

*Sixteenth
Biennial Status Report*

March 2021 – March 2023

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1 Overview

1.1 Organization and Staff

Directors and Departments: The Max Planck Institute for Informatics was established in 1990, with Kurt Mehlhorn as founding director. Harald Ganzinger was appointed shortly afterwards; he passed away in 2004. Currently, the Institute has six directors (with appointment periods given in parentheses): Danupon Na Nongkai (2022–2048), Algorithms & Complexity (D1); Bernt Schiele (2010–2035), Computer Vision and Machine Learning (D2); Anja Feldmann (2018–2033), Internet Architecture (D3); Hans-Peter Seidel (1999–2026), Computer Graphics (D4); Gerhard Weikum (2003–2023), Databases and Information Systems (D5); and Christian Theobalt (2021–2043), heading the newly founded department on Visual Computing and Artificial Intelligence (D6). Thomas Lengauer (2001–2018) and Kurt Mehlhorn (1990–2019) have emeritus status; Kurt Mehlhorn continues as scientist in the department on Algorithms and Complexity (D1). In addition to the departments, the Institute has a permanent independent research group on Automation of Logic, headed by Christoph Weidenbach, and an independent research group on Network and Cloud Systems, headed by Yiting Xia. Yiting Xia successfully applied to the tenure-track openings of the Max Planck institutes in computer science, a joint recruitment campaign. Tenure track openings are an additional instrument for recruiting talent that has been installed recently. In total, the Institute currently has 140 scientists, out of which 96 are doctoral students¹ and 44 have a doctoral degree.

Senior Researchers: The Institute has five scientific ranks: director, senior researcher with tenure, senior researcher on tenure track, senior researcher, and researcher. Senior researchers with tenure and senior researchers roughly correspond to tenured associate professor and non-tenured assistant professor in the North American system. The process for appointing senior researchers is similar to faculty appointment procedures, and involves reference letters from international top researchers. The appointment committee comprises the directors of the Institute and a faculty member of Saarland University. In addition to the typically non-tenured senior researcher appointment process, we have established a tenure-track senior researcher career path. Together with the MPI for Security and Privacy and the MPI for Software Systems we invite applications in all areas of computer science. In the reporting period, the Institute has been home to 12 senior researchers, in addition to its directors.²

Senior researcher positions are not tenure-track, in general. We expect the vast majority of our senior researchers to become professors, ultimately full professors, or leading researchers

¹Including nine students financed together with Saarland University.

²Martin Bromberger, Dengxin Dai, Tobias Fiebig, Oliver Gasser, Andreas Karrenbauer, Karol Myszkowski (tenured), Simon Razniewski, Rishiraj Saha Roy, Paul Swoboda, Christoph Weidenbach (tenured), Philip Wellnitz, Yiting Xia (tenure-track)

in industry. A strong indicator for the success of the model is the high number of faculty positions that our alumni have received at universities all over the world (see Section 1.5).

Figure 1.1 shows the organizational structure and the research areas of the Institute. Each department pursues a number of research areas, and each area has its coordinator(s). The coordinating scientists are senior researchers or postdoctoral researchers with strong potential for becoming senior researchers.

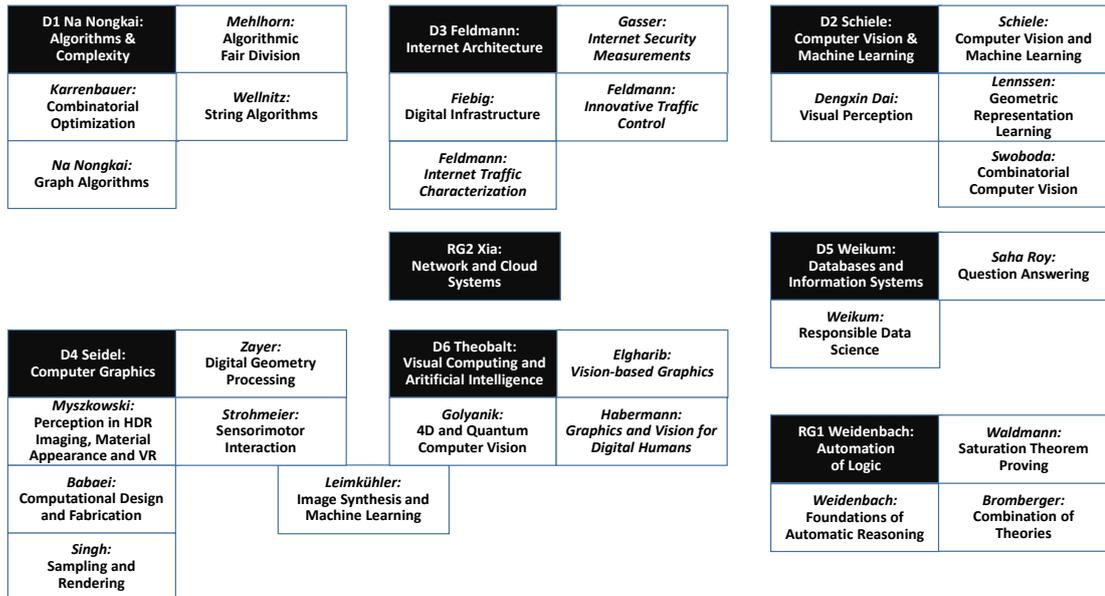


Figure 1.1: Research Areas of the Institute (as of March 2023)

Doctoral Students: As of March 2023, there are 96 doctoral students being supervised by members of the Institute, including 21 women (about 22%). 74 of the 96 students are non-German. The Institute does not grant degrees. In this regard, we closely collaborate with Saarland University. Members of the Institute teach courses at the university and supervise students at all levels. Upon appointment to senior researcher, the Computer Science Department of Saarland University decides whether to grant the senior researcher the right to supervise doctoral students on a case by case basis. Currently, this right has always been granted to all senior researchers of the Institute.

Joint Administration and Technical Support: The Institute shares the IT support group, administration, library, and facility management with the MPI for Software Systems. Both institutes currently count 54 full-time employees including 21 IT support staff in these shared areas.

1.2 Scientific Vision and Strategic Goals

Algorithms and their applications are and have always been the main focus of the Institute. They are the core of what makes computer systems useful and productive. They influence every aspect of our daily lives and are the basis for industrial change. Throughout the last decade, major parts of our research effort have focused on multimodal computing. The grand challenge is to understand, search, and organize large, distributed, noisy, incomplete, and diverse information in a robust, efficient, and intelligent manner. Our research ranges from foundations (algorithms and complexity, automation of logic) to a variety of multimodal domains (computer graphics and vision, geometric computation, intelligent information systems, adaptive networks). In recent years, research on foundations of machine learning, as well as the investigation of machine learning and artificial intelligence methods at the intersection to the aforementioned research domains, has become an important part of the research of our institute. The overarching mission of the Institute is to be one of the world's top players and strategic trend-setters on these topics.

Most of the major advances in computer science have come through the combination of new theoretical insights and application-oriented experimental validation, all driven by outstanding researchers. Our goal is, thus, to have impact through i) *publications*, ii) *software, services, and data resources* enabled by our research, and iii) *people* alike. In the following, Section 1.3 presents our achievements regarding the first two dimensions, and Section 1.5 discusses our performance history with respect to the third dimension.

1.3 Long-Term Achievements and Impact

Over the last twenty years, the Institute has pursued a number of high-risk high-gain endeavors, starting with foundational science and ultimately making great practical impact. In the following, we outline the highlights of the Institute's scientific achievements.

- Danupon Nanongkai's long-term vision is to develop techniques for designing efficient algorithms across computing paradigms and, along the way, achieve the following two goals simultaneously: (i) solutions for notorious long-standing open problems and (ii) efficient algorithms that can fully exploit the characteristics of modern computing devices and data. His group has and continues to make significant progress in this direction with, e.g., algorithms that resolved long-standing questions about shortest paths and graph connectivity that are theoretically efficient in many computing paradigms such as distributed, dynamic, and parallel settings. The former director Kurt Mehlhorn continues his work on fair division problems and algorithm engineering.
- Bernt Schiele's group has made strong contributions both to computer vision as well as machine learning. For example, the group has been contributing to multi-object tracking over the years and has won the Multi-Object Tracking Challenge twice. Another important direction has been person detection and multi-person pose estimation, both of which have led to a wide range of follow-up work in the community. More recently, the group has made ground-breaking contributions to inherently interpretable machine learning methods.

- Anja Feldmann’s research vision is to obtain insights from Internet measurements as foundation for shaping the evolution of the Internet by proposing optimizations and investigating alternative designs. As such her research group has and continues to address many challenges in *Internet measurement*, e.g., via a dead dive into the IoT backend ecosystem, as well as *innovative traffic control*, e.g., collaborative DDoS mitigation.
- The Computer Graphics Group stands out for its integrated view of *3D Image Analysis and Synthesis*. Hans-Peter Seidel has developed groundbreaking results on multiresolution modeling with special emphasis on new metaphors for editing and shape deformation, and novel data structures for high performance geometry processing. Karol Myszkowski has been and continues to be one of the pioneers and a driving force in perception-based graphics.
- The *Visual Computing and Artificial Intelligence Department* headed by Christian Theobalt made groundbreaking contributions to hard research problems at the intersection of computer graphics, computer vision and artificial intelligence, notably machine learning. The department has contributed pioneering methods for high-fidelity capture, modeling, rendering and simulation of virtual humans and general dynamic scenes, recently also on the basis of groundbreaking new neuro-explicit algorithms. It is also did seminal work on neural scene representation and neural (inverse) rendering, generative modeling, robust real world perception and reconstruction, as well as foundational aspects of visual computing and machine learning.
- Christoph Weidenbach’s group is on the next level of automated reasoning systems. While SAT and SMT solving has meanwhile found many places as a daily tool in standard processes in research and industry, we are working on lifting this success to more expressive logics. To this end we develop a new automatic reasoning framework called *SCL: Clause Learning from Simple Models*.
- Gerhard Weikum and his team pioneered the theme of *Knowledge Harvesting*: automatically building comprehensive knowledge bases from Internet contents. This work provided the blueprint for industrial-strength knowledge graphs that are key assets for search engines, question answering and text analytics (at Google, Microsoft, Amazon, Apple etc.). The MPI-INF team has also advanced use cases of large knowledge bases, most notably, for natural language understanding and for question answering. The ground-breaking nature and practical impact of the YAGO project has been recognized by the Influential Paper Award of the Artificial Intelligence Journal and the W3C Test-of-Time Award for the most influential papers in the WWW conference series.
- Yiting Xia’s long-term goal is to re-architect cloud data centers with high-performance network infrastructures and networked systems. Her research group conducts fundamental research combining novel network hardware and software systems to re-design different layers of the network stack. Towards that, her group has built the first end-to-end testing framework for diverse data center network fabrics, proposed routing and transport protocols that challenge the conventional wisdom of TCP/IP, and optimized prominent cloud applications such as machine learning training and disaggregated storage.

High-Risk Research: When the above long-term projects started, they were far from the mainstream in their scientific communities; most were considered elusive and some even characterized as useless. Needless to say, not all of our bold endeavors have worked out. The sections about the six departments name some examples. Nevertheless, most of this work has resulted in novel insights (sometimes about what is, fundamentally or practically, non-viable) and often in influential publications.

1.4 Highlights 2021–2023 and New Research Directions

Danupon Nanongkai joined the Institute as a director for the Department of Algorithms and Complexity in August 2022. Until then, the department was led by the emeritus director, Kurt Mehlhorn, who continued his research as a researcher in the department. Christian Theobalt joined the Institute as a director for the department on Visual Computing and Artificial Intelligence in March 2021. The Institute is involved in the process of the Max Planck Society to establish departments in quantum computing.

The following are selected highlights from the scientific results that the Institute has achieved in the last two years.

- Danupon Nanongkai’s group has been working on algorithms and complexity on graphs, numbers, geometric objects, and strings, as well as algorithmic game theory, and optimization. The group advanced the understanding of fast algorithms for many fundamental questions; results include fast shortest paths algorithms (best paper award at FOCS 2022), fast approximation algorithms for pattern matching and computing edit distance (STOC’22, FOCS’22, STOC’23), and fast algorithms and runtime (conditional) lower bounds for convolution, subset sums and Euclidean traveling salesperson (STOC’21, FOCS’21). The group also advanced the understanding of (i) the theory of fair division (e.g. simplified and stronger proofs for the existence of EFX allocations (EC’21, IJCAI’22, SODA’22, etc.) and (ii) learning algorithms (e.g. approximating the neural kernels (NeurIPS’21, NeurIPS’22) and learning-augmented online algorithms (AAAI’23). One of our works on optimization was also integrated into the production process of our industrial partner.
- In the reporting period, the group of Bernt Schiele has been working on various important areas in both computer vision as well as machine learning. For example, the group has contributed novel 3D scene understanding methods that not only unify 3D representations for a range of tasks such as detection, segmentation and classification, but also have won the Waymo Motion Prediction Challenge in 2022 and 2023. One of the most promising directions of the reporting period has been the investigation of explainability and inherently interpretable machine learning methods. We not only contributed an in-depth analysis of state-of-the-art post-hoc attribution methods, but also contributed inherently interpretable deep neural networks by including the goal of interpretability in the learning process itself. Another important direction was to learn without or with very little supervision. Here, a variety of powerful methods have been researched and proposed ranging from self-supervised, over few-shot-learning to label-efficient semi-supervised learning. Importantly, the above mentions just a few of

the many important directions pursued in the group both by Bernt Schiele as well as by the other senior researchers and research group leaders.

- Anja Feldmann’s group has been working on understanding the capabilities and vulnerabilities of today’s Internet. In recent work they have been highlighting, e.g., new capabilities to support the IoT eco-system (IMC 22), the ongoing evolution of the Internet topology (IMC 22), the cloudification of higher education infrastructure (PETS 22), and novel collaborative DDos mitigation techniques (CCS 22). This work has received an IETF Applied Networking Research award.
- In the Computer Graphics Group we achieved fundamental results on correlated sampling and on bridging the gap between Monte Carlo rendering and neural radiance fields (NeuRIPS’21, SIG’22, SIGAsia’22), and we substantially contributed towards improving the visual experience in VR and games (2x SIGAsia’21, SIG’22, SIGAsia’22, ACM TAP’23) and material appearance perception (SIG’21, TVC’21, SIGAsia’22). We achieved groundbreaking results on neural inverse design in computational design (SIG’22, NeuRIPS’22 (spotlight)), SIGAsia’22), and we significantly advanced tactile rendering (TEI’22, 2x CHI’23). We also continued our successful line of research on the mesh matrix formalism for geometric computing (CGF’21, EG’23).
- The Visual Computing an Artificial Intelligence department developed pioneering methods for human capture and modeling, such as pose estimation with explicit (differentiable) physics-modeling (SIGGRAPH’2021), egocentric motion capture (ECCV’22, CVPR’22), as well as monocular performance capture (DeepCap) (TPAMI’23). State-of-the-art methods for neural capture, modeling, editing, and (free-viewpoint) rendering of entire humans (e.g. (DDC) SIGGRAPH’21, (Neural Actor) SIGGRAPH Asia’21) and human faces (e.g. SIGGRAPH’21, CVPR’21) at highest fidelity were also presented. The team contributed groundbreaking works on neural and neuro-explicit modeling and rendering of general static (e.g. NeuS (NeurIPS’21)) and dynamic scenes (e.g. NR-NerF (CVPR’21), Phi-SfT (CVPR’22)) under illumination control (CVPR’22). Works on robust scene perception with neural analysis-by-synthesis (ECCV’22), and quantum computer vision (e.g. CVPR’21) opened new directions in the department. The works on 3D-aware high-quality generative modeling of shapes (ICLR’22, CVPR’22) and human motion (SIGGRAPH’22) were widely recognized.
- Christoph Weidenbach and his group have been working on arithmetic theory solving, higher-order formalization and mechanization, and SCL (Clause Learning from Simple models). In particular, we put SCL to practice. We showed that we can formalize, verify, and run so called *Supervisors* inside the SCL framework (TACAS’2022, VMCAI’2021, FroCos’2021). Supervisors are software that controls technical systems at a higher level of abstraction such as a lane change assistant in a car, or an electronic control unit for a combustion engine or an aircraft engine.
- Gerhard Weikum’s group has further advanced its work on knowledge base construction, curation and application by spearheading new methods for capturing entities with quantities (such as running times of athletes or energy consumption of cars) and for cultural commonsense knowledge (such as food preferences or general habits in different cultures), and for conversational question answering over combinations of knowledge

graphs, tabular data and text corpora. These methods integrate new ways of leveraging pre-trained language models (such as GPT), but aim to avoid the risks and huge energy footprint of language models as sole source of (latent) knowledge. Results have appeared in top-tier venues like SIGIR, SIGMOD, EMNLP, WSDM and WWW. Also, a 350-page survey on knowledge bases has been published. In the ERC synergy grant imPACT, the focus has shifted from understanding privacy risks and their trade-offs with utility to enhancing the trustworthiness, explainability and controllability of recommenders and other machine-learning systems. The team has developed new methods for user-comprehensible explanations in recommenders, risk analysis for model deployment, and operationalizing fairness models in a practically viable manner. Results have appeared in premier venues like SIGIR, VLDB, NeurIPS, WWW and the Machine Learning Journal. Asia Biega's paper on fairness in rankings is one of the highest cited papers on this topic. Azin Ghazimatin's dissertation won the GI DBIS Dissertation Award.

