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Aims and Scope

The periodical *Dagstuhl Reports* documents the program and the results of Dagstuhl Seminars and Dagstuhl Perspectives Workshops.

In principal, for each Dagstuhl Seminar or Dagstuhl Perspectives Workshop a report is published that contains the following:

- an executive summary of the seminar program and the fundamental results,
- an overview of the talks given during the seminar (summarized as talk abstracts), and
- summaries from working groups (if applicable).

This basic framework can be extended by suitable contributions that are related to the program of the seminar, e. g. summaries from panel discussions or open problem sessions.

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Analysis, Design, and Control of Predictable Interconnected Systems

Edited by

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Abstract

We call “Interconnected Systems” any collection of systems distributed over a metric space whose behavior is influenced by its neighborhood. Examples of interconnected systems exist at very different scales: different cores over the same silicon, different sub-systems in vehicles, communicating nodes over either a physical (e.g., optical) network, or – more recently – virtualized network. Examples also exist in contexts which are not related to computing or communication. Smart Grids (of energy production, distribution, and consumption) and Intelligent Transportation Systems are just two notable examples. The common characteristic among all these examples is the presence of a spatially distributed demand of resources (energy, computing, communication bandwidth, etc.) which needs to be matched with a spatially distributed supply. Often times demands and availability of resources of different types (e.g., computing and link bandwidth in virtualized network environments) need to be matched simultaneously.

Time predictability is a key requirement for above systems. Despite this, the strong market pressure has often led to “quick and dirty” best-effort solutions, which make it extremely challenging to predict the behavior of such systems.

Research communities have developed formal theories for predictability which are specialized to each application domain or type of resource (e.g., schedulability analysis for real-time systems or network calculus for communication systems). However, the emerging application domains (virtualized networks, cyber-physical systems, etc.) clearly require a unified, holistic approach. By leveraging the expertise, vision and interactions of scientists that have addressed predictability in different areas, the proposed seminar aims at constructing a common ground for the theory supporting the analysis, the design, and the control of predictable interconnected systems.

Seminar March 3–8, 2019 – <http://www.dagstuhl.de/19101>

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Analysis, Design, and Control of Predictable Interconnected Systems, *Dagstuhl Reports*, Vol. 9, Issue 3, pp. 1–15

Editors: Kunal Agrawal, Enrico Bini, and Giovanni Stea



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1 Executive Summary

Kunal Agrawal

Enrico Bini

Giovanni Stea

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Computing capacity surrounds our environment more and more. The exploitation of this diffused infrastructure poses a number of challenges. A notable one is the guarantee of predictable performance. Many modern computing platforms require high degrees of predictability in their timing characteristics – for instance, in avionics and automotive applications, it is essential that the tasks complete in a timely manner in order to take appropriate actions in response to a developing situation. With increasing complexity and heterogeneity in functionality required by time-sensitive applications, there is an increasing need for designing distributed interconnected platforms that respond to time-varying requests in a highly predictable way.

The world of networking is undergoing an analogous transformation. There is a major shift towards smarter and more autonomous networks, the so-called self-driving networks. The goal is to mimic the success that cloud-computing techniques and concepts had on the transformation of the IT infrastructure. The latter made it possible to allow physical resources, such as computing and storage nodes, to be shared among users through the use of virtual resources (Network Function Virtualization). Virtualization of network functions offers an efficient way to meet dynamic user demands in a cost-effective manner. However, the guarantee of predictability in NFV is, to date, an open problem.

With increasing complexity and heterogeneity in functionality required by timing-sensitive applications, there is need for designing distributed and interconnected platforms that provide high predictability. On the one hand, with the advent of Cyber-physical systems and Industry 4.0, real-time systems are becoming more and more networked systems. On the other hand, networking scenarios where a-priori quantifiable guarantees on the worst-case traversal time are required as a prerequisite for a correct application-level computation are becoming commonplace. Therefore, it is necessary to develop methods to ensure compliance with end-to-end deadlines in distributed systems where *both* computation and communication are involved.

Dagstuhl seminar “Analysis, design and control of predictable interconnected systems” gathered more than 40 researchers from four continents, with a good balance of seniority and gender. These researchers came from different communities, including Network Calculus, Real-time Systems, Control Theory, Performance Evaluation and Data-flow, which have been discussing similar problems in the recent past, sometimes also using similar methodologies, but different notations and hypotheses, and focusing on different characteristics. The aim of the seminar was to foster cross-fertilization and inter-community networking, using new, contemporary problems which are interesting for and discussed within more than one community. The seminar hosted 26 talks. Some of these were “background-levelling” talks given by well-recognized senior experts in the respective communities, with the aim of crossing the lexicon and notation gap between communities. Other talks, building on the shared background provided by the former, discussed interesting novel problems and promising application areas. The open, schedule-as-you-go format for the talks and the time left open for free networking activities fostered an open environment. The general conclusion, which can be gathered by the (mostly enthusiastic) comments in the final survey, is that the involved communities have more in common with each other than the attendees thought, and cross-fertilization is necessary to tackle new problems in a holistic approach.

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3 Overview of Talks

3.1 Network reservations for dynamic RT systems

Luis Almeida (University of Porto, PT)

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Recent growing frameworks such as the IoT, IIoT, Cloud/Fog/Edge computing, CPS, etc, bring the networking platforms on which they rely to the spotlight, as first class citizens of an increasingly software-dependent landscape. As a result, networks play an increasingly central role in supporting the needed system-wide properties, particularly, scalability, adaptivity, timeliness, safety and security. This trend has been generating many hard challenges and boosted an unprecedented engagement from the research community. Specifically in our case, we have been working to provide openness and adaptivity together with timeliness guarantees. This combination seems fundamental to support inherently dynamic applications in a resource efficient way, covering not only the cases of systems of systems, systems with variable number of users, components or resources but also systems that undergo frequent live maintenance and even reconfiguration during their lifetime. Examples range from autonomous vehicles to collaborative robotics, remote interactions, fog/edge computing, flexible manufacturing, etc. We postulate that combining openness and adaptivity with guaranteed timeliness can only be achieved with an adequate communication abstraction supported on adequate protocols. To this end, we have been proposing channel reservation-based communication as a means to provide scalable and open latency-constrained communication and thus enable a more efficient system design. This presentation will provide a brief tour of our recent work on flexible and composable approaches to real-time communication. We will end highlighting some open challenges towards adequate networking infrastructures for effective dynamic real-time systems.

3.2 Real-Time Scheduling

Sanjoy K. Baruah (Washington University, US)

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Real-time scheduling theory studies problems associated with the objective of achieving efficient implementations of systems that are subject to timing constraints. As do other disciplines, real-time scheduling theory has a (fortunately, rather small) common core of knowledge – assumptions, terminology, basic results. I will provide a high-level introduction to some of this common core of real-time scheduling theory.

3.3 Hierarchical Scheduling, supply functions and friends

Enrico Bini (University of Turin, IT)

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Main reference Enrico Bini, Marko Bertogna, Sanjoy K. Baruah: “Virtual Multiprocessor Platforms: Specification and Use”, in Proc. of the 30th IEEE Real-Time Systems Symposium, RTSS 2009, Washington, DC, USA, 1-4 December 2009, pp. 437–446, IEEE Computer Society, 2009.

URL <https://doi.org/10.1109/RTSS.2009.35>

The term hierarchical scheduling denotes a spectrum of theories developed starting from the 90s to ensure the isolation of real-time applications. In this presentation, I will present the main results of hierarchical scheduling, emphasizing the connections with network calculus (namely the similarity between EDF demand bound function and arrival curves, as well as the similarity between supply bound functions and service curves). Finally, the extension to multiprocessor scheduling will be presented showing the difficulties of a straightforward extension of the single processor concepts.

3.4 Performance in networks with cyclic dependencies

Anne Bouillard (Nokia Bell Labs – Nozay, FR)

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This talk discusses the behaviour of cluster of servers when requests are cloned. In cloud computing cloning a request means generating duplicates of the request and sending these duplicates to a given number of servers – the cloning factor. The response to the request is generated by the first server that terminates the associated computation. Cloning has been extensively studied, but the theoretical results so far have been limited to specific arrival rates and service rates distributions. In this talk, I will relax these assumptions and present our ongoing research on a G/G/1 queuing model that is equivalent to a cloning cluster.

3.5 Analysis of MPPA Network on Chip – Is analysis of FIFO network closed in theory and open in practice?

Marc Boyer (ONERA – Toulouse, FR)

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The MPPA is a many-core with 256 cores, grouped into 16 clusters, connected by a Network on Chip (NoC). This NoC applies Round-Robin arbitration at output ports. With the notion of residual service, this NoC can be reduced into a FIFO (feed-forward) network. Several algorithms and tools can compute an end-to-end delay for each flow (SFA, TFA, deborah, translation into LP problem). They have been compared on this case study, and the unexpected result is that the old TFA algorithm gives the best results, due to the fact that the problem involves link shaping, and considered curves are neither concave nor convex. It opens research on how to enhance the other approaches on such case study.

3.6 Performance Analysis based on Arrivals and Delays

Peter Buchholz (TU Dortmund, DE)

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General performance analysis is based on the availability of arrival and service processes and computes then measures like throughputs, delays, populations. On an abstract level service processes are virtual and bounds on arrivals and delays are specified. In the talk we briefly show how this approach can be integrated in network calculus.

3.7 On Resilient Distributed Control of Dynamical Flow Networks

Giacomo Como (Polytechnic University of Torino, IT)

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Resilience has become a key aspect in the design of contemporary infrastructure networks. This comes as a result of ever-increasing loads, limited physical capacity, and fast-growing levels of interconnectedness and complexity due to the recent technological advancements. The problem has motivated a considerable amount of research within the last few years, particularly focused on the dynamical aspects of network flows, complementing more classical static network flow optimization approaches. In this tutorial, we discuss some notions, techniques, and results concerning the stability, robustness, throughput optimality, and performance analysis of deterministic models of dynamical flow networks. In particular, we focus on distributed architectures for routing, scheduling, and flow control and emphasise the role of structural properties -such as monotonicity, contraction, and separable Lyapunov functions- that enable tractability and scalability.

3.8 Challenges for Assured Autonomy in Safety-Critical CPS

Arvind Easwaran (Nanyang TU – Singapore, SG)

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Modern cyber-physical systems (CPS) such as autonomous vehicles are expected to perform complex functions under highly dynamic operating environments. Increasingly, to cope with the complexity and scale, these functions are being designed (semi) autonomously, including the use of Machine Learning (ML) techniques in some cases. For example, perception systems in autonomous vehicles have been designed using ML techniques such as deep neural networks. A key challenge in the design of such autonomous systems is how to achieve high safety assurance. In this talk, I provide an overview of the key technical challenges for safety assurance of ML based systems, shortcomings of existing approaches in the ML community with respect to those challenges, and some potential research directions to address them.

3.9 Industrial Cloud & 5G

Johan Eker (Lund University / Ericsson Research, SE)

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New technologies such as 5G, cloud & edge computing have the potential to disrupt automation as we know it today, by redefining automation and communication architectures. In this talk we present some opportunities and challenges when digitalizing traditional industries and particularly focus on dynamical aspects such as application mobility and re-orchestration.

3.10 Delay-Constrained Routing Problems

Laura Galli (University of Pisa, IT)

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Main reference Antonio Frangioni, Laura Galli, Giovanni Stea: “QoS routing with worst-case delay constraints: Models, algorithms and performance analysis”, *Computer Communications*, Vol. 103, pp. 104–115, 2017.

URL <https://doi.org/10.1016/j.comcom.2016.09.006>

Delay-Constrained Routing (DCR) problems require to route a new flow in a computer network subject to worst-case end-to-end delay guarantees. The delay of a packet flow has three components, one of which is the “queueing delay”, that depends on the scheduling algorithm implemented by the routers of the network. When flows are not independent of each other, i.e., admitting a new flow changes the delay of the existing ones, admission control policies are necessary to ensure that existing flows do not become latency-unfeasible. It has been recently shown that admission control runs contrary to the usual objective function employed in these models, i.e., minimization of the reserved rates, significantly worsening network performance. In this work we investigate the phenomenon and propose a heuristic way to overcome the problem.

3.11 DeepTMA: Predicting Effective Contention Models for Network Calculus using Graph Neural Networks

Fabien Geyer (TU München, DE)

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Network calculus computes end-to-end delay bounds for individual data flows in networks of aggregate schedulers. It searches for the best model bounding resource contention between these flows at each scheduler. Analyzing networks, this leads to complex dependency structures and finding the tightest delay bounds becomes a resource intensive task. The exhaustive search for the best combination of contention models is known as Tandem Matching Analysis (TMA). The challenge TMA overcomes is that a contention model in one location of the network can have huge impact on one in another location. These locations can, however, be many analysis steps apart from each other. TMA can derive delay bounds with high degree of tightness but needs several hours of computations to do so. We avoid the effort of exhaustive search altogether by predicting the best contention models for each location

in the network. For effective predictions, our main contribution in this paper is a novel framework combining graph-based deep learning and Network Calculus (NC) models. The framework learns from NC, predicts best NC models and feeds them back to NC. Deriving a first heuristic from this framework, called DeepTMA, we achieve provably valid bounds that are very competitive with TMA. We observe a maximum relative error below 6%, while execution times remain nearly constant and outperform TMA in moderately sized networks by several orders of magnitude.

3.12 Information Theory as a Guide to Resource Allocation

Sathish Gopalakrishnan (University of British Columbia – Vancouver, CA)

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In modern embedded systems that process data, we may decide how to allocate resources across competing tasks using the value of information that we may obtain from these tasks. Such an approach differs from the use of utility-loss indices that are more commonly applied when tasks may be standard control tasks.

3.13 Queuing Analysis of Wireless Systems – No Waste of Time!

James Gross (KTH Royal Institute of Technology – Stockholm, SE)

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The recent industrial interest in ultra-reliable low latency wireless communication systems has triggered a significant interest in evaluating different wireless system designs with respect to their delay performance. We show in this talk that stochastic network calculus offers here a suitable tool for the investigation of meaningful questions such as training length choice, antenna configuration, resource allocation and rate adaptation. We finally also discuss our most recent efforts to characterize transient system performance of wireless networks.

3.14 An Introduction to Stochastic Network Calculus

Yuming Jiang (NTNU – Trondheim, NO)

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Stochastic Network Calculus (SNC) is the stochastic extension of Network Calculus (NC), intended for use in finding latency and backlog bounds with targeted violation probability. It belongs to the branch of queueing theory that “deals with methods for finding approximation or bounding behavior for queues [Kleinrock, 1976]”. In the talk, the basic min-plus SNC models, stochastic arrival curve (SAC) and stochastic service curve (SSC), are introduced, followed by a discussion on the need of their variations, based on sample-path analysis. In addition, the inherent dependence between the SAC and SSC models and the consequences on the analysis results are highlighted. Two techniques to exploit independence information

in the arrival and service processes are introduced. At the end of the talk, the development status of max-plus SNC is briefed, followed by a discussion on applying / extending SNC to two fundamental network cases: multi-server and wireless channel.

3.15 Real-Time Calculus – A Tutorial

Pratyush Kumar (Indian Institute of Technology – Madras, IN)

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This tutorial on Real-Time Calculus (RTC) will introduce the foundational concepts of RTC and extends up to advanced applications and results. It will begin with presenting the formal representation of arrival and supply functions, and the greedy processing component which is the fundamental unit of modelling in RTC. We will briefly intuit the different operations under a min-plus algebra and their application to compute bounds on worst-case response time and buffer space usage. We will discuss how to apply these results to compositional analysis of embedded systems. We will then switch gears and see more advanced applications of RTC. First, we will discuss how the abstractions of RTC are also surprisingly applicable for computing thermal bounds on processors. Second, we will discuss the use of RTC for interface-based design. Finally, we will discuss the combination of stateful models with RTC.

3.16 What can arrival curves do for helping online algorithms to meet deadlines?

Kai Lampka (Elektrobit Automotive GmbH – München, DE)

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Online Workload Monitoring with Arrival Curves and its applications

3.17 An Introduction to Network Calculus

Jean-Yves Le Boudec (EPFL – Lausanne, CH)

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Network Calculus is a set of theories and tools that was developed for the deterministic analysis of queuing systems arising in communication networks. It is based on min-plus algebra, and sometimes max-plus algebra. It is used to compute latency and backlog bounds, with proofs that can be formally verified. It can also provide fundamental insights into physical properties of delay systems such as “Pay Bursts Only Once “ or “Re-Shaping is For Free”. In this level-setting talk, we review the basic concepts of arrival curve, service curve, their expression with min-plus algebra, and their composition. We also describe shapers (also called minimal regulators) and their properties. We illustrate the use of these concepts on classical per-flow and class-based networks.

3.18 Actor-Oriented Models of Computation for Predictable Interconnected Systems

Edward A. Lee (University of California – Berkeley, US)

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Broadly, an actor is a software component with private state that communicates with other actors via message passing. Networks of actors form a distributed queuing system amenable to both network calculus analysis and real-time scheduling. Questions of interest include “how can queues be kept bounded?” and “will the system deadlock?” and “will messages be delivered reliably on time?” In this talk, I will review varying semantic models that have an actor-oriented flavor, particularly with an eye towards the suitability of these models for formal analysis. The models I will review include various flavors of dataflow, Hewitt actors, synchronous/reactive systems, and discrete-event systems. I will discuss properties that make such models suitable or unsuitable for the design of predictable interconnected systems. I will illustrate these properties with several variants of software realizations that are in use today and will outline a model that I believe combines the best strengths of these while avoiding many of the pitfalls.

3.19 A Fluid-Flow Interpretation of SCED Scheduling

Jörg Liebeherr (University of Toronto, CA)

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We show that a fluid-flow interpretation of Service Curve Earliest Deadline First (SCED) scheduling simplifies deadline derivations for this scheduler. By exploiting the recently reported isomorphism between min-plus and max-plus network calculus and expressing deadlines in a max-plus algebra, deadline computations no longer require explicit pseudo-inverse computations. SCED deadlines are provided for latency-rate as well as a class of piecewise linear service curves.

3.20 Single queue equivalence for redundant requests and cloning

Martina Maggio (Lund University, SE)

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This talk discusses the behaviour of cluster of servers when requests are cloned. In cloud computing cloning a request means generating duplicates of the request and sending these duplicates to a given number of servers – the cloning factor. The response to the request is generated by the first server that terminates the associated computation. Cloning has been extensively studied, but the theoretical results so far have been limited to specific arrival rates and service rates distributions. In this talk, I will relax these assumptions and present our ongoing research on a G/G/1 queuing model that is equivalent to a cloning cluster.

3.21 Buffer-aware worst-case Timing analysis of wormhole NoCs using Network Calculus

Ahlem Mifdaoui (ISAE – Toulouse, FR)

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Conducting worst-case timing analyses for wormhole Networks-on-chip (NoCs) is a fundamental aspect to guarantee real-time requirements, but it is known to be a challenging issue due to complex congestion patterns that can occur. In that respect, we introduce in this paper a new buffer-aware timing analysis of wormhole NoCs based on Network Calculus. Our main idea consists in considering the flows serialization phenomena along the path of a flow of interest (foi), by paying the bursts of interfering flows only at the first convergence point, and refining the interference patterns for the foi accounting for the limited buffer size. The derived delay bounds are analyzed and compared to available results of existing approaches, based on Scheduling Theory as well as Compositional Performance Analysis (CPA). In doing this, we highlight a noticeable enhancement of the delay bounds tightness with our approach, in comparison to the existing ones.

3.22 Topics on providing end-to-end deadline guarantees in cloud robotics network

Victor Millnert (Lund University, SE)

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In this presentation I will, on a high level, cover some topics explored during my PhD. The focus of these topics has been on how to provide end-to-end deadline guarantees on top of Cloud/IoT/Edge-networks. After starting off by presenting some motivation from a cloud-robotics scenario, I will discuss one way to perform response-time control of a timing-critical cloud service. By then taking a step back, we will see that by properly controlling the response-times of all the nodes in the network, we can provide end-to-end deadline guarantees for the robotic applications using the services of the network. We can also show that this is possible even when the topology of the network is dynamic and changes over time, i.e., when applications join/leave and when cloud services join/ leave. I will conclude my presentation by briefly discussing what I think is an important open problem; how to learn and scale virtual network functions if you know nothing about them. Is it possible to dynamically update simple network calculus models, and still enjoy good guarantees?

