analysis of spatial data in linked views.

Close interdisciplinary collaborations exist with groups in the life sciences and the humanities. Together with multiple groups in biology, the group developes software to study pattern formation ranging from subcelluar structures to the organization of thousands of cells in growing organisms. In a multipdisciplinary effort, the group targets the semi-automatic virtual reconstruction of ancient Khmer temples. On the theoretical side, the group developes novel descriptors and visual encodings for high-dimensional pointcloud data to make this abstract data more comprehendable.

**LEARN MORE**

**Key Publication** Bastian Rieck and Heike Leitte, Structural Analysis of Multivariate Point Clouds Using Simplicial Chains. Computer Graphics Forum, http://onlinelibrary.wiley.com/doi/10.1111/cgf.12398/abstract, accepted 2014.




## Pattern formation in early embryonic development

PhD thesis of Jens Fangerau
Project partners: Steffen Lemke, Jochen Wittbrodt (Heidelberg University); Lars Hufnagel (EMBL)

**Modern imaging techniques, such as digital light-sheet microscopy, facilitate the recording of growing organisms with a high resolution in space and time. In the resulting 3D videos, individual cells of the organism can be reconstructed and tracked over time.The long-term objective in this field is to construct a digital organism based on real data.In his thesis, Jens Fangerau developed methods to extract coherent structures in large cell collections. This requires the description and exploration of multiple properties of each cell such as spatial motion, division patterns, and change of cell parameters such as size, shape, and texture.For each feature he developed methods to quantify and compare these characteristics across thousands of cells. The algorithms are combined in a single software, which also includes means for visual data mining. This enables the biologists to turn their imagery data into meaningful numbers and take an important step towards the digital embryo.**

## Algorithmic Reassembly of Khmer Temples

PhD thesis of Anja Schäfer
Project partners: Hans Georg Bock (Heidelberg University); Pheakdey Nguonphan

**In Cambodia lies the Angkor style temple of Banteay Chhmar. Like most nearly forgotten temples in remote places it crumbles under the ages most of it being only a heap of stones by today. To help modern day archeologists, who are using 3D data acquisition to document such temples, Anja Schäfer works towards the semi-automatic reconstruction of these temples.This approach has the potential to be much faster than the manual one, reduce the further deterioration of the stones and enhance the workers' security. Solving this 3D puzzle is a multi-stage process. The surface meshes of the stones are first simplified to be able to compute matching scores on multiple levels of detail. A classification of the stones based on Khmer-specific standard shapes is performed next to dramatically reduce the set of possible matchings. Finding the most likely combination of a set of stones, is an optimization problem that is solved in the last step. The image shows a part of a digitized temple wall.**

# Forensic Computational Geometry Laboratory (FCGL)

**DR. HUBERT MARA**

**Hubert Mara studied Computer Science at the Vienna University of Technology in Austria. He was a Marie-Curie-Fellow in the CHIRONetwork at the University of Florence, Italy from 2007 to 2008. In 2009 he joined the IWR, where he obtained his PhD in Computer Science in 2012. In 2014 he became head of the Forensic Computational Geometry Laboratory.**

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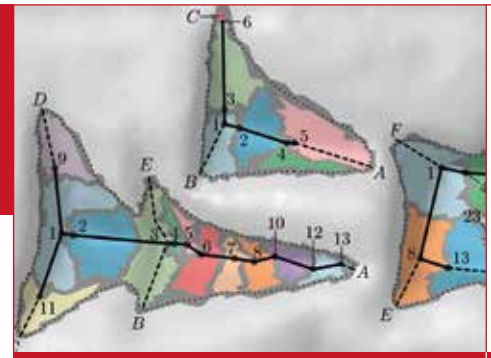
The FCGL is a Junior Research Group established within the institutional strategy of the 2nd German University Excellency Initiative. This concept has the general goal to improve the understanding of complex material, cultural and social topics. The FCGL matches this vision and bridges the well-established fields of the Computational Sciences and the Forensic Sciences by collaborative development of new methods to answer questions arising from Humanities and Life Sciences.

As the forensic science is the scientific method of gathering and examining information about the past, several research fields such as archaeology, geology, palaeography and many more share this aim and the methods of the evident task of law enforcement. The remainders of the past are often fragmented objects with three-dimensional hints about their meaning. These hints are represented as geometric features, which range from tool marks, weathering traces, fingerprints to imprinted characters. Even within the landscape evidence of long past human activity can be found as very unobtrusive changes to the natural topology of terrain. Additional dimensions representing e.g. color or reflectivity have to be included to fully understand the meaning of an object, which are increasingly digitized for virtual autopsy. Methods from Computer Vision and Computational Geometry can assist virtual autopsy by providing additional means of visualizations and allows for objective quantification and extraction of meaningful features.

The GigaMesh software framework and its modular processing pipeline for irregular measurement data as provided by high-resolution 3D-scanners is one of the core tools of the FCGL. As it is based on Open Source technologies it can be swiftly integrated into e.g. archaeological workflows or the preparation of OCR ready vector drawings of inscriptions for further use in the Digital Humanities.

**LEARN MORE**

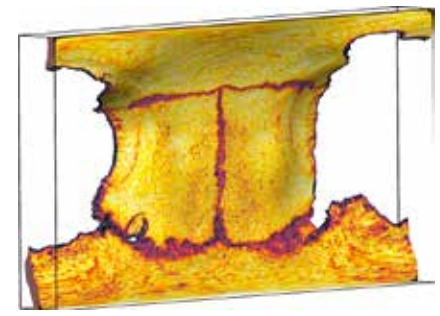
**Key Publication** Vectorization of 3D-Characters by Integral Invariant Filtering of High-Resolution Triangular Meshes, Hubert Mara and Susanne Krömker, Proc. of 12. Int. Conference on Document Analysis and Recognition (ICDAR/IAPR), pp. 62–66, Washington, DC, USA, 2013



## Cuneiform Character Mining for Semantic Tablet Matching

PhD student Bartosz Bogacz with Prof. Michael Gertz as additional supervisor.
Project partners: Assyriology: Prof. Stefan Maul, Stefan Jakob, Frauke Weiershäuser und Kamran Zand

**Half a million of cuneiform tablets have been excavated in modern times. These are important artifacts documenting the language, history and culture of the ancient Near East and constitute one of the greatest and most comprehensive part of antique texts written in many different and continuously evolving languages. We focus on the automatic search of similar characters in different tablets for display during manual translation of unidentified characters. The context in which a character is used significantly shortens the time necessary to understand its meaning. Our approach uses automated handwriting recognition from machine learning and automatic graph matching as used in graph theory. The extracted features are clustered in a high-dimensional feature space. Each cluster is analyzed for relevant features to infer the relative chronology of a character representation. Given this chronology and other features, the semantic puzzle can be solved to piece together text fragments.**



## 3D-Technology and Analysis from Archaeology to Forensic Medicine

Prof. Kathrin Yen (Heidelberg University Hospital); Prof. Bernhard Höfle (LiDAR Research Group, Institute of Geography, Heidelberg University); Christian Seitz (ArchEyeAutomatic and Robotics Lab at IWR, Heidelberg University)

**Having several years of experience in crafting tools and methods for archaeological research questions, we noticed that there is large overlap to forensic medicine. Both disciplines try to reconstruct and understand events in the past and both use a wide variety of 3D-acquisiton technologies for precise documentation of evidence. While documentation e.g. with Structure from Motion, Terrestrial and Airborne laser scanning are increasingly used, the methods for analysis are limited to standard methods typically used in the Computer Graphic domain. Therefore we began to collaborate with experts in 3D-documentation and medical forensics to identify the requirements for developing new methods in 3D Computer Vision. These methods will be incorporated in the FCGL's GigaMesh software framework to assist the interpretation of high-resolution 3D-data from different sources with highly automatable software modules.**

# Applied Analysis and Modeling in Biosciences


## PROF. DR. ANNA MARCINIAK-CZOCHRA

**Anna Marciniak-Czochra studied Mathematics at Warsaw University and obtained PhD from Heidelberg University. In 2007 she won ERC starting grant, in 2008 was granted Emmy Noether group, and in 2011 a Dr. Habil. from Wroclaw University. She is a professor of Applied Mathematics at Heidelberg University, a member of the Exec. Board of MATCH Ctr and deputy director of the IAM.**

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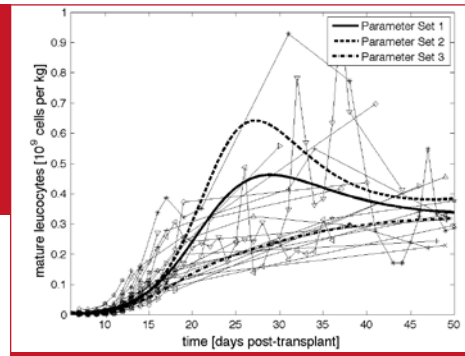
The interdisciplinary expertise of the group lies in the areas of applied mathematics and mathematical and computational biosciences. Specifically, our field of focus is the dynamics of self-organization and structure formation in developmental and regeneration processes, and in cancer. Our aim is to develop and analyse multiscale mathematical models of the dynamics of structure formation in multicellular systems and to develop new mathematical methods for modeling of such complex processes. This aim is achieved through a close collaboration with experimentalists and medical doctors in Heidelberg and byond, and comprehensive analytical investigations of the mathematical problems arising in the modeling of biological processes.

The mathematical areas of focus are partial differential equations, dynamical systems, and multiscale analysis and homogenization. The methods of analysis are used to formulate the models and to study the spatio-temporal behavior of solutions, especially stability and dependence on characteristic scales (spatial and temporal), geometry, initial data and key parameters.

The main lines of our analytical research are (1) analysis of pattern formation mechanisms in the systems of reaction-diffusion type; (2) analysis of nonlinear structured population models; linking continuous and discrete structures; (3) derivation of effective models starting from first-principle modelling to describe transport of cells and molecules through heterogeneous media such as biological tissues. Particular attention is paid to methods of model upscaling and reduction.

**LEARN MORE**

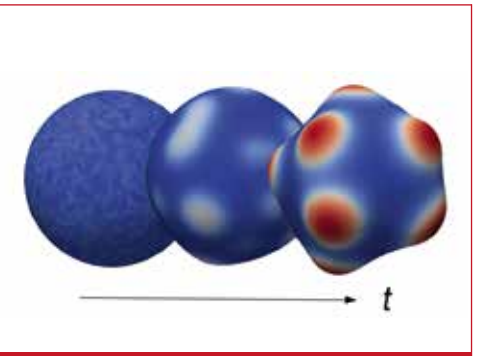
**Key Publication** Applied Research: T. Stiehl, N. Baran, A. D. Ho, and A. Marciniak-Czochra (2014) Clonal selection and therapy resistance in acute leukemias: Mathematical modelling explains different proliferation patterns at diagnosis and relapse. J. Royal Society Interface. 11, 20140079.