- Yiting Xia's group has been working on performance optimization of network and cloud systems. The group pioneers on system support for optical data center networks, a high-performance and low-cost network fabric increasingly adopted by cloud providers. Their Hop-On Hop-Off (HOHO) routing algorithm is revolutionary in reduction of transmission latency in optical data center networks (APNet'22), and OpenOptics is the first end-to-end testing framework that makes optical data center networks accessible to academic researchers. Besides optical networks, the group has improved communication performance of machine learning training systems, through the EchelonFlow network abstraction for efficient collective flow scheduling (HotNets'22) and network-aware GPU sharing. In joint work with Meta, the group has also advanced data center network management with workflows and distributed database.

New Research Directions: We continue focusing on the grand challenge of exploring algorithms that understand, search, and organize large, distributed, noisy, incomplete, and diverse information in a robust, efficient, and intelligent manner. However, we expect a leap in research directions by the ongoing blending of virtual worlds with the real world. This trend involves several grand challenges on which we will embark. As digital contents and output from all kinds of sensors continue to explode, we need to move from data to understanding situations and anticipating user behavior. We need to support immersive interactions across all modalities, considering visual signals like facial expressions, gestures and body language, in conjunction with language, contextual knowledge and social interactions. All of the above entail profound methodical challenges to be able to handle, in the long run, tasks of high real world complexity, and to enable interaction with computing systems on a human-like level. To approach these challenges, we also intensify our investigation of new ways to unite data-driven machine learning-based concepts with explicitly designed methods. We further prepare for the resulting profound computing challenges resulting from this by investigating new algorithms that work across various models of computation, including quantum computing. Finally, with the rapid advance of machine learning and data-driven algorithmic decision-making, we need to better understand how to make computer behavior comprehensible. These challenges are the motivation for our foundational research on algorithms, visual computing, machine learning, internet architecture and knowledge discovery in the coming years.

1.5 Career Mentoring

The Institute has a strong track record on educating and mentoring young researchers, at both the doctoral student level and the postdoctoral level.

Doctoral Student Training: Since the Institute was established in 1990, a total number of 390 doctoral students have graduated. These include 73 women, and 179 non-Germans. A number of students have won prestigious national and international awards: 17 have been awarded the Otto Hahn Medal of the Max Planck Society. Andrey Rybalchenko (2007) and Fabian Suchanek (2012) have received the Otto Hahn Award for the best dissertations in the Chemistry, Physics, Technology Section of the Max Planck Society. This award includes a 5-year scholarship for an independent research group, and only one award per year is granted since 2007. In the reporting period Azin Ghazimatin won the DBIS Dissertation Award in 2023. Marc Habermann received the DAGM MVTec Dissertation Award 2022 and a Eurographics PhD Thesis Award 2022. Franziska Müller was awarded the Dr. Eduard Martin Prize 2021.

Young Scientist Career Advancement: A unique strength of the Institute is its successful fostering of young scientists. Our mentoring and career support efforts are most pronounced at the level of our senior researchers. Since the notion of senior researchers was explicitly introduced in 2007, a total of 85 young scientists have held such positions. 76 of them have meanwhile left the Institute. Out of these, 75 have accepted a tenured or tenure-track position offer at universities or university-like research organizations. We started tenure-track openings for senior researchers in 2019. We see this as an additional instrument for hiring talented researchers and, in particular, women. Several alumni (i. e., who graduated here or spent at least two years at the Institute and have since moved on) and current senior researchers of the Institute have won prestigious awards: Leibniz Prizes³, ERC Grants⁴, and other honors.

Support for Women: The percentage of women at our Institute is currently 22% for doctoral students and 23% at the postdoctoral level (including senior researchers). To increase the representation of women in our field, we have established the Lise Meitner Fellowship for outstanding female scientists at the postdoctoral level. So far, these two-year fellowships have been awarded to 17 women⁵. Out of the 15 recipients of the award who have meanwhile

³Susanne Albers 2008, Leif Kobbelt 2014, Thomas Neumann 2020, Peter Sanders 2012

⁴Susanne Albers 2016, Niko Beerenwinkel 2014, Jasmin Christian Blanchette 2016, 2022, Christoph Bock 2015, Karl Bringmann 2019, Andreas Bulling 2018, Parinya Chalermsook 2017, Piotr Didyk 2018, Jürgen Gall 2015, Bastian Goldlücke 2013, Matthias Hullin, 2018, Leif Kobbelt 2013, Christoph Lenzen 2016, 2020, 2023, Marcus Magnor 2010, Thomas Neumann 2016, Dániel Marx, 2017 Rafal Mantiuk 2016, Antti Oulasvirta 2014, Bodo Rosenhahn 2011, Thomas Sauerwald 2015, Pascal Schweitzer 2018, Jürgen Steimle 2016, 2023, Christian Theobalt 2013, 2017

⁵Anke van Zuylen 2010-2012, Anna Adamaszek 2012-2014, Zeynep Akata 2014-2016, Daria Stepanova 2015-2017, Hang Zhou 2015-2017, Shida Kunz (Beigpour) 2016-2018, Qianru Sun 2016-2018, Qiuhong Ke 2018-2020, Eunjin Oh 2018-2020, Sophie Turret 2018-2020, Lingjie Liu 2019-2021, Erisa Terolli 2019-2021, Ana Serrano 2020-2021, Mengyu Chu 2020-2022, Jiangxin Dong 2020-2022, Roohani Sharma 2020-2022, Xinting Hu 2022-2024

left the Institute, twelve continued their career with a professor appointment. Our recently established senior researcher tenure-track career path constitutes an additional instrument for attracting women. Yiting Xia is the first tenure-track senior researcher at our Institute. A large number of female alumni of the Institute have become professors.⁶

1.6 Collaborations and Strategic Partnerships

An overriding goal that our Institute has been contributing to since its beginning in 1990, is to establish Saarbrücken as one of the world's premier sites in computer science. Indeed, over the last three decades the site as a whole has a unique track record, as exemplified by 7 ACM Fellows, 7 Leibniz Prizes (the highest scientific honor in Germany), and a total of 33 ERC Grants (at all levels).

Saarland Informatics Campus: Our most important partners are the Computer Science Department of Saarland University, the Helmholtz Center for Information Security (CISPA), the MPI for Software Systems and the German Research Center for Artificial Intelligence (DFKI). We have a long-standing tradition of teamwork and joint engagement in research, recruiting, and teaching. In the reporting period the senior researchers Mario Fritz, Dániel Marx, and Jilles Vreeken joined the CISPA faculty, and Karl Bringmann joined the Computer Science Department. There are numerous collaborations with faculty members from the university and with researchers from various institutes on campus, including colleagues from the Department for Computational Linguistics.

The Research Center on Interactive Media, Smart Systems and Emerging Technologies (CYENS): This center is located in Cyprus and was founded in 2017. It is funded within the framework of Horizon 2020. MPI is a strategic international partner of CYENS and represented on the Board by Hans-Peter Seidel.

ERC Synergy Grant imPACT: The ERC Synergy Grant has been awarded to Michael Backes (Helmholtz Center for Information Security), Peter Druschel (MPI for Software

⁶Anna Adamaszek (Univ. Copenhagen, Denmark), Zeynep Akata (Univ. Tübingen), Susanne Albers (TU Munich), Iris Antes (TU Munich), Oana Balalau (INRIA), Hannah Bast (Univ. Freiburg), Mengyu Chu (Peking University), Carola Dörr (CNRS, France), Jiangxin Dong (Nanjing U of Science and Technology), Panagiota Fatourou (Univ. of Crete), Lilia Georgieva (Heriot-Watt Univ., UK), Yulia Gryaditskaya (Univ. of Surrey, UK), Qihong Ke (Monash Univ., Australia), Katja Hose (Aalborg Univ., Denmark), Georgiana Ifrim (UC Dublin, Ireland), Mouna Kacimi (Univ. Bozen-Bolzano, Italy), Ruxandra Lasowski (Univ. of Applied Sciences Furtwangen), Lingjie Liu (Univ. of Pennsylvania, USA), Petra Mutzel (Univ. Bonn), Alice McHardy (TU Braunschweig), Nicole Megow (Univ. Bremen), Ndapa Nakashole (UC San Diego, USA), Marina Papatriantafidou (Chalmers Univ., Sweden), Ruzica Piskac (Yale Univ., USA), Nicoleta Preda (Univ. Versailles, France), Maya Ramanath (IIT Delhi, India), Anna Rohrbach (TU Darmstadt), Ana Serrano (Univ. Zaragoza, Spain), Ina Schäfer (TU Braunschweig), Renate Schmidt (Univ. Manchester, UK), Viorica Sofronie-Stokkermans (Univ. Koblenz-Landau), Qianru Sun (Singapore Management Univ.), Kavitha Telikepalli (Tata Institute, India), Erisa Terolli (Stevens College of Technology), Cara Tursun (Univ. of Groningen, Netherlands), Yafang Wang (Shandong Univ., China), Nicola Wolpert (Univ. of Applied Sciences Stuttgart), Shanshan Zhang (Nanjing Univ. of Science and Technology, China), Hang Zhou (École Polytechnique Paris, France), Anke van Zuylen (Cornell Univ., USA)

Systems), Rupak Majumdar (MPI for Software Systems) and Gerhard Weikum (MPI for Informatics) for joint research on the strategic research theme of “Privacy, Accountability, Compliance, and Trust for the Internet of Tomorrow”. The project has been funded with a total of 10 Million Euros over the timeframe 2015–2022.

IMPRS on Trustworthy Computing (IMPRS-TRUST): The International Max Planck Research School on Trustworthy Computing (IMPRS-TRUST) was established in 2020 as a joint program of the MPI for Informatics, the MPI for Software Systems, Saarland University, and TU Kaiserslautern. Currently, 97 doctoral students of MPI-INF, including 23 women (24%) and 66 non-Germans (68%), are part of the program.

CS@Max Planck Computer science centered research of the Max Planck Society has started a joint presence <https://www.cis.mpg.de/>. The institutes comprise the MPI for Informatics, the MPI for Software Systems, the MPI for Security and Privacy, the MPI for Molecular Genetics, and the MPI for Molecular Cell Biology and Genetics. The effort includes joint recruiting for tenure-track faculty positions and internships.

The Max Planck Graduate Center for Computer and Information Science: The Center is a highly selective doctoral program that grants admitted students full financial support to pursue doctoral research in the broad area of computer and information science, with faculty at the MPI for Informatics, the MPI for Software Systems, the MPI for Intelligent Systems, and top German universities.

Saarbrücken Graduate School for Computer Science: The school was established in 2007 and encompasses all doctoral training in computer science on campus. The school was largely modeled after the IMPRS-CS and adopted many of its elements. IMPRS-CS provides fellowships for doctoral students, within the structural framework of the Graduate School.

VIA Research Center: Saarbrücken Center for Visual Computing, Interaction and Artificial Intelligence: In 2022 the Max Planck Institute (MPI) for Informatics in Saarbrücken (Germany) and Google established a strategic partnership: the “Saarbrücken Research Center for Visual Computing, Interaction and Artificial Intelligence (VIA)” at the MPI for Informatics. The center investigates basic frontier research challenges in computer graphics, computer vision, and human machine interaction, at the intersection to artificial intelligence and machine learning. The VIA center is directed by Christian Theobalt and Bernt Schiele is a PI.

ELLIS Unit SAM: Saarbrücken Artificial Intelligence & Machine Learning: The ELLIS Unit SAM <https://www.ellis-unit-sam.de> has been founded in 2020 as part of the ELLIS Society which seeks to establish internationally visible, top-level research facilities in Europe in the area of machine learning and modern AI. The SAM Principal Investigators have agreed to jointly work on both the foundations for enhanced functionalities of Artificial Intelligence and Machine Learning (AIML) systems and the pressing needs for security, privacy, and trustworthiness that arise from the widespread use of Artificial Intelligence and Machine

Learning systems. Bernt Schiele is the scientific director of the unit, Christian Theobalt is a PI, and overall, the unit brings together nine PIs from the MPI for Informatics, MPI for Software Systems, UdS, and CISPA.

ELIZA: Konrad Zuse School of Excellence in Learning and Intelligent Systems The school is a graduate school in the field of artificial intelligence (AI) funded by the German Academic Exchange Service (DAAD). ELIZA’s research and training activities focus on four main areas: the basics of machine learning (ML), including ML-driven fields like computer vision, Natural Language Processing (NLP), machine learning systems, applications in autonomous systems, as well as trans-disciplinary applications for machine learning in other scientific fields, from life sciences to physics. The ELLIS Unit SAM is one among the seven German partners, including Bernt Schiele (representative of the local ELIZA partner) and Christian Theobalt.

Research Training Group: Neuroexplicit Models of Language, Vision, and Action The research training group (in German ‘Graduiertenkolleg’) has been recently approved by the DFG (German Research Foundation) in 2023. It promotes early career researchers and is funded by the DFG for a period of up to nine years. The training group will lay the systematic foundation for so-called “neuroexplicit models”. Such models attempt to combine the best aspects of previous approaches to create an AI that is safer, more reliable, and easier to interpret. In addition to the Max Planck Institute for Informatics (represented by Bernt Schiele and Christian Theobalt), partners include the Departments of Computer Science, Language Science and Technology and Mathematics at Saarland University, the German Research Center for Artificial Intelligence (DFKI), the Max Planck Institute for Software Systems, and the nearby CISPA Helmholtz Center for Information Security.

1.7 Results 2021–2023

Publications, Software, Startups: In the two-year time-frame 2021–2023, the Institute published more than 600 papers in peer-refereed conferences and journals. Many of these appeared in top-tier venues, with competitive conferences typically accepting only 10 to 20 percent of their submissions. Several publications won best paper awards or best student paper awards (at 3DV 22, CPM 22, DL-2022, FOCS-2022, IVA 21, IWOCA 22, PAM 23, SOFSEM 23).

Two startups that spun off from our research in 2014 and 2012, Capture and Logic4Business, respectively, are gaining traction in their respective markets. Two startups were founded with seed-funding from the EXIST program of the German Ministry for Economy (BMWi): Ambiverse in 2016 and Oraclase in 2022.

People: In the two-year time-frame 2021–2023, 37 of our doctoral students graduated. These include 10 women. In the same time period, 12 of our researchers left the Institute to take a tenured or tenure-track faculty position ⁷. These include 4 women.

⁷Mengyu Chu (Peking University, China), Yulia Gryaditskaya (University of Surrey, UK), Costas Jordanou (European University Cyprus, Cyprus), Petr Kellnoher (TU Delft, Netherlands), Christoph Lenzen

Awards: Members of the Institute won prestigious awards. The following are the most prominent examples; full lists are in the respective sections of the departments. Anja Feldmann won the IETF/IRTF Applied Network Research Prize together with Daniel Wagner in 2022; in 2021, Harald Ganzinger was posthumously awarded with the CAV Award for pioneering contributions to the foundations of the theory and practice of satisfiability modulo theories (SMT); Hans-Peter Seidel became a member of the ACM SIGGRAPH Academy 2022; Gerhard Weikum was recognized with the Korad-Zuse-Medal 2021;

At the level of senior researchers, Vahid Babaei received the Herrmann-Neuhaus-Prize of the Max Planck Society 2022; Dengxin Dai won the German Pattern Recognition Award 2022; Shaoshuai Shi was recognized with the World Artificial Intelligence Conference Rising Star Award 2021;

At the student level, Corinna Coupette was awarded with the Caroline von Humboldt Prize; Ayush Tewari and Marc Habermann both won the Otto-Hahn-Medal in 2022 and 2023, respectively; Marc Habermann also received the DAGM MVTec Dissertation Award and the Eurographics PhD Award in 2022; Azin Ghazimatin was awarded the German GI-DBIS Dissertation Award 2023; Anna Kukleva received the Grace-Hopper Award of the University of Bonn in 2021; Jan Eric Lenssen won the TU Dortmund Dissertation Award in 2022; Franziska Müller received the Dr. Eduard Martin Prize 2021; Karol Wegrzycki was recognized with the Prime Minister of Poland Award for his PhD thesis in 2022 and won the Witold Lipski Prize 2021 as well as the PCC Open Mind Prize 2022; Philip Wellnitz won the Dieter-Rampacher-Prize for the youngest doctoral student at the Max Planck Society 2021;

Further honors with considerable visibility include the following. Kurt Mehlhorn received a Honorary Doctorate Degree from Aalto University in 2023; Bernt Schiele and Thomas Lengauer were both appointed ACM Fellows in 2022; Christian Theobalt has been elected Fellow of the Eurographics Association in 2022; Yiting Xia has been included in the list of the top 10 Rising Stars in Computer Networking and Communications by the N2Women Association in 2021.