3.23 Network Performance Tomography. A Revisit of an “Old” Problem

Kui Wu (University of Victoria, CA)

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Network performance tomography infers performance metrics on internal network links with end-to-end measurements. Existing results in this domain are mainly Boolean-based, i.e., they check whether or not a link is identifiable, and return the exact value on identifiable links. If a link is not identifiable, however, Boolean-based solution gives no performance result for the link. We extended Boolean-based network tomography to bound-based network tomography where the lower and upper bounds are derived for unidentifiable links. We develop efficient algorithms for different objectives, e.g., obtaining the tightest total error bound or minimizing the maximum error bound across all the links. We also present two methods that can significantly reduce the total number of measurement paths required for deriving the tightest bounds. At the end of the talk, some open problems and potential applications of network tomography in domains beyond computer networks will be introduced.

3.24 Multiple supply estimations in compositional real-time systems with mixed-criticality scheduling

Kecheng Yang (Texas State University – San Marcos, US)

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In traditional real-time systems on dedicated physical platforms, controlling and analyzing the task workloads, or the demand, have been the focus to ensure the predictability of the system. In such systems, the processing capacity of dedicated processors, or the supply, is simply linear to the length of the time interval and therefore is predictable. However, component-based design and virtualizations have been the trend in developing advanced modern interconnected systems, in which the supply may be provided in a more complicated form than linear and ensuring the predictability of the supply becomes a new challenge for the predictability of the entire system. On the other hand, to achieve a sweet point between predictability and efficiency, mixed-criticality scheduling theory has been proposed and studied, where the workload may be modeled by multiple estimations of different levels of confidence. Thus, the question arises: can we extend this idea to the supply side in component-based, virtualized systems? That is, can we also use multiple estimations to characterize the processor supply so that multiple levels of guarantees can be provided?

3.25 Network calculus in non-congestion network

Jiayi Zhang (Huawei Technology – Beijing, CN)

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Recently, as time sensitive network (TSN) and deterministic network (DetNet) focus on the bounded latency, both standard groups and industry go to network calculus. Can current network calculus results, based on arrival curve, service curve and min-plus algebra fit the requirements in TSN? How to establish model for Internet traffic as arrival curve, switch or router as service curve? How can we reduce the pessimism when the network scale goes large, maybe by using appropriate NC methods that fit certain scenario, eg. IP carrier network, data center networks? Will network measurements help improve latency and buffering estimation, and guide the network tuning? This presentation summarizes questions and observations from network device vendor's perspective in pursuing IP non-congestion network solution.

3.26 Feedback Control with Stability Guarantees over Wireless Multi-hop Networks

Marco Zimmerling (TU Dresden, DE)

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Closing feedback loops fast and over long distances is key to emerging cyber-physical systems; for example, robot motion control and swarm coordination require update intervals of tens of milliseconds. Low-power wireless technology is often preferred for its low cost, small form factor, and flexibility, especially if the devices support multi-hop communication. So far, however, feedback control over wireless multi-hop networks has only been shown for update intervals on the order of seconds without stability analysis. In this talk, I will present a wireless embedded system design that tames imperfections impairing control performance, such as jitter and message loss. Our approach entails avoiding resource interference throughout the system and decoupling higher-level logic from the time-varying network state. As a result, control design and analysis are greatly simplified, allowing us to provide conditions to formally verify closed-loop stability for physical systems with linear time-invariant dynamics. I will also present results from a cyber-physical testbed with 20 wireless nodes and multiple cart-pole systems that demonstrate the capabilities of our approach and confirm our theoretical results.

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3D Morphable Models

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Abstract

3D Morphable Models is a statistical object model separating shape from appearance variation. Typically, they are used as a statistical prior in computer graphics and vision. This report summarizes the Dagstuhl seminar on 3D Morphable Models, March 3-8, 2019. It was a first specific meeting of a broader group of people working with 3D Morphable Models of faces and bodies. This meeting of 26 researchers was held 20 years after the seminal work was published at Siggraph. We summarize the discussions, presentations and results of this workshop.

Seminar March 3-8, 2019 – <http://www.dagstuhl.de/19102>

2012 ACM Subject Classification Computing methodologies → Computer graphics, Computing methodologies → Computer vision

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1 Executive Summary

Bernhard Egger (MIT – Cambridge, US)

William Smith (University of York, GB)

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Thomas Vetter (Universität Basel, CH)

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A total of 45 people was invited to this seminar in the first round of invitations. The seminar was fully booked after the first round and 26 researchers from academia and industry participated in the seminar. 21 researchers presented their work in around 15-30 minutes presentations, an abstract of each presentation is included in this report. Besides those presentations participants were presenting their shared data and software in a specific slot. We collected this information in a list of shared resources which we made publicly available¹. This overview and exchange was one of the aims we had initially in mind when organizing the workshop. In the beginning of the workshop we collected ideas for discussions in our flexible sessions, those ideas are also contained in this report. We then structured the seminar fixing

¹ <https://github.com/3d-morphable-models/curated-list-of-awesome-3D-Morphable-Model-software-and-data>



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Dagstuhl Reports

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the topics of discussion for the flexible sessions. The summaries of those discussions are also contained in this report. One slot was reserved for a joint group discussion on upcoming ethical concerns on the methods we are developing. This interesting and well organized discussion was an initiative from the participants and not foreseen by the organizers. Another bigger discussion was around the topic of how to compare different approaches and how to establish a benchmark. We did not completely converge on a final solution but we identified currently available benchmarks and we discussed how a gold-standard benchmark would look like. Another aim of the workshop was to initiate an edited book or a survey paper with broad support. Arising from the workshop a group of 13 junior and senior researchers started to work on a joint survey and perspective paper on 20 years of Morphable Face Models. Discussions and presentations were followed by vivid discussions on current challenges and future research directions. To future nurture the ideas of the seminar we started a google group for discussions, sharing news and exchanging students ². The group would like to meet again at Dagstuhl in 2022. The program was more dense than expected and we would like to have more time for discussions in groups after a set of talks. We would like to highlight 5 main discussion points:

- To what degree of detail we need to model in 3D and physically adequate, what can we learn from semi-supervised or unsupervised 2D data?
- Is the model depending on the application or is there a golden standard model that is able to fit all applications?
- The current revolution of deep learning in computer vision enables a lot of novel strategies and speeds up the models, however, other challenges in modeling, synthesis and inverse rendering remain and new deep learning specific challenges are introduced.
- What are the ethical implications of the models and systems we are building?
- How will the field develop in the next 20 years? Which challenges should we focus on?

We started the seminar with a short introduction of everybody. The homework was to introduce themselves with at most one slide and prepare one important question, challenge or goal you would like to discuss during the seminar.

- **Thabo Beeler:** Non-Linear Morphable Models. How to get off Model in a meaningful way?
- **Florian Bernard:** Deeper integration of models of human knowledge and algorithms into learning systems. What are potential perspectives? How to best approach this?
- **Michael J. Black:** What's next? Increasing realism? Deep representations? Something else?
- **Volker Blanz:** Expressive model also reproduces non-face structures! How to discriminate between face and non-face? Future: better regularization, rely on trained regressors, recognize glasses ?
- **Bernhard Egger:** What to model? What to learn?
- **Victoria Fernandez Abrevaya:** How far are we from closing the gap between high-quality and low-quality capture devices, and can we use 3DMM for this?
- **Patrik Huber:** What is missing to reliably reconstruct realistic 3D faces from mostly uncontrolled 2D footage?
- **Ron Kimmel:** Geometry is the art of finding the “right” parametrization. Deep Learning is a technology that exploits convenient parametric spaces (CNN) for classification. Any hope for unification? Is translating geometry into algebra the answer?

² <https://groups.google.com/forum/#!forum/3d-morphable-models>

- **Tatsuro Koizumi:** How to evaluate and assure the robustness of neural network-based reconstruction? How to improve the stability of self-supervised training?
- **Adam Edward Kortylewski:** Can we resolve the limitations of Deep Learning with Generative Object Models?
- **Yera Kozlov:** Can physically based face modeling be replaced by machine learning?
- **Andreas Morel-Forster:** Fast posterior estimation – A contradiction?
- **Nick Pears:** How to build deeper, wider models?
- **Gerard Pons-Moll:** Is the Euclidean 3D space the right space to model humans, clothing and hair?
- **Emanuele Rodolà:** Can we make inverse spectral geometry useful in practice?
- **Sami Romdhani:** How to combine Deep Learning and 3D Equations to generate images?
- **Javier Romero:** How can Deep Nets learn from unstructured, uncalibrated views?
- **Shunsuke Saito:** Is there an unified representation to represent digital human without explicitly having prior for each component?
- **William Smith:** Self-supervision: holy grail or just re-discovering gradient descent-based analysis-by-synthesis? How do we make sure the gradients of our losses are really useful (Appearance loss: meaningless when far from good solution, Landmark loss: ambiguous (and not self-supervised), Rasterization: not differentiable)?
- **Ayush Tewari:** How can we build high quality 3D morphable models from 2D data?
- **Christian Theobalt:** Can we build a 4D Real World Reconstruction Loop? Ethical, Privacy, Security Questions of Parametric/Morphable Model Building and Reconstruction Algorithms
- **Thomas Vetter:** Did we learn much about this optimization problem (inverse rendering)?
- **Stefanie Wuhrer:** How to effectively learn parametric human models from captured data using minimal supervision?
- **Michael Zollhöfer:** What is the best representation for deep learning-based 3D reconstruction and image synthesis?
- **Silvia Zuffi:** How to model skin dynamics from video?

After the individual introductions, we discussed those ideas in discussion groups to identify points to discuss during the seminar. The following list is the unfiltered result of our brainstorming on open questions and challenges.

- Where to spend the next 20 years? Perfection: finer detail? Move it: Movement, new representation, new goals, new data? Break it: hair, clothing, new representation, new goals, new data?
- Why aren't we focusing on fixing the obvious errors?
- Optimization: Why aren't we doing more to understand our objective function and adopt the algorithms?
- How to predict distributions instead of point estimates?
- How much detail to model vs. overfitting?
- How to evaluate Photorealism?
- Should vision people be more aware of graphics standard for photorealism?
- Is it important to understand?
- Do we need correspondences to build 3D models and predictions?
- How to learn 3D from 2D?
- How to adapt models over time (without calibration)?
- How to deal with multi-view and video in CNNs?

- Which courses/skills are required?
- Use for society?
- What to leave for industry?
- What is the role of academia within industry (collaboration vs. isolation)?
- Representations (beyond triangle meshes) to deal with category discontinuities, e.g. smooth surface vs. hair
- Evaluation of shape and appearance reconstruction
- Connections between deep learning and parametric models
- Role of axiomatic models in learning
- Comparability: Benchmark and metrics
- Future prediction of motion
- Self-supervision
- Differentiable inverse rendering

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3 Overview of Talks

3.1 Shape Synthesis with Local-Global Tensors

Thabo Beeler (Disney Research – Zürich, CH)

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Joint work of Thabo Beeler, Mengjiao Wang, Derek Bradley, Stefanos Zafeiriou

Global 3DMMs are extremely popular due to their simplicity and robustness. This robustness, however, comes at the price of flexibility as 3DMMs can only represent data that is ‘within model’. For something that exhibits as much variation as the human face, this effectively means that only coarse scale features and coarse scale deformation may be captured by a global 3DMM. We explore the idea to couple such a global 3DMM with local 3DMMs in order to enrich the expressive power of the statistical model whilst not sacrificing too much of the robustness. We demonstrate our proposed coupling of global/local tensor models on the task to synthesize expressions for a person that are both expressive and preserve the identity of the subject, starting from just a neutral scan of the subject.

3.2 Combinatorial Non-Rigid Shape-to-Image Matching

Florian Bernard (MPI für Informatik – Saarbrücken, DE)

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Joint work of Florian Bernard, Frank R. Schmidt, Johan Thunberg, Daniel Cremers

Main reference Florian Bernard, Frank R. Schmidt, Johan Thunberg, Daniel Cremers: “A Combinatorial Solution to Non-Rigid 3D Shape-to-Image Matching”, CoRR, Vol. abs/1611.05241, 2016.

URL <https://arxiv.org/abs/1611.05241>

We propose a combinatorial solution for the problem of non-rigidly matching a 3D shape to 3D image data. To this end, we model the shape as a triangular mesh and allow each triangle of this mesh to be rigidly transformed to achieve a suitable matching to the image. By penalizing the distance and the relative rotation between neighboring triangles, our matching compromises between image and shape information. We resolve two major challenges: Firstly, we address the resulting large and NP-hard combinatorial problem with a suitable graph-theoretic approach. Secondly, we propose an efficient discretization of the unbounded 6-dimensional Lie group $SE(3)$. In contrast to existing local (gradient descent) optimization methods, we obtain solutions that do not require a good initialization and that are within a bound of the optimal solution.

3.3 Expressive human body models for communication and interaction

Michael J. Black (MPI für Intelligente Systeme – Tübingen, DE)

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Bodies in computer vision have often been an afterthought. Human pose is often represented by 10-12 body joints in 2D or 3D. This is inspired by Johansson’s moving light display experiments, which showed that some human actions can be recognized from the motion of the major joints of the body. The joints of the body, however, do not capture everything

all that we need to understand human behavior. In our work we have focused on 3D body shape, represented as a triangulated mesh. Shape gives us more information about a person related to their health, age, fitness, and clothing size. But shape is also useful because our body surface is critical to our physical interactions with the world. We cannot interpenetrate objects and they cannot interpenetrate us. Consequently we developed the SMPL body model, which is widely used in research and industry. It is simple, efficient, posable, and compatible with most graphics packages. It is also differentiable and easy to integrate into optimization or deep learning methods. While popular, SMPL has drawbacks for representing human actions and interactions. Specifically, the face does not move and the hands are rigid. To facilitate the analysis of human actions, interactions and emotions, we have developed a new 3D model of human body pose, hand pose, and facial expression that we estimate from a single monocular image. To achieve this, we use thousands of 3D scans to train a unified, 3D model of the human body, SMPL-X, that extends SMPL with fully articulated hands and an expressive face. We estimate the parameters of SMPL-X directly from images. Specifically, we estimate 2D image features bottom-up and then optimize the SMPL-X model parameters to fit the features top-down. This is a step towards automatic expressive human capture from monocular RGB data.

3.4 Morphable Texture Coordinates

Volker Blanz (Universität Siegen, DE)

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In 3D Morphable Models, the assignment of texture and surface structures to vertices is usually permanent. The talk presents a method that slides textures and displacement maps along the surface. It proposes a linear model of texture coordinates and is illustrated on the example of eyeball rotation.

3.5 Modeling, Reconstruction, and Animation of 3D Faces

Timo Bolkart (MPI für Intelligente Systeme – Tübingen, DE)

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Joint work of Timo Bolkart, Anurag Ranjan, Soubhik Sanyal, Michael J. Black, Haiwen Feng, Daniel Cudeiro, Cassidy Laidlaw

Learned 3D representations of human faces are useful for computer vision problems such as 3D face reconstruction from images, as well as graphics applications such as character generation and animation.

Traditional models learn a linear or multilinear latent representation of a face. Due to this linearity, they cannot capture extreme deformations and non-linear expressions. Our convolutional mesh autoencoder (CoMA) [1] applies spectral graph convolutions to the mesh surface and introduces mesh sampling operations to enable a hierarchical mesh representation that captures non-linear shape and expression variations in multiple scales. Compared to traditional methods, CoMA requires 75% fewer parameters and reaches a 50% lower reconstruction error.

Second, we present RingNet [3] to reconstruct 3D faces from single images without any 2D-to-3D supervision. Our key observation is that an individual’s face shape is constant across images, regardless of expression, pose, lighting, etc. RingNet leverages multiple images of a person and automatically detected 2D face features. It uses a novel loss that encourages the face shape to be similar when the identity is the same and different for different people. We achieve invariance to expression by representing the face using the statistical FLAME model [2]. Once trained, our method takes a single image and outputs the parameters of FLAME, which can be readily animated.

Audio-driven facial animation from audio has been widely explored, but achieving realistic, human-like performance is still unsolved. This is due to the lack of available 3D datasets, models, and standard evaluation metrics. We introduce a novel 3D speech dataset (12 subjects, 40 sentences each) and train a model that animates 3D faces from speech. Our learned Voice Operated Character Animation model (VOCA) [4] takes any speech signal as input (from any language) and then animates a wide range of adult faces, not seen during training. This makes VOCA suitable for tasks like in-game video, virtual reality avatars, or any scenario when the speaker, speech, or language is not known in advance.

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3.6 Attributes, Illumination and Occlusion

Bernhard Egger (MIT – Cambridge, US)

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Main reference Bernhard Egger: “Semantic Morphable Models” PhD Thesis, University of Basel, 2017.

URL <https://doi.org/10.5451/unibas-006722192>

In my presentation, I was talking about research challenges that were otherwise not covered in the seminar. For occlusions, we proposed a joint segmentation and model adaptation framework [1]. To initialize this hard optimization task we rely on a RANSAC based robust illumination estimation. An illumination prior from real-world images is estimated and arises as a nice side product. We also built a first joint shape, albedo and attribute model using Copula Component Analysis and use it for both Analysis and Synthesis [2, 3]. I proposed that all in our community should focus on obvious problems like occlusions.

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3.7 Interaction between invariant structures for shape analysis

Ron Kimmel (*Technion – Haifa, IL*)

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A classical approach for surface classification is to find a compact algebraic representation for each surface that would be similar for objects within the same class and preserve dissimilarities between classes. Self functional maps were suggested by Halimi and the lecturer as a surface representation that satisfies these properties, translating the geometric problem of surface classification into an algebraic form of classifying matrices. The proposed map transforms a given surface into a universal isometry invariant form defined by a unique matrix. The suggested representation is realized by applying the functional maps framework to map the surface into itself. The idea is to use two different metric spaces of the same surface for which the functional map serves as a signature. As an example we suggested the regular and the scale invariant surface laplacian operators to construct two families of eigenfunctions. The result is a matrix that encodes the interaction between the eigenfunctions resulted from two different Riemannian manifolds of the same surface. Using this representation, geometric shape similarity is converted into algebraic distances between matrices. I will also comment on some of our efforts to migrate geometry into the arena of deep learning, in a sense learning to understand.

3.8 Can we resolve the limitations of deep learning with generative object models?

Adam Edward Kortylewski (*Johns Hopkins Univ. – Baltimore, US*)

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This talk describes major limitations of current deep learning approaches to facial image analysis such as the lack of generalization from biased training data and the sensitivity to partial occlusion. I will discuss the relevant work of our group leveraging synthetically generated face images for overcoming those limitations [1, 2, 3]. Towards the end of the talk, I will hypothesize that integrating generative object models – such as 3DMMs – into deep neural networks would provide a means for overcoming those limitations.

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3.9 Data Driven Inversion of Faces

Yeara Kozlov (ETH Zürich, CH)

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Facial animation is one of the most challenging problems in computer graphics, and it is often solved using linear heuristics like blend-shape rigging. More expressive approaches like physical simulation have emerged, but these methods are very difficult to tune, especially when simulating a real actor's face. We propose to use a simple finite element volume for face animation and present an instrument free, non-intrusive method for recovering the required simulation parameters. Our method involves reconstructing a very small number of head poses of the actor in 3D, where the head poses span different configurations of force directions due to gravity. Our algorithm can then automatically recover both the gravity-free rest shape of the face as well as the spatially-varying physical material stiffness such that a simulation will match the captured targets as closely as possible. We present preliminary results and discuss the challenges in using our method on faces.