## Modeling, analysis and simulation of stem cell dynamics in hematopoiesis and leukemia with clinical applications

PhD thesis of Thomas Stiehl
Project partners: Anthony D. Ho, Natalia Baran, Christoph Lutz (Medical Clinic Heidelberg); Anna Marciniak-Czochra (Heidelberg University)

**The project is devoted to mathematical modeling, analysis, and simulation of dynamics of stem cell self-renewal, differentiation, and clonal evolution in healthy hematopoiesis and leukemia, as a part of the Collaborative Research Center (SFB 873) "Maintenance and Differentiation of Stem Cells in Development and Disease" and is based on a collaboration with hematologists from Heidelberg Medical Clinic. New multi-compartment and structured population models constructed by us allow to explain observations on regeneration process in hematopoiesis, development of leukemia, clone selection and resulting therapy resistance in blood cancers. The study reveals different scenarios of possible cancer initiation and provides qualitative hints to treatment strategies. The models, combined with clinical data, may serve as a tool of personalised (targeted) therapy and provide insight into healthy and leukemic stem cell behavior in addition to molecular or biological classification of these cells.**




## Mathematical modeling and analysis of biological pattern formation

Steffen Härting, Moritz Mercker, Anna Marciniak-Czochra (Heidelberg University), Grzegorz Karch (University of Wroclaw), Izumi Takagi (Tohoku University)

**Inspired by new observations in the experimental group of Prof. Thomas Holstein (COS, Heidelberg Univ.), we model symmetry breaking and pattern formation in development. We focus on models coupling non-diffusive cellular processes with diffusing signaling factors, which we derived using homogenization techniques. Our results transcend the classical Turing theory. We have shown that stable patterns can be formed in systems with a single diffusing factor if the non-diffusing components exhibit hysteresis. In such case a variety of discontinuous structures may develop. We have also proven that coupling of diffusing and non-diffusing factors may lead to an unexpected phenomenon of mass concentration. Additionally, we have proposed a new mechanism based on coupling between a morphogen and tissue curvature. Numerical simulations of the mechano-chemical model, in collaboration with Prof. Thomas Richter (IAM/IWR), have shown spatial structures, in agreement with experiments on Hydra aggregates.**

# Complex Biological Systems


## DR. FRANZISKA MATTHÄUS

**Franziska Matthäus studied Biophysics at the Humboldt-University of Berlin. She obtained her PhD in Computer Science from the Warsaw Academy of Science in association with the Interdisciplinary Center for Mathematical & Computational Modeling. After two postdocs in Heidelberg she became leader of the BIOMS research group Complex Biological Systems.**

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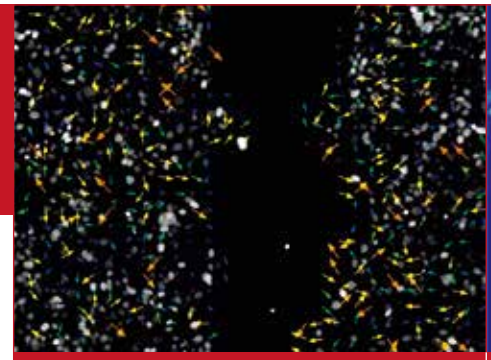
Cell motility is essential for bacteria but also for eukaryotes. Bacteria crawl or swim to find nutrients or to reproduce. In eukaryotic multicell organisms cell migration is crucial for development and regeneration, but also associated with disease. To steer migration, single cells must integrate chemical and mechanical information about the environment and their internal state. Failure in proper processing of these signals can lead to the extinction of a bacterial population, development of disease like cancer, chronic wounds, or defects in development or immune processes.

Our group develops mathematical models of cell motility, which describe phenomenological motility features like random search behavior, chemotaxis or collective motion, with a focus on intracellular signaling processes and (chemical or mechanical) cell-cell interaction. We use individual-based models, which usually incorporate a detailed description of the internal signaling processes in the form of ordinary differential equations, or density-based approaches in the form partial differential equations. To gain quantitative information from experimental approaches we use a wide spectrum of data analysis methods, like single-cell tracking, particle image velocimetry, principal components analysis, and model fitting. To validate the models we apply rigorous mathematical analysis and extensive simulations.

Current applications include the influence of noise and sensory memory on E.coli chemotaxis and search behavior, collective migration of lung cancer cells subject to growth hormone treatments, and the coupling between chemical and mechanical processes in cell polarization. The work is carried out in close collaboration and under intensive discussion with our experimental partners.

**LEARN MORE**

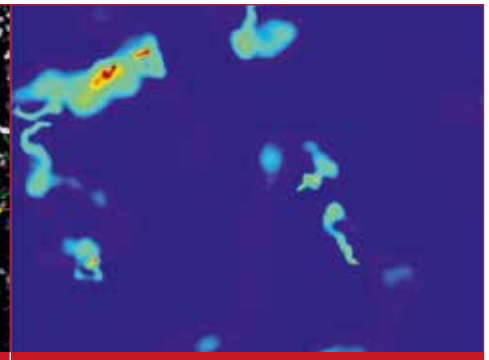
**Key Publication** F. Matthäus, M.S. Mommer, T. Curk, J. Dobnikar, On the origin and characteristics of noise-induced Lévy walks of E. coli, PLOS One 6(4):e18623, 2011.



## Collective migration of lung cancer cells – modeling and data analysis

PhD thesis of Damian Stichel
Project partners: Kai Breuhahn (Heidelberg University Hospital); Ursula Klingmüller (DKFZ Heidelberg); Alistair Middleton & Franziska Matthäus (BIOMS, Heidelberg University)

Lung cancer is characterized by a very high mortality rate, with metastasis being the primary cause. New strategies target specific signaling pathways regulating growth and migration. In collaboration with experimental partners we investigate the migratory characteristics of NSCLC lung cancer cells in response to treatment with different growth hormones. In his thesis, Damian implemented a workflow for efficient image analysis, including single-cell tracking analysis and particle image velocimetry. These approaches yield an exhaustive set of parameters and relations describing the observed collective motion. In collaboration with A. Middleton (postdoc) he is developing a mathematical model of cell migration including mechanical and internal processes. Fitting the model to the data yields single-cell parameters like the adhesion strength or the length of directional memory. Agent-based simulations with the same parameters reproduce the migratory behavior very well.



## Superdiffusion and chemotaxis of E.coli bacteria

Franziska Matthäus (Heidelberg University); Jure Dobnikar (Cambridge University); Victor Sourjik (MPI Marburg)

E.coli bacteria present a model system for chemotaxis, the motion along chemical gradients. The internal signaling pathway controlling the swimming behavior is relatively simple and well understood.

We developed an agent-based model for E.coli motion, which includes a full description of signaling pathway dynamics. The model reproduces swimming patterns in presence and absence of chemical gradients, and also pattern formation processes arising from bacterial interactions. Using this model we investigated the role of stochastic fluctuations in the signaling process, which in the case of E.coli can give rise to Lévy walks, an optimal search strategy in absence of gradients. Noisy signaling has also positive effects on chemotaxis, like increased motility, but on the cost of reduced precision. Presently we are investigating the role of sensory memory and signaling pathway properties on bacterial interactions that give rise to local accumulations.

# Optimization in Robotics & Biomechanics

**PROF. DR. KATJA MOMBAUR**

**Katja Mombaur is professor at IWR since 2010. She holds a diploma degree in Aerospace Engineering from the University of Stuttgart and a Ph.D. degree in Mathematics from Heidelberg University. She spent one year as PostDoc at Seoul National University, South Korea and two years as visiting researcher at LAAS-CNRS in Toulouse, France.**

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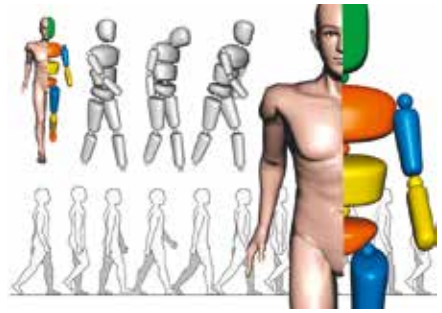
The research focus of the ORB group is on modeling, optimization and simulation of dynamic motions of anthropomorphic systems, i.e. humans, humanoid robots, and virtual human characters. Newer research directions also include motions of industrial robots, flying robots and swarm robots. From a mathematical perspective, we are particularly interested in the application and development of efficient numerical optimal control, inverse optimal control and non-smooth optimization techniques for complex hybrid dynamical system models. We also investigate efficient approaches to set up realistic dynamical optimization models of humans, robots and other technical devices including rigid multibody system models, muscle models and neural control. Our research projects include the:
optimization of humanoid walking motions in different terrains; generation of fast human-like walking, running, jumping, diving and other gymnastics motions; stability optimization of human and robot motions; study of characteristics of pathological gait in orthopedics and of walking motions with prostheses, orthoses and functional electrical stimulation; optimization of physically assistive devices for the elderly; identification of underlying objective functions of human motions in different situations; studies of artistic and emotional aspects of dynamic motions; investigation of processes related to cognition and orientation during locomotion and traffic interaction; optimization of octocopter trajectories for automated photogrammetric reconstruction in archeology; needle path planning in robot assisted prostate brachytherapy.

Our interdisciplinary research creates bridges between scientific computing and many other disciplines, such as robotics, engineering, biomechanics, medicine, orthopedics, sports, computer graphics, cognitive sciences, arts, archeology and philosophy.

**LEARN MORE**

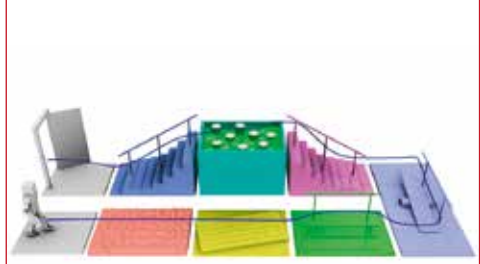
**Key Publication** K. Mombaur, H. Koch, M. Felis: Model-based optimization for robotics Journal of the Robotics Society of Japan, Special Issue on "Optimization used in Robotics Research" (eds: Kensuke Harada and Yuichi Tazaki) vol. 32, no. 6, July 2014.



## Modeling emotional body language in human walking motions

PhD thesis of Martin Felis (HGS MathComp Project)
Supervisors: Katja Mombaur (Heidelberg University), Alain Berthoz (Collège de France, Paris)

The study of emotional facial expressions and of emotional body language is currently receiving a lot of attention in the cognitive sciences. In this project, we are not studying particular emotional gestures, but rather focus on the implicit bodily expression of emotions during standard motions such as walking forwards. An underlying assumption of our work is that all human motion is optimal in some sense and that different emotions induce different objective functions, which result in different "deformations" of normal motion. Efficient algorithms for the generation of personalized whole-body dynamic models of the walking subjects have been implemented and adjusted to the individual kinematics. Based on motion capture and EMG data of walking motions under different emotional conditions (such as joy, anger, fear and sadness) collected in the lab of Prof. Alain Berthoz in Paris, we use inverse optimal control to identify the optimality criteria for each emotion.



## KoroiBot – Improving humanoid walking capabilities by human-inspired mathematical models, optimization and learning

Coordinator: Katja Mombaur, Participating institutions: Heidelberg University, CNRS (LAAS & LIRMM, FR / JRL, JP); KIT, IIT (IT), TU Delft (NL), Weizmann Institute (IL), University of Tübingen; ca. 40 project members. www.koroibot.eu

Teaching humanoid robots a stable, robust "human" way of walking is the goal of the international research project KoroiBot, which receives a 4.16 Mio funding from the EU from 2013 – 2016. In the future, humanoid robots are supposed to support humans in households, disaster sites or space missions, etc., but one of the major challenges is their inability to move on two legs in difficult situations without falling. In this project, we study the way humans walk e.g. on stairs and slopes, on soft and slippery ground or over beams and seesaws, and transfer this knowledge into mathematical models. Besides developing new optimization and learning methods for walking on two legs, we aim to implement them in practice on real robots. In addition, the research results are to flow into new design principles for the next generation of robots. Beyond robotics, we expect possible applications of the methods in medicine for orthoses and prostheses design, as well as in computer animation and game design.