Equal Opportunities Plan: The equal opportunity plan is part of the MPI-INF policy to create a work environment that meets the diverse life situations and needs of all Institute members. For us, having a gender equality policy means establishing and shaping organizational and structural conditions within the Institute in order to optimize individual development opportunities for all our members. We have established continuous efforts to support young families: parent-child room, nursing room, reserved places in day care centers, babysitter agency, pacifier projects, and a high flexibility in home office work also after the pandemic. From the end of 2020 to December 31, 2022 we are allowed to call ourselves “Family-friendly Company”. This certification was awarded to us by the state government in cooperation with the Chamber of Industry and Commerce.

We have been successful in attracting an outstanding woman as a director and as our

(CISPA, Germany), Lingjie Liu (University of Pennsylvania, USA), Habib Mostafaei (TU Eindhoven, Netherlands), Xingang Pan (Nanyang Technological University, Singapore), Ana Serrano (University of Zaragoza, Spain), Joachim Spoerhase (University of Sheffield, UK), Erisa Terolli (Stevens College of Technology, USA), Cara Tursun (University of Groningen, Netherlands), Andrew Yates (University of Amsterdam, Netherlands), Savvas Zannettou (TU Delft, Netherlands), Rhaleb Zayer (University of East Anglia, UK), Quan Zheng (Chinese Academy of Sciences, China)

first tenure-track senior researcher. At the postdoc level, the Institute offers a distinguished fellowship for women, named Lise Meitner Scholarship, since 2013. The interest in this program has been strongly increasing in terms of both quantity and quality of applicants. In the last two years, two young women accepted the fellowship. The best postdocs are often candidates for becoming senior researchers after two years. Out of the 15 fellowship recipients who left the Institute, twelve continued with a professor appointment.

Attracting women to computer science needs to start already at the school level and constitutes a long-term effort. As a part of the BWINF, “Bundesweit Informatik Fördern”, an organization mainly funded by the German government to support young talent in computer science, we have established a number of measures to inspire girls for computer science. In addition to three different competition formats aiming at different levels of skills and age, we are now organizing girl camps and have established a separate girl team participating in the informatics olympiad for pupils.

Outreach and Visibility: To increase the international visibility of Saarbrücken as a world-class CS hub, we have established an agreement for joint branding: almost all CS players on campus now use the label “Saarland Informatics Campus” as part of their official addresses. The label will also be used in Google Scholar profiles, academic rating sites, and other PR efforts (see <http://sic.saarland/>).

The Institute continues its role as a provider of for the BWINF, “Bundesweit Informatik Fördern”, promoting young computer science talent in Germany.

2 The Research Units

3 D1: Algorithms and Complexity

History

The Algorithms and Complexity group (D1) is currently led by Danupon Naongkai who started his position as a Scientific Director in August 2022. Danupon is the successor of Kurt Mehlhorn who established the group in 1990 as one of the two initial groups of the institute. Kurt moved to emeritus status on August 31, 2019, and has been an acting head of the department until Danupon joined the institute. Kurt has continued as a scientist till today.

The group is currently regrowing after it shrunk between 2019–2022. Meanwhile, the algorithm theory community on the campus has become stronger. Karl Bringmann became a Full Professor of Computer Science at Saarland University. Dániel Marx, Christoph Lenzen, and Sebastian Brandt became Faculties at CISPA, the Helmholtz Center for Information Security. The group hosts these researchers as long-term guests to foster collaborations within the campus. In general, the algorithms and complexity community is going strong on campus.

During the reporting period, the senior scientists and research area coordinators are Andreas Karrenbauer, Tomasz Kociumaka, Christoph Lenzen (moved to CISPA in July 2021) Kurt Mehlhorn, Adam Polak, Joachim Spoerhase (moved to the University of Sheffield in February 2023), and Philip Wellnitz. Some of our long-term guests also assisted in coordinating some research areas: Karl Bringmann and Evangelos Kipouridis from Saarland University and Sebastian Brandt, Christoph Lenzen and Dániel Marx from CISPA.

Section 27.1 lists the names of current and recent group members and the current positions of the group members that left during the report period. Our alumni continue to get very good positions, see Page 202; Christoph Lenzen moved to a faculty position at CISPA and Joachim Spoerhase moved to a faculty position at the University of Sheffield. Adam Polak joined the group before joining Bocconi University as a tenure-track assistant professor. Six group members completed their Ph.D., see Page 202. Group members received prestigious awards, see Page 203, for instance, Kurt Mehlhorn obtained an Honorary Doctorate Degree from Aalto University, Karol Węgrzycki received the Open Mind Prize in 2022, the Prime Minister of Poland Award for Ph.D. Thesis in 2022, and the Witold Lipski Prize in 2021, Philip Wellnitz received the Dieter-Rampacher-Prize for the youngest Ph.D. student of the Max Planck Society that graduated in 2021, Corinna Coupette received the Caroline von Humboldt Prize for outstanding female junior researchers in 2022, Roohani Sharma received the best paper award from SOFSEM 2023, Danupon Nanongkai received the best paper award from FOCS 2022, and Tomasz Kociumaka received the best paper awards from IWOCA 2022 and from CPM 2022. A former group member, Paolo Ferragina (now at the University of Pisa), recently received the 2023 ACM Paris Kanellakis Theory and Practice Award.

Some group members hold their own grants, see Page 203, for instance, Christoph held an ERC grant and Joachim Spoerhase holds a DFG grant.

We have published extensively and in excellent venues during the reporting period, for

instance, 14 papers in FOCS and STOC, 12 papers in SODA, 5 papers in SOCG, and 5 papers in NEURIPS and ICML. We are also visible in, for instance, PODS, AAI, IJCAI, KDD, ICLR, AI and Law, and Nature Communications.

Vision and Research Strategy

The vision for D1 is to be a first-class algorithm and complexity group and a trendsetter in this field, and to have an impact on the research community and society through people, research results, techniques, software, and scientific leadership.

Most of our effort is on theoretical works while some group members also contributed to experimental works and software constructions. Our current research activities are organized into five areas.

- Algorithmic Game Theory,
- Algorithms and Complexity on Graphs,
- Algorithms and Complexity on Numbers and Geometric Objects,
- Algorithms on Strings, and
- Optimization.

Together, we span a large part of algorithmic research. The emphasis changes over the years as group members come and go. We hire postdocs mainly based on quality and less on thematic fit. There is considerable interaction and collaboration between the areas. The entire group meets twice a week to discuss science (Tuesday and Thursday noon seminar) and biweekly to discuss administrative matters. Various subgroups meet weekly and even daily. We try to create environments that encourage informal interactions as we believe that it is the best way to create synergies between different research fields.

We teach at all levels; see Page 200 for details. Frequently group members pair for lectures.

Research Areas and Achievements

We discuss some of the main results obtained in the reporting period.

Algorithmic game theory. We worked mainly on fair division problems. In fair division, a set of items has to be allocated to a set of agents. The goal is to find a “fair” and “efficient” allocation. There are several notions of fairness. Envy-freeness up to any good (EFX) is arguably the most compelling fairness notion in the context of allocating indivisible goods. Indivisible goods are items that the agents would like to have as much as possible and they cannot be divided. In an EFX allocation, removing any good allocated to any agent A makes A ’s remaining bundle not interesting to other agents (no envy from other agents). The *existence* of EFX allocations is one of the most important problems in fair division.

Hannaneh Akrami, Bhaskar Ray Chaudhury, Kurt Mehlhorn, Pranabendu Misra, and their co-authors (EC 2021, arXiv 2022) simplified the proof (originally established by our group in the previous reporting period) that EFX-allocations exist for three agents and extended it to a larger class of valuations. They also showed that there exists an approximate EFX allocation

with a sublinear number of unallocated goods by establishing an intriguing connection to a problem in zero-sum extremal combinatorics. They further studied a relaxation of $\text{EF}kX$, where k goods can be removed to remove envy (IJCAI 2022), and the fair division of divisible chores where chores (or “bads”) are items that agents dislike (SODA 2022).

Nash Social Welfare (NSW) is the oldest notion of fairness (Nash, 1950); the NSW of an allocation is the geometric mean of the utilities of the agents. An allocation maximizing NSW is Pareto-optimal, that is, there is no other allocation in which no agent is worse-off and some agent is strictly better-off. Finding an allocation maximizing NSW is NP-complete even for additive valuations.

Hannaneh Akrami, Bhaskar Ray Chaudhury, Kurt Mehlhorn, Golnoosh Shahkarami, and their collaborators (AAAI 2022, arXiv 2022) studied the case of 2-value additive valuations where each good is valued either 1 or p/q , for some fixed co-prime numbers $p, q \in \mathbb{N}$ such that $1 \leq q < p$, and the value of a bundle is the sum of the values of the contained goods. They gave a complete characterization of polynomial-time tractability of NSW maximization that solely depends on the values of q .

Algorithms and Complexity on Graphs. Paths, cuts, and matchings are fundamental graph problems studied extensively for decades. In this reporting period, we made much progress on these problems. Karl Bringmann, Alejandro Cassis, Nick Fischer, Danupon Nanongkai and their collaborators developed techniques that resolved the long-standing negative-weight single-source shortest paths problem with an $\mathcal{O}(m \log^2(n) \log(nW) \log \log n)$ -time algorithm, where m , n and W denote the number of edges, number of vertices, and the upper bound on the magnitude of the smallest negative-weight edge, respectively. One of the results received the best paper award at FOCS 2022 and was covered in the Quanta Magazine.

Another basic question about paths is constructing a data structure to report shortest-path distances called distance oracles. For sparse graphs and any constant $k \geq 1$, the state of the art is Thorup-Zwick distance oracle which achieves an approximation ratio (a “stretch”) of $2k - 1$, preprocessing time $\mathcal{O}(kn^{1+1/k})$ and query time $\mathcal{O}(k)$.

Karl Bringmann, Nick Fischer, and their collaborators (STOC 2022, STOC 2023) addressed the following open question: *What is the best stretch $f(k)$ we can achieve if we insist on preprocessing time $\mathcal{O}(n^{1+1/k})$ and almost-constant query time $n^{o(1)}$?* They showed that $f(k) \geq k$ under the 3Sum Hypothesis, narrowing the gap to $f(k) \in [k, 2k - 1]$.

For computing graph cuts and connectivity, we highlight two results in the distributed setting (the CONGEST model):

- Yonggang Jiang and his co-author (STOC 2023) achieved a vertex connectivity algorithm that works in sublinear time on distributed networks, and
- Christoph Lenzen and Hossein Vahidi (SIROCCO 2021) showed a tighter relationship between $(1 + \varepsilon)$ -approximate shortest paths and approximate minimum directed spanning trees, implying improved distributed algorithms for the latter problem.

For a harder variant of *weighted or directed multicut problems*, Roohani Sharma, our guests from CISPA (Dániel Marx and Philipp Schepper) and their collaborators developed techniques to show that weighted multicut on trees and directed multicut with three terminal pairs are both FPT (WG 2022, SODA 2023).

For matching and its generalization to matroid problems, our main results are in the dynamic setting. We highlight two results:

- Peter Kiss (main affiliation: University of Warwick) and his co-authors achieved a dynamic $(1 + \varepsilon)$ -approximate matching algorithm with truly sublinear update time, making the first progress in a decade for one of the most central problems about dynamic matching, and
- Danupon Nanongkai, Ta-Wei Tu, and their collaborators introduced the model of dynamic matroid oracle and showed their applications in achieving fast graph algorithms.

Additionally, based on results on parameterized complexity for Perfect Matching and Generalized Matching problems on bounded tree-width graphs, Philip Wellnitz, our long-term guests from CISPA (Jacob Focke, Dániel Marx, Fionn Mc Inerney, and Philipp Schepper) and their collaborator studied the related vertex-selection problem about Counting “Generalized Dominating Sets” in Bounded-Treewidth Graphs (SODA 2023). They improve the time complexity significantly for many special cases such as the Perfect Code problem.

Other results include reducing the random bits needed for the Isolation Lemma for NP-complete problems (Karol Węgrzycki et al. STACS 2022) and some applied and experimental works such as analyzing graphs and hypergraphs (Corinna Coupette et al. KDD 2021, AAAI 2022, ICLR 2023) and computing graph hyperbolicity (André Nusser et al. ALENEX 2022).

Algorithms and Complexity on Numbers and Geometric Objects. Through the lens of fine-grained complexity, we improved and in some cases settled algorithmic questions about numbers and geometric objects. We highlight two results on numbers:

- Given integer vectors A and B , the convolution problem is to compute $\sum_{i+j=k} A[i]B[j]$ for every k . This is a fundamental computational primitive that has been a vital component in computer algebra, signal processing, computer vision, and deep learning. In the reporting period, Karl Bringmann, Nick Fischer, and Vasileios Nakos showed a new algorithm and fine-grained reductions that imply essentially-optimal runtime for the sparse nonnegative variant of this problem (STOC 2021).
- A central problem in fine-grained complexity is the subset sum problem: given a set of n integers and a target integer t , and the task is to find a subset of these numbers that sum to precisely t . Karol Węgrzycki and his collaborator (STOC 2021) improved over the four-decade-old time and space bounds for this problem. Adam Polak, Karol Węgrzycki, and a collaborator (ICALP 2021) also developed an improved pseudopolynomial-time algorithm.

Our highlights for geometric problems are as follows.

- The Euclidean traveling salesperson problem (TSP) has a well-known approximation scheme. In this reporting period, Sándor Kisfaludi-Bak and Karol Węgrzycki and their collaborator (FOCS 2021) developed a new algorithm and a reduction from the Gap-Exponential-Time Hypothesis (Gap-ETH) to achieve essentially tight runtime for this problem.
- Given simple polygons P and Q , a basic problem is to determine the largest copy of P that can be placed into Q . Despite a long line of research since the 1980s, it

remained open whether we can establish (a) hardness beyond quadratic time and (b) any superlinear bound for constant-sized P or Q . André Nusser and Marvin Künnemann affirmatively answered these questions under the k -Sum Hypothesis in their SODA 2022 paper.

Other results include improved pseudopolynomial-time, approximation, and online algorithms for the knapsack problem by Karl Bringmann, Alejandro Cassis, Andreas Karrenbauer, Adam Polak, Karol Węgrzycki, and collaborators, computing the vertices of maximum level in an arrangement of lines, where Kurt Mehlhorn and his co-authors found that this textbook problem is not as easy as it looks, computing generalized convolution that unifies many convolution procedures under one general umbrella, various distance measures (for instance dynamic time warping, Fréchet and Hausdorff distances), problems on geometric intersection graphs, robot motion planning, and many foundational results of Fine-Grained Complexity Theory.

Algorithms on Strings. Two central topics in the area of computations on strings are pattern matching and similarity measures such as the edit distance. One of our highlights is on fast approximate pattern-matching: for the classic problem of finding the occurrences of a pattern P in a long text T where some edits are allowed, Tomasz Kociumaka, Philip Wellnitz, and their collaborator (FOCS 2022) developed an algorithm that breaks the long-standing bound from 1998.

Another highlight is computing the edit distance between two input strings (the number of edits to change one string to the other string). Karl Bringmann, Alejandro Cassis, Nick Fischer, Tomasz Kociumaka, Vasileios Nakos, and their collaborators (STOC 2022, FOCS 2022) developed adaptive approximate algorithms with sublinear time complexities, which are almost optimal in some regimes.

For computing the edit distance exactly, an optimal algorithm that is linear-time in the low-distance regime has been long known. Tomasz Kociumaka and collaborators (FOCS 2022, STOC 2023) showed that a similar complexity can be achieved for more general distance measures such as weighted edit distance and tree edit distance.

Other results include data structures that allow preprocessing or that can handle dynamic input, approximating various distances, approximating longest common subsequence, a compressibility measure, and a construction of compressed suffix arrays by Karl Bringmann, Alejandro Cassis, Nick Fischer, Tomasz Kociumaka, Karol Węgrzycki, and collaborators.

Optimization. Contributions by our researchers span from discrete optimization to continuous optimization and to machine learning applications. The *sample complexity* of a function-learning task is the smallest number of correctly labeled examples needed to successfully learn a target function. It can be characterized by the well-known VC-dimension but also the PB-dimension, NC-dimension, etc. Pieter Kleer, Hans U. Simon, and collaborators (NEURIPS 2022, JMLR 2023, etc.) studied these various dimensions including the relation between the primal and dual of various combinatorial dimensions for multi-valued function classes, the NC-teaching dimension in comparison to the teaching dimension induced by any collusion-free model, and the separation between NC-dimension and PB-dimension.

The Neural Tangent Kernel (NTK) characterizes the behavior of infinitely-wide neural

networks trained under least squares loss by gradient descent. Amir Zandieh and collaborators (NEURIPS 2021) designed a near-input-sparsity time approximation algorithm for NTK via sketching algorithms to accelerate learning with NTK. His first algorithm can approximate the neural kernels with ReLU activation. His follow-up work (NEURIPS 2022) showed an extension to general activations.