3.10 Inside and Outside the Scanner Room: On How to Capture and Model People from Data.

Gerard Pons-Moll (MPI für Informatik – Saarbrücken, DE)

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The research community has made significant progress in modeling people's faces, hands and bodies from data, and currently several models are publicly available. The standard approach is to capture data coming from 3D/4D scanners and learn models from it. Such an approach provides a very useful first step, but it does not scale to the real world. If we want to learn rich models that include clothing, interactions of people, and interactions with the environment geometry, we require new approaches that learn from ubiquitous data such as plain RGB-images and video. In this talk, I will describe some of our works on capturing and learning models of human pose, shape, soft-tissue, and clothing from 3D scans as well as from plain video. I will conclude the talk outlining the next challenges in building digital humans and perceiving them from sensory data.

3.11 Isospectralization, or How to Hear Shape, Style, and Correspondence

Emanuele Rodolà (*Sapienza University of Rome, IT*)

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Main reference Luca Cosmo, Mikhail Panine, Arianna Rampini, Maks Ovsjanikov, Michael Bronstein, Emanuele Rodolà: “Isospectralization, or how to hear shape, style, and correspondence”. to appear in Proc. CVPR 2019, Long Beach, CA, USA, 2019.

The question whether one can recover the shape of a geometric object from its Laplacian spectrum (‘hear the shape of the drum’) is a classical problem in spectral geometry with a broad range of implications and applications. While theoretically the answer to this question is negative (there exist examples of iso-spectral but non-isometric manifolds) little is known about the practical possibility of using the spectrum for shape reconstruction and optimization. In this talk, I will introduce a numerical procedure called isospectralization [1], consisting of deforming one shape to make its Laplacian spectrum match that of another. By implementing isospectralization using modern differentiable programming techniques, we showed that the *practical* problem of recovering shapes from the Laplacian spectrum is solvable. I will finally exemplify the applications of this procedure in some of the classical and notoriously hard problems in geometry processing, computer vision, and graphics such as shape reconstruction, style transfer, and non-isometric shape matching.

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3.12 Deep 3D Morphable Models

Sami Romdhani (*IDEMIA, FR*)

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Recently, Generative Adversarial Networks (GANs) have addressed a lot of attention. Indeed, this is because they are capable to generate synthetic face images at an unprecedented level of realism and quality. One of the main limitation of the GANs, though, is their inability to let the user control the type of face image generated. For instance, even though a face with some pose or some illumination can be generated, there is no control over these parameters. Hence, it is not possible to generate a face image of a random individual at different poses or different illumination conditions. This is, however, something that the 3D Morphable Model does very well, by leveraging the 3D equations grounded in physics. Hence, there is a need to build a generator that can synthesize highly realistic images as GAN can, while giving control over semantic parameters such as pose or expression, as 3D MM can.

3.13 Deep Learning from Unstructured, Uncalibrated Views

Javier Romero (Amazon Research – Barcelona, ES)

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It is said that one of the most important professors in our field once described the three main problems in computer vision to be correspondences, correspondences, and correspondences. Deep networks have attacked successfully the problem of extracting correspondences between two images in a number of problems (optical flow, stereo matching, etc). However, there is still little work on deep networks producing coherent output (keypoint estimation, segmentation) representations when presented with unstructured, non-calibrated multiview RGB data. This work probably requires deep networks to either consume some notion of correspondences or producing it internally in a way that its estimations are preserved across them. In a world in which it is common to have multiple images or videos from a particular object of interest, it is important to let neural networks exploit effectively this input. I would like to present this challenging, unsolved question to the audience of the workshop, with the focus on extracting key points and dense registrations of people from multiple images.

3.14 Top-Down Human Digitization In the Wild

Shunsuke Saito (USC – Los Angeles, US)

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3D morphable models have been a popular choice for compact facial shape and appearance representation for two decades. However, extending such representation to non-parametric structures such as hair and clothed human bodies poses a significant challenge due to their immense variation in shape and topology. To this end, we introduce an effective and unified data representation based on deep learning that can represent the entire human body, including the face, hair, body, and clothing. I will present several possible representations for human digitization and show several highlights of our recent progress on high-fidelity geometry/texture using deep convolutional neural networks. I will also discuss the pros and cons when inferring both parametric and non-parametric data when modeling humans.

3.15 Three Ambiguities

William Smith (University of York, GB)

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Joint work of William Smith, Anil Bas, Ye Yu, Chao Zhang, Behrend Heeren, Martin Rumpf

The problem of providing a physical explanation of an image, i.e. inverse rendering geometry, reflectance and illumination from a single image, is an ill-posed problem. In this talk, I will consider three specific ambiguities that arise. First, when using a morphable model to solve the shape-from-correspondence problem (e.g. fitting a model to landmarks) there is a nonlinear subspace of 3D shapes that all project to the given 2D positions. In particular, this is significant when camera calibration is unknown and hence distance from the camera to

object is unconstrained. Second, the general task of single image inverse rendering is highly ambiguous. For example, the shaded versus painted hypothesis and ambiguity between low-frequency lighting and texture effects. I described InverseRenderNet, a self-supervised deep neural network that learns this task by exploiting a prior on natural illumination and multiview supervision to ensure photometric invariants are consistently estimated across lighting. Third, I considered the problem of dealing with rigid body motion superposed on top of nonlinear shape deformation. Building a statistical model of the intrinsic shape variation, invariant to how the shapes are aligned requires RBM-invariant modeling. I proposed a hybrid statistical/physical model that uses the discrete shell energy as a local distance measure and time-discrete principal geodesic analysis to build the statistical model.

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3.16 Building 3D Morphable Face Models from Videos

Ayush Tewari (MPI für Informatik – Saarbrücken, DE)

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Joint work of Ayush Tewari, Florian Bernard, Pablo Garrido, Gaurav Bharaj, Mohamed Elgharib, Hans-Peter Seidel, Patrick Pérez, Michael Zollhöfer, Christian Theobalt

Main reference Ayush Tewari, Florian Bernard, Pablo Garrido, Gaurav Bharaj, Mohamed Elgharib, Hans-Peter Seidel, Patrick Pérez, Michael Zollhöfer, Christian Theobalt: “FML: Face Model Learning from Videos”. The IEEE Conference on Computer Vision and Pattern Recognition (CVPR), Long Beach, CA, USA 2019.

Reconstructing the 3D geometry and appearance of faces from monocular images is challenging, as it requires inverting the image formation process. Parametric face models (3DMMs), built using limited 3D scan data are used to constrain this ill-posed problem. However, these models lack details and can only represent a very limited subset of identities. I will talk about building large-scale face models just from videos, which allows for reconstruction in-the-wild. The presented method learns to reconstruct all faces in a large video dataset while building a low dimensional 3D face model at the same time. Models built from videos can generalize better across identities, compared to classical morphable models, due to the abundance of video data on the internet. I will talk about how this idea can be used for building higher quality and detailed 3D morphable models of faces.

3.17 To Optimize, To Learn, Or to Integrate

Christian Theobalt (MPI für Informatik – Saarbrücken, DE)

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Reconstructing models of the real world in motion from sparse or even single camera images is a focus of research in my group Graphics, Vision and Video at the Max-Planck-Institute for Informatics in Saarbruecken. In particular, reconstructing the space-time coherent geometry, deformation, material and illumination of the scene is of interest. Using our work on monocular face performance capture, I discuss several classes of algorithms developed for models of the world in motion from a single color camera. In particular, I visited model-based analysis-by-synthesis approaches, learning-based regression or classification approaches, as well as new algorithms we developed that deeply integrate model-based and deep learning-based algorithms in an end-to-end trainable manner. I also discuss the pros and cons of the different classes of methods and opened up the question of how the deeply integrated approaches could be able to drive a real-world reconstruction loop.

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3.18 Probabilistic Morphable Models

Thomas Vetter (*Universität Basel, CH*)

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Main reference Thomas Gerig, Andreas Morel-Forster, Clemens Blumer, Bernhard Egger, Marcel Lüthi, Sandro Schönborn, Thomas Vetter: “Morphable Face Models – An Open Framework”, in Proc. of the 13th IEEE International Conference on Automatic Face & Gesture Recognition, FG 2018, Xi’an, China, May 15–19, 2018, pp. 75–82, IEEE Computer Society, 2018.

URL <https://doi.org/10.1109/FG.2018.00021>

Probabilistic Morphable Models extend the classical Morphable Model approach in two terms. First the shape and texture variability of the models is formalized as Gaussian Process and second, the model to target registration utilizes data-driven Markov Chain Monte Carlo optimization. The step from PCA based representations to Gaussian Processes unifies several different deformations models, such as spline, free-form or data based to a single formal description. This is of conceptual importance since it connects the rich field of Gaussian Processes to the Morphable Model approach. On the practical side, it is now sufficient to implement only a single software framework for a whole class of different deformation models. The second novelty, the stochastic optimization framework aims for two main improvements. The model fitting problem is inherently difficult since its non-convexity and the high dimensional parameter space. The model fitting starts in general by some initial parameter guess. But the local optima problem makes it necessary to consider a certain uncertainty of these initialization steps to avoid that a bad initial guess hinders to overall optimization. Another shortcoming of previous methods is that the optimization results only in a single “optimal” value but does not inform about the quality of the result or similar results. We propose to compute the full posterior parameter distribution for a given target image. This leads to a full Bayesian Approach for model to image registration. We propose to compute an approximation of the full posterior based on a stochastic optimization framework using Metropolis-Hastings Filtering. This approach does not only inform about the certainty of the solution it also enables an easy approach to integrate uncertain guesses for the initialization of the optimization procedure. Overall our Probabilistic Morphable Model technique is a fully probabilistic approach enabling Bayesian inference on images.

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3.19 Building 3D Morphable Models with Minimal Supervision

Stefanie Wuhler (INRIA – Grenoble, FR)

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Joint work of Timo Bolkart, Victoria Fernandez Abrevaya, Adnane Boukhayma, Edmond Boyer, Stefanie Wuhler

3D Morphable Models (3DMMs) are commonly used in many virtual and augmented reality applications. Recently, a number of static and dynamic databases of 3D face scans have been published, whose acquisition was facilitated by increasingly affordable 3D face scanners. In spite of this progress, building high-quality 3DMMs that can benefit from these datasets remains challenging in practice as the raw 3D face scans need to be registered. We are interested in models that decouple different factors of variation (e.g. identity, expression or age), and in this case, the data additionally needs to be labeled. As inaccuracies in the registrations and labeling directly deteriorate the quality of the resulting 3DMM, these steps are often completed with manual interaction in practice. The goal of our work is to build 3DMMs with minimal supervision. To achieve this, we have developed groupwise methods that take advantage of the full training database. I will present our works that allow to improve registration accuracy by taking advantage of the minimum description length principle [1]. We will further discuss how autoencoders [2] and generative adversarial networks [3] can be used to efficiently train from datasets that combine existing 3D face databases where only sparse label information is available. For the second part of this presentation, I will give an outlook on upcoming challenges. A first challenging problem is to learn models of dynamic 3D face deformations. In this scenario, minimal supervision is critical. A second open problem we will discuss is how to model correlations between different dynamically deforming body parts, such as face and tongue movements.

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3.20 Learning 2D and 3D Deep Generative Models

Michael Zollhöfer (Stanford University, US)

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Joint work of Hyeonwoo Kim, Pablo Garrido, Ayush Tewari, Weipeng Xu, Justus Thies, Matthias Nießner, Patrick Pérez, Christian Richardt, Michael Zollhöfer, Christian Theobalt, Vincent Sitzmann, Felix Heide, Gordon Wetzstein

Generative 2D rendering-to-video translation networks that take renderings of parametric model instances as input enable to bridge the domain gap between synthetic computer graphics and real imagery. With the ability to freely control the underlying parametric face model, we are able to demonstrate a large variety of video rewrite applications. For instance, we can reenact the full head using interactive user-controlled editing and realize high-fidelity visual dubbing. While this approach of bridging the domain gap in 2D screen

space enables several existing applications, it has limited generalization capabilities and does not easily scale to large head rotations. We address this lack of 3D understanding of such generative neural networks by introducing a persistent 3D feature embedding. At its core, our approach is based on a Cartesian 3D grid of embedded features that learn to make use of the underlying 3D scene structure. Our approach thus combines insights from 3D geometric computer vision with recent advances in learning image-to-image mappings based on adversarial loss functions.

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3.21 Modeling Animal Shape

Silvia Zuffi (IMATI – Milano, IT)

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I will present our recent work on modeling animal shape, the SMAL model. SMAL model is a 3D articulated model that can represent animals including lions, tigers, horses, cows, hippos, dogs. We learn the model from a small set of 3D scans of toy figurines in arbitrary poses that we align to a common template using a novel approach. From the aligned toys, brought into a reference pose, we learn a linear shape space over a large variety of animal species.

4 Working groups

4.1 Discussion: The Ethics and Regulation of Photo-realistic Human Generation

Michael J. Black (MPI für Intelligente Systeme – Tübingen, DE)

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Advances in 3DMMs and related technologies have created the ability to synthesize images of people that are indistinguishable from real images, to manipulate photos of people to change identity or expression, and to edit videos to change what people are saying. Photo-realistic face generation and manipulation have the ability to change our perception of history and our perception of each other. By doing so, it has the power to change behavior and the future. There are both positive and negative applications of this technology and the question is if and how it should be regulated. In this session, we explored several case studies at different levels from regulating the research, the technology, the output of the technology, particular uses, and users themselves. As an outcome of this session, there are plans to

write a position paper and to possibly organize a Dagstuhl seminar focused on the ethical questions that would bring together people with different levels of expertise from science, business, government, history, psychology, sociology, law enforcement, and ethics.

4.2 Discussion: 3D Morphable Models – 10 Years Perspective

Patrik Huber (University of Surrey, GB)

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In this session, the topic was to discuss where our field might be in 10 years time. The discussion was started with a comment that recent work done in Unity by Vicon, puppeteering a Chinese woman, involved a lot of manual work, but the results are much better than what our computer vision algorithms can currently produce. In 10 years time, we can perhaps achieve such quality with computer vision algorithms and with much fewer manual intervention. Another way would be to look at the question from the future and ask ourselves what the additional value is that our tech can provide. Simple answers would be that there are many uses in health care, for example, entertainment specifically for elderly or lonely people, or to detect when a person falls – and then we could work towards reliable algorithms for these tasks.

It was pointed out that in vision, we would like to understand images. We work hard to generate priors for image analysis or generation, here with the 3D morphable models. We can model the world in the way we understand it from physics (which would be the more traditional way with morphable models and a rendering pipeline), or, being done more and more recently, model it with some sort of function that we don't fully understand anymore (which would correspond to many of today's deep-learning based approaches). Traditionally, we have been able to understand each parameter of our models and have an intuition about them, and they were not just abstract latent variables of a neural network. One big question, therefore, is how we will create priors in the future: Will we have machines creating priors automatically, or will we still teach the machines? One general point of the audience was that we are likely to continue the "black-box-way", but develop the tools to understand those more abstract models and latent spaces much better. There will likely also be a process to record and diagnose failures of those systems, and then improve them accordingly – much like in today's complex airplane systems, where it is also nigh impossible to test for all potentially occurring events. It was further pointed out how good of a representation linear models and PCA specifically are. One needs only a small number of data points to represent quite complex things, and there will always be cases where only few data is available, so those simple models are unlikely to disappear.

It was also briefly discussed how in the last few years, the community got a lot better at optimization, for example, 3D human pose estimation. A lot of information can be estimated already with a few sparse points, for example, facial landmarks or body joints. One important and continuing research direction is selecting descriptive features of an object, where currently neural networks do a very good job at learning the feature selection. In that case, the prior is contained in the training data (often with biases we may and may not be aware of), which ties back to the earlier discussion about learning priors and whether we will still be using "manual" priors in a few years time. In essence, where a few decades ago students were tweaking optimization parameters, in a very similar way, we are today tweaking optimization parameters of neural networks.

A final point discussed was that most current research only tackles one specific task, like face or full-body reconstruction, in isolation. There is research starting to emerge that combines those individual tasks, and it has been brought up whether to put together those individual methods is only an engineering task, or whether it is a fundamental research question that also requires new methods and models. It is also still an unanswered question whether we can use the same technology, for example, full-body models, to model the whole world. We are currently learning all these specialized models, which coincides with the mental models that exist in our brains, but at some points, we have to put those separate bits together. In our brains we have hierarchical concepts that we seamlessly relate and connect with each other – for example a chair can be seen as a global object, with many different varieties, and if we inspect a chair much closer, we might go down to the level of the materials that the chair consists of, which is a different generic concept. This is something that we will likely have to address more deeply in the computer vision community. Currently, most of those models that we are using are also “forward-only”, meaning they are trained once, and then when deployed, are not able to adapt or learn new things.

The discussion didn’t come to too much of a conclusion, but the audience would probably agree that learning priors from data will continue to be a hot topic in the next 10 years, and models and algorithms for specific tasks will be put together to yield a more holistic reconstruction of human bodies including detailed reconstruction of their faces, hands, and clothing, up to a level that is currently only achievable by computer graphics with laboursome manual work.

4.3 Discussion: Representation Group 1

Adam Edward Kortylewski (Johns Hopkins Univ. – Baltimore, US)

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Main reference Adam Kortylewski, Bernhard Egger, Andreas Schneider, Thomas Gerig, Andreas Morel-Forster, Thomas Vetter: “Empirically Analyzing the Effect of Dataset Biases on Deep Face Recognition Systems”, in Proc. of the 2018 IEEE Conference on Computer Vision and Pattern Recognition Workshops, CVPR Workshops 2018, Salt Lake City, UT, USA, June 18-22, 2018, pp. 2093–2102, IEEE Computer Society, 2018.

URL <http://dx.doi.org/10.1109/CVPRW.2018.00283>

We discussed the properties of good representations and found that this is highly dependent on the down-stream task. An open research question is whether universal representations can be learned that suit multiple-down stream tasks (see Multi-task learning literature). Finally, it is important to be aware of a trade-off in the properties of representations w.r.t the interpretability of the representation. An interpretable representation is likely not the most efficient possible. This trade-off should be taken into account in the discussion on interpretable representations.

4.4 Discussion: Representation Group 2

Yeara Kozlov (ETH Zürich, CH)

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The representations used in computer graphics and vision influence the available toolset and the problems the community chooses to address. A good representation would have the following properties: semantic, compact, complete, has specificity, is differentiable, unique and allow for high-quality rendering. A representation that might be useful to solve technical problems might not be able to give insight into the problem of vision and vice-versa. It was suggested that the community should revisit historical representations such that we can deal with challenging problems that are not currently addressed.

4.5 Discussion: Levels of Detail for Modeling

Javier Romero (Amazon Research – Barcelona, ES)

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We talked about three topics related to levels of detail. One discussion was focused on geometry statistics at different levels of detail. Classic 3D Morphable models have done a good job in fitting and sampling low-frequency details but typically fail at modeling high frequencies. Adversarial nets, one of the current solutions to increase details in reconstructions, exploits exactly the differences between real crisp data and smooth models by encouraging the generator to make them indistinguishable. There are also classic solutions to increase detail in models, like multilinear wavelet models (<https://arxiv.org/pdf/1401.2818.pdf>). These models have shown good fitting power but are not suitable for sampling. A second discussed topic was the dependency between the level of detail and the task to be solved. Hollywood movies require a great level of detail to achieve photorealism. However, synthetic data generated for training deep networks probably have very different requirements. It has been shown that one of the important aspects of synthetic data for this problem is the blending between foreground and background (<https://arxiv.org/pdf/1710.10710.pdf>), but it's unclear what is important for more fine-grained tasks like a detailed 3D reconstruction of faces and bodies. Intuitively, it seems like reconstruction would benefit from material estimation in the synthetic assets, but maybe not to the level of subsurface scattering or facial microstructures. Finally, a third topic we discussed is the perceived level of detail by humans. The field focuses on capturing and reproducing high frequencies in the face with high accuracy, although it is unclear how much of that detail can be kept in memory by us humans. An individual would still be recognizable even when rendered with the wrinkles from a different person, as soon as the wrinkles are consistent with his age and general facial features. This maybe suggests adversarial functions that try to push generators for consistency rather than precise high-frequency matching.