# Computer Vision


## PROF. DR. BJÖRN OMMER

**Björn Ommer is full professor for Scientific Computing and is leading the HCI Computer Vision Group since 2009. He received a diploma in computer science from Uni Bonn, a PhD in CS from ETH Zurich and served as postdoc at UC Berkeley. He is one of the HCI directors and member of HGS executive board.**

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The primary goal of Computer Vision is to enable machines to "see", that is to recognize objects in images and videos. Therefore algorithms are needed that allow computers to learn the characteristics of objects so that they can be detected in novel images. The main challenges of category-level object recognition are the large within-class variability of object categories and intense scene clutter. Thus, powerful object models are required, which capture the large variability of all the instances of a category. To turn the learning of these models into a feasible problem, we utilize the compositional nature of visual object categories. Compositionality significantly limits the representation complexity and renders the learning of structured object models tractable. A particular modality we are investigating is object shape. As a global feature that is complementary to the widely used semi-local appearance descriptors, shape provides a much needed orthogonal representation. Moreover, we are investigating the integration of grouping, shape analysis, and object recognition into a common, probabilistic framework that extends the widely used concept of probabilistic voting. We are actively exploring this modeling strategy in the context of object and action detection, categorization, and analysis. Besides conducting basic research in computer vision, the methodology is also applied in application fields ranging from cultural heritage to biomedical image analysis.

**LEARN MORE**

**Key Publication** B. Ommer and J. M. Buhmann. Learning the compositional nature of visual object categories for recognition. IEEE Transactions on Pattern Analysis and Machine Intelligence, 32(3):501–516, IEEE, 2010


## Shaping Art with Art: Morphological Analysis for Investigating Artistic Reproductions

Antonio Monroy, Peter Bell, Björn Ommer

Artistic reproductions have a similar importance for art history as the original artworks, since reception provides valuable information about relationships between artworks, artists, and different schools of style and thought. In this project an approach for automatically analyzing the alterations of an original artwork in its reproductions is developed. The overall deformation of the artwork is modeled by a piecewise linear model, where regions of the artwork that feature similar alterations are automatically inferred and assigned to the different model components. Model complexity, that is, the required number of affine components required for registration, is automatically estimated using a statistical stability analysis. The main challenge is to simultaneously solve three tasks: (i) inferring the correspondences between both shapes, (ii) identifying the groups in the image that share the same transformation, and (iii) estimating the transformation of these groups.

## From Meaningful Contours to Discriminative Object Shape

Pradeep Yarlagadda, Antonio Monroy, Björn Ommer

Shape is a natural, highly prominent characteristic of objects that human vision utilizes everyday. But despite its expressiveness, shape poses significant challenges for category-level object detection in cluttered scenes: Object form is an emergent property that cannot be perceived locally but becomes only available once the whole object has been detected and segregated from the background. Thus this project addresses the detection of objects and the assembling of their shape, simultaneously. A dictionary of meaningful contours is obtained by grouping based on contour co-activation in all training images. We seek a joint, consistent placement of all contours in an image. Therefore, the characteristic object shape is learned by discovering spatially consistent configurations of all dictionary contours using maximum margin multiple instance learning. During recognition, objects are detected and their shape is explained simultaneously by optimizing a single cost function.

# Software Engineering


## PROF. DR. BARBARA PAECH

**Barbara Paech holds a Habilitation in Computer Science from the TU München. Between 1999 and 2003 she was department head at the Fh IESE. Since 2003 she is professor at Heidelberg University. She was spokeswoman of the section "Software Engineering" in the GI for 6 years and is founding member of the International Requirements Engineering Board.**

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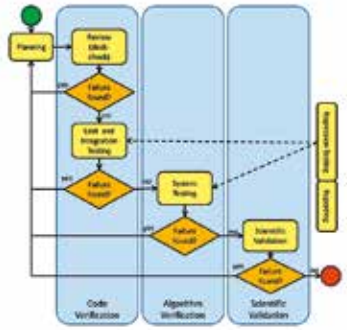
The focus of the group is Quality Engineering: the engineering of quality products and the quality of the engineering process. We provide methods to create and capture the organization of distributed working groups during projects and beyond, the knowledge necessary for a joint understanding of all process participants, the decisions and their rationale, the experience of process participants to allow for continuous improvement, and the understanding of the developed software on different levels of abstraction. The methods are supported by the tool UNICASE (www.unicase.org) developed jointly with the TU München, and we apply software analytics to cope with the wealth of data of software development.

Example methods deal with task-oriented requirements engineering, alignment of business process and software quality, communication between users and developers, release planning, semi-automatic generation of a software feature model, quality assurance of a scientific framework, or software evolution decision making support.

**LEARN MORE**

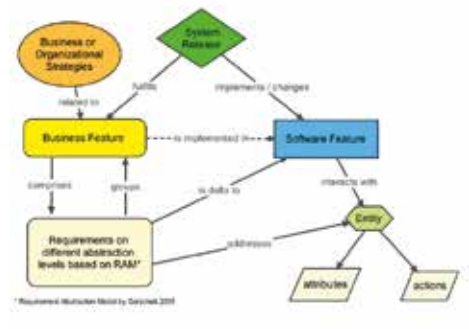
**Key Publication** Hanna Remmel, Barbara Paech, Christian Engwer, Peter Bastian: A Case Study on a Quality Assurance Process for a Scientific Framework, Computing in Science and Engineering, vol. 16 no.3, pg 58–66, 2014



## Software Engineering for Computational Science Software

PhD thesis of Hanna Remmel
Project partners: Peter Bastian, Barbara Paech (Heidelberg University); Christian Engwer (University of Münster)

**The quality assurance of scientific software has to deal with special challenges like missing test oracles, high performance computing, and the high-priority of non-functional requirements. In addition to these challenges the quality assurance of a scientific framework needs to deal with large variability. In her PhD thesis Hanna Remmel applies software product line engineering principles to deal with these challenges. She provides a process for the creation of reengineering variability models which are used to systematically develop system test applications for the framework and a method for test case derivation. Furthermore she provides a test strategy for scientific frameworks and an overall quality assurance process. She evaluates the approach in the context of the scientific framework DUNE developed at the IWR and provides prototypical tool support based on FeatureIDE.**




## Feature Generation Decision-Making Support for Requirements Evolution

Gabriele Zorn-Pauli
Project partners: Hannes Karey, Roland Kohl (Roche Diagnostics GmbH; Mannheim); Barbara Paech (Heidelberg University)

**Feature generation is a continuing activity and an essential part of the strategic release planning process of evolving and bespoke IT systems. To generate features IT stakeholders group requirements into useful requirements bundles that contribute to business, organizational or product strategies. The occurrence of (1) requirements evolution at different levels of abstraction and (2) delta requirements specifications isolated from context, complicate the feature generation task. In this project we developed a feature generation decision-making support method that addresses the mentioned problems. The major idea is to provide an abstract representation of the software system from a business view (business features), a system view (software features), a data view (entity model) and a change intension view (requirements intension labels). The method has been successfully applied in case studies at Roche Diagnostic.**

# Theoretical and Quantum Chemistry


## DR. MARKUS PERNPOINTNER

**Markus Pernpointner studied Chemistry at the University of Tübingen and obtained his doctoral degree from the University of Stuttgart. After being a post-doc at the Universities of Auckland and Amsterdam he came to Heidelberg for his habilitation in the group of professor Cederbaum. Since 2006 he is an independent group leader and researcher.**

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The presence of heavy atoms in molecules or clusters invokes substantial changes in the electronic structure concerning energies, densities and the symmetry of the underlying wave function. These relativistic effects directly influence the corresponding physical properties of the system and appropriate methods have to be designed for an adequate quantum chemical treatment. Our research is focused on development and efficient implementation of relativistic electronic structure methods built on the Dirac equation.

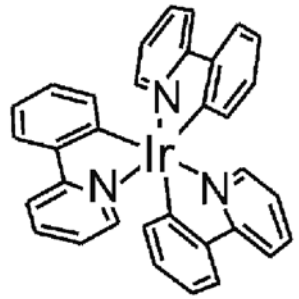
In weakly bound clusters electronic decay reactions can be initiated by highly energetic electromagnetic radiation liberating an inner valence electron. Subsequent stabilization by a secondary electron emission is strongly influenced by scalar relativistic and spin-orbit effects and the corresponding emission spectrum differs substantially from the nonrelativistic one. Intensive research is done on noble gas clusters broadening the understanding of radiation-induced electronic processes also relevant for biological systems.

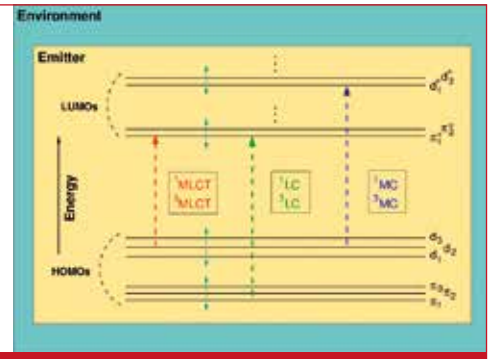
Another important field of research is concerned with the investigation of excited state dynamics in small organic molecules like coumarin and its derivatives. It was observed that ring substitutions alter the relaxation dynamics substantially and can enable fluorescence. Detailed insight could be gained in cooperation with local experimental groups (Motzkus/Buckup) who performed pump/probe experiments leading to a good kinetic model for the decay processes. Coumarin and its derivatives serve as a generic system for the light-induced liberation of active agents in the eye needed for glaucoma treatment. Research is currently extended to light emitting organic substances based on heavy metal ions like iridium. Here an adequate treatment of relativistic effects is mandatory for accurate results.

**LEARN MORE**


**Key Publication** C. M. Krauter, J. Möhring, T. Buckup, M. Pernpointner and M. Motzkus, Ultrafast branching in the excited state of coumarin and umbelliferone, Phys. Chem. Chem- Phys. 15, 17846 (2013), DOI: 10.1039/c3cp52719k.






## New relativistic propagator approaches for the theoretical treatment of metal-based organic light emitting diodes (OLEDs)


Markus Pernpointner (Heidelberg University), Christoph Jacob (Theoretical Chemistry, KIT Karlsruhe), Andre S. P. Gomes (University of Lille).


**Heavy metal ions complexated by organic ligands exhibit extremely high quantum yields and serve as key ingredients in organic light emitting diodes (OLEDs). This is achieved by facilitating very fast recombination for both the injected singlet (25 %) and triplet (75 %) excitons via efficient intersystem crossing induced by strong spin-orbit coupling. In organic materials composed of light atoms only, the generated triplet excitons undergo phosphorescence at a time scale not suitable for technical purposes. Excitons localized at the emitter center such as Ir(ppy)3 (see left Picture) can hereby be described as localized excited states in an environment that undergo deexcitation under photon emission.**

**For a detailed understanding of the corresponding electronic processes spin-orbit coupling and electron correlation in the heavy metal complexes need to be described accurately which is achieved by our new implementation of the four-component polarization propagator based on the algebraic diagrammatic construction (ADC) for its solution. The transitions in the emitter system are influenced by the nature of the central ion, the ligands and the environment (see right Picture) and need to be well understood in order to make theoretical predictions. The ADC scheme hereby provides complete spectral information such as transition energies and moments together with a state analysis in one shot. The increased numerical effort accompanying relativistic electronic structure calculations is hereby managed by modern parallelization techniques and screening approaches. Employing these advanced methods helps to gain deeper insight required for the design of new efficient triplet emitters.**

# Model-Based Optimizing Control


## DR. ANDREAS POTSCHKA

**Andreas Potschka studied Mathematics in Heidelberg. After a research stay at Rice University, USA, he obtained his doctorate degree at the IWR. He was awarded the Klaus Tschira Prize 2012 for a summary article of his thesis. His group is associated with the homonymous ERC Advanced Investigator grant of Prof. Engell (Dortmund) and Prof. Bock.**

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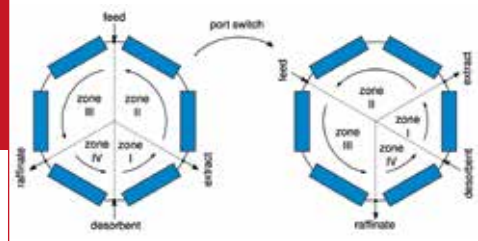
Our mission is to develop fast numerical methods for real-time feedback control of large-scale, real-world processes. Our efforts are focused on the challenges of large-scale nonlinear processes that are for instance modeled with parabolic partial differential equations, involve difficult boundary conditions, for example periodicity in time, involve switches in the dynamics, need to be optimized with respect to economic objective functions, and are subject to uncertainties. Our approach comprises the discovery of mathematical structures in suitable problem formulations that can be exploited computationally in novel algorithms in order to extend the range of treatable applications and the quality of their model-based control in real-time.