An emerging subfield of algorithms and complexity is learning-augmented online algorithms. The goal is to improve online algorithms using predictions provided by machine learning techniques. Golnoosh Shahkarami and collaborators (SWAT 2022, AAAI 2023) explored this topic in the context of deadline-based speed-scaling scheduling and the Traveling Salesperson Problem (TSP) on the Line.

The slime mold *Physarum polycephalum* was experimentally demonstrated to be able to solve several algorithmic problems on graphs, including shortest path problem. A mathematical model defined via a system of differential equations for the dynamic behavior of the *Physarum* was shown to converge to the shortest path for all graphs and can solve positive linear programs. In this reporting period, Yuan Gao, Andreas Karrenbauer, Pavel Kolev, Kurt Mehlhorn, Golnoosh Shahkarami, and collaborators (Physical Review E 2021, TCS 2022, arXiv 2022) extended this research to study the influence of noise on the convergence behavior, a *Physarum*-inspired multi-commodity flow dynamics, and a *Physarum*-inspired Dynamics to Solve Semi-Definite Programs.

Other results include algorithms to determine car build sequence in assembly lines by Andreas Karrenbauer, Leonie Krull, Kurt Mehlhorn, Paolo Luigi Rinaldi, Anna Twelsiek, and a collaborator, where one of their results was integrated into the production process in a plant of an industrial partner, a computational approach for designing multi-modal electro-physiological sensors and for designing menu systems by Andreas Karrenbauer and collaborators, and clustering algorithms by Martin Herold, Evangelos Kipouridis, and Joachim Spoerhase.

4 D2: Computer Vision and Machine Learning

Group Overview

The Computer Vision and Machine Learning group (D2) was established in 2010 with the appointment of Bernt Schiele. The group was called ‘Computer Vision and Multimodal Computing’ initially and, during the last reporting period, the group was renamed to become the Computer Vision and Machine Learning group. There were two main reasons for this: first, multimodal computing has become less of a research focus for the group over the years; and second, while machine learning always was an important component of our research, its importance has increased significantly both for our research in computer vision but also in general. Therefore, renaming the group is both underlining the importance of machine learning for our research in computer vision as well as clearly stating that machine learning is an integral part of our research agenda. This has also resulted in an increased presence of our group at top-tier machine learning venues.

During the reporting period, the group was home to six groups of senior researchers/research group leaders, of which three were fully financed by MPI, and three groups are affiliated and partially funded by MPI. The three senior researcher groups fully funded by MPI were the ones of Dengxin Dai, Jan Eric Lenssen, and Paul Swoboda, and the three affiliated research group leaders were Zeynep Akata (U Tübingen), Margret Keuper (U Siegen), and Gerard Pons-Moll (U Tübingen). Each of the six group leaders have their own PhD-students (and PostDocs) to conduct research in their respective area. Also, the group was home to six postdocs, and 28 PhD students. Among those 27.5% are female (two research group leaders, three postdocs, and six PhD students). Eight group members completed their PhD during the reporting period. Our researchers get very good offers for faculty positions in academia¹, postdoc positions in academia², and research positions in industry³.

Vision and Research Strategy

Understanding visual information and more generally multi-modal information is a fundamental problem in computer science. Scientific challenges cover the entire pipeline from uni-modal processing, over spatial and temporal fusion of multiple and divergent modalities to the complete description of large-scale multi-modal data. At the same time we observe a tremendous increase in both the quantity as well as the diversity of visual and multi-modal

¹Jiangxin Dong (Nanjing U of Science and Technology), Li Jiang (Chinese U of Hong Kong), Margret Keuper (U Siegen), Gerard Pons-Moll (U of Tübingen, U of Luxembourg), Paul Swoboda (U of Mannheim).

²Stephan Alaniz (U of Tübingen), Apratim Bhattacharya (U of Tübingen), Yaoyao Liu (John Hopkins U), Yongqin Xian (ETH Zurich).

³Bharat Bhatnagar (Meta Reality Labs), Andrea Hornakova (Blindspot Solutions), Mohamed Omran (Qualcomm), Rakshith Shetty (Amazon), David Stutz (DeepMind), Yongqin Xian (Google).

information due to the increasing number of sensors embedded in a wide variety of digital devices and environments as well as due to the increasing storage of visual and multi-modal data (such as surveillance data, personal and multimedia databases, or simply the Internet). While storing and indexing large amounts of visual and multi-modal data has made tremendous progress, understanding of this data still lacks behind. Therefore the long-term goal of D2 is to make progress on how to process, structure, access, and truly understand visual and multi-modal data both for online use as well as for large-scale databases.

In the reporting period, the group focused on two main areas, namely computer vision and machine learning. In the area of computer vision we address some of the most fundamental problems of image and video understanding such as object class recognition, people detection and tracking, and scene understanding. In the area of machine learning, we are focusing, on the one hand, on problems at the intersection of computer vision and machine learning (such as semi-supervised learning or adversarial robustness), and on the other hand on more foundational problems in machine learning (such as interpretability of deep learning and continual learning).

Research Areas and Achievements

In the following, we report highlights from our research largely following the sub-group structure of D2. As you will notice, there are substantial cooperations among the various sub-groups with many joint topics, cooperations and publications.

Computer Vision and Machine Learning *Investigator: Bernt Schiele*

Since the establishment of D2 at the Max Planck Institute for Informatics, the sub-group headed by Bernt Schiele has been working at the intersection of computer vision and machine learning. The range of topics in Bernt’s subgroup ranges from computer vision topics such as 3D scene understanding and multi object tracking, over machine learning topics such as inherently interpretable models and semi-supervised learning, to topics at the intersection of machine learning and computer vision such as adversarial robustness. In the following we briefly summarize contributions to three specific topics, namely interpretability, 3D scene understanding and robustness. More details are given in section 28.4.

The motivation to aim for explainable and interpretable machine learning methods is obvious: despite the apparent success of deep learning for an incredibly wide range of tasks, it is still difficult to understand the ‘decision making process’ within deep neural networks and how information is aggregated and processed. Given how ubiquitously these models are employed in our everyday lives, however, it is of paramount importance to gain a better understanding of their inner workings. Especially in safety-critical tasks—such as autonomous driving, health care, or in the judicial system—one needs to ensure that decisions are made for the right reasons. In our work on Interpretable Machine Learning, we approached this problem setting from a variety of different angles. On the one hand, we performed an in-depth evaluation of the state-of-the-art post-hoc attribution methods to understand their promises and shortcomings. On the other hand, we developed inherently interpretable deep neural networks by including the goal of interpretability in the optimization process, thereby foregoing the need for post-hoc explanations. In this context, we evaluated and

developed model guidance techniques that allow us to ensure that the models are indeed right for the right reasons. Finally, we explored how to increase the inherent interpretability of conventional models: for this, we propose to fine-tune conventional DNNs to use more human-interpretable concepts by inserting semantic bottlenecks into the model architectures.

3D scene understanding aims to enable machines to perceive, interpret, and reason about the 3D world in a way that mimics human perception. As the world we live in is inherently three-dimensional, understanding the spatial structures and relationships between 3D objects is essential for a wide range of applications, such as robotics, autonomous driving, augmented and virtual reality, and smart city planning. In the reporting period we made various contributions to 3D scene understanding using point cloud data. In particular, we proposed a versatile and unified backbone architecture for 3D point cloud understanding, efficient methods to learning in point clouds, as well as object level understanding for 3D indoor scenes. Last, but not least, we have been researching novel and powerful approaches for 3D perception and prediction for autonomous driving, which won both the 2022 and the 2023 Waymo Open Dataset Motion Prediction Challenge.

Robustness is an essential property of deep neural networks. In particular in high-stakes applications robustness, proper uncertainty calibration and understanding misuse become essential for deployment. In this context we looked at various ways to both better understand but also improve robustness. For example, we proposed a novel approach to improve robustness of deep neural networks by enhancing weak subnets during training. Also, we investigated how adversarially robust generalization is related to flat minima during optimization.

Vision for Autonomous Systems *Investigator: Dengxin Dai*

Over the last two years, the Vision for Autonomous Systems Group has followed a coherent research line making visual perception algorithms more robust and scalable. As widely known, adverse weather and lighting conditions (e.g. fog, rain, snow, low-light, nighttime, glare and shadows) create visibility problems both for people and the sensors that power automated systems. Many real-world applications such as autonomous cars, agriculture robots, rescue robots, and security systems can hardly escape from ‘bad’ weather, challenging lighting conditions, dust, smoke, and so on. Our group has developed multiple novel approaches to increase the adaptability of visual recognition models to real-world adverse weather/lighting conditions such as Domain Flow (IJCV’21), Fog Simulation (ICCV’21) and Snowfall Simulation (CVPR’22) for LiDAR Data, and the adverse-condition dataset ACDC (ICCV’21). The approaches and dataset represent the state of the arts in this important research area.

Current robotic perception systems are typically trained in a rather fixed environment, allowing them to succeed in specific settings, but leading to failure in others. In the last two years, we have developed multiple influential work in domain adaptation, including learning domain adaptation with auxiliary tasks (ICCV’21), continual test-time domain adaptation (CVPR’22), new network architecture DAFormer (CVPR’22) and the multi-resolution domain adaptation framework HRDA (ECCV’22). They have all become fundamental approaches.

Machine learning has been advancing rapidly, and ever growing data is at the center of this evolution. While the recipe of learning with large-scale annotated datasets is still effective, this can hardly scale due to the high annotation cost. We have developed multiple innovative methods for the low data regime. These include LiDAR semantic segmentation with 3D

scribbles (CVPR'22), universal pre-training with multiple self-supervised tasks (CVPR'22), supervision transfer between data modalities such as from video to audio (T-PAMI'22), and ZegFormer for zero-shot learning (CVPR'22). These approaches have advanced the research in this area significantly.

Geometric Representation Learning *Investigator: Jan Eric Lenssen*

The newly founded Geometric Representation Learning group is concerned with designing and exploring effective representations and algorithms to bridge the gap between 2D observations and 3D reconstruction. Most observable parts of the 3D world consists of visually structured objects and repeating patterns, following rules of composition. It is our current understanding that it is this inherent structure and repetitiveness that allows humans to map out their surroundings just from a few sparse 2D observations, by combining observations with structured a priori knowledge. The GRL group aims to replicate this ability in computer vision systems by exploring the most efficient ways of learning 3D data priors.

One part of such a system could include an explicit model of symmetries in natural or man-made objects. In our work SymNP (ICCV'23 submission), we show that we can represent an object category as a set of characteristic symmetries between local areas, which are learned from a large amount of images showing objects from this category. These learned symmetries allow to perform full 3D reconstruction just from a single image. We were able to show that this abstract data prior is more efficient and more capable than simply learning the full function space as existing deep learning methods do. The representation is able to better transfer details to symmetric parts and is better in fusing information from multiple views, if available. Of utmost importance for the presented method are novel neural point representations, which allow to encode symmetries explicitly as connections between local point embeddings. We hypothesize that research on efficient 3D representations is deeply entangled with the ability to learn data priors for vision, which is why it will be in the focus of future work.

Data Priors for Pose Estimation *Investigators: Gerard Pons-Moll and Jan Eric Lenssen*

Pose estimation from different data modalities using parameterizable models like SMPL or MANO has been of increasing importance for several applications in computer vision and graphics, such as creating and driving virtual avatars, action recognition, or 3D reconstruction. A big challenge in pose estimation from incomplete observations are ambiguities, i. e. multiple possible poses that would perfectly explain the given observation. Naturally, it is desired to solve these ambiguities by learning data priors from a vast amount of available data.

In the last year our group has developed multiple methods that aim to introduce data priors in pose estimation for human bodies and human hands. In our work Pose-NDF (ECCV'22), we show that manifold learning can be used to learn pose manifolds of plausible human poses and that it is a viable alternative to previously existing data priors based on VAEs and GANs. The presented method outlines a completely new way of modeling and using data priors, which was acknowledged by reviewers and committee through awarding a Best Paper Honorable Mention Award of ECCV'22. Further, our TOCH method (ECCV'22) demonstrates how estimation of hand-object interaction sequences in motion can also heavily benefit from learning on existing datasets. TOCH solves several technical challenges that

arise from fitting a MANO hand model by introducing a novel, object-centric representation for hand-object interaction.

Real Virtual Humans *Investigator: Gerard Pons-Moll*

Modelling humans is vital to understand the world around us. It is also central to a wide range of applications in gaming, animation, robotics, augmented and mixed reality, etc. At Real Virtual Humans we aim to build models of digital humans that look, move and behave like the real ones, in order to better understand the humans and the world we live in. Broadly, speaking we have been focusing on (i) modelling the appearance of the digital humans, (ii) modelling the objects and scenes around them, and (iii) using our models of humans and surroundings to jointly model human-object interactions in 3D.

Our work (PoseNDF, Tiwari et al. ECCV'22) demonstrated that implicit functions can be used to model high dimensional data manifolds such as 3D poses and not just 3D shapes as is commonly understood. Our model can act as data prior, correct unrealistic poses and animate along the pose manifold. This work received “Best student paper award” at ECCV'22 as it opened new avenues for learning data distributions. Apart from this we improved upon classical tasks like 3D registration, proposed a generative model of people in clothing, and addressed real world tasks like character animation.

To better understand the world around us we've proposed novel methods for 3D scene segmentation with very sparse data annotations (Box2Mesh, Chibane et al. ECCV'22 oral), scene editing and novel view synthesis. Our focus in this direction is to learn scene representations that are generalisable and can be learnt with limited data, as obtaining annotated 3D data in real world setting is hard.

Studying 3D scenes and humans in isolation is limiting as it does not capture the continuous and rich interactions between them. Our research is at the forefront of this new and challenging research avenue. We proposed the first large scale dataset of human-object interactions in 3D, BEHAVE (Bhatnagar et al. CVPR'22). Apart from this we proposed the first learning based methods to track human-object interactions using multi-view depth, monocular RGB as well as body mounted sensor.

Multimodal Deep Learning *Investigator: Zeynep Akata*

Our Multimodal Deep Learning group aims to develop deep learning methods that observe and process multimodal input coming from the environment, make further connections through inference and communicate the system output to the user. The group's current research focus is exploring the interplay between vision and language for several machine learning tasks. The research of Multimodal Deep Learning group is broadly divided into three subfields: disentangled and compositional representation learning, learning with less supervision and explainable machine learning.

In disentangled and compositional representation learning, our premise is that if there exists some basic kind of compositional structure in the world (i.e., smaller parts that make up larger objects), then adaptive algorithms should exploit that structure. We aim to develop truly compositional models that combine the generalization and interpretability of symbolic structures with the learning capabilities of contemporary deep learning algorithms.

In learning with less supervision subfield, our aim is to learn a model about the environment given a set of observations that belongs to a certain set of classes. The main challenge of this task is that the set of classes at training and at test time are disjoint or the supervision signal is not always clean. As, the classic supervised learning algorithms that rely on the full set of class labels can not be employed for the extreme case of this task, i.e. zero-shot learning, we use language as auxiliary information to build a structure in the label space.

To enable trust of the user, one aspect of deep learning to strengthen that has been getting increasingly popular is to understand the internal decision process of a network. Another one is to justify the output of the decision maker given the input in human understandable terms. These explanations either come in the form of language or visual justifications such as machine attention. The group focuses on generating visual explanations and pointing to the evidence for a classification decision of a deep multimodal learning framework.

Combinatorial Computer Vision *Investigator: Paul Swoboda*

Combinatorial optimization is a fundamental tool in machine learning that offers the promise to improve performance of deep learning systems further by incorporating explicit prior knowledge in the optimization. The research group Combinatorial Computer Vision studies mathematical abstractions of computer vision tasks posed as combinatorial optimization problems. One focus is on developing efficient algorithms to solve the ensuing problems and to benchmark them w.r.t. metrics defined by the application. Another field of research is on integrating combinatorial optimization problems into deep networks to jointly train the network end-to-end. Application areas include tracking, clustering, segmentation and correspondence problems. Moreover, the group conducts basic research into algorithm design.

Achievements during the reporting period include: (i) A general purpose solver for combinatorial problems from structured prediction tasks and a highly parallel extension of it. (ii) Tracking systems that achieve state of the art results for tracking objects observed by a single or multiple cameras. (iii) Highly parallel as well as densely connected clustering with multicut. Our works have been published in top-tier conferences such as CVPR, ICML, NeurIPS, AACL, ECCV and ICCV.

Robust Visual Learning *Investigator: Margret Keuper*

The susceptibility of neural network based models to common corruptions as well as targeted attacks is a crucial problem that hampers the real-world deployment of otherwise well performing models in safety critical environments. Facilitating the learning of robust models is thus a key challenge for my group. Therefore, we have studied robust and non-robust models with respect to various properties that relate to the models' training schemes as well as to their architecture, with the aim to identify key properties that allow to build more robust models.

Regarding architectures, we have investigated the impact of aliasing in the feature maps and have leveraged our findings to build better architectures for adversarially robust models (Springer Machine Learning, ECCV'22). We also contributed a dataset that relates neural architectures to their robustness (ICLR'23) and we proposed an approach that allows for efficient multi-objective architecture search (ECCV'22). This way, the architecture of a

network can not only be optimized for the resulting validation accuracy but also for additional criteria such as energy consumption or latency on specific hardware.