4.6 Discussion: Academia and Industry

Shunsuke Saito (USC – Los Angeles, US)

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In this session, we discussed the current issues and future of relationship between industry and academia. Throughout the discussion, we all agreed that we should actively seek the collaboration on the premise that society should support different interests. The main discussion point is three-fold: 1) openness vs protectionism 2) human resource 3) education. First, while academia prefers openness to facilitate knowledge creation as community, industry tends to keep knowledge within a company to keep superiority in the market. Therefore it is essential to incentivize industry to release their knowledge and data (e.g., making a challenge/competition on open questions in a conference). Another short-term solution is to encourage targeted collaboration, where a company provides a specific university or group with their proprietary data to solve open questions together. Such collaboration can benefit both academia and industry by bringing another aspect to the problems. Secondly regarding human resources, it has been increasingly difficult for universities to hire not only competitive students but also senior researchers due to large gap in terms of monetary rewards. However, given the fact that internet bubble in early 90s created the exact same situation between industry and academia, we conclude that we should learn how to handle the situation from the history rather than finding out a solution from scratch. Lastly, industry has been more influential on academia by occupying committee members of a conference or creating new demand in the market, which creates pressure on universities to change the curriculum. To avoid conflict of interest and encourage diversity in research, the entire research community may need to take responsibility on educating junior researchers by providing guideline on this matter including paper review. In conclusion, we view siblings as an ideal form of relationship between industry and academia, where they can play in harmony but do not always seek the same interest.

4.7 Discussion: Inverse Rendering

Ayush Tewari (MPI für Informatik – Saarbrücken, DE)

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The goal of inverse rendering is to estimate parameters of a forward rendering model. Estimating these rendering parameters from a single image is difficult, because of the ambiguities between different parameters. Priors (for e.g. 3D Morphable Models) of different objects help in resolving many of these ambiguities. Certain applications like image editing might not require accurate estimation of different parameters. In that case, we can make strong assumptions about the world. However, the accurate inverse can be required for other applications. Differentiable rendering is the key to solve inverse rendering problems. However, rendering techniques are usually non-differentiable. Occlusions and gradients around the boundary of the 3D surface lead to non-differentiability of the rendering function. Rasterization techniques are fast but cannot deal with transparency and complex light effects. Ray tracing can deal with these phenomena but is typically slower. However, with faster hardware and better software, differentiable raytracing could be widely used in the near future.

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Theoretical Foundations of Storage Systems

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Abstract

This report documents the program and the outcomes of Dagstuhl Seminar 19111 “Theoretical Foundations of Storage Systems.” This seminar brought together researchers from two distinct communities – algorithms researchers with an interest in external memory and systems researchers with an interest in storage – with the objective of improving the design of future storage systems.

Seminar March 10–15, 2019 – <http://www.dagstuhl.de/19111>

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Keywords and phrases Storage Systems, External Memory Algorithms

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Edited in cooperation with Michael A. Bender

1 Executive Summary

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Storage systems, including databases and file systems, are at the heart of all large data applications. Recently, some storage systems have incorporated theoretical advances in data organization techniques, with substantial improvements in performance. However, there is little contact between the systems designers who build storage systems and theoreticians who design new ways to organize data. This Seminar worked to bridge this gap, to the benefit of both communities and to improve the design of all storage systems.

External-memory algorithms are those where the data is too large to fit in memory, and hence needs to be stored on disk and accessed using I/O. Algorithmic analysis of such algorithms therefore focuses on the number of I/Os needed to complete a computation,



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Editors: Martin Farach-Colton, Inge Li Gørtz, Rob Johnson, and Donald E. Porter



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rather than the number of instructions. This is because an I/O can be many orders of magnitude slower than a machine instruction and therefore I/Os can be the bottleneck in such computations.

The theoretical analysis of such external-memory algorithms has produced many exciting results in the last two decades. Many of these are directly relevant to practical applications, but only a few have made the leap to deployment. This Seminar brought together theoreticians, who have an extensive understanding of the state of the art in external-memory data structures, and storage systems researchers and practitioners, who understand the details of the problems that need to be solved.

Specific questions that were addressed in the workshop include the following:

- How can we use the huge improvements in string data structures to improve storage systems that manipulate strings? Many data structures, such as LSMs and B^{ϵ} -trees, rely heavily on the assumption that keys are indivisible and small.
- How can we use new multi-dimensional data indexes in working systems?
- Many indexes suffer from fragmentation. Are there data structure improvements that would allow efficient storage on disks that are nearly full? Currently, disks are kept only a fraction full because the performance of existing data structures decays dramatically as the disk fills. This suggests another problem:
- How can theoretical models be improved to capture such issues as:
 - full disk: The external memory model, the disk is of unbounded size.
 - sequential access: Both hard disks and SSDs require very large blocks of sequential I/O to capture a large fraction of bandwidth. The external-memory model assumes that disks are random access.
- Concurrency: Can data structures be designed to exploit memory locality on disk while maintaining concurrency in RAM?

The storage system world is in a ferment as new hardware becomes available. Now is the time to establish deep partnerships across disciplines in computer science to solve some of the most pressing big data infrastructure problems.

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3 Cross-Community Communication

3.1 Tutorials

The workshop comprised systems and theory tutorials to help participants get on the same page. These included tutorials on write-optimized data structures, deduplication, SSDs, hard drives, shingled hard drives, formal methods and file systems. All participants of the workshop—theoreticians and practitioners alike—were encouraged to target their talks for more general audiences and to make their talks tutorial-like.

3.2 “Say What?” Sessions

Any community has its own set of buzzwords and its own corpus of common knowledge. These make communication easier with a community but harder across communities. The workshop dealt with these communication challenges by having what we called *say what?* sessions—whenever any audience member heard an unfamiliar term from a speaker, they would call out “say what?” and the speaker wrote the term on the chalkboard. One side of the board was devoted to system terms that were foreign to most theoreticians, and the other side was devoted to theory terms that were foreign to most system researchers. During the Say What? sessions, which took place in the evenings, these terms were demystified. These sessions lead to what was described by many participants as a warm and collegial atmosphere throughout the conference.

3.3 Talk Karaoke

One of the cross-community activities of the conference was an activity called talk karaoke. In this activity, speakers were given a slide deck that they had never seen before, and needed to give a three-minute talk based on the slide deck. Systems speakers were given theory slides and theory speakers were given systems slides. This was a wonderful bonding activity full of laughter even after several hours, and several participants commented that this was one of the most enjoyable activities that they had seen at any conference or workshop.

4 Overview of Talks

4.1 The Design of the File Storage Service for Oracle’s Cloud

Bradley C. Kuszmaul (Oracle Corporation – Burlington, US)

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File Storage Service is an elastic filesystem provided as a managed NFS service in Oracle Cloud Infrastructure. Using a pipelined Paxos implementation, we implemented a scalable block store that provides linearizable multipage limited-size transactions. On top of the block store, we built a scalable B-tree that provides linearizable multikey limited-size transactions. By using self-validating B-tree nodes and performing all B-tree housekeeping operations as separate transactions, each key in a B-tree transaction requires only one page in the

underlying block transaction. The B-tree holds the filesystem metadata. The filesystem provides snapshots by using versioned key-value pairs. The entire system is programmed using a nonblocking lock-free programming style. The presentation servers maintain no persistent local state, with any state kept in the B-tree, making it easy to scale up and failover the presentation servers. We use a non-scalable Paxos-replicated hash table to store configuration information required to bootstrap the system. The system throughput can be predicted by comparing an estimate of the network bandwidth needed for replication to the network bandwidth provided by the hardware. Latency on an unloaded system is about 4 times higher than a Linux NFS server backed by NVMe, reflecting the cost of replication.

4.2 Tutorial on Write Optimization

Michael A. Bender (Stony Brook University, US)

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Write-optimized dictionaries (WODs), such as LSM trees and B^ε-trees, are increasingly used in databases and file systems. Such data structures support very fast insertions without sacrificing lookup performance.

This talk explains how WODs can substantially reduce the I/O cost of many workloads, enabling some applications to scale by orders of magnitude. In contrast, traditional data structures, such as B-trees, are often I/O bound on these workloads. The talk explores write-optimization from the perspective of foundational theory, parallelization, and applications.

4.3 Formal methods and file systems

Thomas J. Ridge (University of Leicester, UK)

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This is a short talk giving an overview of formal methods (in particular, theorem provers such as Isabelle), and their application to file systems and related technologies (key-value stores, databases).

4.4 Tutorial on Nonvolatile Memory, including flash memory

Sam H. Noh (Ulsan National Institute of Science and Technology, KR)

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This talk was on the introduction of nonvolatile memory (including flash memory) and the issues it raises in regards to storage systems. For flash memory based storage, in particular, we describe how Ultra Low Latency SSDs are changing the view of secondary storage. For byte addressable nonvolatile memory, we describe issues such as consistency and persistency that arises when using this new media. Such issues forces us to revisit data structure that have traditionally been used in storage systems.

4.5 File System Aging

Martin Farach-Colton (Rutgers University – Piscataway, US)

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Joint work of Alexander Conway, Ainesh Bakshi, Yizheng Jiao, William Jannen, Yang Zhan, Jun Yuan, Michael A. Bender, Rob Johnson, Bradley C. Kuszmaul, Donald E. Porter, Martin Farach-Colton

Main reference Alexander Conway, Ainesh Bakshi, Yizheng Jiao, William Jannen, Yang Zhan, Jun Yuan, Michael A. Bender, Rob Johnson, Bradley C. Kuszmaul, Donald E. Porter, Martin Farach-Colton: “File Systems Fated for Senescence? Nonsense, Says Science!”, in Proc. of the 15th USENIX Conference on File and Storage Technologies, FAST 2017, Santa Clara, CA, USA, February 27 – March 2, 2017, pp. 45–58, USENIX Association, 2017.

URL <https://www.usenix.org/conference/fast17/technical-sessions/presentation/conway>

File systems have heuristics to avoid fragmentation and aging, where aging is the degradation of performance due to fragmentation. However, a theoretical analysis suggests that modern file systems are unable to stay ahead of fragmentation under normal workloads. On the other hand, Be-tree file systems should be able to avoid fragmentation and aging by using large block sizes that amortize the cost of a seek.

We show a simple workload that elicits aging in a variety of file systems. Indeed, it is easy to make file systems slow down by a factor of 20 under normal workloads. In contrast, BetrFS, a Be-tree file system, avoids aging, as predicted.

4.6 What is a sector (and why should I care)?

Gala Yadgar (Technion – Haifa, IL)

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This short tutorial explained the basic concepts of hard-disk drives: arm movements, rotation delays, and logical organization of data on disk. It was constructed to highlight the difference between the current theoretical model used to measure the I/O efficiency of algorithms and data structures (DAM), and the real costs incurred by these mechanisms in practical systems. A better understanding of this gap by the theoretical community will hopefully motivate new theoretical models and constructions.

4.7 Tutorial on SMR Disks

William Jannen (Williams College – Williamstown, MA, US)

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This talk gives an introduction to SMR disks.

4.8 Tales from the Algorithm Engineering Trenches: STXXL, Thrill, NVMe SSDs, and RDMA

Timo Bingmann (KIT – Karlsruher Institut für Technologie, DE)

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Joint work of Roman Dementiev, Lutz Kettner, Peter Sanders, Timo Bingmann, Michael Axtmann, Emanuel Jöbstl, Sebastian Lamm, Huyen Chau Nguyen, Alexander Noe, Sebastian Schlag, Matthias Stumpp, Tobias Sturm

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URL <http://dx.doi.org/10.1109/BigData.2016.7840603>

This talk starts with a retrospective on STXXL [1], which is a library of external memory algorithms and data structures started back in 2003. STXXL contains multiple efficient external containers such as a sorter, a B-tree, and a priority queue, which were integral for developing many larger external algorithms in later years. STXXL also pioneered pipelining of algorithm stages to save constant factors due to round trips of data to disks.

Thrill [2] is our new parallel distributed computation framework in C++ which draws on the experiences from STXXL. Using Thrill one can pipeline scalable parallel primitives such as Map, Sort, Reduce, and PrefixSum to construct larger complex algorithms.

In the talk we motivate why parallelism in algorithms, as used in Thrill, is absolutely necessary to fully utilize the current generation of fast external memory storage devices. To underline this, we presented fresh experiments of sequential scanning speed and random access latency on rotational disks, NAND SSDs, and NVMe SSDs.

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4.9 Operating Systems Class: A Series of Algorithmic Disappointments

Donald E. Porter (University of North Carolina at Chapel Hill, US)

This talk walks through several examples of practical OS challenges where the textbook solutions are unsatisfying, and perhaps standard theory models do not capture essential requirements for a practical solution. These examples include CPU rebalancing, physical page allocation, and directory caching.

4.10 High-Performance Computing Storage System Challenges for Theoreticians

Jonathan Berry (Sandia National Laboratories – Albuquerque, US)

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Joint work of Jonathan Beryy, Cynthia Phillips, Steven Plimpton, Alexandra Porter, Timothy Shead

I present some I/O challenges associated with high-performance computing. For scientific computing, a primary challenge is doing checkpoint/restart. This differs from checkpointing in transactional database systems since the constraints are different. For data analysis, I outline some challenges with streaming computation. Limited storage decreases accuracy of analytics, motivating work that combines high-speed streaming with external-memory algorithms.

4.11 Traversal and generation of very large graphs in memory hierarchies

Ulrich Carsten Meyer (Goethe-Universität – Frankfurt a. M., DE)

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Very large graphs arise naturally in such diverse domains as social networks, web search, computational biology, machine learning and more. Even simple tasks like traversing these graphs become challenging once they cannot be stored in the main memory of one machine. If the graph is stored in external memory, then many algorithms that perform very well on graphs that are stored in internal memory, become inefficient because of the large number of I/Os they incur. In order to alleviate the I/O bottleneck, a number of external memory graph algorithms have been designed with provable worst-case guarantees. In the talk I highlight some techniques used in the design and engineering of such algorithms and survey the state-of-the-art in I/O-efficient graph traversal algorithms. In the engineering process mentioned above, artificially generated input graphs play an important role for systematic testing and tuning. In big data settings, however, not only processing huge graphs but also the efficient generation of appropriate test instances itself becomes challenging. Hence, I will also discuss two recent results for large-scale graph generation under resource constraints.

4.12 Maintaining connected components for infinite graph streams

Cynthia A. Phillips (Sandia National Labs – Albuquerque, US) and Jonathan Berry (Sandia National Labs – Albuquerque, US)

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We present an algorithm to maintain the connected components of a graph that arrives as an infinite stream of edges. We show how to use distributed parallel processors to avoid file read/writes for a multi-pass streaming algorithm. This then allows us to run a version of the algorithm in a setting where there is no end to the input, as is the case when monitoring event streams. We describe our design decisions/tradeoff choices when trying to manage large storage and provide fast, accurate query response.

4.13 Introduction to Deduplication

Gala Yadgar (Technion – Haifa, IL) and Geoff Kuenning (Harvey Mudd College – Claremont, US)

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Deduplication has become an essential method for reducing storage requirements. This talk covered the fundamentals of how deduplication works and some of the challenges involved in making it efficient.

It turns out that many of the challenges posed by deduplication are theoretical problems, including, chunking, fingerprinting, approximate lookups, and indexing in general. The purpose of this talk was to place these theoretical challenges in their system-level context, thus promoting joint (theory-systems) research on the subject

4.14 Adaptive Bloom and Cuckoo Filters

Shikha Singh (Williams College – Williamstown, US) and Samuel McCauley (Williams College – Williamstown, US)

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Main reference Michael A. Bender, Martin Farach-Colton, Mayank Goswami, Rob Johnson, Samuel McCauley, Shikha Singh: “Bloom Filters, Adaptivity, and the Dictionary Problem”, CoRR, Vol. abs/1711.01616, 2017.
URL <https://arxiv.org/abs/1711.01616>

When a large set is stored remotely, membership queries (that is, checking if an element is present in the set) can be expensive. Instead of querying the remote set each time, usually a small in-memory sketch is consulted first to determine “approximate membership.” Bloom filters are one such widely-used approximate-membership query data structures (AMQs). A Bloom filter maintains a compact probabilistic representation of a set S . On a query for an element in S , it guarantees a correct response of “present” but on a query for an element not in S , it may return “present” with a small false-positive probability ε .

The false-positive probability guarantee ε of most AMQs holds for a single query or a random query workload. In particular, an adversary who discovers a false positive of a Bloom filter can query it repeatedly driving its false-positive rate to 1.

We say an AMQ is adaptive if it guarantees a false-positive probability of ε for every query, regardless of answers to previous queries. In this talk, we will present adaptive variants of popular filters like Bloom filters and Cuckoo filters.

4.15 Achieving Optimal Backlog in Multi-Processor Cup Emptying Games

William Kuszmaul (MIT – Cambridge, US)

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Joint work of Michael A. Bender, Martin Farach-Colton, William Kuszmaul

Main reference Michael A. Bender, Martin Farach-Colton, William Kuszmaul: “Achieving Optimal Backlog in Multi-Processor Cup Games”, CoRR, Vol. abs/1904.02861, 2019.

URL <http://arxiv.org/abs/1904.02861>

Many problems in processor scheduling, deamortization, and buffer management can be modeled as single- and multi-processor cup games.

At the beginning of the single-processor n -cup game, all cups are empty. In each step of the game, a d distributes $1 - \varepsilon$ units of water among the cups, and then a selects a cup and removes up to 1 unit of water from it. The goal of the emptier is to minimize the amount of water in the fullest cup, also known as the d . The greedy algorithm (i.e., empty from the fullest cup) is known to achieve backlog $O(\log n)$, and no deterministic algorithm can do better.

We show that the performance of the greedy algorithm can be exponentially improved with a small amount of randomization: After each step and for any $k \geq \Omega(\log \varepsilon^{-1})$, the emptier achieves backlog at most $O(k)$ with probability at least $1 - O(2^{-2^k})$. We call our algorithm the d because it follows from a smoothed analysis of the (standard) greedy algorithm.

In each step of the p -processor n -cup game, the filler distributes $p(1 - \varepsilon)$ unit of water among the cups, with no cup receiving more than $1 - \delta$ units of water, and then the emptier selects p cups and removes 1 unit of water from each. Proving nontrivial bounds on the backlog for the multi-processor cup game has remained open for decades. We present a simple analysis of the greedy algorithm for the multi-processor cup game, establishing a backlog of $O(\varepsilon^{-1} \log n)$, as long as $\delta > 1/\text{poly}(n)$.

Turning to randomized algorithms, we find that the backlog drops to constant. Specifically, we show that if ε and δ satisfy reasonable constraints, then there exists an algorithm that bounds the backlog after a given step by 3 with probability at least $1 - O(\exp(-\Omega(\varepsilon^2 p)))$.

We prove that our results are asymptotically optimal for constant ε , in the sense that no algorithms can achieve better bounds, up to constant factors in the backlog and in p . Moreover, we prove robustness results, demonstrating that our randomized algorithms continue to behave well even when placed in bad starting states.

4.16 Online Bipartite Matching with Amortized $O(\log^2 n)$ Replacements

Eva Rotenberg (DTU – Copenhagen, DK)

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Joint work of Aaron Bernstein, Jacob Holmm, Eva Rotenberg

In this talk, we introduce the online with recourse model, and give an example: online bipartite matchings. Here, all the vertices on one side of the bipartition are given, and the vertices on the other side arrive one by one with all their incident edges. The goal is to maintain a maximum matching while minimizing the number of changes (replacements) to the matching. With Aaron Bernstein and Jacob Holm, we recently showed that the greedy

algorithm that always takes the shortest augmenting path from the newly inserted vertex (denoted the SAP protocol) uses at most amortized $O(\log^2 n)$ replacements per insertion, where n is the total number of vertices inserted, where the previous best strategy achieved amortized $O(\sqrt{n})$.

4.17 A Practical Approach to Filter Adaptivity

Sam MacCauley (Williams College – Williamstown, US)

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Filters (such as Bloom Filters) are a fundamental data structure that speed up dictionary accesses by storing a compressed representation of a set. Filters are very space efficient, but can make one-sided errors: they may report that a query element is stored in the filter when it is not (a false positive). Recent research has focused on designing methods to dynamically adapt filters. Dynamically adapting to queries reduces the number of false positives in the case that elements are queried over and over again. Such adaptations have the potential to greatly improve performance in many practical use cases.