In a genuinely interdisciplinary approach, the development, analysis, and implementation of new algorithms, especially in the field of NMPC (Nonlinear Model Predictive Control), addresses important questions from applications, in particular chemical engineering in cooperation with the Chair of Process Dynamics and Operations lead by Prof. Engell at the Department of Biochemical and Chemical Engineering, TU Dortmund, and with BASF, Ludwigshafen.

Our scientific contributions affect various areas of numerical analysis: We develop new preconditioners for saddle-point systems and provide spectral estimates for their convergence analysis. We also establish and analyze a novel globalization approach for Newton-type methods based on differential geometric arguments. In the fields of linear and quadratic programming we investigate homotopy-based numerical methods. For applications subject to large uncertainties, we develop novel approaches for parallel numerical methods in scenario tree NMPC and for the problem of dual control that balances the highly interrelated but often contradictive goals of process information gain and control performance.

**LEARN MORE**

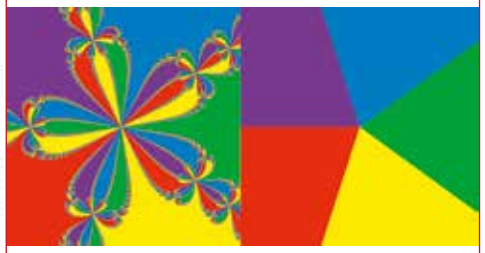
**Key Publication** Andreas Potschka, A direct method for parabolic PDE constrained optimization problems, in Advances in Numerical Mathematics, Springer Spektrum, Wiesbaden, 2014.




## Newton-Picard Nonlinear Model Predictive Control

Alexander Buchner, Andreas Potschka

For fine chemicals, in particular in biochemistry, the purification of single species from a mixture cannot be carried out by distillation because of heat degradation. Instead, adsorption-based processes like chromatography are the separation method of choice. Because a certain amount of diffusion of the species cannot be avoided the separation becomes a challenging task. High purities can only be achieved by complex, non-intuitive process operation computed on the basis of mathematical models. Interestingly, we can exploit the "problematic" diffusion for the control of adsorption processes computationally, because spatial concentration modes with high frequency get damped out quickly. Mathematically speaking, we can discover a problem formulation which comprises compact operators whose range can be approximated well by zero except for a few slowly decaying modes. We currently investigate this approach in the framework of a Newton-Picard Multi-Level Real-Time Iteration NMPC scheme.



## Backward Step Control for global Newton-type methods

Andreas Potschka

We develop and analyze a new damping approach called Backward Step Control for the globalization of the convergence of Newton-type methods for the numerical solution of nonlinear root-finding problems. We provide reasonable assumptions that imply convergence of Backward Step Control on the basis of generalized Newton paths in conjunction with a backward analysis argument. In particular, convergence to a specific solution and a-priori estimates on the residual reduction can be shown. Furthermore, we can guarantee a transition to full steps in the vicinity of a solution, which implies fast local convergence. If, for instance, we use the Newton method to compute the fifth complex roots of unity for each starting iterate on the complex unit square and color it with respect to the argument of the respective fixed point, we can observe a fractal dependence with respect to the initial guess (image, left). Backward step control (image, right) nearly eliminates this undesired behavior.

# Numerical Methods


## PROF. DR. ROLF RANNACHER

**Rolf Rannacher studied Mathematics in Frankfurt, PhD in 1974, and habilitated in 1978 at Bonn. He spent one year at the University of Michigan and had professor positions in Erlangen 1980 and Saarbrücken 1983. Since 1988 he is professor for Numerical Analysis in Heidelberg and member of IWR. From 2010–2014, he served as Dean of the Faculty for Mathematics and Computer Science.**

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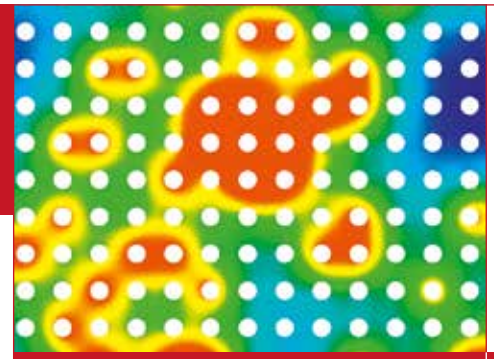
The group works on numerical methods for simulating PDE-based mathematical models in science and engineering. Special interest is in finite element methods, model and mesh adaptivity for complexity reduction, multiscale techniques, efficient multigrid solvers, parallelization and software systems. The adaptivity follows the concept of "goal-orientation" realized within the "Dual Weighted Residual" (DWR) method, which has been developed in the work group over the last 20 years. This duality-based approach yields a systematic way for the simultaneous control and balancing of modeling errors, discretization errors and algebraic iteration errors in the numerical simulation of general linear and nonlinear, stationary and nonstationary ODE- and PDE-based models. Though largely heuristically based the DWR method has proven very successful in various concrete situations.

Applications are to fluid and gas flows, chemically reacting flows, elasto-plastic deformation, radiative transport, fluid-structure interaction, signal transduction in biological systems, eigenvalue problems, and optimal control as well as parameter estimation with PDEs.

**LEARN MORE**

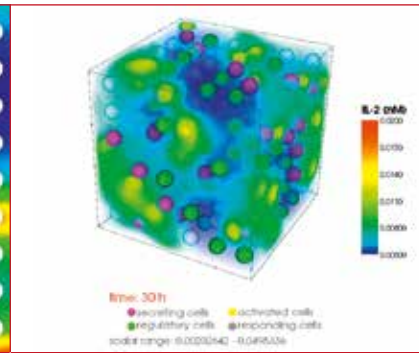
**Key Publication** R. Rannacher and J. Vihharev: Adaptive finite element analysis of nonlinear problems: balancing of discretization and iteration error, J. Numer. Math. 21, 23–62 (2013).



## Development of a numerical method for 3d simulations of the competition between T cells in lymph nodes

PhD thesis of Dipl.-Math. Daniel Gerecht
Project partners: Prof. Dr. Thomas Höfer (DKFZ Heidelberg); Dr. Kevin Thurley (Charité-Universitätsmedizin, Institute for Theoretical Biology, Berlin)

Understanding the molecular mechanism of the immune response is the subject of intense research in medicine and biology. In the lymph node responding T cells are activated by T helper cells to trigger an immune response, while regulatory T cells suppress the activation. One way of activation is the diffusion of Interleukin-2 in the intercellular space. Using a recently proposed mathematical model, we develop a numerical method for 3d simulations of the competition between T cells for Interleukin-2. The model consists of a reaction-diffusion-equation coupled with ordinary differential equations. The aim is to solve the coupled nonlinear system in three dimensions with a multilevel approach. Computational effort will be reduced by applying “goal-oriented” spatial mesh and time-step adaptation.



## Numerical method for coupled PDE/ODE systems in 3d

Dr. Thomas Carraro, Dr. Elfriede Friedmann, Dipl.-Math. Daniel Gerecht, Prof. Rolf Rannacher (Numerics Group, IWR)

A numerical approach has been developed within the deal.II package for simulating the immune response in the lymphnode in 2d and 3d. The model, which was developed by Prof. Höfer in 2010, consists of a reaction-diffusion-equation coupled with ordinary differential equations. Several approaches have been tested to obtain an efficient solver for the coupled equations:

- Coupled vs decoupled solution: coupling is more efficient in most cases than decoupling; for the coupled solver a multigrid preconditioner has been developed.
- An a posteriori error estimator has been developed within the Dual Weighted Residual (DWR) framerwork and has been used on the coupled system for complexity reduction.
- The developed software has been used for investigating the behaviour of the model in the 3d intercellular space. It turned out that the model can qualitatively reproduce the influence of Regulatory T cells on the immune response as observed in experiments.

# Discrete and Combinatorial Optimization


## PROF. DR. GERHARD REINELT

**Gerhard Reinelt studied in Bonn. He received his doctoral degree in Augsburg where he habilitated in 1991. Since 1992 he is professor for Computer Science in Heidelberg. Reinelt is member of the HGS MathComp and the Research Training Group "Spatio/Temporal Graphical Models and Applications in Image Analysis".**

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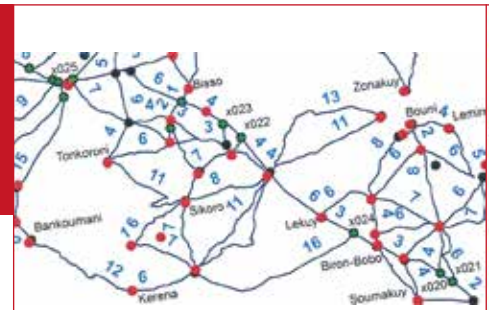
Discrete and combinatorial optimization is concerned with linear and nonlinear optimization models where all or some of the variables have to have integer values in feasible solutions (of particular interest are models where all variables are binary) and with optimization problems which are modelled using undirected or directed graphs. Our research is dedicated to the development and implementation of effective algorithms which are able to solve the problems to proven optimality. However, since most of the optimization problems are usually NP-hard, also approximative heuristics are needed.

A main expertise of the group is in the area of the development of so-called branch-and-cut algorithms. The success of these algorithms depends heavily on profound knowledge of the facet structures of polytopes. Since many years the group has implemented most effective tools for obtaining the linear structure of polytopes defined by their vertices. Recently the software has been parallelized and can also make use of symmetry information. It certainly belongs to the most powerful tools on an international level.

The group is interested in the theoretical advancement of the methodological approaches, but also in their application in interdisciplinary projects. Current projects are dealing with the planning of health surveys in underveloped countries, the identification of roles in social networks and the development of algorithms for image segmentation.

**LEARN MORE**

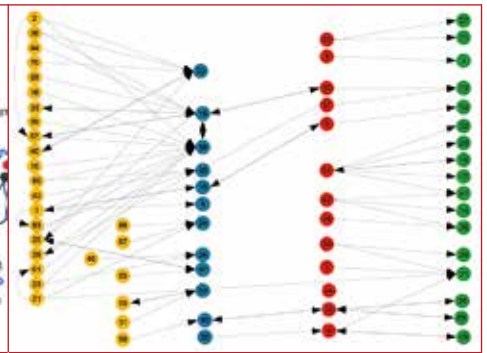
**Key Publication** Bonato, T., Jünger, M., Reinelt, G., Rinaldi, G, Lifting and separation procedures for the cut polytope, Mathematical Programming 146, 351–378, 2014.




## Planning of health surveys in under-developed countries

PhD thesis of Elham Farhangian
Project partners: Henrike Lietz, Rainer Sauerborn (Heidelberg University)

The topic of this project is the scheduling of health surveys in under-developed countries, in this case in the district of Nouna, Burkina Faso. In regular intervals about 13,000 households in 59 villages have to be visited by interviewers to collect statistical data. Most interviews are short, but for a selection of 1,000 households extensive surveys have to carried out once per year which can even take longer than one day. About 20 interviewers are available. A cost optimal assignment of these interviewers to households and a corresponding schedule including the determination of travel routes has to be found. Besides by its size, the problem is complicated by the fact that only few roads allowing for fast travel are available and that some roads cannot be used in the rainy season. A planning tool employing heuristic algorithms as well as exact algorithms for suitable subproblems will be developed.