Regarding training schemes, we have studied the impact of adversarial training on different model generalization properties and their calibration (CVPRw'23, NeurIPS'22). Further, we have investigated two specifically relevant aspects: the effect of realistic optical aberrations on a model's behavior (NeurIPS'22 workshop) and adverse weather conditions, and provide training data for both (WACV'23 and ICCV'23 submission).

Regarding generative models, we have contributed methods to shape the learned representation space of deterministic autoencoders using Gaussian mixture models to promote more robust behavior (NeurIPS'21, NeurIPS'22). We also investigated spectral artifacts and their impact on image generation and sustainable deepFake detection (AAAI'21, IJCAI'21).

In light of the rather low robustness and poor interpretability of most current deep neural models, we have also conducted research in a different direction: the combination of deep learning models and a graphical model based optimization. We have been working on improving the expressiveness of graph-based grouping formulations (TPAMI'22) as well as on the end-to-end optimization of neural networks in conjunction with graph-based grouping formulations (ECML-PKDD'22, GCPR'22).

Publications and Awards

Chapter 28 contains a detailed report of the publications, cooperations and awards of the reporting period. From the journal publications 17 have been published or accepted at either IEEE PAMI, IJCV, ACM TOG, or TACL. From the conference publications, 64 have been published or accepted at one of the major computer vision conferences (CVPR, ICCV, ECCV). An additional 19 have been published at major conference in machine learning (15 at NeurIPS, ICML, and ICLR; 4 at AAI).

Members of the group received a range of prizes including: (i) personal awards such as early career awards (the German Pattern Recognition Awards for both 2021 (Zeynep Akata) and 2022 (Dengxin Dai), as well as the ECVA Young Researcher Award 2022 (Zeynep Akata)), a dissertation award (Jan Eric Lenssen), as well as master level awards (Julian Chibane, Anurag Das, Anna Kukleva); (ii) best paper awards such as ECCV 2022 Best Paper Honorable Mention, Best Student Paper Awards 3DV 2022, and Best Paper Honorable mention 3DV 2022; (iii) fellowships and research awards such as a Meta PhD Fellowship Award, a Snap Research Award, and a Huawei Research Award; and (iv) winning competitions such as the WAYMO Motion Prediction Challenge 2022 and CVPR SHARP'21 Workshop Winner. Also, members of the group have been awarded 14 outstanding or top reviewer awards at conferences such as NeurIPS, CVPR, ICCV and ECCV.

5 D3: Internet Architecture

History and Group Organization

The Research Group Internet Architecture (D3) was established in January 2018. The group’s organizational structure and more details of the members are provided later in this report.

Due to the COVID-19 pandemic, the overall research group grew slower than may have been expected. During the reporting period, the group hosted three senior researchers/research group leaders (financed by MPI), namely, Oliver Gasser, Tobias Fiebig (from April 2022), and Savvas Zannettou (until October 2021). Each of the group leaders supervise their own PhD-students (co-supervised by myself) and conduct research in their areas. Also the group hosted four postdocs (2 female) and 20 Ph.D. students (4 female). During the reporting period five new students joined and five Ph.D. students (2 female) handed in their thesis at Saarland University (two still have to defend). Moreover, the “last” student from Berlin graduated.

Yiting, who joined MPI-INF as independent W2-tenure track faculty in Fall 2020, set up her research group. Anja Feldmann acts as her mentor and her research group is associated with D3 with regards to infrastructure and administrative support. Yiting’s research follows a cross-layer approach and covers broad topics for optimizing the network stack, including switch hardware, network protocols, software systems, and cloud applications.

Vision and Research Strategy

The Internet is an immensely successful human-made artifact that has fundamentally changed society. In becoming such an immensely successful infrastructure, the use of the Internet and, consequently, the Internet itself has changed and continues to change, as highlighted by this group’s research efforts.

These changes are in part driven by the user or eye-ball interests as and how content, including user-generated data, is made available. The AS-level topology of the Internet has also experienced significant changes over time: It has evolved from a highly hierarchical topology to a flatter (non-hierarchical, simpler) topology. Service providers, e.g., IoT platforms, and content delivery networks are relying on sophisticated back-office infrastructures.

The future challenges in this context are (i) continual observation of the underlying infrastructure, (ii) locating and fixing current performance and functionality, bottlenecks, (iii) Internet security measurements, (iv) understanding and building dependable digital infrastructure as a socio-technical system, (v) online societies, and (vi) understanding the interactions of the infrastructure with the society.

We follow a data-driven systems research agenda to tackle these challenges: Collect data from operational networks, analyze them using big-data analytics to identify invariants, revisit assumptions, and detect and localize performance bottlenecks in the Internet. We

also use simulation environments to validate our analysis and to support “what-if” studies. The insights obtained from the measurements form the foundation for shaping the future Internet via optimizations and alternative designs. Hereby, our output includes protocol enhancements, novel network management tools, concepts for software-defined networking, as well as studies of the impact of the technology on the society.

Research Areas and Achievements

The main research areas of the department are Internet traffic analysis, innovative traffic control to future proof the Internet, Internet security measurement, dependable digital infrastructure, online social networks, as well as network neutrality and the sharing economy. The latter is addressed within the context of the Weizenbaum Institute.

Internet Traffic Analysis *Investigator: Anja Feldmann*

The Internet is a massively heterogeneous and also continuously evolving ecosystem. Naturally, not one vantage point can accurately capture the breadth of these changes. This limitation notwithstanding, there is a dire need to monitor and analyze the use of the Internet infrastructure as well as the characteristics of the infrastructure itself, especially given the constantly evolving nature of this ecosystem. Therefore, our research focuses on meticulously gathering measurements from diverse vantage points. We systematically analyze these measurements to characterize the performance and the operation of the Internet ecosystem.

Research Highlight: Deep Dive into the IoT Backend Ecosystem *Investigators: Said Jawad Saidi, Oliver Gasser, Anja Feldmann in cooperation with Srdjan Matic (IMDEA Software Institute) and Georgios Smaragdakis (TU Delft)*

Internet of Things (IoT) devices are becoming increasingly ubiquitous, e.g., at home, in enterprise environments, and in production lines. To support the advanced functionalities of IoT devices, IoT vendors as well as service and cloud companies operate IoT backends—the focus of this research project. In this project we follow up on our previous work of detecting IoT devices in the wild, and propose a methodology to identify and locate them IoT backends by (a) compiling a list of domains used exclusively by major IoT backend providers and (b) then identifying their server IP addresses. Our methodology relies on a fusion of information from public documentation, passive DNS, and active measurements.

Innovative Traffic Control to Future-Proof the Internet *Investigator: Anja Feldmann*

The continually evolving nature of the Internet ecosystem routinely introduces new, unforeseen challenges. With the increasing adoption of sensors and Internet of Things (IoT) devices, we are generating an unprecedented volume of data. As if this immense amount of data was not enough, such data now comes from divers endpoints, widely distributed throughout the network (at its edge). Still, this opens new opportunities, e.g., for scalable DDoS analysis.

The changes in the Internet ecosystem also provide new opportunities to revisit some long standing networking problems and design new practical, scalable solutions that exploit

or leverage these recent changes, e.g., DDoS mitigation, revisiting congestion control, or exploiting new opportunities for video transmissions.

Research Highlight: Collaborative DDoS Mitigation *Investigators: Daniel Wagner, Anja Feldmann, and Christoph Dietzel, in cooperation with Daniel Kopp, Matthias Wichtlhuber (DE-CIX), Oliver Hohlfeld (Brandenburg University of Technology), and Georgios Smaragdakis (TU Delft)*

Despite ongoing research on DDoS detection and mitigation paired with improved understanding about adversary strategies, DDoS attacks are still on the rise and at an all time high. To date, attackers incorporate more sophisticated techniques and exploit by far more different mechanisms and protocols to form DDoS attacks at unparalleled threat levels.

In this project, we measure the ability of Internet Exchange Points (IXPs) to mitigate amplification DDoS attacks. Located in the heart of the Internet, they are closer to the source of attacks than conventional mitigation facilities that are typically located at the attack's destination. However, the IXPs' location usually lacks a holistic view on the attack traffic, as routes exist towards the target that bypass IXPs. The remaining fraction of the attack that crosses the IXP may not be large enough for local detection mechanisms to detect the traffic as malicious. To cope with this, we propose a collaboration between IXPs to get a more informed view on the attacks and improve the local attack detection. We unify the data of 11 IXPs across Europe and North America and identify 120k amplification DDoS attack events throughout a period of 6 months.

Internet Security Measurements *Investigator: Oliver Gasser*

As the Internet is becoming more and more ubiquitous in people's everyday lives—pushed even more so by the COVID-19 pandemic—aspects of security in Internet-connected systems are increasing in importance. In addition, the deployment of IPv6-enabled devices in the Internet is steadily increasing, with more than 40% of Google users using IPv6 as of March 2023. To analyze the security of Internet-connected devices, we devise measurement techniques to reach many different devices in the IPv4 and IPv6 Internet, and we conduct Internet measurements and characterize different aspects of security of these devices.

Research Highlight: Illuminating Large-Scale IPv6 Scanning in the Internet

Investigators: Oliver Gasser in cooperation with Philipp Richter and Arthur Berger (Akamai)

While scans of the IPv4 space are ubiquitous, today little is known about scanning activity in the IPv6 Internet. In this project, we present a longitudinal and detailed empirical study on large-scale IPv6 scanning behavior in the Internet, based on firewall logs captured at some 230,000 hosts of a major Content Distribution Network (CDN). We develop methods to identify IPv6 scans, assess current and past levels of IPv6 scanning activity, and study dominant characteristics of scans, including scanner origins, targeted services, and insights on how scanners find target IPv6 addresses. Where possible, we compare our findings to what can be assessed from publicly available traces. Our work identifies and highlights new challenges to detect scanning activity in the IPv6 Internet, and uncovers that today's scans of the IPv6 space show widely different characteristics when compared to the more well-known IPv4 scans.

Dependable Infrastructure as a Socio-Technical System *Investigator: Tobias Fiebig*

Over the past half century, the rise and accelerating evolution of digital technology shaped society as much as social dynamics shape this technology. Our research in this area focuses on the key questions in this interaction, ranging from how building digital infrastructure is shaped by social and societal interactions, to how technical developments ultimately shape how we live together as humans, from the smallest to the societal scale. Ultimately, the key-question of our work is: “How can we build IT systems that are reliable and secure, which support society in answering the practical problems of our time without introducing new threats?”

To tackle this question we combine the core-competencies of our group in Internet measurement with methods from social sciences, human factors, and the governance domain. This allows us to systematically leverage quantitative data for large scale perspectives, e.g., to assess societal shifts towards centralization, and combine this with qualitative methods to *explain* the root causes behind our quantitative findings, may it be interviews with operators and decision makers regarding root-causes for centralization or an in-depth protocol analysis to explain effects protocol’s complexity had on the Internet as a whole.

Research Highlight: Analyzing the Cloudification of Higher Education *Investigators: Tobias Fiebig, Mannat Kaur, and Simran Munnot*

The digital transformation of academia is one of the major technical challenges of our time. However, as all challenges, this transformation is not without risks. Following common industry paradigms, universities now commonly look at infrastructure provided just by a few major cloud operators.

In this work, we investigate in how far universities depend on an small set of digital infrastructure providers. We were the first to conduct comprehensive measurements characterizing these developments from 2015 onwards, and published further analyses on the organizational implications of these developments. Our work illustrates how the progressing cloudification of academia impacts core-values like academic freedom, and ties differences in cloud adoption between several countries to stark differences in academic culture. Furthermore, we provide a clear long-term agenda to preserve academic freedom, as well as researchers and students privacy.

Online Social Networks *Investigator: Savvas Zannettou*

Over the past decade, Online Social Networks (OSN) have exploded in popularity, mainly because they help people in addressing their communication, information acquisition, and entertainment needs. At the same time, OSNs offer a fertile ground for the creation and amplification of important socio-technical issues like the spread of false information and hate speech. Therefore, it is imperative to analyze data from OSNs to understand, detect and mitigate these issues to minimize possible consequences both on the online and offline world (e.g., extensive dissemination of false information affecting people’s voting decisions). In this research area, we aim to analyze activity on OSNs to understand emerging socio-technical issues, develop tools/techniques to detect potentially harmful information and develop and assess the effectiveness of various mitigation strategies.

Research Highlight: Do Platform Migrations Compromise Content Moderation?

Evidence from r/The_Donald and r/Incels *Investigators: Savvas Zannettou in cooperation with Shagun Jhaver (Rutgers University, USA), Jeremy Blackburn (Binghamton University, USA), Emiliano De Cristofaro (University College United Kingdom), Gianluca Stringhini (Boston University), Robert West (EPFL, Switzerland), Krishna P. Gummadi (MPI-SWS, Germany)*

Analyzing content moderation online is important for several reasons. First, social media and other online platforms have become major sources of information and communication, shaping public discourse and opinions. The content shared on these platforms can have significant consequences for individuals, communities, and society as a whole. Thus, understanding the challenges and complexities of moderating online content is crucial for ensuring that these platforms are safe and inclusive spaces for all users. Second, content moderation involves a range of technical, social, and ethical issues that require interdisciplinary expertise. Studying content moderation online involves understanding the technical mechanisms used to identify and remove harmful content, as well as the social and cultural contexts in which these mechanisms operate. Moreover, content moderation online is a constantly evolving field, as new technologies and social dynamics emerge. In this line of work, our goal is to analyze and understand multiple aspects of content moderation, including how soft moderation interventions (i.e., warning labels are applied online) and effective they are, what happens after online platforms take moderation action on specific online communities (i.e., community bans), and how we can design systems to automatically identify accounts that are state-sponsored trolls and are involved in misinformative campaigns online.

Projects and Cooperations

Since 2017, Anja Feldmann is PI at the Weizenbaum Institute, Berlin. The Weizenbaum Institute for Networked Society is the German Internet Institute, a place of excellent research on the transformation and design processes of digital change. In the spirit of Joseph Weizenbaum, we research the necessary framework conditions, means, and processes for individual and social self-determination in a networked society. The project is funded by the Federal Ministry of Education and Research.

In addition we are involved in the BMBF SupraCoNex project—a cooperation with Hochschule Nordhausen, Technische Universität Braunschweig, NewMedia-Net GmbH and Fraunhofer-Gesellschaft zur Förderung der angewandten Forschung e.V.; the 6G Research and Innovation Cluster (6G-RIC)—a research hub designed to lay the scientific and technical foundations for the next generation of mobile communications (6G) across all technology levels; the Quantum Internet Alliance—a collaboration between the TU Delft and TNO to develop a full-stack prototype network connecting distant cities.

Publications, Awards, and Media Coverage

Despite all pandemic-related obstacles, members of the group were able to publish more than 60 papers, among them many at top-tier conferences and journals, e.g., 5(+7) papers at Internet measurement conferences (IMC+PAM), 5 papers at security venues (CCS, USENIX,

NDSS, S&P), and 9 papers at Web related conferences (WebSci, CSCW, WWW, ICWSM), win multiple awards for our research, including the IETF applied networking research prize for the CCS 2022 paper and the best paper award at PAM 2023, receive excellent press coverage for some of our work, serve on steering committees of ACM ToN, ACM IMC, ACM CoNEXT, and PAM, conduct online/hybrid lectures and even an in-person seminar. Moreover, three former members of the group got their first assistant professorship positions.

Additionally, we (Anja Feldmann and Lars Prehn) contributed to the community by organizing a shadow TPC for the ACM Internet Measurement Conference 2022 as Shadow TPC Chairs. The feedback of the students was excellent. They all agreed that they are much better able to understand the process with all its pros and cons.

Anja Feldmann also contributes to the MPG environment by participating in a multitude of different MPG Commissions. She is, e.g., member of the presidential commission governance, the CPTS perspective commission, the advisory board digitalization, as well as the IT-Sicherheitskommission. Oliver Gasser is the elected Scientific Staff Member Representative of the Institute since mid 2021.