In this talk I will discuss a new Adaptive Cuckoo Filter with theoretical guarantees on its performance. Specifically, I will show that the new Adaptive Cuckoo Filter is support sensitive—the number of false positives it incurs depends on the number of unique queries performed. This captures the notion of fixing previously-seen false positives, and gives greatly improved performance guarantees on skewed datasets. I will also show lower bounds on the performance of a large family of filters against a worst-case adversary. In particular, I will show that by carefully tailoring the query sequence based on the results of previous queries, the adversary can cause most queries to be a false positive.

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Engineering Reliable Multiagent Systems

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Abstract

This report documents the program and outcomes of Dagstuhl Seminar 19112 “Engineering Reliable Multiagent Systems”. The aim of this seminar was to bring together researchers from various scientific disciplines, such as software engineering of autonomous systems, software verification, and relevant subareas of AI, such as ethics and machine learning, to discuss the emerging topic of the *reliability* of (multi-)agent systems and autonomous systems in particular. The ultimate aim of the seminar was to establish a new research agenda for engineering reliable autonomous systems.

Seminar March 10–15, 2019 – <http://www.dagstuhl.de/19112>

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1 Executive Summary

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The multi-disciplinary workshop on Reliable Multiagent Systems attracted 26 leading international scholars from different research fields, including theoretical computer science, engineering multiagent systems, machine learning and ethics in artificial intelligence.

This seminar can be seen as a first step to establish a new research agenda for engineering reliable autonomous systems: clarifying the problem, its properties, and their implications for solutions.

In order to move towards a true cross-community research agenda for addressing the overarching challenge of engineering reliable autonomous systems we have chosen a slightly different organization than usual: the seminar was comprised of (short) talks (days 1 and 2), and extensive discussions and dedicated group work (days 3-5).

* Michael was still at University of Otago, NZ, when he prepared and attended the seminar.



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Engineering Reliable Multiagent Systems, *Dagstuhl Reports*, Vol. 9, Issue 3, pp. 52–63

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The first two days were opened by two longer (45 minutes each) tutorials, followed by short “teaser talks” (10 + 5 minutes) related to the main topic of *reliable multiagent systems*. Almost all participants gave their view of the topic and highlighted possible contributions. The talks were meant to be less “conference-style”, and more inspiring and thought-provoking.

At the end of the second day, we established four working groups to dive deeper into the following questions:

1. What **(detailed) process** can be used to identify properties that a particular reliable autonomous system or MAS needs to satisfy?
2. How can we engineer reliable autonomous systems that include **learning**?
3. How can we engineer reliable autonomous systems that include **human-machine interaction** (including human-software teamwork)?
4. How can we engineer reliable autonomous systems comprising **multiple agents** (considering teamwork, collaboration, competitiveness, swarms, ...)?

The groups met on Wednesday and Thursday for extensive discussions and reported back intermediate results in plenary sessions. Participants were encouraged to move between groups to enrich them with their expertise. The seminar concluded on Friday morning with a general discussion where all groups presented their results.

We summarise below the key results from the four discussion groups.

Identifying properties: This group discussed the challenge of identifying requirement properties to be verified. It focused in particular on autonomous systems that replace humans in domains that are subject to regulation, since these are most likely to require and benefit from formal verification.

The group articulated the following arguments:

- That autonomous systems be viewed in terms of three layers: a continuous control layer at the bottom, a “regulatory” layer in the middle, and an “ethical” layer at the top. The distinction between the regulatory and ethical layers are that the former deals with the expected normal behaviour (e.g. following the standard rules of the domain), whereas the latter deals with reasoning in situations where the rules need to be broken. For example, breaking a road rule given appropriate justification.
- That for these sorts of systems we can derive verification properties by considering the licencing that is used for humans and how human skills and capabilities are assessed, as well as relevant human capabilities that are assumed, and relevant laws and regulations. The group sketched a high-level process for identifying requirement properties by considering these factors.

The group considered a range of domains, for each one showing how these points would apply.

These ideas were developed into a draft paper during the workshop, and work on this paper has continued subsequently.

Learning in reliable autonomous system: The second group was concerned with methods for engineering reliable autonomous systems that involve learning.

The notion of sufficient reliability varies from domain to domain. For example, in planning of telecommunication networks there are simulators that are trusted to be a good model of reality. Hence the simulation rules could be used for formal verification. In other domains, such as autonomous driving, there is no established trusted model of reality.

Assuming a formal model exists and safety properties can be formulated with temporal logic, there are still remaining challenges: complex models with a large state space and hybrid continuous and discrete behavior can make formal verification intractable,

especially when the learned policies are equally complex. On the other hand learning methods (e.g. reinforcement learning) often “discover” key strategies that do not depend on all details of the system. The group discussed ideas for abstracting/discretizing transition systems based on learned policies.

Human-machine interaction in reliable autonomous systems: The third group focused on how to engineer reliable human-agent interaction.

For that, the first step was to carve out what it means for human-machine communication to be reliable. Values and norms are definitely involved. Drawing from human communication, being truthful, up-to-date with relevant knowledge and honouring commitments are major parts. Another important building block is transparency: is it always clear, which values are in play, what the agent’s purpose is, or what happens with the collected data? The desired result would be reliable outcomes, e.g. through reliably following a protocol, effective communication and getting to a shared understanding. A number of tools and methods to achieve this were identified: stakeholder analysis, plan patterns/activity diagrams, interaction design patterns, appropriate human training, and explainability (i.e. explainable AI) were among the most prominent engineering solutions. This group also concluded their discussions early and distributed themselves among the other groups after that.

Multiple agents in reliable autonomous systems: The fourth group focussed on the challenges of ensuring reliability in systems comprising multiple, possibly heterogeneous, agents interacting in complex ways.

A number of issues emerged from the discussion, including what does it mean for a multiagent system to be “collectively reliable”, and what is the relationship between the reliability or otherwise of individual agents and the coordination mechanisms through which they interact, and the collective reliability of the system of a whole. These issues were broken down into more specific engineering challenges, including which languages should be used to express collective reliability properties (which is closely related to the discussion of the first group) and how such properties should be verified, how to engineer reliable coordination mechanisms when we have only partial access to the states of agents, how to decompose and/or distribute the monitoring and control of individual agents (and associated failure recovery) necessary for reliable coordination, how to do all of the above in systems where agents learn (closely related to the discussion of the second group), and, finally, how to allocate responsibility to individual agents when behaviour is not reliable.

A more detailed research agenda for engineering reliable multiagent systems is in preparation, which we plan to publish as a “position paper” in a journal special issue arising from the work at the workshop.

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3 Overview of Talks

3.1 Exploring properties of reliable multi-agent systems through simulation

Tobias Ahlbrecht (TU Clausthal, DE)

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One specific question for this seminar is aimed at methods to identify properties that a particular reliable multi-agent system should satisfy. We argue, that simulation can be used as a tool for requirements engineering, especially when there is no clear position on where or how to start eliciting these properties. Simulations are then well suited, since they are rather tangible, allow to focus on key elements, while abstracting the more intractable parts of the environment, and can be used early in the process to explore the problem space. Then, mechanisms for explaining agent behaviour could be used (a) to identify the causes of problematic behaviour in the simulation (i.e. where unknown properties still have to be satisfied) and (b) to check whether acceptable simulation runs can be ascribed to previous changes and not only chance.

3.2 Challenges in Self-Driving Cars

Stefano Albrecht (University of Edinburgh, GB)

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Joint work of FiveAI
URL <https://five.ai>

The coming decades will see the creation of autonomous vehicles (AVs) capable of driving without human intervention. Among the expected benefits of AVs are a significant reduction in traffic incidents and congestion while improving cost-efficiency. The UK aims to be a leader in the AV industry and is investing significantly in this area. The Innovate UK-funded project “StreetWise”, led by UK-based company FiveAI, is the largest project to date and aims to demonstrate safe autonomous driving in London by 2020. Supported by a Royal Society Industry Fellowship, I work with FiveAI to develop artificial intelligence technologies for safe autonomous driving. I will present some of the research challenges along the road to AVs: How can an AV predict the behaviour of other vehicles in an uncertain and dynamically changing environment? And how can the AV make robust decisions and drive safely in such environments?

3.3 High level specifications and some associated problems

Natasha Alechina (University of Nottingham, GB)

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This talk attempts to summarise some common themes in the preceding talks, and challenges related to them.

In order to engineer reliable multi-agent systems, we need to be able to either formally verify them, or synthesise provably correct systems. However given the systems are very

complex and there are very many properties that they should satisfy, exhaustively enumerating and verifying the required properties seems impossible. A possible way forward would be specifying properties on a very high abstract level and coming up with some way of decomposing them (a theme from Michael Winikoff's talk, and also from Michael Fisher's talk, cf everyone agrees the system should be "safe", but what exactly is involved in being "safe"?). Examples of high level properties are: high-level descriptions of actions the agent should perform ("make furniture") or the abstract properties such as "do this safely".

With high level actions, automatic decomposition into concrete steps is possible; in fact this is what HTN (Hierarchical Task Networks) planning does.

With high level properties, this is harder. To do this automatically requires a domain theory which supports deriving definitions of high level properties in terms of low level ones. This may be possible if all low level properties are specified in terms of actions; then it is possible to derive a disjunction of low-level properties/actions as in Michael Winikoff's talk, e.g. "do no harm = (not)action 1 or (not)action2 ... or not(action_n)" where actions with "not" in front of them have "harm" in their effects, and actions without "not" prevent harm somehow. The situation is harder if there is no domain theory, no action theory, or action theory is undecidable (like movement in 3D space). Then the possible way forward may be to produce an approximation/abstraction of the corresponding transition system (discrete actions and discrete time, abstracted state descriptions, state test for "unsafe"); generate states as needed; use run-time monitoring with bounded lookahead (a bit like in Stefano Albrecht's talk).

3.4 Engineered Adaptivity through Clonal Plasticity

Rem Collier (University College Dublin, IE)

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This talk explores the use of an adaptation strategy, known as clonal plasticity, to inject run-time adaptation mechanisms into Agent Oriented Programming languages. The strategy is formed through the combination of two processes present in plants: Clonal Reproduction and Phenotypic Plasticity. The former process relates to the fact that daughter plants are genetically identical to parent plants, hence the term clone. Conversely, the latter process refers to the ability of an organism to vary its structure (height of stem, width of leaves, etc.) or behaviour (connect to its clonal sibling or disconnect) according to environmental influences. The resulting strategy is distinguished from other evolutionary mechanisms, such as genetic algorithms, in that the genome of the organism is not modified at all.

In the talk, we explore three ways in which Clonal Plasticity could be integrated with the AgentSpeak(L) language: parameter-based adaptation, statement-based adaptation and rule-based adaptation. The former technique refers to an approach in which adaptation arises through the modification of various well-defined parameters within the program. Statement-based adaptation refers to an approach where adaptation operators are embedded within the core planning language. This allows for the specification of variant plans. Adaptation arises through the selection of a specific variant of that plan. Finally, rule-based adaptation refers to the use of multiple rules to capture variant plans that could be used to achieve a given goal. Rule order, which is commonly used to select which of a set of applicable plans should be selected is then adapted, enabling rules that were previously unreachable to be selected.

3.5 What can go wrong when running AgentSpeak?

Niklas Fiekas (TU Clausthal, DE)

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Classical programming languages come with tools to catch programming mistakes as early as possible, at compile time, and strongly typed versions of popular languages keep appearing (e.g., TypeScript, typing for Python).

When designing agent programming languages, we should consider static analysis early on.

In the talk we look at common mistakes in Jason-style AgentSpeak programs, if we can catch them at compile time, or which design elements of the Jason programming language make this difficult.

3.6 Verification of Autonomous Systems Software

Michael Fisher (University of Liverpool, GB)

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Joint work of Louise Dennis, Michael Fisher

An overview of issues in the verification of software involved in autonomous systems.

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3.7 Reliable Supportive Agents – What do Agents need to know about the user?

Malte S. Kließ (TU Delft, NL)

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An agent system intended to provide support for a user’s daily routines should be informed about the user’s needs in order to be considered reliable – in the sense that the agent delivers support in the right way at the right time.

This implies that the user needs to trust the system to act according to the user’s norms and values. Thus the system needs the capability of handling and reasoning about norms and values.

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3.8 Synthesising Reliable Multi-Agent Programs

Brian Logan (University of Nottingham, GB)

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Joint work of Giuseppe De Giacomo, Paolo Felli, Fabio Patrizi, Sebastian Sardina

I present some work in progress on the synthesis of controllers that implement the abstract actions in a high-level multi-agent program in terms of low-level programs performable by individual agents. In contrast to previous work, we consider this problem in a first-order setting, allowing us to synthesise controllers for data-aware multi-agent systems and programs. I sketch a controller synthesis framework based on Situation Calculus action theories and ConGolog programs in which states have a first-order representation, and briefly describe techniques for the synthesis of controllers for the special case of bounded action theories.

3.9 What can we prove about Ethical Reasoning Systems?

Louise Dennis

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Joint work of Louise Dennis, Michael Fisher, Paul Bremner, Alan Winfield, Marija Slavkovik, Martin Bentzen, Felix Lindner, Matt Webster

Prompted by a question in the seminar proposal I discussed work on the verification using model-checking of ethical reasoning and specifically the properties that were validated and tentatively assigned these to a taxonomy. Some properties sought to check the implementation of the relevant ethical theory and generally involved checking the property “the least worst outcome according to the theory was selected” on highly abstract models. Models then became more concrete and also more specific, in some cases the property verified was still of

the form “least worst...” but in other cases specific desired outcomes were checked (e.g., “in the event of a fire, evacuation will be performed”) and served as a kind of ‘sanity check’ that the encoding of the ethics aligned with user values.

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3.10 Threat-oriented engineering of autonomous systems

Viviana Mascardi (University of Genova, IT)

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A system is reliable if it can be relied on to meet its requirements consistently. Nevertheless, a system may be considered reliable even in situations where it does not meet its requirements, provided there is a convincing/acceptable explanation of why the requirement was not met. The explanation might be related with the trade-off of achieving some different requirements, including the “always present” requirement of keeping users (and people in general) safe. The explanation could be better understood if the notion of threat to a goal was explicitly associated with the goal. The idea of making “threats-to-goal” explicit in the engineering process is discussed in this presentation, as well as its connections with explainability.

3.11 Programming Reliable Agent-Based Systems in the Software 2.0 Era (?)

Alessandro Ricci (Università di Bologna, IT)

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Recent advances and results in AI are paving the way to a “Software 2.0 era”, where a software system or a part of it is not hand-coded by programmers but learnt by exploiting e.g. machine learning techniques. In the case of BDI agent-oriented programming, this accounts for introducing learning in the loop of agent development, so that e.g. a part of the plans of an agent are programmed and a part is learnt by the agent itself, through e.g. reinforcement learning techniques. In that perspective, a main question interesting for the Dagstuhl seminar is about reliability, how to engineer reliable agents and MAS that integrate machine learning at that level.

3.12 RoboCup Rescue Simulation and Reliable Multi-Agent Systems

Holger Schlingloff (HU Berlin, DE)

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In this talk, we propose the RoboCup Junior Rescue Simulation (formerly called CoSpace) Challenge as a case study for the design of reliable multi-agent systems. In the game, two simulated robots compete in collecting objects and depositing them in a dedicated safety zone. Thus, the setting is related to real scenarios as in cleaning robots or driverless automated transport robots in industrial production. In the competition, which is targeted towards 12-16 year old high school students, the participants have to design rules for the robots which control their moves. Depending on the available information (map, location of objects, own position, position of the opponent) different variants of the game can be defined. Thus, it is a well-suited example for the engineering of reliable MAS: The focus is on logical, not mechanical challenges; it is simple enough to be approached by current technologies; it can be adapted to different software engineering aspects; and it is of industrial relevance. Specifically, we are asking for techniques to verify the control program with respect to the objectives and rules of the game. An even more challenging question is asking for synthesis techniques to generate the control program automatically from the given rules and objectives.

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3.13 Multi-reward Learning for Reliable Long-term Autonomy

Kagan Tumer (Oregon State University, US)

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Many real world problems are too complex to allow the agent-environment interaction to be captured by a well-formulated, single reward function. Using multiple rewards to learn different aspects of the problem, potentially across different time scales, offers a promising solution. But this approach introduces a new problem: how does an agent determine which reward is relevant in which state and at what time? Put another way, how does an agent know “what matters when?”

This talk addresses how to navigate multiple rewards to enable learning in complex, long-term tasks. In addition, this paradigm naturally extends to multiagent settings and enables the injection of concepts such as a reliability into the system.

3.14 Towards Deriving Verification Properties

Michael Winikoff (Victoria University of Wellington, NZ)

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Main reference Michael Winikoff: “Towards Deriving Verification Properties”, CoRR, Vol. abs/1903.04159, 2019.

URL <https://arxiv.org/abs/1903.04159>

Formal software verification uses mathematical techniques to establish that software has certain properties. For example, that the behaviour of a software system satisfies certain logically-specified properties. Formal methods have a long history, but a recurring assumption is that the properties to be verified are known, or provided as part of the requirements elicitation process. This working note considers the question: where do the verification properties come from? It proposes a process for systematically identifying verification properties.

3.15 Reliable Alignment of Goals and Norms

Neil Yorke-Smith (TU Delft, NL)

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Joint work of Pankaj R. Telang, Munindar P. Singh, Neil Yorke-Smith

Main reference Pankaj R. Telang, Munindar P. Singh, Neil Yorke-Smith: “A Coupled Operational Semantics for Goals and Commitments”, J. Artif. Intell. Res., Vol. 65, pp. 31–85, 2019.

URL <https://doi.org/10.1613/jair.1.11494>

Commitments capture how an agent relates to another agent, whereas goals describe states of the world that an agent is motivated to bring about. Commitments are elements of the social state of a set of agents whereas goals are elements of the private states of individual agents. It makes intuitive sense that goals and commitments are understood as being complementary to each other. More importantly, an agent’s goals and commitments ought to be coherent, in the sense that an agent’s goals would lead it to adopt or modify relevant commitments and an agent’s commitments would lead it to adopt or modify relevant goals. However, despite the intuitive naturalness of the above connections, they have not been adequately studied in a formal framework. This article provides a combined operational semantics for goals and commitments by relating their respective life cycles as a basis for how these concepts (1) cohere for an individual agent and (2) engender cooperation among agents. Our semantics yields important desirable properties of convergence of the configurations of cooperating agents, thereby delineating some theoretically well-founded yet practical modes of cooperation in a multiagent system.

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Computational Complexity of Discrete Problems

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Abstract

The following report archives the presentations and activities of the March 2019 Dagstuhl Seminar 19121 “Computational Complexity of Discrete Problems”. Section 1 summarizes the topics and some specific results offered in selected talks during the course of the week. Section 2 provides a table of contents, listing each of the talks given in alphabetical order. Section 3 contains the abstracts, indicating both the main reference and other relevant sources (where applicable) to allow the reader to investigate the topics further.

Seminar March 17–22, 2019 – <http://www.dagstuhl.de/19121>

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Edited in cooperation with Matthew J. Katzman

1 Executive Summary

Anna Gál (*University of Texas – Austin, US*)

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Computational complexity theory is the study of computation under bounded resources, and the tradeoffs thereof offered by specific problems and classes of problems in various computational models. Such resources include time and space for classical computation, randomness, non-determinism, and oracles for more advanced uniform machines, size/advice for circuits/non-uniform computation, interaction for communication protocols, length and depth for proof complexity, and much more. The goals of work in this field are not only to discover and improve these tradeoffs, but ideally to find tight lower bounds to match the solutions that have been found, and use such results in one of the models to inform results in the others. Despite decades of work on these problems, the answers to many foundational questions (such as **P** vs **NP**, **P** vs **BPP**, **NP** vs **co-NP**) still remain out of reach.