## Identification of roles in social networks

Stefan Wiesberg (Heidelberg University)

The project is concerned with identifying group structures in social networks. Basically, there are two common notions of grouping. In structural partitioning approaches one tries to find groupings in which each pair of groups is connected by either very many of very few links leading to a pattern of density and sparsity between the groups. The second method searches for regular partitionings, where all members of a group have the same interaction patterns with other groups. So, structural approaches identity patterns of link quantity whereas regular approaches aim at patterns of link existence. The latter is suited for identifying so-called roles of actors in networks. In this project we develop and implement algorithms for finding regular partitions. Suitable models are nonlinear and effective techniques for optimizing them have to be found. First computational results exhibit that our algorithms can find optimum solutions significantly faster than comparable methods from the literature.

# Numerical Methods for Partial Differential Equations


## JPROF. DR. THOMAS RICHTER

**Thomas Richter studied Mathematics in Düsseldorf and Heidelberg. In 2005, he obtained his doctoral degree as part of the SFB 359 "Reactive Flows, Diffusion and Transport" . After a one year PostDoc stay at the Massachusetts Institute of Technology, he accepted in 2010 his current position as junior professor at the University of Heidelberg.**

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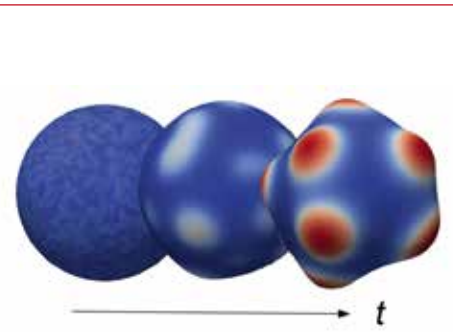
The group works on modeling and finite element analysis of complex coupled multiphysics problems. Special focus is on new models, discretizations and solver technologies for fluid-structure interactions. Applications are found in technical problems, biological applications and in computational medicine. Key interest is in configurations, where the usual well-established approaches fail, such as fluid-structure interaction problems with very large deformation and contact or flow problems under extreme conditions as very large pressures.

One key technology is the adaptive finite element method. The algebraic systems resulting from the discretization of complex partial differential equations are often so large, that they exceed the capability of modern computer systems. By adaptivity, it is possible to enhance accuracy of discretizations only where it is important. These regions with a substantial error contribution are automatically detected with the help of a posteriori error estimators. While adaptivity is a universal approach, the design and analysis of a posteriori error estimators for complex multiphysics problems is subject to active research.

The research group develops the finite element software library Gascoigne 3D, that is widely used for various complex problems in fluid and structure dynamics. Gascoigne 3D includes a parallel geometric multigrid solver based on adaptive finite elements.

**LEARN MORE**

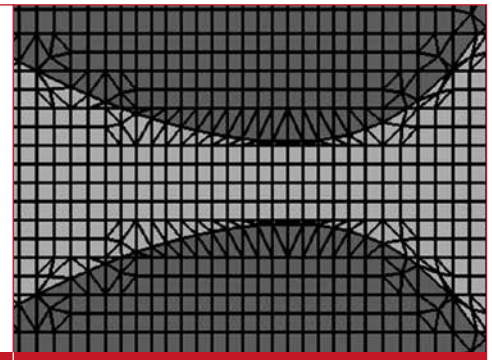

**Key Publication** T. Richter, T. Wick "Finite Elements for Fluid-Structure Interaction in ALE and Fully Eulerian Coordinates", Computer Methods in Applied Mechanics and Engineering 199, pp. 2633–2642, 2010


## Mechanics of Pattern Formation

PhD thesis of Felix Brinkmann
Project partners: Prof. Dr. Anna-Marciniak-Czochra (Institue for Applied Mathematics); Dr. Moritz Mercker (Institute for Applied Mathematics, BioQuant)

The fundamental principals that are responsible for the evolution of patterns in biological material, e.g. the development of embryos, are not fully understood. It is generally accepted, that these processes are caused by an interplay of chemical reactions and mechanical response. Detailed models for this coupling, that is vice versa, do not exist. In this project, we develop models for mechano-chemical interactions of elastic structures. The fundamental technique is a multiplicative decomposition of deformation gradients into an active part, that is caused by growth, and the elastic parts.
To study processes of biological pattern formation, it is essential to first develop powerful numerical simulation tools based on three-dimensional adaptive finite elements and strongly coupled and efficient parallel multigrid solvers.



## Fluid-Structure Interactions in Fully Eulerian coordinates

PhD thesis of Stefan Frei
Project partners: Prof. Dr. Stefan Turek (TU Dortmund); Dr. Thomas Wick (ICES, UT Austin)

Models for Fluid-Structure interactions must align the natural Eulerian coordinate system of fluid dynamics with the Lagrangian coordinate systems of solid dynamics. The standard approach, the ALE method overcomes this problem by mapping the flow problem onto a reference framework. This approach fails, if deformations are so large, that such a mapping cannot be regular and invertible. We have developed a new technique, that is based on Eulerian coordinates. The great advantage of the Eulerian model is the use of physical coordinate systems only. Large deformation and motion cannot cause problems. The Eulerian formulation is a front-capturing method with a fixed background mesh (see the Figure). The model is strictly monolithic, implicit solution and discretization techniques are available. This project has a high impact for several applications in hemodynamics, where the coupling between fluid and solid is very stiff and where very large deformations up to contact are possible.

# Statistical Natural Language Processing


## PROF. DR. STEFAN RIEZLER

**Prof. Stefan Riezler is head of the chair of Linguistic Informatics at Heidelberg University since 2010, after spending a decade in the world's most renowned industry research labs (Xerox PARC, Google). He received his PhD from the University of Tübingen in 1998, and conducted post-doctoral work at Brown University in 1999.**

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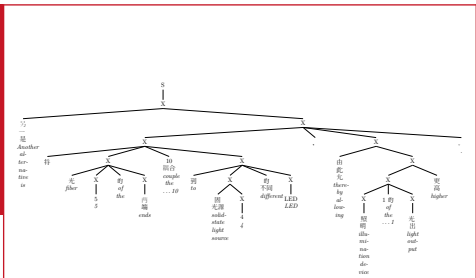
Organizing information across language barriers is one of the most important problems of the modern information society. For example, communication and collaboration in social media such as Twitter or Wikipedia is happening in multiple languages in parallel, with insufficient support to communicate across language. As another example, patent lawyers are required to assess the novelty of a patent by searching for prior art in publications worldwide, and thus need to conduct cross-lingual patent retrieval and translation of patent texts. The research group focuses on solutions to these industry-vital and communication-enabling technologies by a combination of statistical machine learning techniques and natural language processing technology. One of the central themes of the group's research is the grounding of multilingual technology in the applications in question. For example, in cross-lingual patent prior art search, instead of a pipeline of query translation and information retrieval, this means to formalize objective functions and algorithms that allow to optimize the cross-lingual systems directly and efficiently for the problem of ranking over a very large search space. This is done by incorporating stochastic learning techniques into a distributed learning framework, for efficient and effective computation of models with millions of features. The group has worked on applications of statistical machine translation and cross-lingual information retrieval to large complex datasets such as patents, social media texts, and spoken language, for languages such as Chinese, Japanese, Russian, English, or German. The group contributes to the development of an open-source platform for statistical machine translation and cooperates with various research groups on grounded translation technology.

**LEARN MORE**

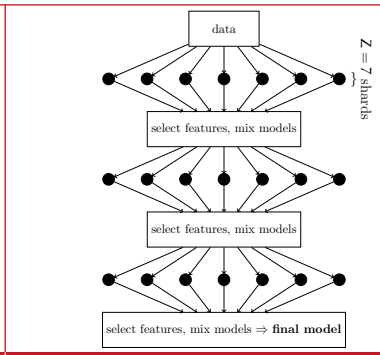
**Key Publication** Patrick Simianer, Stefan Riezler, Chris Dyer (2012). Joint Feature Selection in Distributed Stochastic Learning for Large-Scale Discriminative Training in SMT. In Proceedings of the 50th Annual Meeting of the Association for Computational Linguistics. (http://www.cl.uni-heidelberg.de/~riezler/publications/papers/ACL2012.pdf)



## Large-scale Discriminative Training for Statistical Machine Translation

PhD thesis of Patrick Simianer
Project partners: Prof. Stefan Riezler (Heidelberg University); Prof. Chris Dyer (Carnegie Mellon University, Pittsburgh, USA)

With a few exceptions, discriminative training in statistical machine translation (SMT) has been content with tuning weights for large feature sets on small development data. Evidence from machine learning indicates that increasing the training sample size results in better prediction. The goal of this project is to show that this common wisdom can also be brought to bear upon SMT. In this project, we deploy local features for SMT based on synchronous context-free grammars (SCFGs) that can be read off from rules at runtime, and present a learning algorithm that applies l1/l2 regularization for joint feature selection over distributed stochastic learning processes. We present experiments on learning weights for 5 millions features on 1.5 million training sentences, and show significant improvements over tuning discriminative models on small development sets. The picture shows the effect of sparse syntax features in hierarchical phrase-based translation of patents from Chinese to English.




## Improved Discriminative Training in SMT by Multi-Task Learning from Random Shards

M.A. Patrick Simianer, Prof. Stefan Riezler

Multi-task learning has been shown to be effective in various applications, including discriminative SMT. In the context of the DFG-funded project "Cross-language Learning-to-Rank for Patent Retrieval", we investigated the question whether multi-task learning depends on a "natural" division of data into tasks that balance shared and individual knowledge, or whether its inherent regularization makes multi-task learning a broadly applicable remedy against overfitting. We conducted an experimental comparison where "natural" tasks are defined as sections of the International Patent Classification versus "random" tasks defined as random shards in the context of patent SMT. Both versions of multi-task learning yield significant improvements over independentand pooled training, however, the difference between "natural" and "random" tasks ismarginal. This is an indication for the usefulness of multi-task learning as a generic regularization tool.

# Terrestrial Systems

**PROF. DR. KURT ROTH**

**Kurt Roth studied Physics and Mathematics at ETH Zürich, where he also received his doctoral degree. Following postdoc years at UC Riverside, he became a professor of soil physics at University of Hohenheim and then a professor of experimental physics (environmental physics) at Heidelberg.**

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Terrestrial systems evolve as the interface between atmosphere and lithosphere. Major components are sediments, soils, and vegetation. They play key roles in the transfer of energy in the Earth system, in the global water cycle, and in the transfer and storage of carbon and nitrogen. Terrestrial systems are easily the most complicated and complex part of our physical environment due to their multiscale nature that covers more than 14 linear orders of magnitude, due to the multitude of closely coupled processes that are already individually highly nonlinear, and due to the resulting self-organization and evolution.

Our group approaches these systems along two lines: (A) focussing on a subset of processes – flow and transport in the soil-atmosphere continuum at scales of 0.1...1'000 m –, integrate experimental studies, monitor natural sites, model and numerically simulate them to gain a comprehensive and quantitative representation of the specific reality, and (B) starting from highly abstracted representations, explore the chaotic and complex dynamics of various environmental systems, the effects of coupling between different such systems, and the feasibility to control them. Line A is our demonstrated expertise, line B is just starting.

We installed permafrost monitoring stations on Svalbard and on the eastern (Qinghai province) and western (Xinjiang province) Tibetan plateau. They produce a flow of data on profiles of soil temperature and water content, meteorological and radiative variables. A numerical model we developed represents the dynamics at both, arctic and high-altitude sites. We operate two test sites near Heidelberg to develop and demonstrate the integration of ground-penetrating radar (GPR), traditional measurements, and hydrologic experiments. Tools include numerical solutions of Maxwell's (electromagnetic fields) and Richards' (soil water) equation in heterogeneous media, and ensemble Kalman and particle filters for data assimilation.