During the last two years, the result of multiple research works from our group was covered in the media including:

- Positionspapier zur Technologische Souveränität und die Rolle der Kommunikationssysteme in einer digitalisierten Gesellschaft Fachkreis Kommunikationstechnologien, Beraterkreis für das Referat „Vernetzung und Sicherheit digitaler Systeme“ im Bundesministerium und Bildung und Forschung, **April 2021**.
- A Year in Lockdown: How the Waves of COVID-19 Impact Internet Traffic by Anja Feldmann, Oliver Gasser, Franziska Lichtblau, Enric Pujol, Ingmar Poesse, Christoph Dietzel, Daniel Wagner, Matthias Wichtlhuber, Juan Tapiador, Narseo Vallina-Rodriguez, Oliver Hohlfeld, Georgios Smaragdakis. Communications of the ACM, July 2021, Vol. 64 No. 7, Pages 101-108, **July 2021**.
- “Trotz Privacy Extensions: IPv6-Adressen für andauerndes Tracking nutzbar” by Stefan Krempl, heise online <https://www.heise.de/news/Trotz-Privacy-Extensions-IPv6-Adressen-fuer-andauerndes-Tracking-nutzbar-7186203.html>, **July 2022**.
- “Three-quarters of Dutch student data stored on American tech giants’ cloud” by Tobias Fiebig <https://nltimes.nl/2022/10/17/three-quarters-dutch-student-data-stored-american-tech-giants-cloud>, **October 2022**. This research led to an official request in the Dutch Parliament: <https://www.tweedekamer.nl/kamerstukken/kamervragen/detail?id=2022Z19631&did=2022D45952>

Teaching

Our group is active in teaching and has offered the Data Networks Core Lecture in Summer Term 2021 (online), Summer Term 2022 (hybrid), and Summer Term 2023 (in person with hybrid option). In addition we offer the seminar Hot Topics in Data Networks Seminar in the Fall terms. In addition, group members have supervised 13 Master and Bachelor Thesis during the reporting period.

6 D4: Computer Graphics

Group Overview

The computer graphics group (D4) was established in 1999 with the appointment of Hans-Peter Seidel. Karol Myszkowski joined in 2000. Christian Theobalt, who had been a tenured senior researcher with the group since 2009, was appointed director in 2021 and is now heading his own department on Visual Computing and Artificial Intelligence (D6).

Over the last two decades the group has attracted a highly talented pool of young researchers, and we have been home to an exceptional team of PhD students and postdocs. Meanwhile, more than 70 former group members hold faculty positions at other places.

At the time of writing, the group encompasses one senior researcher with tenure (K. Myszkowski), five group leaders and senior researchers without tenure (V. Babaei, G. Singh, R. Zayer, Paul Strohmeier and T. Leimkühler (co-appointed with D6)), three postdocs, and 12 PhD students. Three group members completed and handed in their PhD thesis during the reporting period, and several of our young researchers and former PhD students got offers for faculty appointments¹, or postdoc and senior postdoc positions². Full details on current and recent group members are provided in the main part of the report.

Vision and Research Strategy

During the last few decades computer graphics firmly established itself as a core discipline within computer science. New and emerging technologies such as digital media, social networks, digital television, digital photography and the rapid development of new sensing devices, telepresence, virtual and augmented reality, computational fabrication, further indicate its potential and pose new challenges in the years to come.

To address these challenges, and to seamlessly blend real and synthetic footage, we had early on adopted a new and more integrated scientific view of computer graphics as *3D Image Analysis and Synthesis* that takes into account the whole image processing pipeline from scene acquisition to scene reconstruction to scene editing to scene rendering. We also take into account human perception on all levels of the pipeline, and we exploit the abundance of digital visual data and novel concepts from machine learning to extract powerful priors that can assist us during the acquisition, reconstruction, editing, and image formation processes.

Our vision and long term goal are completely immersive, interactive, and visually rich environments with sophisticated scene representations and the highest visual quality, fused

¹M. Chu (Beijing Univ., China, 2022), Y. Gryaditskaya (Univ. of Surrey, UK, 2022), P. Kellnhofer (TU Delft, NL, 2021), A. Serrano (Univ. Zaragoza, Spain, 2021), C. Tursun (Univ. Groningen, NL, 2021), R. Zayer (Univ. East Anglia, UK, 2023), Q. Zheng (Chinese Academy Sciences, Inst. Software, Beijing, China, 2021)

²J. Hladky (Huawei Research, Munich), C. Reed (King's College London, UK)

seamlessly with the real world. Standard 2D screens are being replaced with high dynamic range displays, stereo and automultiscopic screens, portable and wearable displays. Imaging algorithms with embedded perceptual models ensure that the perceived quality and viewing comfort is maximized. Interaction is intuitive and light weight. We are also reach out into new domains, such as computational fabrication, and sensorimotor interaction.

Research Areas and Achievements

Our research is currently organized into the following six research areas (coordinators in brackets):

- Digital Geometry Processing (R. Zayer)
- Sampling, Image Synthesis, and Machine Learning (T. Leimkühler and G. Singh)
- Perception: HDR Imaging, VR, and Material Appearance (K. Myszkowski)
- Computational Design and Fabrication (V. Babaei)
- Sensorimotor Interaction (P. Strohmeier)

However, we are not organized into disjoint subgroups, and there is little hierarchy. While each of the areas has its specific focus, some of them also have significant overlaps. Likewise, the students and researchers working in each area are dynamically formed teams rather than specifically dedicated staff. The senior researchers and group leaders together with Hans-Peter Seidel serve as an internal steering committee for the group. They also act as advisors or co-advisors of doctoral students.

During the reporting period we achieved fundamental results on correlated sampling and on bridging the gap between Monte Carlo rendering and neural radiance fields, and we substantially contributed towards improving the visual experience in VR and games and material appearance perception. We achieved groundbreaking results on neural inverse design in computational design, and we significantly advanced tactile rendering. We also continued our successful line of research on the mesh matrix formalism for geometric computing.

Digital Geometry Processing

We continued our successful line of research on casting geometric computations and modifications in terms of concise linear algebra operations, based on the mesh matrix representation. During the reporting period we focused on the analysis of topological features on surfaces and developed a variational loop shrinking algorithm for handle and tunnel detection and Reeb Graph construction on surfaces. Our formulation tracks the evolution of a diffusion front randomly initiated on a single location on the surface. We develop a dynamic data structure for tracking the evolution on the surface encoded as a sparse matrix which serves for performing both diffusion numerics and loop detection and acts as the workhorse of our fully parallel implementation. As a byproduct, our approach can be used to construct Reeb graphs by diffusion (CGF'21, EG'23).

In a second line of research, together with researchers from D6, we investigated neural representations for the reconstruction and meaningful control of fluids. In particular, we proposed a novel data-driven conditional adversarial model that solves the challenging and

theoretically ill-posed problem of deriving plausible velocity fields from a single frame of a density field (SIG'21). Besides density modifications, our generative model is the first to enable the control of the results using all of the following control modalities: obstacles, physical parameters, kinetic energy, and vorticity. Our method is based on a new conditional generative adversarial neural network that explicitly embeds physical quantities into the learned latent space, and a new cyclic adversarial network design for control disentanglement. In follow-up work we developed the first method to reconstruct dynamic fluid phenomena by leveraging the governing physics (ie, Navier-Stokes equations) in an end-to-end optimization from a mere set of sparse video frames (without taking lighting conditions, geometry information, or boundary conditions as input) (SIG'22).

Sampling, Image Synthesis, and Machine Learning

Synthesizing realistic images typically involves computing high-dimensional light transport integrals. Traditional rendering algorithms aim towards designing sampling strategies that can ameliorate the error during the estimation of these integrals. Recent advances in neural rendering have opened an exciting line of research where the goal is to synthesize images with the help of deep learning. We develop state-of-the-art algorithms that operate at the intersection between traditional rendering and machine learning-based approaches. At the core, we focus on sampling problems for computer graphics, vision and machine learning, while integrating neural generative priors into the pipeline. We are also interested in interactive rendering and editing of traditional and neural scene representations.

View-dependent effects such as reflections pose a substantial challenge for image-based and neural rendering algorithms. Curved reflectors are particularly hard, as they lead to highly non-linear flows as the camera moves. We have introduced a new point-based representation to compute Neural Point Catacaustics allowing novel-view synthesis of scenes with curved reflectors, from a set of casually-captured input photos (SIGAsia'22).

Neural Radiance Fields (NeRFs) have revolutionized novel-view synthesis for captured scenes, but their implicit representation makes them difficult to edit. We have introduced NeRFshop, a novel end-to-end method that allows users to interactively select and deform objects through cage-based transformations, thus enabling fine user control for the selection of regions or objects to edit (ACM I3D'23). Another limitation of NeRFs is that they are limited to synthesize images under the original fixed lighting conditions. To tackle relighting, several recent methods propose to disentangle reflectance and illumination from the radiance field. These methods can cope with solid objects with opaque surfaces, but participating media are neglected. We propose to learn neural representations for participating media with a complete simulation of global illumination (NeurIPS'21). We estimate direct illumination via ray tracing and compute indirect illumination with spherical harmonics. Our approach avoids computing the lengthy indirect bounces and does not suffer from energy loss. This project is a proof of concept work that demonstrates how to bridge the gap between traditional Monte Carlo rendering and neural radiance fields.

Current 2D Generative Adversarial Networks (GANs) produce photorealistic renderings of portrait images. Embedding real images into the latent space of such models enables high-level image editing. We have introduced FreeStyleGAN, a new approach that generates

an image with StyleGAN defined by a precise 3D camera. Our solution provides the first truly free-viewpoint rendering of realistic faces at interactive rates, using only a small number of casual photos as input, while simultaneously allowing semantic editing capabilities, such as facial expression or lighting changes (SIGAsia'21).

We introduced QuadStream, a new streaming rendering content representation that reduces motion-to-photon latency by allowing clients to efficiently render novel views without artifacts caused by disocclusion events. The approach achieves superior quality compared both to video data streaming methods, and to geometry base streaming. (EG'21, SIGAsia'22)

Sampling is at the core of many applications in computer graphics. Our research aims at the theoretical understanding of sampling distributions, and we build tools to analyze the local and non-local correlations in sample patterns. We proposed a novel multi-class point optimization based on continuous Wasserstein barycenters. Our formulation is designed to handle hundreds to thousands of optimization objectives and comes with a practical optimization scheme (SIGAsia'22). For perceptual rendering, the samples are optimized irrespective of the scene. We therefore developed a novel perceptual error optimization scheme for Monte Carlo rendering that can be tailored to a given scene. The method distributes the error as visually pleasing blue noise in image space (ACM TOG'22).

We reformulate Monte Carlo estimation as a regression-based problem where traditional Monte Carlo estimation can be seen as fitting a constant to the function evaluations. By using a polynomial function to fit the function values, the variance of the estimator is reduced, resulting in a provable improvement over the classical Monte Carlo estimator (SIG'22). We built a powerful pipeline for point-pattern synthesis using Gabor and random filters (requiring significantly less feature maps compared to existing VGG-19-based methods) (EGSR'22), and we are actively investigating the editing of point patterns by image manipulation.

Perception: HDR Imaging, VR, and Material Appearance

Our research aims to advance our knowledge on image perception and to apply this knowledge to the development of imaging algorithms with embedded computational models of the human visual system (HVS). This approach offers significant improvements in both computational performance and perceived image quality. In particular, we aim for the exploitation of perceptual effects as a means of overcoming the physical limitations of display devices and enhancing the apparent image quality. During the reporting period we continued our successful and long standing line of research on HDR imaging, and we put special emphasis on Improving the Visual Experience in VR, and on Material Appearance.

While HDR content is becoming ubiquitous, the dynamic range of common display devices is still limited, therefore tone mapping (TM) remains a key challenge for image visualization. Neural networks have shown promise in TM, but their performance has been limited by training data. We proposed a novel self-supervised TM operator trained at test time for each HDR image using a carefully designed loss function based on contrast perception (by reformulating classic VGG feature maps into feature contrast maps) (CGF'22). We also addressed HDR video reconstruction (Comp.& Graph.'22).

Recently, neural scene representations have become a viable alternative for novel view synthesis, but the handling of transparent objects with complex refraction has been problematic.

In our work on eikonal fields for refractive novel-view synthesis we have demonstrated how to integrate the physical laws of eikonal light transport into the general NeRF setup and adapt an implicit representation that can model transparent and refractive objects with a spatially varying index of refraction, leading to high-quality novel view reconstruction of refractive objects (SIG'22).

The rendering performance is an important requirement in VR applications. Recently, there is a shift in real-time graphics from rendering with a fixed resolution and refresh rate to a more adaptive approach, in which we control spatiotemporal resolution in order to maximize the quality under a given rendering budget. We proposed a novel rendering method that takes advantage of the limitations of the visual system to reallocate the rendering budget to the most vital part of the spatiotemporal domain. The key component of the method is a novel metric, which considers how the judder, aliasing, and blur artifacts introduced by variable rate shading (VRS) at a given refresh rate are masked by hold-type blur, eye motion blur, and limited spatiotemporal sensitivity of the visual system (SIGAsia'21). Another important aspect of VR is image reproduction on head-mounted displays. Dimming a display can be beneficial for the VR experience as it reduces the visibility of flicker, saves power, prolongs battery life, and reduces the cost of the device. A downside of this approach is the reduced sensitivity to stereoscopic depth cues. This motivates our method for enhancing contrast at low luminance levels, intended to improve the reliability of stereoscopic depth cues. The proposed method improves the user experience for VR headsets that need to operate at low power and those that cannot achieve high refresh rates (SIG'22). Foveated rendering can greatly improve the computational performance in VR setups. The use of Generative Adversarial Networks (GANs) has recently been shown to be a promising solution for such a task, as they can successfully hallucinate missing image information. We addressed the problem of efficiently guiding the training of foveated reconstruction techniques such that they are able to recover perceptually important image features (ACM TAP'23). Faces are widely used in gaming, entertainment, and social applications, and humans are particularly sensitive to their appearance. In collaboration with Reality Labs (Meta), we generated a new dataset of high-quality and demographically-balanced face scans and conducted a large-scale perceptual study to subjectively evaluate them. Our dataset consists of over 84,000 quality comparisons, making it the largest-ever psychophysical dataset for geometric distortions. We demonstrated how our data can be used for applications like state-of-the-art metrics calibrations, compression, and level-of-detail rendering (SIGAsia'22).

Material appearance is determined not only by material reflectance, but also by surface geometry and illumination. We have analyzed these effects by collecting a large-scale dataset of perceptual ratings of appearance attributes with more than 215,680 responses for 42,120 distinct combinations of material, shape, and illumination, and by using this dataset to train a deep-learning architecture for predicting perceptual attributes that correlate with human judgments. We demonstrate the consistent and robust behavior of our predictor in various challenging scenarios, which, for the first time, enables perceived material attributes from general 2D images (SIG'21, TVC'21). In recent follow-up work, we investigated the problem of gloss appearance matching between the real world and display depiction as a function of material glossiness, surface geometry, scene illumination, and display luminance (SIGAsia'22).

Computational Design and Fabrication

The recent wide availability of advanced manufacturing hardware has triggered huge interest in academia and industry. We have a particular interest in the visual appearance of objects and strive for better algorithms for appearance 3D printing and for novel digital manufacturing platforms, such as laser marking. In addition, we develop algorithmic tools to evaluate, represent, and synthesize products with improved or completely novel functions, and we aim to integrate the fabrication hardware into the computational pipeline.

In computational design and fabrication, neural networks are becoming important surrogates for bulky forward simulations. A long-standing, intertwined question is that of inverse design: how to compute a design that satisfies a desired target performance? We demonstrated that the piecewise linear property, very common in everyday neural networks, allows for an inverse design formulation based on mixed-integer linear programming. Our mixed-integer inverse design uncovers globally optimal or near optimal solutions in a principled manner. Furthermore, our method significantly facilitates emerging, but challenging, combinatorial inverse design tasks, such as material selection (SIG'22).

The key property of a successful neural inverse method is the performance of its solutions when deployed in the real world, i.e., on the native forward process (and not only the learned surrogate). We developed Autoinverse, a highly automated approach for inverting neural network surrogates. Our main insight is to seek inverse solutions in the vicinity of reliable data which have been sampled from the forward process and used for training the surrogate model. Autoinverse finds such solutions by taking into account the predictive uncertainty of the surrogate and minimizing it during the inversion (NeurIPS'22 (spotlight)).

Dissolution processes are fascinating. Objects with the same mass but different shapes can dissolve via different dynamics, resulting in vastly different release profiles. We developed Shape from Release, a novel method for the inverse design and fabrication of controlled release structures. We start with a simple physically inspired differentiable forward model of dissolution and formulate our inverse design as a PDE-constrained topology optimization that has access to analytical derivatives obtained via sensitivity analysis (SIGAsia'22).

Despite the ongoing advances of computational methods in creating innovative content for manufacturing, the potential of these methods for optimizing or controlling the manufacturing processes in an intelligent way is largely untapped. Our research advocates the integration of the fabrication hardware into the computational pipeline and not treating the hardware merely as a "consumer" of the created content. We developed reinforcement learning based controllers for challenging additive manufacturing setups, such as direkt ink writing with low-viscosity materials (SIG'22), and multi-material fusion (ICRA'23).

Sensorimotor Interaction

Our research aims to advance the understanding of sensorimotor interactions and apply this knowledge to the development of new technologies. We are currently exploring sensorimotor loops in three domains. The first is Mediation & Tacton Design, in which we explore ways in which technology can represent information. Next, we investigate vibrotactile rendering, particularly within the context of augmented tactile reality. Finally, we explore how we might enhance the experience of our body through human augmentation. Through the combination

of these research areas, we try to develop a comprehensive understanding of how sensorimotor interaction can be used in the broader field of human-computer interaction (HCI).