For the 2019 instalment of the seminar series *Computational Complexity of Discrete Problems* – which evolved out of the seminar series *Complexity of Boolean Functions* that dates back to the founding of Dagstuhl – Anna Gál, Oded Regev, Rahul Santhanam, and Till Tantau invited 40 participants to Dagstuhl to work towards discovering new results in the field. The seminar started with the assembly of a large “graph of interests” that allowed



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Computational Complexity of Discrete Problems, *Dagstuhl Reports*, Vol. 9, Issue 3, pp. 64–82

Editors: Anna Gál, Rahul Santhanam, and Till Tantau



Dagstuhl Reports

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the participants both to present their own research interests and to see how these align with the other present researchers. The bulk of the research work was then done in the form of, on the one hand, talks in the morning and late afternoon and, on the other hand, break-out sessions and small discussions in the afternoon by smaller groups.

A distinguishing feature of the seminar talks were the lively discussions during and after the talk: given the often highly abstract and specialized topics presented by the experts in the field, lively discussions are by no means a given and they proved to be both rewarding and helpful for all participants. In the informal afternoon sessions, smaller groups of researchers had ample time to tackle the open problems of the field; with some discussions still going on after midnight. Two events – the traditional Wednesday hike and the traditional wine-and-cheese party on Thursday – allowed everyone well-earned breaks from doing research on computational complexity.

The range of topics covered by the participants during the seminar was broad and included derandomization, lower bounds for specific problems, communication complexity, complexity classes, graph algorithms, learning theory, coding theory, and proof complexity. Specific selected results presented throughout include:

- A proof that the Log-Approximate-Rank Conjecture is false, yielding the first exponential gap between the logarithm of the approximate rank and randomized communication complexity for total functions.
- An oracle separation of **BQP** and the polynomial hierarchy, showing a strong converse to the Bennett et al. oracle relative to which **BQP** cannot solve **NP**-complete problems in sub-exponential time.
- Improved lower bounds for the Minimum Circuit Size Problem, including
 - $\text{MCSP} \notin \text{AC}^0[\text{p}]$,
 - MCSP requires $N^{3-o(1)}$ -size de Morgan formulas,
 - MCSP requires $N^{2-o(1)}$ -size general formulas,
 - MCSP requires $2^{\Omega(N^{1/d+2.01})}$ -size depth- d AC^0 circuits,
 where the first result is achieved by showing MCSP can solve the coin problem and the others using properties of local pseudorandom generators.

Open problems were posed by Amit Chakrabarty, Alexander Golovnev, Or Meir, and Omri Weinstein.

The organizers, Anna Gál, Oded Regev, Rahul Santhanam, and Till Tantau, would like to thank all participants at this point for the many contributions they made, but we would also like to especially thank the Dagstuhl staff for doing – as always – an excellent job and helping with organizational matters and with making everyone feel welcome.

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3 Overview of Talks

3.1 Planarity, Exclusivity, and Unambiguity

Eric Allender (Rutgers University – Piscataway, US)

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Joint work of Eric Allender, Archit Chauhan, Samir Datta, Anish Mukherjee

Main reference Eric Allender, Archit Chauhan, Samir Datta, Anish Mukherjee: “Planarity, Exclusivity, and Unambiguity”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 26, p. 39, 2019.

URL <https://eccc.weizmann.ac.il/report/2019/039>

We provide new upper bounds on the complexity of the s - t -connectivity problem in planar graphs, thereby providing additional evidence that this problem is not complete for **NL**. This also yields a new upper bound on the complexity of computing edit distance. Building on these techniques, we provide new upper bounds on the complexity of several other computational problems on planar graphs. All of these problems are shown to solvable in logarithmic time on a concurrent-read exclusive-write (CREW) PRAM. The new upper bounds are provided by making use of a known characterization of CREW algorithms in terms of “unambiguous” **AC**¹ circuits. This seems to be the first occasion where this characterization has been used in order to provide new upper bounds on natural problems.

Joint work with Archit Chauhan, Samir Datta, and Anish Mukherjee.

3.2 Time-Space Tradeoffs for Learning Finite Functions from Random Evaluations, with Applications to Polynomials

Paul Beame (University of Washington – Seattle, US)

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Joint work of Paul Beame, Shayan Oveis Gharan, Xin Yang

Main reference Paul Beame, Shayan Oveis Gharan, Xin Yang: “Time-Space Tradeoffs for Learning Finite Functions from Random Evaluations, with Applications to Polynomials”, in Proc. of the Conference On Learning Theory, COLT 2018, Stockholm, Sweden, 6-9 July 2018., pp. 843–856, 2018.

URL <http://proceedings.mlr.press/v75/beame18a.html>

We develop an extension of recent analytic methods for obtaining time-space tradeoff lower bounds for problems of learning Boolean functions from uniformly random labelled examples. With our methods we can obtain bounds for learning arbitrary concept classes of finite functions from random evaluations even when the sample space of random inputs can be significantly smaller than the concept class of functions and the function values can be from an arbitrary finite set.

To obtain our results, we reduce the time-space complexity of learning from random evaluations to the question of how much the corresponding evaluation matrix amplifies the 2-norms of ‘almost uniform’ probability distributions. To analyze the latter, we formulate it as a semidefinite program, and analyze its dual. (Similar results to ours using related but somewhat different techniques were independently shown by Garg, Raz, and Tal.)

As applications we show that any algorithm that learns an n -variate polynomial function of degree at most d over any prime field F_p with probability $p^{-O(n)}$, or with prediction advantage $p^{-O(n)}$ over random guessing, given evaluations on randomly chosen inputs either requires space $\Omega((nN/d) \log p)$ or time $p^{\Omega(n/d)}$ where $N = (n/d)^{\Theta(d)}$ is the dimension of the space of such polynomials. These bounds, which are based on new bounds on the bias of

polynomials over F_p , are asymptotically optimal for polynomials of arbitrary constant degree and constant p since they match the tradeoffs achieved by natural learning algorithms for the problems.

3.3 Randomness and intractability in Kolmogorov complexity

Igor Carboni Oliveira (University of Oxford, GB)

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Main reference Igor Carboni Oliveira: “Randomness and Intractability in Kolmogorov Complexity”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 26, p. 64, 2019.

URL <https://eccc.weizmann.ac.il/report/2019/064>

We introduce randomized time-bounded Kolmogorov complexity (rKt), a natural extension of Levin’s notion of Kolmogorov complexity. A string w of low rKt complexity can be decompressed from a short representation via a time-bounded algorithm that outputs w with high probability.

This complexity measure gives rise to a decision problem over strings: **MrKtP** (The Minimum rKt Problem). We explore ideas from pseudorandomness to prove that **MrKtP** and its variants cannot be solved in randomized quasi-polynomial time. This exhibits a natural string compression problem that is provably intractable, even for randomized computations. Our techniques also imply that there is no $n^{1-\epsilon}$ -approximate algorithm for **MrKtP** running in randomized quasi-polynomial time.

Complementing this lower bound, we observe connections between rKt, the power of randomness in computing, and circuit complexity. In particular, we present the first hardness magnification theorem for a natural problem that is unconditionally hard against a strong model of computation.

3.4 Quantum Exact Learning of k -sparse functions and improved Chang’s Lemma for sparse Boolean functions

Sourav Chakraborty (Indian Statistical Institute – Kolkata, IN)

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Joint work of Srinivasan Arunachalam, Sourav Chakraborty, Troy Lee, Ronald de Wolf

Main reference Srinivasan Arunachalam, Sourav Chakraborty, Troy Lee, Ronald de Wolf: “Two new results about quantum exact learning”, CoRR, Vol. abs/1810.00481, 2018.

URL <https://arxiv.org/abs/1810.00481>

We show how to exactly learn a k -Fourier-sparse n -bit Boolean function from $O(k^{1.5}(\log k)^2)$ uniform quantum samples from that function. This improves over the bound of $\Theta(kn)$ uniformly random classical examples [1]. Our main tool is an improvement of Chang’s lemma for sparse Boolean functions. This result appears in paper “Two new results about quantum exact learning” written jointly with Srinivasan Arunachalam, Troy Lee, Manaswi Paraashar and Ronald de Wolf.

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3.5 The Log-Approximate-Rank Conjecture is False

Arkadev Chattopadhyay (TIFR – Mumbai, IN)

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Joint work of Arkadev Chattopadhyay, Nikhil S. Mande, Suhail Sherif

Main reference Arkadev Chattopadhyay, Nikhil S. Mande, Suhail Sherif: “The Log-Approximate-Rank Conjecture is False”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 25, p. 176, 2018.

URL <https://eccc.weizmann.ac.il/report/2018/176>

We construct a simple and total XOR function F on $2n$ variables that has only $O(\sqrt{n})$ spectral norm, $O(n^2)$ approximate rank and $n^{O(\log n)}$ approximate nonnegative rank. We show it has polynomially large randomized bounded-error communication complexity of $\Omega(\sqrt{n})$. This yields the first exponential gap between the logarithm of the approximate rank and randomized communication complexity for total functions. Thus F witnesses a refutation of the Log-Approximate-Rank Conjecture (LARC) which was posed by Lee and Shraibman [5] as a very natural analogue for randomized communication of the still unresolved Log-Rank Conjecture for deterministic communication. The best known previous gap for any total function between the two measures is a recent 4th-power separation by Göös, Jayram, Pitassi and Watson [1].

Additionally, our function F refutes Grolmusz’s Conjecture [2] and a variant of the Log-Approximate-Nonnegative-Rank Conjecture, suggested recently by Kol, Moran, Shpilka and Yehudayoff [3], both of which are implied by the LARC. The complement of F has exponentially large approximate nonnegative rank. This answers a question of Lee [4] and Kol et al. [3], showing that approximate nonnegative rank can be exponentially larger than approximate rank. The function F also falsifies a conjecture about parity measures of Boolean functions made by Tsang, Wong, Xie and Zhang [6]. The latter conjecture implied the Log-Rank Conjecture for XOR functions. Our result further implies that at least one of the following statements is true: (a) The Quantum-Log-Rank Conjecture is false; (b) The total function F exponentially separates quantum communication complexity from its classical randomized counterpart.

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3.6 A Route Towards Advances on the BPL versus L problem

Gil Cohen (Princeton University, US)

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Joint work of Mark Braverman, Gil Cohen, Ankit Garg

The **BPL** vs. **L** problem is a fundamental question in complexity theory. The best known result by Saks and Zhou from the late 90s puts **BPL** in $\mathbf{L}^{3/2}$ where the common belief is that **BPL** = **L**. In this talk, I'll present a potential program towards improving the Saks-Zhou result to $\mathbf{BPL} \subseteq \mathbf{L}^c$ for some constant $c < 3/2$. One step of this program was implemented in a joint work with Braverman and Garg. The missing step is related to a beautiful paper by Raz and Reingold.

3.7 Identifying low-dimensional functions in high-dimensional spaces

Anindya De (University of Pennsylvania – Philadelphia, US)

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Joint work of Anindya De, Elchanan Mossel, Joe Neeman

Main reference Anindya De, Elchanan Mossel, Joe Neeman: “Is your data low-dimensional?”, CoRR, Vol. abs/1806.10057, 2018.

URL <https://arxiv.org/abs/1806.10057>

Motivated by the problem of feature selection in machine learning, the problem of testing juntas, i.e., checking if a Boolean function on the n -dimensional hypercube only depends on $k \ll n$ coordinates, has attracted a lot of attention in theoretical computer science. However, in many settings, there is no obvious choice of a basis and a more meaningful question is to ask if a function only depends a k -dimensional subspace. We show that while such “linear juntas” are not testable with any finite number of queries, assuming an upper bound of s on their surface area, such functions can be tested with $\text{poly}(k, s)$ queries, i.e., independent of the ambient dimension n . We also show a $\text{poly}(s)$ lower bound on the query complexity of any non-adaptive tester for linear-juntas showing that the dependence on s is tight up to polynomial factors. As a consequence of our upper bound, we show that intersections of a constant number of halfspaces (as well as several related concepts) are testable with constant query complexity.

3.8 Graph Communication Protocols

Lukáš Folwarczný (Charles University – Prague, CZ)

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Graph communication protocols are a generalization of classical communication protocols to the case when the underlying graph is a directed acyclic graph. Motivated by potential applications in proof complexity, we study variants of graph communication protocols and relations between them.

Our results establish the following hierarchy: Protocols with disjointness are at least as strong as protocols with equality and protocols with equality are at least as strong as

protocols with inequality. Furthermore, we establish that protocols with a conjunction of two inequalities have the same strength as protocols with equality. Lower bounds for protocols with inequality are known. Obtaining lower bounds for protocols higher in the hierarchy would directly lead to applications in proof complexity. In particular, lower bounds for resolution with parities (R(LIN)) and DNF-resolution (DNF-R) would be obtained this way.

3.9 Static Data Structure Lower Bounds Imply Rigidity

Alexander Golovnev (Harvard University – Cambridge, US)

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Joint work of Zeev Dvir, Alexander Golovnev, Omri Weinstein

Main reference Zeev Dvir, Alexander Golovnev, Omri Weinstein: “Static Data Structure Lower Bounds Imply Rigidity”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 25, p. 188, 2018.

URL <https://eccc.weizmann.ac.il/report/2018/188>

We show that static data structure lower bounds in the group (linear) model imply semi-explicit lower bounds on matrix rigidity. In particular, we prove that an explicit lower bound of $t \geq \omega(\log^2 n)$ on the cell-probe complexity of linear data structures in the group model, even against arbitrarily small linear space ($s = (1 + \epsilon)n$), would already imply a semi-explicit ($\mathbf{P}^{\mathbf{NP}}$) construction of rigid matrices with significantly better parameters than the current state of art [1]. Our results further assert that polynomial ($t \geq n^\delta$) data structure lower bounds against near-optimal space, would imply super-linear circuit lower bounds for log-depth linear circuits (a four-decade open question). In the succinct space regime ($s = n + o(n)$), we show that any improvement on current cell-probe lower bounds in the linear model would also imply new rigidity bounds. Our results rely on a new connection between the “inner” and “outer” dimensions of a matrix [2], and on a new reduction from worst-case to average-case rigidity, which is of independent interest.

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3.10 Recent Applications of High Dimensional Expanders to Coding

Prahladh Harsha (TIFR – Mumbai, IN)

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Expander graphs, over the last few decades, have played a pervasive role in almost all areas of theoretical computer science. Recently, various high-dimensional analogues of these objects have been studied in mathematics and even more recently, there have been some surprising applications in computer science, especially in the area of coding theory.

In this talk, we’ll explore these high-dimensional expanders from a spectral viewpoint and give an alternate characterization in terms of random walks. We will then see an application of high-dimensional expanders towards efficient list decoding.

3.11 New Circuit Lower Bounds for Minimum Circuit Size Problem

Valentine Kabanets (*Simon Fraser University – Burnaby, CA*)

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- Joint work of** Mahdi Cheraghchi, Alexander Golovnev, Rahul Ilango, Russell Impagliazzo, Valentine Kabanets, Antonina Kolokolova, Avishay Tal, Zhenjian Lu, Dimitrios Myrisiotis
- Main reference** Alexander Golovnev, Rahul Ilango, Russell Impagliazzo, Valentine Kabanets, Antonina Kolokolova, Avishay Tal: “ $\text{AC}^0[\text{p}]$ Lower Bounds Against MCSP via the Coin Problem”, in Proc. of the 46th International Colloquium on Automata, Languages, and Programming, ICALP 2019, July 9-12, 2019, Patras, Greece., pp. 66:1–66:15, 2019.
URL <http://dx.doi.org/10.4230/LIPIcs.ICALP.2019.66>
- Main reference** Mahdi Cheraghchi, Valentine Kabanets, Zhenjian Lu, Dimitrios Myrisiotis: “Circuit Lower Bounds for MCSP from Local Pseudorandom Generators”, in Proc. of the 46th International Colloquium on Automata, Languages, and Programming, ICALP 2019, July 9-12, 2019, Patras, Greece., pp. 39:1–39:14, 2019.
URL <http://dx.doi.org/10.4230/LIPIcs.ICALP.2019.39>

Minimum Circuit Size Problem (MCSP) asks if a given truth table of an n -variate boolean function is computable by a boolean circuit of size at most s , for a given $s > 0$. While MCSP is believed to be outside of $\mathbf{P}$, it’s not known if MCSP is $\mathbf{NP}$ -hard.

It is natural to ask for circuit lower bounds for MCSP against restricted circuit models. In this talk, I will show some new circuit lower bounds for MCSP against constant-depth circuits ($\mathbf{AC}^0$ and $\mathbf{AC}^0[\text{p}]$) and de Morgan formulas, essentially matching the known state-of-the-art lower bounds for the corresponding circuit models.

This talk is based on two joint works with Alexander Golovnev, Rahul Ilango, Russell Impagliazzo, Antonina Kolokolova, and Avishay Tal, as well as Mahdi Cheraghchi, Zhenjian Lu, and Dimitrios Myrisiotis.

3.12 An Optimal Space Lower Bound for Approximating MAX-CUT

Michael Kapralov (*EPFL – Lausanne, CH*)

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- Joint work of** Michael Kapralov, Dmitry Krachun
- Main reference** Michael Kapralov, Dmitry Krachun: “An Optimal Space Lower Bound for Approximating MAX-CUT”, CoRR, Vol. abs/1811.10879, 2018.
URL <https://arxiv.org/abs/1811.10879>

We consider the problem of estimating the value of MAX-CUT in a graph in the streaming model of computation. At one extreme, there is a trivial 2-approximation for this problem that uses only $O(\log n)$ space, namely, count the number of edges and output half of this value as the estimate for the size of the MAX-CUT. On the other extreme, for any fixed $\epsilon > 0$, if one allows $\tilde{O}(n)$ space, a $(1 + \epsilon)$ -approximate solution to the MAX-CUT value can be obtained by storing an $\tilde{O}(n)$ -size sparsifier that essentially preserves MAX-CUT value.

Our main result is that any (randomized) single pass streaming algorithm that breaks the 2-approximation barrier requires $\Omega(n)$ -space, thus resolving the space complexity of any non-trivial approximations of the MAX-CUT value to within polylogarithmic factors in the single pass streaming model. We achieve the result by presenting a tight analysis of the Implicit Hidden Partition Problem introduced by Kapralov et al. [1] for an arbitrarily large number of players. In this problem a number of players receive random matchings of $\Omega(n)$ size together with random bits on the edges, and their task is to determine whether the bits correspond to parities of some hidden bipartition, or are just uniformly random.

Unlike all previous Fourier analytic communication lower bounds, our analysis does not directly use bounds on the ℓ_2 norm of Fourier coefficients of a typical message at any given weight level that follow from hypercontractivity. Instead, we use the fact that graphs received by players are sparse (matchings) to obtain strong upper bounds on the ℓ_1 norm of the Fourier coefficients of the messages of individual players using their special structure, and then argue, using the convolution theorem, that similar strong bounds on the ℓ_1 norm are essentially preserved (up to an exponential loss in the number of players) once messages of different players are combined. We feel that our main technique is likely of independent interest.

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3.13 Improved soundness for proving proximity to Reed-Solomon codes

Swastik Kopparty (Rutgers University – Piscataway, US)

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Joint work of Eli Ben-Sasson, Lior Goldberg, Swastik Kopparty, Shubhangi Saraf

Main reference Eli Ben-Sasson, Lior Goldberg, Swastik Kopparty, Shubhangi Saraf: “DEEP-FRI: Sampling outside the box improves soundness”, CoRR, Vol. abs/1903.12243, 2019.

URL <https://arxiv.org/abs/1903.12243>

Given oracle access to some string w , we would like to verify (using few queries, with the aid of an interactive prover), that w is a codeword of the Reed-Solomon code. An ingenious FFT-based protocol called FRI (Fast Reed-Solomon IOPP) was recently given by [1]. Follow-up work of [2] showed that FRI rejects any w that is very far from the Reed-Solomon code with quite large probability.

We give an improved analysis for the soundness of FRI, and show that this is tight.

We then give a new protocol called *DEEP-FRI* which has both (a) a better name, and (b) further improved (and possibly optimal) soundness for this problem.

The list-decodability of Reed-Solomon codes plays an important role in these results.

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3.14 Stronger Lower Bounds for Online ORAM

Michal Koucký (Charles University – Prague, CZ)

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Joint work of Pavel Hubáček, Michal Koucký, Karel Král, Veronika Slívová

Main reference Pavel Hubáček, Michal Koucký, Karel Král, Veronika Slívová: “Stronger Lower Bounds for Online ORAM”, CoRR, Vol. abs/1903.03385, 2019.