**LEARN MORE**

**Key Publication** Buchner, J. S., U. Wollschläger, and K. Roth, 2012: Inverting surface GPR data using FDTD simulation and automatic detection of reflections to estimate subsurface water content and geometry, Geophysics, 77, H45-H55, doi: 10.1190/geo2011-0467.1

## ASSESS – Hydrogeophysics (Line A)

PhD: Hannes Bauser, Daniel Berg, Lisa Feustel, Stefan Jaumann; Postdoc: Patrick Klenk; Lead: Kurt Roth

**The ASSESS site is a 20 x 4 x 2 m³ tank filled with partly parallel layers of different sands, instrumented to measure soil moisture and temperature, and a fully controllable water table (image). The spatial distribution of the soil water and its dynamics during transient experiments is observed with different multi-channel ground-penetrating radar instruments. Through extensive calibrations and corresponding data analysis we currently enjoy a precision that is an order of magnitude better than what is achieved by other groups. Detailed numerical simulation of the propagation of electromagnetic waves and of the soil water flow, both in a rather complicated architecture, enables us to identify the form of the hydraulic parameterization and to estimate the values of its parameters. Current efforts aim at expanding data assimilation methods to gain an optimal representation of the system, acknowledging that formulation of the dynamics, architecture and material properties, external forcings, and measured data are all inaccurate.**

## Self-organized soil-atmosphere coupling (Line B)

Students: Jasper Franke (now at PIK Potsdam), Eric Gleiß, Jannes Jegminat, Valentin Kratzsch, Lukas Riedel, Juliane Weber; PhD: Marian Piatkowski (in Parallel Computing Group of Peter Bastian); Lead: Kurt Roth

**The soil-atmosphere interface is the determining factor in a number of important phenomena, e.g., the droughts in the US Southwest (image). A number of processes make it highly self-organizing and often lead to critical states. We conceptually and numerically explore key aspects of this interaction: (i) the role of the combination of climate- and soil-types on the evaporation regime that leads to the soil moisture-precipitation feedback, (ii) the self-organization of vegetation patterns in semi-arid regions and their stability in fluctuating environments, (iii) the morphology of root systems and their development with different soil water regimes, and (iv) the role of topography. We started to integrate these aspects into a process-based numerical model in the DUNE framework. This will allow realistic simulations with balanced representations of all processes, eventually including turbulent transport in the atmosphere.**

# Image and Pattern Analysis


## PROF. DR. CHRISTOPH SCHNÖRR

**Christoph Schnörr received his degrees in Electrical Engineering and Computer Science from the Technical University of Karlsruhe. He moved to Hamburg and Mannheim and then joined Heidelberg University where he is co-directing the Heidelberg Collaboratory for Image Processing (HCI) and coordinating the Research Training Group on Probabilistic Graphical Models and Applications in Image Analysis, that is funded by the German Research Foundation (DFG).**

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Images and video data abound nowadays. Their analysis and computer-assisted interpretation requires models that bridge several levels of abstraction, from raw image data processing up to high-level decisions based on the context of the entire scenario. The design of systems that computationally analyse image data in a reproducible way, without ad-hoc engineering and the need to carefully set tuning parameters, constitutes a long-term problem of mathematical research.

The group focuses on hierarchical probabilistic models from a variational viewpoint, at the interface between continuous models of low-level image data and decisions in a spatial or spatio-temporal context. A major issue is to balance model expressiveness and amenability to variational analysis in view of computational inference based on large data sets.

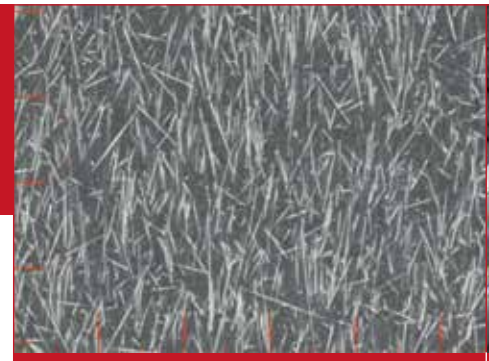
Examples of theoretical research include average-case performance bounds that enable to apply the compressed sensing paradigm to realistic imaging sensors and quantitative prediction, the derivation of tight convex relaxations that integrate local data models and statistical prior knowledge in a mathematically novel and principled way, the extension of convex analysis and programming to geometric settings involving basic manifolds, and the derivation of problem splitting techniques that facilitate the implementation of resulting algorithms on various (parallel, sequential, asynchron, etc) architectures.

Recently, as part of the mission of the Research Training Group 1653, the group initiated and coordinated a software framework for benchmarking and assessing the performance of a broad range of state-of-the-art solvers for inference with probabilistic graphical models (http://hci.iwr.uni-heidelberg.de/opengm2/).

The group is cooperating with various industrial partners on concrete and challenging image analysis problems that directly relate to the above sketched basic research projects.

**LEARN MORE**

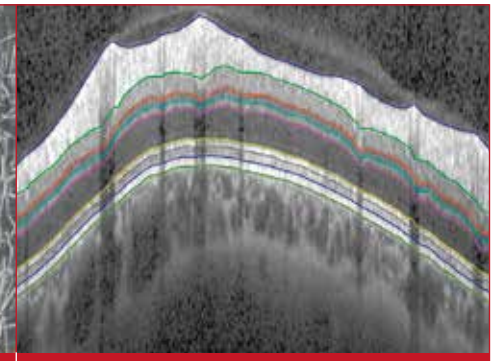
**Key Publication** Paul Swoboda, Christoph Schnörr, Convex Variational Image Restoration with Histogram Priors, SIAM Journal Imaging Science, 6(3), 1719–1735, 2013



## Analysis of Low-Dimensional Structure in 3D Image Data

PhD thesis of Peter Markowsky
Project Partners: Gabriele Steidl, Claudia Redenbacher (TU Kaiserslautern); Joachim Ohser (Darmstadt); Evgeny Spodarev (University of Ulm); BASF GmbH, MANN+HUMMEL GmbH, Harting KGaA

**Accurate segmentation and statistical modelling of fiber structures in 3D tomographic image data are key to optimising mechanical properties of composite materials produced by injection molding. Both established and state-of-the-art methods of image processing fail to extract reliably the geometry of high-density structure while effectively coping with measurement noise. This project develops novel mathematical methods for such image analysis tasks that combine low-level image signal processing for single structure detection and segmentation with a high-level stochastic model of structure interaction in terms of a marked point process. The consortium involves 5 academical groups from statistics, stochastics, optimisation and image analysis, and industrial partners focusing on various scenarios that involve low-dimensional structure in 3D image data.**



## Intra-Retinal Layer Segmentation in 3D OCT Images

Fabian Rathke (Heidelberg University); Stefan Schmidt (Heidelberg Engineering GmbH); Christoph Schnörr (Heidelberg University)

**Optical coherence tomography (OCT) is an in vivo imaging technique, measuring the delay and magnitude of backscattered light. Providing micrometer resolution and millimeter penetration depth into retinal tissue, OCT is well suited for ophthalmic imaging and hence has become a standard in clinical ophthalmology. The introduction of spectral-domain OCT dramatically increased the imaging speed and enabled the acquisition of 3-D volumes containing hundreds of B-scans. Since manual segmentation of retinal layers is tedious and time-consuming, a graphical model has been developed that enables to infer topologically correct and geometrically accurate segmentations along with uncertainties by evaluating the full a-posteriori distribution over segmentations. Further details: Medical Image Analysis 18(5): 781–794, 2014.**

# Theoretical Physics of Complex Biosystems

**PROF. DR. ULRICH SCHWARZ**

**Ulrich Schwarz holds the chair for theoretical physics of complex systems at the Institute for Theoretical Physics. His group uses concepts and methods from physics and materials science to investigate the mechanics of biological cells, including their adhesion and migration in response to environmental stimuli.**

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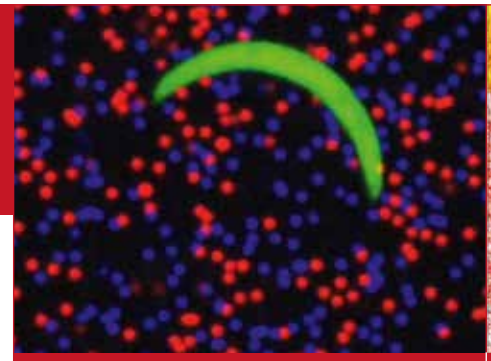
Biological cells and organisms are among the most complex systems that we know. Traditionally the analysis of cellular behaviour has been focused mainly on the underlying genetic and biochemical mechanisms. However, recently it has become clear that also mechanical aspects are essential for understanding the way in which biological cells make decisions. For example, it has been shown that stem cell differentiation can be guided not only by soluble factors, but also by the stiffness of the environment.

Our group uses concepts and methods from theoretical and computational physics to investigate how cells interact mechanically with their environment. First we work on a computational procedure called “traction force microscopy” that allows us to measure cellular forces on soft elastic substrates with high spatial resolution. Second we develop models for force generation by cells, in particular through polymerization of biopolymers like actin filaments and molecular motors like myosin II. Third we study the coupling between the substrate and intracellular force generation at localized sites of adhesion, which can be considered as stress gauges that the cell uses to measure the mechanical properties of its environment. Fourth we develop models for the global coupling of these processes through cell shape and signaling. Fiveth we study the consequences of cellular mechanosensing for cell migration and tissue dynamics.

In the long run, this research effort should result in a systems level understanding of cells that considers not only their genetic and biochemical, but also their mechanical basis. Our research is strongly shaped by a close collaboration with experimental groups and by using recent advances in the computational sciences, including new developments in image analysis, finite element methods and particle-based computer simulations.

**LEARN MORE**

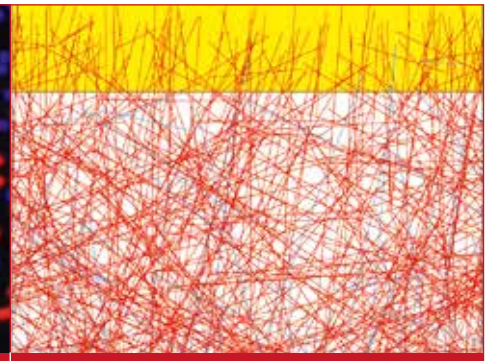
**Key Publication** Ulrich S. Schwarz and Samuel A. Safran. Physics of adherent cells. Reviews of Modern Physics 85:1327–1381, 2013.



## Migration of malaria parasites

PhD project of Anna Battista
Collaboration partners: Prof. Dr. Friedrich Frischknecht (Medical School); Prof. Dr. Joachim Spatz and Dr. Heike Böhm (Physical Chemistry)

**At the beginning of a malaria infection, a mosquito injects the parasite into the human skin in the form of a crescent-shaped sporozoite (compare image). While sporozoites move in circles on flat culture substrates, they follow irregular trajectories with locally circular characteristics in the skin. In order to understand the physical principles underlying sporozoite movement, we combine microfabricated obstacle arrays, image processing and mathematical modelling. Using geometrical considerations and agent-based computer simulations, Anna Battista investigates if sporozoites might be guided by the mechanical interactions with their environment towards blood vessels. She applies a similar approach to dense populations of sporozoites that are typical for the situation in the salivary gland of the mosquito and that lead to swirls on flat culture substrates.**



## Structural transitions in growing actin networks

PhD project of Julian Weichsel
Collaboration partners: Prof. Dr. Vic Small and Dr. Urban (Vienna)

**Migrating tissue cells use rapidly polymerizing networks of the filamentous protein actin to push their membrane forward. In order to avoid long filaments that bend under force and to distribute the mechanical load over the network, cells make use of proteins that lead to filament capping and branching. Using computer simulations (compare image) and linear stability analysis of an ODE-model, Julian Weichsel has shown that two fundamentally different network architectures can be stable (PNAS 2010). Analyzing electron microscopy data from the collaborating experimental group, he indeed found evidence that in migrating keratocytes, such different network structures exist at the front versus the sides (Cytometry 2012). In subsequent work, he generalized the mathematical model to also describe non-flat obstacle geometries (New Journal of Physics 2013) and different orders of the branching reaction (Physical Review E 2013).**

# Theoretical Astrophysics

**PROF. DR. VOLKER SPRINGEL**

volker.springel@h-its.org www.h-its.org/tap

**Volker Springel's primary scientific interests lie in theoretical cosmology and computational astrophysics, with a focus on galaxy formation, large-scale structure of the Universe, gas dynamics in the intergalactic medium, formation and evolution of supermassive black holes, structure of dark matter halos, and on constraining dark energy.**

Galaxies are comprised of up to several hundred billion stars and display a variety of shapes and sizes. Their formation involves a complicated blend of astrophysics, including gravitational, hydrodynamical and radiative processes, as well as dynamics in the enigmatic "dark sector" of the Universe comprised of dark matter and dark energy.