We have developed TactJam, a software and hardware suite for designing vibrotactile icons on the body (TEI'22), and we have explored the use of such pre-reflective cues in the design of hermeneutic symbols, demonstrating that incorporating embodied mediation can enhance the efficacy of symbol encoding and broaden the affective range of tactile symbols (CHI'23).

Many material experiences can be created using only vibration, including friction, compliance, torsion, bending, and elasticity. Our work on vibrotactile rendering demonstrates that these experiences all rely on the same perceptual mechanism, and suggests that the specifics of a material experience depend less on the rendering algorithm but largely on the action performed when interacting with the material (CHI'23). In HCI research, such haptic systems are seldom used, due to their complexity. We created Haptic Servos, accessible haptic rendering devices with low latency, which allows novices to set up a basic rendering system in minutes (CHI'23 (Honorable Mention)).

We have engaged in human augmentation by designing novel interfaces: In collaboration with Saarland University, we created a handheld printer for collaborative circuit design, where control is shared between user and computer (CHI'22). We have also worked on textile-based devices, such as SingingKnit, which measures muscle activity during singing to augment vocal performances and demonstrates how biofeedback can change body perception and artistic action (AH'22, 2xTEI'23)

Software and Datasets

As part of our research we have developed several libraries, tools, and large corpora of reference data sets that are being made available to the research community at large. This includes our award-winning deeptech startup Oraclase for AI aided laser material processing, our software on profile detection for automatic door and window profile classification, the PFSTOOLS for processing high dynamic range images and video, the LocVis dataset of locally annotated images, the TactJam suite for creating and sharing low fidelity prototypes of on-body vibrotactile feedback, Haptic Servo for creating and augmenting material experiences, and our Interactive Shoe platform for augmented shoe design.

Some Performance Indicators

We made significant progress in all of our research areas. In the reporting period from spring 2021 to spring 2023, we have published 58 peer-reviewed papers in high quality conferences and journals. This includes 18 papers at SIGGRAPH/SIGGRAPH Asia/ACM TOG, 5 papers at CHI, 14 papers at Eurographics/CGF/ACM TAP/TEI, and 10 papers at ICCV/ECCV/CVPR/NeuRIPS (see the main part of the report for details).

We actively participate in the program committees of major conferences (SIGGRAPH, SIGGRAPH Asia, CHI, Eurographics, Pacific Graphics, EGSR, TEI, AH, VMV, ICCV, ECCV, CVPR), and we hold editorial board seats with journals such as ACM TAP, CAGD, GMOD, J. Virtual Reality and Broadcasting, Int. J. Shape Modeling, and Visual Informatics. We have given numerous invited talks and tutorial presentations at major national and international events (see main part). Our software and datasets have been successfully used

in a variety of projects (see main part), and many young researchers from the group have spread out to other institutions.

The group has been cooperating with a wide range of research groups worldwide. Cooperations that have led to joint publications during the reporting period include Stanford, MIT, Princeton, U. Waterloo, McGill, U. Maryland, UC David, Cambridge U., UCL London, CNRS, INRIA, TU Delft, IST Austria, TU Graz, USI Lugano, U. Zaragoza In addition, we also collaborated with some leading industrial research labs, including Google, Reality Labs (Meta), Nvidia, and Adobe. On a European level we cooperate with the CYENS Research Centre of Excellence in Cyprus (Member of the Board), and we participate in the Horizon 2020 Training Networks DISTRO and RealVision. There are also several collaborations within the institute and with other groups on campus.

Awards and Selected Academic Activities

Hans-Peter Seidel became a member of the ACM SIGGRAPH Academy in 2022. He acted as a member of the DFG Senate and as a member of the Senate Evaluation Committee (SAE) of the Leibniz Association. Karol Myszkowski became Technical Papers Co-Chair for Eurographics'23. Vahid Babaei co-chairs Short Papers, and Gurprit Singh co-chairs the posters program for the event.

Vahid Babaei won the Hermann Neuhaus Prize 2022 of the Max Planck Society. His deeptech start-up effort (Oraclase) on laser marking won both a MAX!mize startup grant by the Max Planck Society and an EXIST Transfer Grant by the German Federal Ministry for Economic Affairs and Climate Action (BMWK). Our former postdoc Ana Serrano won the Eurographics Young Research Award 2023. Several group members won best paper awards at leading international venues.

7 D5: Databases and Information Systems

History and Group Organization

D5 was established in 2003. With the upcoming retirement of its director (Gerhard Weikum: August 31, 2023), it has largely been phasing over the past years. At the time of the previous biennial report (May 2021), the group comprised 5 senior researchers, 19 doctoral students and 4 postdocs. As of now (May 2023), the group has shrunk to 1 senior researcher, 8 doctoral students and 1 postdoc. Except for some of the students whose graduation is expected in 2024, all researchers will leave the institute by the end of 2023.

Scientific Vision and Research Areas

Our general objective is to develop methods for *knowledge discovery* in a broad sense: extracting, organizing, searching and exploring various kinds of knowledge from structured, semistructured, textual and multimodal information sources. Our approaches combine concepts, models and algorithms from several fields, including database systems, information retrieval, natural language processing, web science, data mining and machine learning.

Our long-term research has been driven by the overarching vision of automatically constructing, growing and curating large-scale and high-quality knowledge bases from Internet sources. We have spearheaded this research avenue, referring to it as *knowledge harvesting*. To boost search, data analysis and language understanding, machines need to be equipped with comprehensive knowledge about the world’s entities, their semantic properties and their relationships among each other. In addition to such encyclopedic facts, machines should also have commonsense knowledge about properties of everyday objects and human activities, and should even capture socio-cultural contexts of propositions.

With the success of web-scale knowledge bases (KBs, aka KGs: knowledge graphs), from early blueprints (including our work) to wide industrial adoption, the research focus over the last years has shifted to advancing the scope and coverage of “machine knowledge” and supporting the KB life-cycle in terms of growth and quality assurance. Also, with the advent of new applications like question answering, conversational bots and other tasks that involve natural language understanding, major efforts have been going into leveraging KBs for these use cases. Methodologically, all this involves machine learning, often based on Transformers and large language models. The latter can be viewed as latent knowledge capturing the content of huge corpora into many billions of neural-network parameters. There is speculation that these trends could make explicit KBs obsolete. We do not share this opinion and rather believe that machine learning and machine knowledge are both needed and complement each other: the more a computer knows the better it can learn, and the better learner can acquire more and deeper knowledge.

Within this scope, our research has been organized into four technical areas, each coordinated by a senior researcher:

- Knowledge Base Construction and Curation (coordinated by Simon Razniewski)
- Information Retrieval and Content Analysis (coordinated by Andrew Yates)
- Question Answering (coordinated by Rishiraj Saha Roy)
- Responsible Data Science (coordinated by Gerhard Weikum)

Contributions and Impact: Long-Term Results

Enhancing computers with “machine knowledge” that can power intelligent applications by an epistemic backbone, has been a long-standing goal of computer science. Major advances in *knowledge harvesting* from web contents, with our group as a trendsetter, have made this formerly elusive vision practically viable.

Our work on knowledge harvesting and automatic knowledge base construction was motivated by the objective of semantic search, starting in 2004. Later it became the Yago-Naga project, with the first release of the Yago knowledge base (<https://yago-knowledge.org>) in February 2007. The unique strength of Yago is its high-quality type system with hundred thousands of classes. When IBM Watson won the Jeopardy quiz show, it leveraged Yago’s knowledge of fine-grained entity types for semantic type checking.

Impact: Knowledge harvesting has been adopted at big industrial stakeholders, and knowledge bases (or knowledge graphs, as industry calls them) have become a key asset in semantic search (for queries about entities), question answering, analytics (e. g., aggregating by entities or types), recommendations and data integration (i. e., to combine heterogeneous datasets). Examples are the knowledge graphs for search engines (e. g., Google, Bing, Baidu) as well as domain-specific knowledge bases (e. g., Amazon, Alibaba, Bloomberg, Mayo Clinic). In addition, knowledge bases have found wide use as a distant supervision source for a variety of tasks in natural language processing. Our Yago-Naga project has served as a blueprint for many of these follow-up endeavors. The original Yago paper at WWW 2007 has nearly 5000 citations, and the Yago2 paper from 2013 has about 1500 citations. The influence and value of Yago has been recognized by the research community through the AIJ Influential Paper Award 2017 (<http://aij.ijcai.org/aij-awards-list-of-previous-winners>) for the 2013 Yago2 paper in the Artificial Intelligence Journal, and the W3C Seoul Test of Time Award 2018 (<https://www.iw3c2.org/ToT>) for the original WWW 2007 paper on Yago. We published a 350-page survey article in the Foundations-and-Trends series 2021, informally called “the machine knowledge book” (<https://www.nowpublishers.com/article/Details/DBS-064>).

High-Risk Research: The Yago-Naga project has been a high-risk (and high-gain) endeavor. In the first few years, hardly any of our colleagues believed that large knowledge bases would become viable and make impact. Some dimensions of this research theme did not work out, though. We started with the goal of developing a search engine that understands semantic concepts for computing precise and concise answers to sophisticated queries. This branch of our research led to insights and novel methods, influential publications and

advanced prototypes like Bingo!, TopX and Naga, but did not succeed in building a full-scale system that could be deployed for Internet search. We also had the ambition to build the envisioned search engine in a completely decentralized manner as a peer-to-peer system. On this theme as well, we were very successful in terms of insight and publications, but our advanced prototype system, Minerva, did not make the practical impact that we had aimed for.

Further Highlights: The Yago-Naga theme spun off various side projects which have been very influential. One of these is the RDF-3X database engine for efficient storage and querying of subject-predicate-object triples, primarily developed by Thomas Neumann who is now a professor at TU Munich and has received the VLDB Early Career Award 2014 for this work (he also won the DFG Leibniz Award in 2019). The four main papers on this research together have more than 2000 citations, and the RDF-3X system has been widely used in the Semantic Web community.

Another contribution with high impact is the AIDA method and software for Named Entity Recognition and Disambiguation. Here, the knowledge base is leveraged as a background asset for better language understanding and text analytics. The EMNLP 2011 paper has about 1200 citations; it is among the most-cited papers on named entity disambiguation. This work has spawned a startup called Ambiverse and the development of the ambiverseNLU software suite, available as open source code.

In terms of methodology, the Yago-Naga project involved bridging the worlds of structured data (DB methods) and unstructured text (IR methods). One of our foundational works, on language models for temporal expressions, won the ECIR Test of Time Award in 2020.

Finally, our recent work on fairness for classifiers and rankings (jointly with colleagues of the Max Planck Institute for Software Systems) has received great attention in the research community. Our publication in the SIGIR 2018 conference, with Asia Biega as lead author (graduated in 2019, now an independent group leader at the Max Planck Institute for Security and Privacy), is one of the most cited papers on fair ranking (ca. 350 citations).

Contributions and Impact: Major Results 2021–2023

We publish our results in top-tier conferences in several communities: Web research (Web), data mining and machine learning (DM&ML), database systems (DB), information retrieval (IR) and natural language processing (NLP). In the two-year timeframe 2021–2023, the group had 11 papers in first-rate Web venues (WWW, WSDM, ISWC, ICWSM, IJCAI), 6 in DM&ML (KDD, ICDM, SDM, ICML, ICLR), 3 in DB (VLDB, SIGMOD), 14 in IR (SIGIR, CIKM, ECIR), and 6 in NLP (ACL, EMNLP). In addition, we are successful in building prototype systems and publishing demo papers at top venues like ACL, SIGIR, SIGMOD, WWW and more.

Advancing Knowledge Base Coverage: Despite their enormous size, even Web-scale knowledge bases (KBs, aka KGs: knowledge graphs) have major gaps in the scope and depth of their contents. In particular, they often lack knowledge about long-tail entities (e.g., African musicians), non-standard predicates for notable entities (e.g., cover versions of songs,

or the key and instrumentation of songs), quantitative properties (e.g., energy efficiency of car models), and commonsense properties of everyday objects (e.g., saxophones having a shiny surface, or SUVs consuming more energy than compact cars). To overcome these limitations we have pursued a number of research directions, with good progress towards advancing KB coverage and quality. Our contributions have been published in premier venues (including EMNLP, ACL, CIKM, VLDB, WSDM and WWW), and we released open-source code and value-added data resources. Also, our senior researcher Simon Razniewski and his co-workers gave tutorials on these directions at flagship conferences like AAAI, VLDB and WSDM.

First, we devised new techniques for assessing the (in-)completeness of KBs and identifying the best web sources to specifically tap into, thus boosting the benefit/cost ratio of KB population and curation. Second, we spearheaded the direction of automatically identifying salient negative properties, to reduce the uncertainty between “unknown” and “false” under the open world assumption. Third, we advanced techniques for extracting statements from long non-standard texts, such as fiction books. Fourth, on the theme of counts and quantities, our contributions include methods to support search as well as KB population (see also below). Last but not least, we successfully explored new ways of representing commonsense KB statements (with faceted detail not captured in any prior work), extracting them at the scale of huge web crawls (like the C4 corpus that underlies the T5 language model), and inferring culture-specific statements (conditioned on the dimensions of geo regions, religions, age groups and professions).

Entities with Quantities: We have been among the first to address the issue of extracting and semantically organizing quantities that appear in ad-hoc tables and text sources on the Web. Quantities are numeric expressions that denote financial, physical and other measures with units and a reference frame, such as annual revenue of companies, battery-only range of hybrid cars, carbon footprint of data centers, or conductivity of thermoelectric materials. We developed methods for extracting quantity-centric facts from text corpora and web tables, and for answering queries with quantity-filter conditions such as “sprinters who ran 100 meters under 9.9 seconds”. Internet search engines support looking up quantities for a given entity, but often fail on evaluating quantity filters (lacking the proper understanding of queries and web contents). Knowledge bases, such as Wikidata, are rich in entities but very sparse in capturing quantity properties. This work has been published in premier venues like ISWC, WSDM, SIGMOD and WWW. Demonstrator systems with large-scale data collections are publicly accessible on our website (<https://qsearch.mpi-inf.mpg.de/>).

Question Answering over Knowledge Bases, Text and Tables: Question answering (QA) is a major use case for knowledge bases (KBs) and pretrained language models (LMs) alike, and today’s search engines are also geared for this task. Starting with our early work on question-to-query translation (using ILP for semantic parsing (EMNLP 2012) and learned templates (WWW 2018)), we have broadened our scope and advanced our methods by leveraging a suite of machine learning techniques.

We have been among the first to devise methods that can handle complex questions seamlessly over knowledge bases (with multi-hop inference), text corpora, and collections

of tables (HTML, JSON, spreadsheets etc.). Our methods are able to compensate for the limited coverage of KBs by tapping into text and tables, and they are able to counter the inherent noise from text and tables by incorporating structured knowledge (e.g., for answer-type checking). Unlike much of the literature, we carefully devised our solutions for efficiency as well; our prototype systems provide interactive response times. We achieved this by combining information-retrieval techniques for obtaining candidate passages, KB triples and table rows, with neural Transformers for answer extraction and ranking. Our latest method is based on graph neural networks for uniform handling of KB, text and tables. An additional benefit over many baselines is that the answers of our systems come with explanatory evidence for transparency, interpretability and trustworthiness towards end-users.

A particular focus in the last two years has been on *conversational QA*, where the user’s input for follow-up questions is often very informal and all but self-contained. For this setting, we have devised novel methods that capture the relevant conversational context towards computing good answers with user-comprehensible explanations. Our methods are based on graph neural networks (GNNs) as well as reinforcement learning (RL).

In addition to publications in top-tier conferences (SIGIR, WSDM, WWW, EMNLP), our senior researchers Rishiraj Saha Roy and Andrew Yates co-authored two state-of-the-art surveys in the Morgan&Claypool series. Prototype systems and benchmarking datasets for this line of research are publicly accessible on our website <https://qa.mpi-inf.mpg.de>.

Transparency and Trustworthiness of AI Systems: On the theme of explainability and scrutability of recommender systems, we have developed new ways of generating user-comprehensible explanations for recommended items, using only information about the user herself – that is, not disclosing any cues about other users, for privacy preservation. Additionally, we developed a method to leverage user feedback on both a newly recommended item and the item that is shown as explanatory support. A user may, for example, dislike the recommendation but express liking the explanation item. Our method learns latent aspects that the user pays attention to when comparing different items. It uses pair-wise feedback to enhance a matrix-factorization model for capturing item-item similarities as well as user profiles, with latent aspects. Experiments and user studies show the practical viability of our method. This work, published in SIGIR 2021 and WWW 2021, is part of Azin Ghazimatin’s dissertation, which won the GI-DBIS dissertation award 2023.

Another project on transparency and robustness has focused on assessing and mitigating deployment risks of machine-learning models, where bias and errors can adversely affect people’s lives. The risks can arise from different kinds of uncertainty: data variability, especially near classifiers’ decision boundaries, limitations of the learning models (e.g., not being expressive enough in terms of non-linear elements, capturing long-range dependencies etc.), or data shifts between training and deployment as the characteristics of production data are evolving. We have developed information-theoretic methods that allow quantifying different risks, and thus being able to recommend specific mitigation steps towards trustworthy applications. The latter include judicious abstention in classifiers and obtaining additional training data for critical regions. This work, published in ICDM 2021 and the Machine Learning journal 2022, is part of Preethi Lahoti’s dissertation.