URL <http://arxiv.org/abs/1903.03385>

Oblivious RAM (ORAM), introduced in the context of software protection by Goldreich and Ostrovsky [1], aims at obfuscating the memory access pattern induced by a RAM computation. Ideally, the memory access pattern of an ORAM should be independent of the data being processed. Since the work of Goldreich and Ostrovsky, it was believed that there is an inherent $\Omega(\log n)$ bandwidth overhead in any ORAM working with memory of size n . Larsen and Nielsen [2] were the first to give a general $\Omega(\log n)$ lower bound for any *online* ORAM, i.e., an ORAM that must process its inputs in an online manner.

In this work, we revisit the lower bound of Larsen and Nielsen, which was proved under the assumption that the adversarial server knows exactly which server accesses correspond to which input operation. We give an $\Omega(\log n)$ lower bound for the bandwidth overhead of any online ORAM even when the adversary has no access to this information. For many known constructions of ORAM this information is provided implicitly as each input operation induces an access sequence of roughly the same length. Thus, they are subject to the lower bound of Larsen and Nielsen. Our results rule out a broader class of constructions and specifically, they imply that obfuscating the boundaries between the input operations does not help in building a more efficient ORAM.

As our main technical contribution and to handle the lack of structure, we study the properties of access graphs induced naturally by the memory access pattern of an ORAM computation. We identify a particular graph property that can be efficiently tested and that all access graphs of ORAM computation must satisfy with high probability. This property is reminiscent of the Larsen-Nielsen property but it is substantially less structured; that is, it is more generic.

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3.15 Improving OBDD-Attacks and Related Complexity-Theoretic Problems

Matthias Krause (Universität Mannheim, DE)

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Joint work of Matthias Hamann, Matthias Krause, Alex Moch

We present and discuss new algorithmic ideas for improving OBDD-attacks against stream ciphers. Standard OBDD-attacks compute the secret initial state behind a given piece z of keystream by generating a sequence $Q_1, Q_2, \dots, Q_s$ of ordered binary decision diagrams

(OBDDs), where Q_1 is small, the intermediate OBDDs become not larger than $2^{(1-a)/(1+a)n}$, and Q_s contains the secret initial state behind z as only satisfying assignment. Here, n denotes the inner state length of the cipher, and $a \in (0, 1)$ the compression rate, a constant defined by the cipher. The motivation of our research is to circumvent the bottleneck of standard OBDDs attack consisting in the huge storage of $2^{(1-a)/(1+a)n}$ needed for some of the intermediate OBDDs.

For reaching this goal we propose the following strategy

1. Generate in parallel two OBDDs P and Q of moderate size such that P and Q have only a few common satisfying assignments.
2. Compute these satisfying assignments, including the secret inner state, by a new breadth-first-search based algorithm.

We show at hand of experiments that this approach improves standard OBDD-attacks drastically. For understanding the theory behind this phenomenon we study in a first step the complexity of the Bounded Synthesis Problem (given two OBDDs P and Q for which it is known that they have only one common satisfying assignment, compute this assignment). The question to discuss here is if there are algorithms for the Bounded Synthesis Problem which are asymptotically better than synthesizing and minimizing $P \wedge Q$.

3.16 Building strategies into QBF proofs

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Joint work of Olaf Beyersdorff, Joshua Blinkhorn, Meena Mahajan

Main reference Olaf Beyersdorff, Joshua Blinkhorn, Meena Mahajan: “Building Strategies into QBF Proofs”, in Proc. of the 36th International Symposium on Theoretical Aspects of Computer Science, STACS 2019, March 13–16, 2019, Berlin, Germany, LIPIcs, Vol. 126, pp. 14:1–14:18, Schloss Dagstuhl – Leibniz-Zentrum fuer Informatik, 2019.

URL <http://dx.doi.org/10.4230/LIPIcs.STACS.2019.14>

Quantified Boolean Formulas (QBF) are a natural extension of the SAT problem, with more sophisticated semantics: functions witnessing the truth of a QBF can be interpreted as strategies in a two-player game. A lot has been written regarding the extraction of strategies from QBF proofs, in various proof systems. Here we devise a new system – Merge Resolution – in which strategies are built explicitly within the proofs themselves. We investigate some advantages of Merge Resolution over existing systems; in particular, we find that it lifts naturally to DQBF, a further extension of QBF.

Joint work with Olaf Beyersdorff and Joshua Blinkhorn. STACS 2019.

3.17 Exponential Lower Bounds for Weak Pigeonhole Principle and Perfect Matching Formulas over Sparse Graphs

Jakob Nordström (KTH Royal Institute of Technology – Stockholm, SE)

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Joint work of Susanna F. de Rezende, Jakob Nordström, Kilian Risse, Dmitry Sokolov

We show exponential lower bounds on resolution proof length for pigeonhole principle (PHP) formulas and perfect matching formulas over highly unbalanced, sparse expander graphs, thus answering the challenge to establish strong lower bounds in the regime between balanced constant-degree expanders as in [1] and highly unbalanced, dense graphs as in [2], [3], and [4]. We obtain our results by revisiting Razborov’s pseudo-width method for PHP formulas over dense graphs and extending it to sparse graphs. This further demonstrates the power of the pseudo-width method, and we believe it could potentially be useful for attacking also other longstanding open problems for resolution and other proof systems.

This is joint work with Susanna F. de Rezende, Kilian Risse, and Dmitry Sokolov.

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3.18 Extractors for small zero-fixing sources

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Joint work of Pavel Pudlák, Vojtech Rödl

Main reference Pavel Pudlák, Vojtech Rödl: “Extractors for small zero-fixing sources”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 26, p. 58, 2019.

URL <https://eccc.weizmann.ac.il/report/2019/058>

A random variable X is an (n, k) -zero-fixing source if for some subset $V \subset [n]$, X is the uniform distribution on the strings $\{0, 1\}^n$ that are zero on every coordinate outside of V . An ϵ -extractor for (n, k) -zero-fixing sources is a mapping $F : \{0, 1\}^n \rightarrow \{0, 1\}^m$, for some m , such that $F(X)$ is ϵ -close in statistical distance to the uniform distribution on $\{0, 1\}^m$ for every (n, k) -zero-fixing source X . Zero-fixing sources were introduced by Cohen and Shinkar in [1] in connection with the previously studied extractors for bit-fixing sources. They constructed, for every $\mu > 0$, an efficiently computable extractor that extracts a positive fraction of entropy, i.e., $\Omega(k)$ bits, from (n, k) -zero-fixing sources where $k \geq (\log \log n)^{2+\mu}$.

We have found two different constructions of extractors for zero-fixing sources that are able to extract a positive fraction of entropy for k essentially smaller than $\log \log n$. The first extractor works for $k \geq C \log \log \log n$, for some constant C . The second extractor extracts a positive fraction of entropy for $k \geq \log^{(i)} n$ for any fixed $i \in \mathbb{N}$, where $\log^{(i)}$ denotes i -times iterated logarithm. The fraction of extracted entropy decreases with i . The first extractor

is a function computable in polynomial time in $\sim n$ (for $\epsilon = o(1)$, but not too small); the second one is computable in polynomial time when $k \leq \alpha \log \log n / \log \log \log n$, where α is a positive constant.

In the talk we sketch the main idea of the first construction.

Joint work with Vojtech Rodl.

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3.19 Majority Quantifiers, Complexity Classes and Games

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An overview is given on logical/syntactical descriptions of complexity classes based on quantifiers. Existential and universal quantifiers together with predicates in **P** suffice to characterize the polynomial hierarchy, **PSPACE** and 2 person full information games. Zachos and coauthors have investigated probabilistic quantifiers and shown that a pair of sequences of quantifiers can be used to characterize the classical probabilistic complexity classes and 2 person games involving randomness – Arthur Merlin games. We discuss technical tools to prove relations between these complexity classes based on such characterizations and to investigate hierarchies built on quantifier sequences. The essential technique here is swapping of quantifiers.

3.20 Computational Two Party Correlation

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Joint work of Iftach Haitner, Kobbi Nissim, Eran Omri, Ronen Shaltiel, Jad Silbak
Main reference Iftach Haitner, Kobbi Nissim, Eran Omri, Ronen Shaltiel, Jad Silbak: “Computational Two-Party Correlation: A Dichotomy for Key-Agreement Protocols”, in Proc. of the 59th IEEE Annual Symposium on Foundations of Computer Science, FOCS 2018, Paris, France, October 7-9, 2018, pp. 136–147, IEEE Computer Society, 2018.
URL <https://doi.org/10.1109/FOCS.2018.00022>

Let π be an efficient two-party protocol that (given security parameter κ) both parties output single bits X_κ and Y_κ , respectively. We are interested in how (X_κ, Y_κ) “appears” to an efficient adversary that only views the transcript T_κ . We make the following contributions:

- We develop new tools to argue about this loose notion, and show (modulo some caveats) that for every such protocol π , there exists an efficient *simulator* such that the following holds: on input T_κ , the simulator outputs a pair (X'_κ, Y'_κ) such that $(X'_\kappa, Y'_\kappa, T_\kappa)$ is (somewhat) *computationally indistinguishable* from $(X_\kappa, Y_\kappa, T_\kappa)$.
- We use these tools to prove the following *dichotomy theorem*: every such protocol π is:
 - either *uncorrelated* – it is (somewhat) indistinguishable from an efficient protocol whose parties interact to produce T_κ , but then choose their outputs *independently* from some product distribution (that is determined in poly-time from T_κ),
 - or, the protocol implies a key-agreement protocol (for infinitely many κ 's).

Uncorrelated protocols are uninteresting from a cryptographic viewpoint, as the correlation between outputs is (computationally) trivial. Our dichotomy shows that every protocol is either completely uninteresting or implies key-agreement.

3.21 Near-Optimal Erasure List-Decodable Codes

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Joint work of Avraham Ben Aroya, Dean Doron, Amnon Ta-Shma

Main reference A. Ben-Aroya, D. Doron, A. Ta-Shma, “Near-Optimal Strong Dispersers, Erasure List-Decodable Codes and Friends,” *Electronic Colloquium on Computational Complexity (ECCC)* 25: 65 (2018).

URL <https://eccc.weizmann.ac.il/report/2018/065/>

A code C is $(1 - \tau, L)$ erasure list-decodable if for every word w , after erasing any $1 - \tau$ fraction of the symbols of w , the remaining τ -fraction of its symbols have at most L possible completions into codewords of C .

Non-explicitly, there exist binary $(1 - \tau, L)$ erasure list-decodable codes having rate $O(\tau)$ and tiny list-size $L = O(\log 1/\tau)$. Achieving either of these parameters explicitly is a natural open problem (see, e.g., [5],[3],[4]). While partial progress on the problem has been achieved, no prior explicit construction achieved rate better than $\Omega(\tau^2)$ or list-size smaller than $\Omega(1/\tau)$. Furthermore, Guruswami showed no linear code can have list-size smaller than $\Omega(1/\tau)$ [3]. We construct an explicit binary $(1 - \tau, L)$ erasure list-decodable code having rate $\tau^{1+\gamma}$ (for any constant $\gamma > 0$ and small τ and list-size $\text{poly}(\log 1/\tau)$), answering simultaneously both questions, and exhibiting an explicit non-linear code that provably beats the best possible linear code.

The binary erasure list-decoding problem is equivalent to the construction of explicit, low-error, strong dispersers outputting one bit with minimal entropy-loss and seed-length. For error ϵ , no prior explicit construction achieved seed-length better than $2 \log 1/\epsilon$ or entropy-loss smaller than $2 \log 1/\epsilon$, which are the best possible parameters for extractors. We explicitly construct an ϵ -error one-bit strong disperser with near-optimal seed-length $(1 + \gamma) \log 1/\epsilon$ and entropy-loss $O(\log \log 1/\epsilon)$.

The main ingredient in our construction is a new (and almost-optimal) unbalanced two-source extractor. The extractor extracts one bit with constant error from two independent sources, where one source has length n and tiny min-entropy $O(\log \log n)$ and the other source has length $O(\log n)$ and arbitrarily small constant min-entropy rate. When instantiated as a balanced two-source extractor, it improves upon Raz’s extractor [7] in the constant error regime. The construction incorporates recent components and ideas from extractor theory with a delicate and novel analysis needed in order to solve dependency and error issues that prevented previous papers (such as [6],[1],[2]) from achieving the above results.

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3.22 Oracle Separation of BQP and the Polynomial Hierarchy

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Joint work of Ran Raz, Avishay Tal

Main reference Ran Raz, Avishay Tal: “Oracle Separation of BQP and PH”, Electronic Colloquium on Computational Complexity (ECCC), Vol. 25, p. 107, 2018.

URL <https://eccc.weizmann.ac.il/report/2018/107>

In their seminal paper, Bennett, Bernstein, Brassard, and Vazirani [2] showed that relative to an oracle, quantum algorithms are unable to solve **NP**-complete problems in sub-exponential time (i.e., that Grover’s search is optimal in this setting).

In this work, we show a strong converse to their result. Namely, we show that, relative to an oracle, there exist computational tasks that can be solved efficiently by a quantum algorithm but require exponential time for any algorithm in the polynomial hierarchy (that captures **P**, **NP**, and **co-NP** as its first levels).

The tasks that exhibit this “quantum advantage” arise from a pseudo-randomness approach initiated by Aaronson [1]. Our core technical result is constructing a distribution over Boolean strings that “look random” to constant-depth circuits of quasi-polynomial size, but can be distinguished from the uniform distribution by very efficient quantum algorithms.

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3.23 Different methods to isolate a perfect matching in bipartite graphs

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Joint work of Stephen A. Fenner, Rohit Gurjar, Thomas Thierauf

Main reference Stephen A. Fenner, Rohit Gurjar, Thomas Thierauf: “A deterministic parallel algorithm for bipartite perfect matching”, Commun. ACM, Vol. 62(3), pp. 109–115, 2019.

URL <https://doi.org/10.1145/3306208>

We give different proofs of our result that the perfect matching problem for bipartite is in **quasi-NC**. In particular, we present three different ways how to construct a weight function that isolates the minimum weight perfect matching. Each method yields different parameters for the size of the weights. We think that is interesting to see different methods because still it is an open problem to improve our result to **NC**.

3.24 Lower Bounds for Matrix Factorization

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Joint work of Mrinal Kumar, Ben Lee Volk
Main reference Mrinal Kumar, Ben Lee Volk: “Lower Bounds for Matrix Factorization”, CoRR, Vol. abs/1904.01182, 2019.
URL <https://arxiv.org/abs/1904.01182>

We consider the problem of constructing explicit matrices which cannot be expressed as a product of a few sparse matrices. In addition to being a natural mathematical question, this problem appears in various areas in computer science, such as algebraic complexity, data structures, and machine learning.

We outline an approach for proving improved lower bounds through a certain derandomization problem, and use this approach to prove asymptotically optimal quadratic lower bounds for natural special cases, which generalize many of the common matrix decompositions.

We then discuss some open problems related to this approach.

3.25 Oblivious Lower Bounds for Near-Neighbor Search

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Joint work of Kasper Green Larsen, Tal Malkin, Omri Weinstein, Kevin Yeo
Main reference Kasper Green Larsen, Tal Malkin, Omri Weinstein, Kevin Yeo: “Lower Bounds for Oblivious Near-Neighbor Search”, CoRR, Vol. abs/1904.04828, 2019.
URL <http://arxiv.org/abs/1904.04828>

We prove an $\Omega(d \lg n / (\lg \lg n)^2)$ lower bound on the dynamic cell-probe complexity of statistically *oblivious* approximate-near-neighbor search (ANN) over the d -dimensional Hamming cube. For the natural setting of $d = \Theta(\log n)$, our result implies an $\tilde{\Omega}(\lg^2 n)$ lower bound, which is a quadratic improvement over the highest (non-oblivious) cell-probe lower bound for ANN. This is the first super-logarithmic *unconditional* lower bound for ANN against general (non black-box) data structures. We also show that any oblivious *static* data structure for decomposable search problems (like ANN) can be obliviously dynamized with $O(\log n)$ overhead in update and query time, strengthening a classic result of Bentley and Saxe ([1]).

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Algorithmic Problems in Group Theory

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Abstract

Since its early days, combinatorial group theory was deeply interwoven with computability theory. In the last 20 years we have seen many new successful interactions between group theory and computer science. On one hand, groups played an important role in many developments in complexity theory and automata theory. On the other hand, concepts from these computer science fields as well as efficient algorithms, cryptography, and data compression led to the formulation of new questions in group theory. The Dagstuhl Seminar *Algorithmic Problems in Group Theory* was aimed at bringing together researchers from group theory and computer science so that they can share their expertise. This report documents the material presented during the course of the seminar.

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Edited in cooperation with Georg Zetsche

1 Executive summary

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The field of combinatorial group theory, a part of abstract algebra, is tightly linked to computational problems from its early days. Already in 1911, i.e., 25 years before Turing’s work on the halting problem appeared, Max Dehn introduced and investigated three fundamental group theoretical decision problems: the *word problem*, the *conjugacy problem*, and the *isomorphism problem*. Dehn’s problems had a strong influence on the development of modern theoretical computer science. It took more than 40 years before the work of Novikov, Boone, Adjan, and Rabin showed the undecidability of Dehn’s decision problems in the class of finitely presented groups. Despite these negative results, for many groups the word



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problem turned out to be decidable in many important classes of groups. With the rise of complexity theory in the 1960's, also the computational complexity of group theoretic problems moved into the focus of research. From the very beginning, this field attracted researchers from mathematics as well as computer science. Using algorithmic techniques from complexity theory, researchers were able to exhibit highly efficient algorithms for groups, where initially only pure decidability results have been known. A milestone in this context is Lipton and Zalcstein's logspace algorithm for the word problem of finitely generated linear groups. This was the first result putting the word problem for an important class of groups into a complexity class below polynomial time. In the last 10 years, researchers pushed the limits further towards small circuit complexity classes. In particular the class $\mathbf{TC}^0$ turned out to be very important in this context. Despite its limited computational power many important group theoretical problems were shown to be in $\mathbf{TC}^0$.

Complexity theoretical questions are not the only area where we have seen fruitful interactions between group theory and theoretical computer science in recent years. Other examples can be found in automata theory, data compression, model theory, and reachability problems for infinite state systems. The following paragraphs put some of the seminar talks into the context of these topics and mentions some of the open problems that were discussed during the seminar.

Groups and circuit complexity

Howard Straubing gave an excellent survey on circuit complexity that was particularly addressed to non-experts in complexity theory. Barrington's famous result according to which the word problem for every finite non-solvable group is hard for $\mathbf{NC}^1$ was explained and several important results centered around the circuit complexity class $\mathbf{TC}^0$ were surveyed. In recent years, $\mathbf{TC}^0$ turned out to be the right class for characterizing the complexity of several group theoretical problems. Two seminar talks presented further examples of group theory problems in $\mathbf{TC}^0$: Armin Weiß gave a talk about the power word problem which is a succinct version of the classical word problem, where powers g^n of group elements with binary encoded integer exponents n are allowed in the input. Despite this succinctness, several power word problems (e.g. for nilpotent groups and certain wreath products of finitely generated abelian groups) can be still solved in $\mathbf{TC}^0$. Moses Ganardi talked on the knapsack problem for finitely generated groups which asks for the solvability of certain exponent equations over a group. Among other results he gave a simple proof showing that the knapsack problem for unary encoded integers is in $\mathbf{TC}^0$. This result generalizes to all finitely generated abelian groups.

Several promising open problems related to the circuit complexity of group theoretical problems were discussed in the open problem sessions: The above mentioned result of Barrington on finite non-solvable groups motivates the question whether the word problem for every finitely generated solvable group is $\mathbf{NC}^1$ -hard. Also finding new classes of infinite groups with a word problem in $\mathbf{TC}^0$ is an open research problem that was intensively discussed during the seminar. So far, it is known that solvable linear groups have a word problem in $\mathbf{TC}^0$ and that the class of groups with a word problem in $\mathbf{TC}^0$ is closed under wreath products.