Because the governing equations are too complicated to be solved analytically, numerical simulations have become a primary tool in theoretical studies of cosmic structure formation.

The Theoretical Astrophysics group led by Volker Springel at the Heidelberg Institute for Theoretical Studies (HITS), the Zentrum für Astronomie (ZAH) and the IWR, develops advanced numerical simulation codes for following structure growth far into the non-linear regime. Using large parallel supercomputers, the team models representative pieces of the Universe and aims to predict how galaxies formed and how they cluster in space. Their calculations connect the comparatively simple initial state left behind by the Big Bang some 13.5 billion years ago with the complex, evolved state of the Universe today.

A well-known simulation software developed by the group is the GADGET code, which is the most widely employed simulation code currently used in the field. It has allowed the computation of the Millennium Simulation, and of the Millennium XXL with more than 300 billion particles. More recently, the group has developed AREPO, a novel moving-mesh code for cosmological hydrodynamics that uses a finite-volume approach on a three-dimensional dynamic Voronoi tessellation. This code is particularly well suited to the high dynamic range in space and time posed by the galaxy formation problem. Thanks to its improved accuracy, important progress in forming realistic disk galaxies like the Milky Way could recently been made, including the prediction of magnetic fields very similar to those actually observed.

**LEARN MORE**

**Key Publication** M. Vogelsberger, S. Genel, V. Springel, P. Torrey, D. Sijacki, D. Xu, G. Snyder, S. Bird, D. Nelson, L. Hernquist, "Properties of galaxies reproduced by a hydrodynamic simulation", Nature, 509, 177 (2014)

## The Illustris Simulation

Volker Springel, Mark Vogelsberger, Shy Genel, Paul Torrey, Debora Sijacki, Dandan Xu, Greg Snyder, Simeon Bird, Dylan Nelson, Lars Hernquist

**A recent highlight of the group's work is the "Illustris Simulation" reported in Nature (May 8th, 2014), the currently largest and most advanced hydrodynamical simulation of galaxy formation. Carried out together with colleagues at Harvard University, the MIT, and the University of Cambridge, the team employed a refined treatment of galaxy formation physics implemented in the AREPO code. Besides gravity in the dark matter and cosmic baryons, the processes modeled include radiative cooling, star formation and stellar evolution, energy feedback by supernova explosions and growing black holes, as well as metal enrichment by stellar and galactic winds.**

**The calculation was carried out in a periodic box comoving with the cosmic expansion, covering a region of about 350 million lightyears across. It yielded for the first time a realistic mix of elliptical and spiral galaxies, thereby overcoming a decade old impasse in the field. Moreover, the simulation can explain the enrichment of heavy elements (so-called metals) in neutral hydrogen gas. Also, carefully prepared mock observations of the simulated universe show that the calculated galaxies are distributed in space as observed with telescopes. It thus appears that the standard model of cosmology is in principle capable of explaining galaxy formation, despite our present ignorance of the true physical nature of dark matter and dark energy.**

**The Illustris simulation produced more than 200 terabyte of data and required the combined power of 8,192 processors for several months, using the supercomputers CURIE in France and SuperMUC in Germany. It employed more than 18 billion particles and cells and bridged a dynamic range of more than one million per space dimension. The total CPU cost of the main simulation was about 19 million hours, with a total memory requirement of over 25 TB RAM. The rich data set of Illustris now allows a variety of novel predictions as well as comprehensive tests of cosmological theories of galaxy formation.**

# Physical Organic Chemistry


## PROF. DR. OLIVER TRAPP

**Oliver Trapp studied chemistry and obtained a doctoral degree from the University of Tübingen in 2001. After a postdoc at Stanford University he became Emmy Noether Group Leader at the MPI für Kohlenforschung in Mülheim in 2004. Since 2008 he is professor in Heidelberg. His awards include the Heinz Maier-Leibnitz Award and an ERC Starting Grant.**

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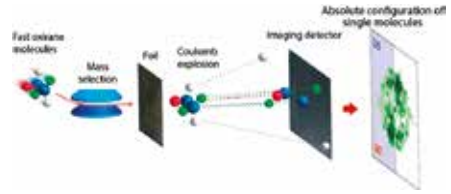
The Trapp research group is involved in the investigation and development of novel self-amplifying catalytic reactions, high-throughput screening of catalysts and the development of Coulomb Explosion Imaging as technique to directly image molecules and to visualize reactions in the future. The fields of research are manifold including a) on-column reaction chromatography, b) dynamic chromatography and determination of reaction kinetics, c) investigation of self-amplifying catalytic reactions, d) multiplexing chromatography and e) Coulomb Explosion Imaging. All these fields include calculations based on simulations of reaction networks and quantum chemical calculations to obtain insights into reaction mechanisms.
Finding new catalysts is of great importance for sustainable chemical processes in industrial applications as well as for expanding the spectrum of synthetic strategies in chemistry. Investigating reaction kinetics, particularly of catalyzed reactions is of fundamental importance in chemistry, biochemistry, and related sciences, because the understanding to control the transition state of a reaction allows the optimized design of new catalysts and benign processes. Therefore, the development of techniques for the comprehensive investigation of reaction kinetics is central importance, and especially the investigation of individual pathways in stereoselective transformations requires techniques to directly measure enantioselectivities.

Furthermore we are interested in imaging of molecules to determine absolute configurations by Coulomb Explosion Imaging.

**LEARN MORE**

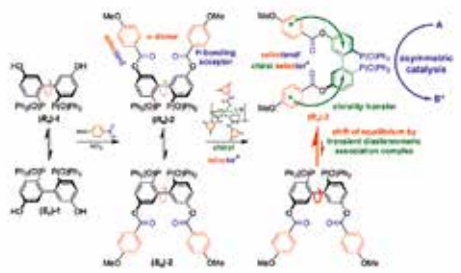

**Key Publication** P. Herwig, K. Zawatzky, M. Grieser, O. Heber, B. Jordon-Thaden, C. Krantz, O. Novotny, R. Repnow, V. Schurig, D. Schwalm, Z. Vager, A. Wolf, O. Trapp, H. Kreckel, Science 2013, 342, 1084–1086. Imaging the absolute configuration of a chiral epoxide in the gas phase


## Imaging the absolute configuration of a chiral epoxide in the gas phase


Kerstin Zawatzky
Project partners: Zeev Vager (Weizmann Institute Rehovot, Israel); Dirk Schwalm, Andreas Wolf, Holger Kreckel (Max-Planck-Institut für Kernphysik, Heidelberg)


**In chemistry and biology, chirality, or handedness, refers to molecules that exist in two spatial configurations which are incongruent mirror images of one another. Almost all biologically active molecules are chiral, and the correct determination of their absolute configuration is essential for the understanding and the development of processes involving chiral molecules. Anomalous X-ray diffraction and vibrational optical activity measurements are broadly used to determine absolute configurations of solid or liquid samples. Determining absolute configurations of chiral molecules in the gas phase is still a formidable challenge. Here we demonstrate the determination of the absolute configuration of isotopically labeled (R,R)-2,3-dideuterooxirane by foil-induced Coulomb explosion imaging of individual molecules. Our technique provides unambiguous and direct access to the absolute configuration of small gas-phase species, including ions and molecular fragments.**



## Self-amplifying enantioselective catalysts


Dr. Frank Maier, Kerstin Zawatzky, Golo Storch
Marie-Louise Morkos, Matthias Kamuf


**Stereolabile interconverting catalysts open up the possibility of directing enantioselectivity in asymmetric synthesis by formation of diastereomeric complexes with chiral auxiliaries and deracemization. However, the stoichiometrically used auxilliaries can significantly limit the potential applications of such systems. We synthesized new tropos ligands containing achiral selectands in the backbone, which forms transient diastereomeric associates with amylose-tris-3,5-dimethylphenyl carbamate as a selector and thus deracemizes. The obtained enantiomerically enriched BIPHEPO was successfully used in the organocatalytic asymmetric double aldol addition of substituted methyl ketones to form benzaldehyde. This strategy combines an on-column deracemization with the high stereoinduction of chiral biarylphosphineoxides and opens up new possibilities in the field of self-amplified asymmetric syntheses. Simulation of this reaction network gives further insights into self-amplifying processes.**

# Molecular and Cellular Modeling


## PROF. DR. REBECCA WADE

**Rebecca Wade studied at Oxford University, obtaining a doctorate in Molecular Biophysics in 1988. Following postdocs in the USA, she became a group leader at EMBL in Heidelberg. She moved to the Heidelberg Institute for Theoretical Studies (HITS) in 2001. She is professor at the Zentrum für Molekulare Biologie der Universität Heidelberg (ZMBH).**

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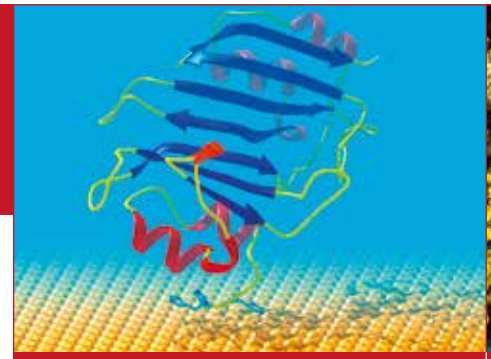
Molecular recognition, binding and catalysis are fundamental processes in cell function. The ability to understand how macromolecules interact with their binding partners and participate in complex cellular networks is crucial to the prediction of macromolecular function, and to applications such as protein engineering and structure-based drug design. The Molecular and Cellular Modeling group works on the development and application of computer-aided methods to model, simulate and predict how biomolecules interact. The focus is on the interactions of proteins and the computational approaches are mostly based on three-dimensional macromolecular structures. An interdisciplinary approach is taken, entailing collaborations with experimentalists and a concerted use of physics- and bio-/chemo-informatics-based computational approaches. Techniques cover a wide spectrum from interactive, web-based visualization tools to atomic-detail molecular and Brownian dynamics simulations. Recent projects have included Brownian dynamics simulations to investigate the effects of macromolecular crowding on protein diffusion and association, molecular dynamics simulations to study how membrane binding affects the dynamics of ligand tunnels in cytochrome P450 enzymes, molecular modeling to study species-specific allosteric regulation of enzymes of the central metabolism of lactic acid bacteria, the design of enzyme inhibitors with anti-parasitic activity, and the development of a methods to identify and analyze transient binding pockets in proteins.