Young Researchers

Our group has a strong track record in promoting young researchers in their careers. The academic offspring of D5 includes internationally visible scientists.¹ A good fraction of our graduates joined leading research labs in industry.²

Among our alumni, 11 women have achieved faculty positions: Oana Balalau (INRIA, France), Asia Biega (MPI for Security and Privacy, Germany), Anna Guimaraes (Warwick University, UK), Katja Hose (at U Aalborg, Denmark), Georgiana Ifrim (at UC Dublin, Ireland), Mouna Kacimi (at U Bolzano, Italy), Ndapa Nakashole (at UC San Diego, USA), Koninika Pal (at IIT Palakkad, India), Nicoleta Preda (at U Versailles, France), Maya Ramanath (at IIT Delhi, India), Erisa Terolli (Stevens Institute of Technology, USA).

In the two-year timeframe 2021–2023, we had 12 doctoral students graduating, including 5 women (Azin Ghazimatin, Anna Guimaraes, Preethi Lahoti, Sreyasi Nag Chowdhury, Anna Tiginova).

Awards

Our research on responsible data science has earned GI-DBIS dissertation awards (by the German Computer Society) for the doctoral theses of two of our female graduates: Asia Biega (2021) on fairness and Azin Ghazimatin (2023) on explainability. The long-term contributions and impact of our group have been honored by Gerhard Weikum receiving the Konrad Zuse Medal (2021).

Teaching

A total of 12 doctoral dissertations and 7 Bachelor's and Master's theses in the 2021-2023 timeframe were completed under the supervision of the group's senior researchers. Our course offers were rather limited, as the department is phasing out.

Cooperations

Collaborations within MPG: Over two decades, the group has conducted a variety of joint research works with the other departments of MPI-INF as well as faculty of MPI-SWS. The group also participated in the MaxNet research network on Big Data Driven Materials Science, which involves 9 institutes of the MPG.

¹Exemplary faculty are: Srikanta Bedathur (IIT Delhi, India), Mario Boley (Monash University, Australia), Gerard de Melo (Hasso Plattner Institute, Germany), Rainer Gemulla (U Mannheim, Germany), Sebastian Michel (TU Kaiserslautern, Germany), Ndapa Nakashole (UC San Diego, USA), Thomas Neumann (TU Munich, Germany), Maya Ramanath (IIT Delhi, India), Ralf Schenkel (U Trier, Germany), Fabian Suchanek (U Telecom ParisTech, France), Martin Theobald (U Luxemburg).

²Examples are: Ralitsa Angelova (Google), Maximilian Dylla (Google), Patrick Ernst (Amazon), Azin Ghazimatin (Spotify), Johannes Hoffart (SAP), Preethi Lahoti (Google), Subhabrata Mukherjee (Microsoft), Josiane Parreira (Siemens), Stephan Seufert (Amazon), Daria Stepanova (Bosch), Mohamed Yahya (Bloomberg), and others.

External Partners and Competitive Grants: The department has successfully collaborated with high-caliber partners, both industrial labs (e.g., Amazon, Bosch, Google, Microsoft, Siemens, Volkswagen) and academic organizations (e.g., CMU, IIT Delhi, U Glasgow, U Melbourne, U ParisTech, UW Seattle). In the last few years, the most important collaboration has been the ERC Synergy Grant 610150 on Privacy, Accountability, Compliance and Trust for Tomorrow's Internet (imPACT), with Michael Backes (Helmholtz Center CISPA), Peter Druschel (MPI for Software Systems), Rupak Majumdar (MPI for Software Systems) and Gerhard Weikum as principal investigators (with a total budget of 10 Million Euros for the timeframe 2015-2022). This joint project has been finalized in July 2022.

Future Plans

With the official retirement of its director, Gerhard Weikum, the department D5 will be effectively closed by the end of 2023. A handful of doctoral students will likely need 2024 for completing their dissertations. They will be supported by the institute, and Gerhard Weikum will continue supervising them. As an emeritus, Gerhard Weikum personally plans to further advance the research on question answering, particularly for entities with quantities (see above) and including coding work for our prototype systems.

8 RG1: Automation of Logic

History

The Automation of Logic Group was established in September 2005 and is headed by Christoph Weidenbach. The group covers the complete pipeline from basic research on logics and their automation up to applications in research and industry.

There are currently four researchers, four PhD students, and four long-term guests in the group. Fajar Haifani has finished his PhD thesis during the reporting period. Martin Bromberger has recently been appointed senior researcher.

Group Organization and Development

Our four PhD students are co-supervised by two senior members of the group, including our long-term guests. We have weekly meetings with the PhD Students. There are additional meetings for the joint software development, where we are currently focusing on implementing SCL (Clause Learning from Simple Models).

Thomas Sturm, working in computer algebra, Jasmin Blanchette, working in interactive theorem proving and its mechanization, Sophie Tourret working on first-order logic reasoning and its formalization, and Mathias Fleury, working on CDCL and its formalization are long-term guests of the group. They interact with the group through regular meetings, joint projects such as VeriDis and Matrioshka, and joint PhD student supervision. Martin Bromberger has started his own subgroup on the combination of theories and is supervising one PhD student. Uwe Waldmann is continuing his close collaboration with Alexander Bentkamp and Jasmin Blanchette on adding higher order reasoning techniques to superposition. Sibylle Moehle has recently joined the group and continues her work on propositional logic model counting.

Vision and Research Strategy

The vision of the group is to increase the productivity of formal analysis/verification/problem solving technology through a higher degree of automation of the underlying logics. The following challenges motivate main parts of our work: (i) drive the development of first-order, and beyond first-order reasoning calculi, (ii) understand the mechanics of reasoning with respect to concrete models, (iii) build specific reasoning procedures for arithmetic theories, (iv) show applicability of our methods to reasoning challenges from other areas, (v) formally verify our own results, and (vi) scale the applicability of our methods to the size of real world industrial applications.

About half of our work is of a theoretical nature and the other half is experimental, in particular on the basis of developed tools. The considered problems are typically NP-hard and

beyond. Therefore, implementation of our methods is important to check their automation potential in practice, to increase the impact of our theoretical results by providing our software to other people and eventually to detect further challenges in theory development. In 2012 we founded the company “Logic for Business” (L4B), providing consulting and software for the overall life-cycle management of complex products. It was sold in 2021.

We have structured our research along the following topics: (i) Foundations of Automated Reasoning, (ii) Arithmetic, (iii) Saturation Theorem Proving, (iv) Formalizing Logic, (v) Software and Applications. The structure does not impose a structure on the group. In fact, most of us contribute to several areas and almost all of us to the development of software.

A selection of scientific results for topics (i), (ii), (iii), and (iv), respectively, are:

Applications of SCL to Real-World Scenarios (TACAS 2022, VMCAI 2021, FroCos 2021) The SCL variant modulo linear arithmetic SCL(LA) and its underlying logic BS(LA), the Bernays-Schönfinkel fragment extended with linear arithmetic constraints, turns out to be a perfect base for the formalization and automatic verification of so called Supervisors. Supervisors are simple, high-level software controllers for technical systems. We studied a lane-change supervisor and a supervisor controlling a combustion engine. In both cases we could formalize the respective software and automatically prove correctness. This was established by a reduction to pure first-order Horn logic, called our Datalog Hammer. Eventually, a Datalog engine did the verification work.

Verification and Development of SCL (CADE 2023, Arxiv 2023) There is a long tradition in the group to formally verify our pen and paper results on automated reasoning calculi in Isabelle. We developed several variants of the SCL calculus from 2019-2021 including pen and paper proofs for correctness. Our goal was to unify all aspects of the calculi for the case of first-order logic without equality. In parallel the calculus was formalized and verified in Isabelle. Both the formalization and the unification of the variants were done in parallel and contributed to each other. Through the formalization we found one bug in a former SCL variant and minimized invariants on the calculus compared to the pen and paper proofs. The formalization profited a lot from our new proof technique on termination which no longer relies on an overall measure but on the fact that SCL learns only non-redundant clauses.

Connection-Minimal Abduction (IJCAR 2022, DL 2022, SOQE 2021) As automated reasoning becomes more and more a part of the overall life cycle of systems, being able to explain reasoning results, becomes more and more important. We developed a new notion on abduction that in particular rules out hypotheses that are not connected to the actual formulas. It is implemented through a tool chain and a first-order logic translation for the description logic \mathcal{EL} . This work won the best student paper award at DL 2022.

Parametric Qualitative Analysis of Reaction Networks and Epidemic Models (CASC 2021) Chemical reaction network theory provides constructive mathematical modeling approaches for a wide range of biological networks, e.g., reaction networks and epidemic models. Examples are the well-studied MAP kinase and SEIR models, respectively. Variants of SEIR are used, e.g., for various subtypes of influenza A and quite recently also for Covid-19.

The dynamics of the networks are described by ordinary differential equations (ODE) in time, assuming mass action kinetics. Traditional approaches have been based on numerical simulations of the ODE for fixed measured or estimated parameters. Our principal approach, in contrast, combines symbolic methods and automated reasoning with model reduction methods aiming at a *qualitative* analysis of biological networks.

In the previous report we have reported on a comprehensive study, which exhibited that a significant number of models from the BioModels.net repository has steady state regions that are geometrically toric. Technically, we had applied decision methods to characterizations of toricity as first-order sentences. We have now taken an important step from fixed measured or estimated parameters to formal parameters. Quantifier elimination takes the place of decision procedures and provides necessary and sufficient constraints for toricity in terms of the parameters. We have studied both the real domain and the complex domain, providing rigorous formal foundations along with paractical computations on models from our previous study.

Projects and Cooperations

Together with Stephan Merz's group (Inria Nancy) we constitute the Inria project VeriDis (<http://www.inria.fr/en/teams/veridis>), where we investigate automated reasoning support for the verification of distributed algorithms. In the interdisciplinary project SYMBIONT we apply reasoning in non-linear arithmetic to problems from biology. We constitute the core of the ERC starting grant Matryoshka on the mechanization of higher-order logic. In the transregional collaborative research center TRR 248, "Perspicuous Systems", established in January 2019 and finished in December 2022, we investigate automated reasoning in the context of perspicuous software systems in close cooperation with researchers from TU Dresden.

Prizes and Awards

Fajar Haifani won the best student paper award at the Description Logic workshop 2022. It was a joint paper with Patrick Koopmann from Dresden, Sophie Turret and Christoph Weidenbach.

Teaching

We regularly teach and supervise bachelor and master students at Saarland university. We are responsible for the core lecture "Automated Reasoning" of the master curriculum. In addition, we provided the lecture "Competitive Programming" together with colleagues from the CS department in the reporting period.

9 RG2: Network and Cloud Systems

History

Yiting Xia joined MPI-INF as a tenure-track faculty in September 2020. She is currently leading the Network and Cloud Systems (NCS) research group. Yiming Lei joined NCS as a Ph.D. student in October 2021. Jialong Li joined NCS as a postdoctoral researcher in November 2021. The NCS research group is actively growing.

Group Organization and Development

At present, the research group consists of one tenure-track faculty, one postdoctoral researcher, one Ph.D. student, and a secretary. A new Ph.D. student will join the research group in October, 2023.

Yiting Xia is leader of the group. Her research interests include computer networks, cloud systems, and machine learning systems. Jialong Li is a postdoctoral researcher. His research interests include optical networks, data center networks, and optical communications. Yiming Lei is a second-year Ph.D. student. He is interested in programmable switches and network system implementation. Iris Wagner is now the secretary of the group.

Besides, two Master's students are doing their Master's theses in the group, and we will host three interns in the summer.

Federico De Marchi is a Master's student at Saarland University. He is doing his Master's thesis in the group. His topic is designing transport protocols for fast-switched optical data center networks. He will join the research group as a Ph.D. student after he obtains the Master's degree. Vadim Farutin is also a Master's thesis student from Saarland University. His topic is improving GPU sharing efficiency for distributed training jobs.

Xiaoxiang Shi, a Master's student from Shanghai Jiao Tong University, will join the group in July as an intern. He will work on the system implementation for improving GPU sharing efficiency. Haotian Gong, an undergraduate student from the University of British Columbia, will join the group in May as an intern. He will work on the topology design for optical data center networks. Parham Chavoshian, an undergraduate student from Sharif University of Technology, will join the group as an intern in July. He will work on congestion control for data center networks.

We had one Master's student and one intern in the past year. Zhengqing Liu, was from Ecole Polytechnique, Paris and now is a Ph.D. student in Imperial College London. He finished his Master's thesis—*System Implementation for Hop-On Hop-Off Routing via Programmable Switches*. Rui Pan, was from University of Wisconsin–Madison and now is a Ph.D. student at Princeton University. He finished the internship project on network abstraction for distributed deep learning training and published a HotNets paper as the first author.

Vision and Research Strategy

Emerging services and hardware advancements are reshaping the landscape of cloud computing. One trend is edge computing, where small data centers known as cloudlets are built close to users as easy access points for Internet of Things (IoT). The other trend is the increasing modular placement of hardware resources. For example, computing racks with disaggregated functions have become fundamental building blocks of data centers; and a number of data centers are interconnected as a region in dense metro areas. These changes motivate networking research that blends the boundary of traditional data center networks and backbone networks as well as distributed systems research that involves new hardware, network design, and cloud systems. The scope of the Network and Cloud Systems group is to build network infrastructure and distributed systems for cloud computing. We follow a cross-layer approach and cover broad topics for optimizing the network stack, including switch hardware, network protocols, software systems, and cloud applications.

Research Areas and Achievements

Optical Data Center Networks. Optical data center network (DCN) fabrics are renovating the infrastructure design in the cloud. However, there is a gap between the diverse optical hardware architectures and system integration work to realize the architectures as end-to-end workable systems. This research direction is to design and implement practical systems to enable different optical architectures in production DCNs. Towards that, we abstract fundamental building blocks for optical DCNs, including global time synchronization with nanosecond-scale accuracy, generic routing regardless of the optical hardware, and an application-agnostic host stack. Up till now, we have implemented a prototype system with P4 on Tofino2 switches and libvma on Mellanox NICs. Extensive micro-benchmark studies with production DCN traffic show that our system keeps synchronization errors under 15ns and ensures zero packet loss with 99.93% achievable network utilization. We demonstrate three optical architectures on the system with real DCN applications and observe similar flow completion times for mice flows compared to electrical DCNs. We are open-sourcing the system, as a tool for the networking community to test, improve, and deploy optical DCNs.

Network-Accelerated Machine Learning Systems. Recent years have witnessed the rapid development of deep learning. Various parallel strategies have been adopted by distributed deep learning training (DDLT) frameworks to accommodate the ever-growing model sizes. As a result, communication among distributed workers, especially over a shared, highly dynamic network with competing training jobs, has become a notable bottleneck of the training process. We aim to accelerate inter-node communications in machine learning systems. In one project, we propose the first network abstraction for DDLT and devise a generic method to model the drastically different computation patterns across training paradigms. We use the abstraction for flow scheduling in DDLT jobs and demonstrate its effective with case studies. In another project, we introduce network-aware GPU sharing to improve efficiency of job placement and GPU scheduling in machine learning clusters. Compared to previous scheduling mechanisms that assume fixed data transmission time, we for the first time

model the network dynamically and provide tighter bounds on the data transmission time. Simulation results show our scheduling method achieves high GPU utilization with minimal slowdown of training time.

Reliable Network Management. The complexity of large networks makes their management a daunting task. State-of-the-art network management systems program workflows of operational steps with arbitrary scripts, which pose substantial challenges to reliability. We leverage the fact that most modern network management systems are backed with a source-of-truth database and customize database techniques to the context of network management. The network management framework exposes a programming model to network operators for conveying the key management logic. Then the operators are completely shielded from reliability concerns, such as distributed devices, operational conflicts, task atomicity, and failures, which are instead handled by the runtime system using database techniques. Our simulation evaluation and production case studies demonstrate the system’s effectiveness in minimizing network vulnerable time and resolving task conflicts. We open-source our simulator and task traces for academic researchers to contribute to this industrial problem.

Projects and Cooperations

We have collaborated with National University of Singapore and Vrije Universiteit Amsterdam on optical data center networks, and we have collaborated with ETH Zürich on network-accelerated machine learning systems. We have collaborated with Meta and Rice University on reliable network management. We have an ongoing collaboration with Microsoft on transport protocols for optical data centers.

Prizes and Awards

Yiting Xia won the N2Women Rising Star Award in 2021.

Teaching

Yiting Xia co-taught Distributed Systems with Krishna Gummadi and Jonathan Mace in summer 2021, and with Deepak Garg and Laurent Binschaedler in summer 2023. Yiting Xia and Jialong Li co-taught Data Networks with Anja Feldmann and Oliver Gasser in summer 2022. Yiting Xia and Jialong Li co-organized the Hot Topics in Data Networks seminar with Anja Feldmann and Oliver Gasser in winter 2021 and 2022.