**LEARN MORE**

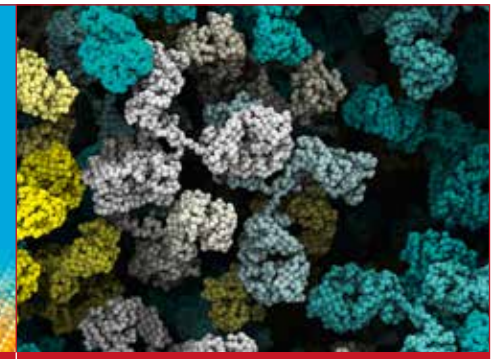

**Key Publication** Kokh DB, Richter S, Henrich S, Czodrowski P, Rippmann F, Wade RC: TRAPP: a tool for analysis of transient binding pockets in proteins. J Chem Inf Model., 53: 1235–52, 2013.

## Modeling and Simulation of Protein-Surface Interactions

PhD thesis of Musa Özboyaci
Project partners: Daria Kokh, Rebecca Wade (HITS); Stefano Corni, Giorgia Brancolini (Center S3, CNR Nanoscience Institute Italy); Gideon Schreiber (Weizmann Institute); Peter Bastian (IWR)

Proteins interact with inorganic and metal surfaces in many biological systems, and these interactions are critical to applications in biotechnology and medicine. Our understanding of the mechanisms and determinants of these interactions at the molecular level is, however, very limited. We have focused on the simulation of protein-nanoparticle interactions that have been characterized biophysically by our cooperation partners. We perform rigid-body Brownian dynamics (BD) simulations followed by flexible-body molecular dynamics (MD) simulations. The BD simulations using our ProMetCS (Protein-Metal Continuum Solvent) model enable us to study how proteins recognize and diffuse towards surfaces, the MD simulations to observe changes in protein conformation and hydration after binding. In this project, we are working on efficient data storage techniques to decrease memory requirements in the BD simulations. These are implemented in our Simulation of Diffusional Association (SDA) software.



## Simulation of protein diffusion at high macromolecular concentrations: towards understanding crowded cellular environments

Paolo Mereghetti, Daria Kokh, Julia Romanowska, Rebecca Wade (HITS); Jessica Balbo, Dirk-Peter Herten (Bioquant, Heidelberg University)

Proteins have evolved to function in an environment that is densely packed with macromolecules. How this crowded environment influences the motion of the proteins and their binding and catalytic properties is not well understood. Simulations of protein solutions provide a way to investigate the different factors that contribute to the effects of macromolecular crowding. We have developed a Brownian dynamics simulation procedure with an atomic-detail protein-protein interaction model and a mean-field model of hydrodynamic interactions. Our simulations provide insights into the effects of high protein concentrations on protein diffusion and association. For example, the importance not only of the excluded volume but also of the shape of crowding proteins for the diffusion of (tracer) proteins was shown by comparison of simulations of solutions of two proteins with different shapes (bovine serum albumin and $\gamma$-globulin) with measurements by fluorescence correlation spectroscopy.

# Differential Geometry

**PROF. DR. ANNA WIENHARD**

**Anna Wienhard obtained her doctoral degree in Mathematics from the University of Bonn. She was assistant professor at Princeton before coming to Heidelberg, where she holds the Chair for Differential Geometry. She is PI of the NSF-funded Research Network GEAR and speaker of the Partnership Mathematics and Physics at Heidelberg University.**

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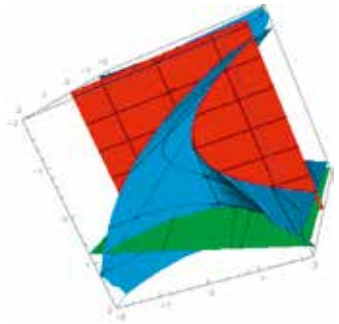
Symmetries arise everywhere in nature and play an important role in biology, chemistry, physics and mathematics. Mathematically symmetries are described the group of transformations, which preserve the inherent symmetries of a pattern or space. Patterns with many symmetries are often optimal configurations, which consequently are rigid. But sometimes special patterns with many symmetries arise in families and form so called moduli spaces. Our research is concerned with such rigidity phenoma as well as with moduli spaces of flexible patterns.

We study geometric structures on surfaces, three-dimensional and higher dimensional objects, and the corresponding moduli spaces. Information about such structures can be gathered from the fundamental group of these spaces and their representation into various transformation groups. This relates the moduli spaces of such geometric structures intimately to the moduli spaces of flat bundles. This moduli space is a central object in several mathematical fields. These spaces often arise as spaces of solutions to basic geometric problems, and their global properties provide powerful topological invariants. The ubiquity of these spaces demands the interplay of methods and viewpoints from multiple mathematical communities. These communities include: Classical Teichmueller theory, Kleinian groups, 3-manifold topology, Moduli of vector bundles and gauge theory, Mathematical physics, Dynamical systems, Invariant theory, and Geometric PDE's.
The research group is also working on visualizations of different geometric structures.

**LEARN MORE**

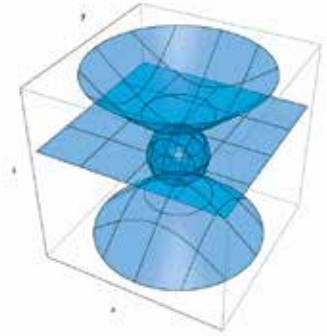
**Key Publication** Olivier Guichard, Anna Wienhard, Anosov representations: Domains of discontinuity and applications, Inventiones Mathematicae, Volume 190, Issue 2 (2012), 357–438.



## Anosov representations

Anna Wienhard (Heidelberg University); Olivier Guichard (Strasbourg); Francois Gueritaud, Fanny Kassel (Université Lille)

**Transformation groups of spaces with rich symmetries are semisimple Lie groups, as e.g. the matrix group SL(n,R). Consequently symmetries of patterns are often discrete subgroups of these groups. Since the celebrated rigidity theorems by Mostow and Margulis in the 1960's and 1970's, Lie groups of higher rank, such as SL(n,R) for n>2, have been predominantly linked with rigidity phenomena.**
**In the past 15 years various discoveries led to rich classes of discrete subgroups in higher rank Lie groups which are not rigid, but have interesting dynamical, geometric or arithmetic properties. A particular nice class of such subgroups is given by Anosov representations.**
**In this research project, we show that Anosov representations are intimately linked to holonomy representations of geometric structures. We also establish a strong link between Anosov representations and proper actions on homogeneous spaces, which allows to answer several questions about Clifford-Klein forms.**



## Geometric Transitions

Anna Wienhard, Nico Treib (Heidelberg University); Jeff Danciger (UT Austin); Daryl Cooper (UC Santa Barbara)

**In his Erlangen Program (1872) Felix Klein proposed a new definition of geometry, which has been very influential in mathematics and physics until today. His approach allows to see classical Euclidean geometry, spherical geometry and the newly developed hyperbolic geometry in a common framework.This allows to transition continuously from one geometry to another. Such geometric transitions play a role in Thurston's geometrization program.**
**In this research project we develop a general framework for geometric transitions of various geometries. We intend to describe the complete graph of transitions for the eight three-dimensional Thurston geometries.**

**The big challenge is to transfer geometrical properties from one side of the geometric transition to the other. This is of particular interest for transitions between hyperbolic geometry on one and anti de-Sitter geometry on the other hand.**

# GIScience Research Group


## PROF. DR. ALEXANDER ZIPF

**Alexander Zipf studied Mathematics & Geography in Heidelberg and did his PhD at the European Media Laboratory. He was Professor for Applied Computer Science at FH Mainz and afterwards the Chair of Cartography at Bonn University before returning to Heidelberg. He is speaker of the graduate school CrowdAnalyser and an editor of „Transactions in GIS".**

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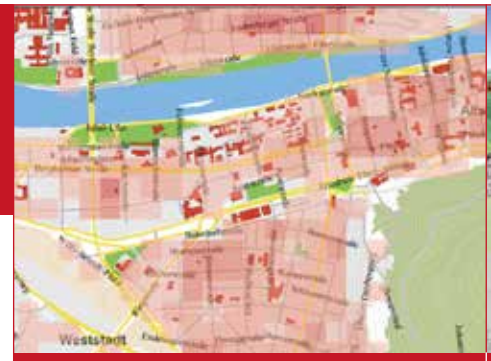
The primary research focus is reflected by the PhD graduate school CrowdAnalyser. Here the group investigates and enhances the quality and usage potential of user-generated geographical information using spatial data mining, machine learning, spatial analysis and geocomputation. The group develops new methods for spatio-temporal analysis, spatial data fusion (e.g. map matching) and applications of so called Volunteered Geographic Information (VGI) such as OpenStreetMap or from social media. Beside of investigating VGI and developing new methods for its spatio-temporal analysis and automated enrichment, the group has a strong focus on 3D geo-information. In particular also new methods for crowdsourcing 3D geoinformation are being developed. Corresponding research areas comprise data acquisition and retrieval using state-of-the-art 3D remote sensors such as laser scanning enriched by other potential sources such as crowdsourced data provided by human sensors. The focus here is the development of GIS-based algorithms for 3D data processing and analysis in order to improve the understanding of geographical phenomena. Applications cover the natural environment (e.g. geomorphology, precision farming and forestry) and the man-made landscape (e.g. Archeology and digital cultural heritage, solar potential assessment for buildings and hedonic price modeling).

Further we work on enhancements of Web-based Geographic Information Services (GIS) in different domains such as disaster management, eHumanities, agriculture, traffic, energy and environment. The research extends so called Spatial Data Infrastructures (SDI) by adding the third dimension (3D city & landscape models), location based services (LBS, e.g. specialized applications in routing- , navigation and traffic management), dynamic sensor data and of course web-based geoprocessing and geographic analysis functionalities.

**LEARN MORE**

**Key Publication** Over, M., Schilling, A., Neubauer, S. & Zipf, A. (2010): Generating web-based 3D City Models from OpenStreetMap: The current situation in Germany. CEUS. Computers, Environment and Urban Systems. Volume 34, Issue 6, November 2010, Pages 496–507. DOI: 10.1016/j.compenvurbsys.2010.05.001



## PsychoGeoinformatics – Methods for the fusion and analysis of geodata for the epidemiological analysis of mental diseases

Helen Dorn (GIScience); Prof. Dr. Andreas Meyer-Lindenberg (ZI Mannheim)

According to epidemiological research mental diseases like depressions and anxiety disorder can be related to socio-economic and to environmental risk factors. In this project it is the aim to address the specific relationship between mental stress and urban characteristics. Therefore heterogeneous spatial data from a various sources (administrative, private and crowd sourced) has to be collected, processed and integrated. The approach is to create a homogenous spatial database that includes relevant socio-economic data (e.g. population density, crime statistics, migration- and unemployment ratio etc.) and data regarding the urban environment (e.g. noise, air quality, access to public green space, among others) for the study area in the Rhine-Neckar region. The relationship between mental stress and the urban environment will thereafter be addressed by spatial correlating data (diaries, trajectories, health data etc.) from probands and patients with the spatial urban environment data.


## OSM-3D – Generating global 3D landscape and city models from Volunteered Geographic Information

Nicolas Billen, Michael Auer, Dr. Hongchao Fan

Within the last years Volunteered Geographic Information (VGI) has become a promising new data source. Most prominently, the OpenStreetMap (OSM) project maps our world in high detail. However, this data is mostly restricted to two dimensions. In order to come closer to an Open 3D Digital Earth new approaches and methods for enriching and converting 2D data into 3D urban models and 3D landscape models at different Levels of Detail (LoD) are being developed. This includes the investigation of methods for the fusion of spatial data, the automated generation of 3D objects, as well as for the visualization and the respective client-server infrastructure for the Web-based delivery of the generated 3D scenes on a global scale. Currently over 128 millions of buildings are managed in the projects 3D geodatabase and visualized in 3D through specific Web-services worldwide. Further methods for crowdsourcing and integrating richer 3D geodata through new low cost sensor are being investigated.

## IMPRINT

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