Compression techniques in group theory

Compression techniques turned out to be an important tool for obtaining efficient algorithms in group theory. The general philosophy is trying to avoid storing extremely long words by

computing on a compressed representation of these words. This led to the formulation of several succinct versions of classical group theoretical problems, where the group elements in the input are given a succinct version. The power word problem that was introduced by Armin Weiß (see the previous paragraph) is such a succinct problem. The main result of Armin Weiß' talk was an efficient reduction of the power word problem for a free group to the (ordinary) word problem of a free group. It is open whether similar reductions also exist for right-angled Artin groups and hyperbolic groups.

In the context of solving equations over groups and monoids, the so-called recompression technique led to several important results in recent years. Arthur Jež (the inventor of this technique) gave a talk on recompression and outlined his non-deterministic linear time algorithm for solvability of word equations. Ciobanu and Elder presented their recent work on equations in hyperbolic groups where they use recompression in order to show that the set of all solutions for a system of equations over a hyperbolic group is an EDT0L language.

Groups and model theory

This research area directly relates to the previous paragraph. The goal is to understand the first-order theory of groups. Of particular interest is the Diophantine theory. Decidability of the Diophantine theory means that one can decide whether a boolean combination of word equations has a solution. Olga Kharlampovich gave a talk about Diophantine theories of metabelian groups. She proved decidability for several important metabelian groups: Baumslag-Solitar groups $BS(1, n)$ and wreath products $\mathbb{Z} \wr \mathbb{Z}$ and $\mathbb{Z}_n \wr \mathbb{Z}$. Albert Garreta continued this topic and talked about Diophantine theories of solvable groups. He presented a large class of solvable groups (containing for instance all finitely generated non-virtually abelian nilpotent groups and all polycyclic groups that are not virtually metabelian) for which the Diophantine theory is at least as hard as the Diophantine theory of a suitable ring of algebraic integers. This leads to the conjecture that for each member of his family the Diophantine theory is undecidable.

Montserrat Casals-Ruiz talked on the positive theory of groups acting on trees. The positive theory of a group contains all negation-free statements from the full first-order theory. Montserrat Casals-Ruiz proved that many natural examples of groups acting on trees have the same positive theory as a free group of rank two. Ilya Kazachkov presented new results on the full first-order theory of free products and, more generally, graph products of groups. He showed that under certain conditions, elementary equivalent free products (meaning that their first-order theories coincide) must have elementary equivalent factors.

Groups and automata

Besides complexity of algorithmic problems, a very interesting connection between group theory and theoretical computer science is provided by automata theory, using the very flexible and algorithmically efficient finite state automata to somehow describe an infinite group. This led to the development of automatic groups and automaton groups. Automaton groups are a subclass of so-called self-similar groups. Laurent Bartholdi gave a talk on algorithmic results on self-similar groups and outlined the proof of a recent breakthrough result of Bartholdi and Mitrofanov stating that there exist self-similar groups with an undecidable word problem. For the particular case of automaton groups the word problem belongs to **PSPACE**. The question whether there exist automaton groups with a **PSPACE**-complete word problem was intensively discussed during the seminar. Recently, as a direct outcome of the seminar, an automaton group with this property was constructed by Jan Philipp

Wächter and Armin Weiß [An automaton group with PSPACE-complete word problem, arXiv, 2019. <https://arxiv.org/abs/1906.03424>]. Volodia Nekrashevych presented in his talk a generalization of automaton groups based on non-deterministic synchronous automata-transducers and discussed their algorithmic properties and relationship to dynamical systems.

Reachability problems

The study of reachability problems for matrix semigroups has a long tradition in theoretical computer science. Formulated in terms of algebra, the reachability problem is equivalent to the subsemigroup membership problem. Several variants and generalization (rational subset membership problem, knapsack problem) have been recently investigated as well. Igor Potapov gave a survey talk on recent progress on the matrix reachability problem from a computer science perspective. Georg Zetsche presented several new decidability results for the rational subset membership problem in wreath products. Moses Ganardi talked on wreath products as well, but put the focus on the knapsack problem.

The above talks and the open problem session identified several interesting open problems related to reachability problems. An outstanding open problem in this context asks whether the submonoid membership problem for the group $GL_3(\mathbb{Z})$ is decidable. Recently it was shown that the submonoid membership problem for the Heisenberg group (a subgroup of $GL_3(\mathbb{Z})$) is decidable. This result suggests two generalizations: (i) the rational subset membership problem for Heisenberg groups and (ii) the submonoid membership problem for groups of unitriangular integer matrices. In both case it is open whether the problem is decidable. Georg Zetsche mentioned in his talk the submonoid membership problem and the rational subset membership problem in the Baumslag-Solitar group $BS(1, 2)$ as open research problems.

Concluding remarks and future plans

The seminar was well received as witnessed by the high rate of accepted invitations. There was a good balance between participants from computer science and pure mathematics, and this mixture led to many active discussions and the discovery of new connections and promising open problems. The organizers regard this seminar as a great success. With steadily increasing interactions between such researchers, we foresee another seminar focusing on the interplay between computer science and group theory. Finally, the organizers wish to express their gratitude to the Scientific Directors of the Dagstuhl Centre for their support of the seminar.

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3 Overview of talks

3.1 Decision problems in self-similar and automata groups

Laurent Bartholdi (Institute of Advanced Studies, ENS Lyon, FR & Universität Göttingen, DE)

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Joint work of Laurent Bartholdi, Ivan Mitrofanov

A self-similar group is a group acting on a regular rooted tree, in such a way that the action on subtrees are given recursively by a permutation and by elements of the group itself. Thus such a group is “presented” by a table giving, for each generator, its permutation of the top branches and, for each branch, a word in the generators giving recursively the action on it.

We show that very little can be deduced from such a “self-similar presentation”: in particular, the word problem is not decidable.

The proof uses a reduction to Minsky machines.

3.2 On the positive theory of groups acting on trees

Montserrat Casals-Ruiz (University of the Basque Country, ES & Ikerbasque – Bilbao, ES)

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Joint work of Montserrat Casals-Ruiz, Albert Garreta, Ilya Kazachkov, Javier de la Nuez

Many classical problems in group theory revolve around laws, verbal subgroups and their width. Results run from the generalisation of the classical Ore’s Conjecture, proven by Liebeck, O’Brien, Shalev and Tiep, stating that every verbal subgroup has uniformly bounded width in the class of finite simple groups to the Bestvina-Bromberg-Fujiwara result showing that all verbal subgroups of an acylindrically hyperbolic group have infinite width.

In this talk, we will address these questions in a more general setting from the model-theoretic perspective. More precisely, we will discuss the positive theory of groups acting on trees. As a corollary, we will deduce that many interesting classes of groups have trivial positive theory, namely all acylindrically hyperbolic groups acting on trees and most one-relator groups including non-solvable Baumslag-Solitar groups. We also provide the first examples of finitely generated simple groups with trivial positive theory and so in particular, with all verbal subgroups of infinite width.

3.3 One relator quotients of partially commutative groups.

Andrew Duncan (Newcastle University, GB)

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Joint work of Andrew Duncan, Arye Juhasz

A generalisation of Magnus’s Freiheitssatz to one relator quotients of partially commutative (right angled Artin) groups is stated. The theorem holds for arbitrary pc groups, as long as certain conditions on the relator hold. In particular the relator must be at least a 3rd power;

but this is not sufficient. Sufficient conditions are detailed. (Some improvements in the proof were obtained as a result of discussions at the workshop).

For certain graphs (cycle graphs with an added 3-cycle) it can be seen that almost all cyclically reduced words in the corresponding pc group satisfy the conditions stated in our theorem. This depends on the fact that such groups have very well behaved normal forms for elements. This allows us to compute asymptotic densities, of subsets of the group, and show the theorem nearly always holds.

3.4 Conjugacy problems in $\mathrm{GL}(n, \mathbb{Z})$

Bettina Eick (TU Braunschweig, DE)

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Joint work of Bettina Eick, Tommy Hofmann, Eamonn O'Brien

Main reference Bettina Eick, Tommy Hofmann, Eamonn O'Brien: "The conjugacy problem in $\mathrm{GL}(n, \mathbb{Z})$ ". To appear in J. London Math. Soc., 2019.

Let T, T' be two invertible rational matrices. The *rational conjugacy problem* asks to decide if there exists $g \in \mathrm{GL}(n, \mathbb{Q})$ satisfying $g^{-1}Tg = T'$ and, if so, then to determine one such g . It is well-known that this problem can be solved readily using a variation of the Gaussian elimination algorithm.

The *integral conjugacy problem* asks to decide if there exists $g \in \mathrm{GL}(n, \mathbb{Z})$ satisfying $g^{-1}Tg = T'$ and, if so, then to determine one such matrix g . This problem is significantly harder to solve than its rational analogue. Dual to the integral conjugacy problem is the *integral centralizer problem* which asks to determine a finite generating set for $C_{\mathbb{Z}}(T) = \{g \in \mathrm{GL}(n, \mathbb{Z}) \mid g^{-1}Tg = T\}$. Grunewald [4] and Sarkisyan [5] both proved independently that the integral conjugacy and centralizer problems are decidable. Neither of their algorithms for this purpose appears to be practical.

This talk describes a first *practical* algorithm to solve both the integral conjugacy and centralizer problems. The algorithm is based on Grunewald's ideas [4] and improves these in various ways. An implementation in Magma [1] is available.

The talk ends by noting two related open problems. First, Sarkisyan [5] also proved that the *multiple integral conjugacy problem* is decidable; that is, given two lists $T_1, \dots, T_m$ and $T'_1, \dots, T'_m$ of integral matrices, decide if there exists $g \in \mathrm{GL}(n, \mathbb{Z})$ with $g^{-1}T_i g = T'_i$ for $1 \leq i \leq m$. A practical algorithm to solve this problem and to find an explicit conjugating element g are still open. Secondly, Grunewald & Segal [3] proved that the *subgroup conjugacy problem* for unitriangular subgroups of $\mathrm{GL}(n, \mathbb{Z})$ is decidable. A practical algorithm to solve this problem and to compute the centralizer in $\mathrm{GL}(n, \mathbb{Z})$ of a unitriangular subgroup is a still open problem.

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3.5 On the intersection problem for free-abelian by free groups

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Joint work of Jordi Delgado Rodríguez and Enric Ventura Capell

Main reference Jordi Delgado, “Extensions of Free Groups: Algebraic, Geometric, and Algorithmic Aspects”, Ph.D. Thesis, Universitat Politècnica de Catalunya, Sept. 2017.

URL https://www.researchgate.net/publication/319902473_Extensions_of_free_groups_algebraic_geometric_and_algorithmic_aspects

The idea of using covering spaces to understand subgroups of the free group $\mathbb{F}_n$ goes back to the eighties with the seminal work of Stallings in [2]. It soon became clear that this theory admitted a neat description in terms of automata (labeled digraphs), and was very convenient to attack algorithmic problems. The success of this interpretation (of subgroups as automata) generated a growing interest in extending Stallings machinery to other families of groups.

In [1, Chapter 5], we extend Stallings theory to free-abelian by free groups ($\mathbb{Z}^m \rtimes \mathbb{F}_n$) by “enriching” the arcs in the automata with abelian labels and modifying accordingly the folding process. This approach provides a clean description of the subgroups of $\mathbb{Z}^m \rtimes \mathbb{F}_n$ as “enriched automata”, and an efficient solution to the membership problem within this family.

However, obstructions appear when we try to adapt to our scheme the pullback construction to describe intersections of subgroups. I will discuss the obtained results for $\mathbb{Z}^m \times \mathbb{F}_n$ and where the difficulties lie to extend our proof to the general case.

This is joint work with Enric Ventura.

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3.6 Solving equations in hyperbolic groups

Laura Ciobanu (Heriot-Watt University – Edinburgh, GB) and Murray Elder (University of Technology Sydney, AU)

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Joint work of Laura Ciobanu, Murray Elder

Main reference Laura Ciobanu, Murray Elder: “Solutions sets to systems of equations in hyperbolic groups are EDT0L in PSPACE”, ICALP 2019

For a group G , solving equations where the coefficients are elements in G and the solutions take values in G can be seen as akin to solving Diophantine equations in number theory, answering questions from linear algebra or more generally, algebraic geometry. Moreover, the

question of satisfiability of equations fits naturally into the framework of the first order theory of G . In these talks we will give a short overview of what is known about the satisfiability of equations in infinite non-abelian groups, with an emphasis on free and hyperbolic groups.

More precisely, in the first talk (Ciobanu) we will outline the approaches of Rips & Sela [2], and Dahmani & Guirardel [1] to solving equations in hyperbolic groups. In the second talk (Elder) we will show that the full set of solutions to systems of equations and inequations in a hyperbolic group, with or without torsion, as shortlex geodesic words, is an EDT0L language whose specification can be computed in $\mathbf{NSPACE}(n^2 \log n)$ for the torsion-free case and $\mathbf{NSPACE}(n^4 \log n)$ in the torsion case.

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3.7 Knapsack problems for wreath products

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Main reference Moses Ganardi, Daniel König, Markus Lohrey, Georg Zetsche: “Knapsack Problems for Wreath Products”, in Proc. of the 35th Symposium on Theoretical Aspects of Computer Science, STACS 2018, February 28 to March 3, 2018, Caen, France, LIPIcs, Vol. 96, pp. 32:1–32:13, Schloss Dagstuhl – Leibniz-Zentrum fuer Informatik, 2018.
URL <http://dx.doi.org/10.4230/LIPIcs.STACS.2018.32>

In recent years, knapsack problems for (in general non-commutative) groups have attracted attention. We study the knapsack problem for wreath products. It turns out that decidability of knapsack is not preserved under wreath product. On the other hand, the class of knapsack-semilinear groups, where solutions sets of knapsack equations are effectively semilinear, is closed under wreath product. As a consequence, we obtain the decidability of knapsack for free solvable groups. Finally, it is shown that for every non-trivial abelian group G , knapsack (as well as the related subset sum problem) for the wreath product $G \wr \mathbb{Z}$ is **NP**-complete.

3.8 Equations in solvable groups

Albert Garreta (University of the Basque Country – Bilbao, ES)

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Joint work of Albert Garreta, Alexei Miasnikov, Denis Ovchinnikov

We study the Diophantine problem (decidability of systems of equations) in different families of solvable groups. We show that for any group G in each of these families there exists a ring of algebraic integers O that is interpretable in G by systems of equations. This reduces the Diophantine problem of O –conjectured undecidable– to the same problem in G , and it leads us to conjecture that the Diophantine problem in G is undecidable. The families where such result is obtained include all finitely generated non-virtually abelian nilpotent groups and all

polycyclic groups that are not virtually metabelian. Note that the Diophantine problem of virtually abelian groups has long been known to be decidable (their first-order theory is). We also show undecidability of the Diophantine problem in free solvable groups and in ‘most’ nilpotent groups by studying asymptotic properties of random nilpotent groups.

3.9 Automaticity for graphs of groups, and applications

Susan Hermiller (University of Nebraska – Lincoln, US)

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Joint work of Susan Hermiller, Derek F. Holt, Sarah Rees, Tim Susse
Main reference Susan Hermiller, Derek F. Holt, Sarah Rees, Tim Susse: “Automaticity for graphs of groups”, CoRR, Vol abs/1905.05943, 2019.
URL <https://arxiv.org/abs/1905.05943>

In this I will discuss new closure properties for the class of automatic groups with respect to taking fundamental groups of graphs of groups. Applications include automaticity of fundamental groups of graphs of groups in which each vertex group is either a graph product group, a Coxeter group, or an Artin group of sufficiently large type, and each edge group is a subgraph product or special subgroup, respectively, in its adjacent edge groups. The constructions are used to find automatic structures for a new family of Artin groups, and new automatic structures for acylindrical graphs of groups that are hyperbolic relative to abelian subgroups, including fundamental groups of 3-manifolds with hyperbolic pieces. This is joint work with Derek Holt, Sarah Rees, and Tim Susse.

3.10 Satisfiable word equations are context-sensitive

Artur Jeż (University of Wrocław, PL)

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Main reference Artur Jeż: “Word Equations in Nondeterministic Linear Space”, in Proc. of the 44th International Colloquium on Automata, Languages, and Programming, ICALP 2017, July 10-14, 2017, Warsaw, Poland, LIPIcs, Vol. 80, pp. 95:1–95:13, Schloss Dagstuhl – Leibniz-Zentrum fuer Informatik, 2017.
URL <http://dx.doi.org/10.4230/LIPIcs.ICALP.2017.95>

Word equations are an important problem on the intersection of formal languages and algebra. Given two sequences consisting of letters and variables we are to decide whether there is a substitution for the variables that turns this equation into true equality of strings. The computational complexity of this problem remains unknown, with the best lower and upper bounds being **NP** and **PSPACE**. Recently, a novel technique of recompression was applied to this problem, simplifying the known proofs and lowering the space complexity to (nondeterministic) $O(n \log n)$. In this talk I will show that word equations are in nondeterministic linear space, thus the language of satisfiable word equations is context-sensitive. The algorithm uses the known recompression-based algorithm and additionally employs Huffman coding for letters. The proof, however, uses analysis of how the fragments of the equation depend on each other as well as a new strategy for nondeterministic choices of the algorithm, which uses several new ideas to limit the space occupied by the letters.

3.11 Generic-case complexity of Whitehead’s algorithm, revisited

Ilya Kapovich (City University of New York, US)

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Main reference Ilya Kapovich: “Generic-case complexity of Whitehead’s algorithm, revisited”, CoRR, Vol. abs/1903.07040, 2019.

URL <https://arxiv.org/abs/1903.07040>

We generalize to a much larger class of random processes, including group random walks and graph random walks, the previously known generic-case complexity results regarding the behavior of Whitehead’s algorithm algorithm for the automorphic equivalence problem in free groups. The main tool used is the machinery of geodesic currents and the geometric intersection number between currents and $\mathbb{R}$ -trees.

3.12 On the elementary theory of graph products of groups

Ilya Kazachkov (University of the Basque Country, ES & Ikerbasque – Bilbao, ES)

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When studying the model theory of groups, it is natural to ask which group-theoretic constructions preserve the elementary theory. In 1959, Feferman and Vaught studied the first-order properties of direct products and showed, in particular, that the direct products of elementarily equivalent groups are elementarily equivalent. In contrast, invariance of the elementary equivalence for free products of groups was a long-standing conjecture which was recently solved by Sela (2017).

In this talk, we will first address the converse question: given two elementary equivalent free products of groups (or more generally, graph product of groups), when are the factors elementarily equivalent? We discuss some sufficient conditions and use our results to describe finitely generated groups elementarily equivalent to RAAGs whose underlying graph is a transitive forest.

3.13 Equations and model theory in one relator groups

Olga Kharlampovich (The City University of New York, US)

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Joint work of Olga Kharlampovich, Laura Lopez, Alexei Miasnikov

O. Kharlampovich gave a talk about results with L. Lopez and A. Miasnikov on solvability of equations in some classes of metabelian groups like Baumslag Solitar groups $BS(1, k)$, and wreath products $\mathbb{Z} \wr \mathbb{Z}$ and $\mathbb{Z}_n \wr \mathbb{Z}$. Some model theoretic questions for one relator groups were also discussed.

3.14 Malcev's problems, weak second order logic, and bi-interpretability

Alexei Myasnikov (Stevens Institute of Technology – Hoboken, US)

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Joint work of Olga Kharlampovich, Alexei Myasnikov, Mahmood Sohrabi

Malcev's problems on definable subgroups of a free non-abelian group F were solved a few years ago by Kharlampovich and Myasnikov and also by Perin, Pillay, Sklinos, and Tent. It turned out that only cyclic subgroups are definable proper subgroups of F . Similar results hold for torsion-free hyperbolic groups. On the other hand, in finitely generated abelian groups only subgroups of finite index and the trivial subgroup are definable. One may consider the following question: what are finitely generated infinite groups where all finitely generated subgroups are definable? Furthermore, are there any interesting infinite groups G where finitely generated subgroups are uniformly definable, i.e., for each natural n there exists a first-order formula $D_n(x, y_1, \dots, y_n)$ such that for any elements $g_1, \dots, g_n$ in G the formula $D_n(x, g_1, \dots, g_n)$ defines in G the subgroup generated by $g_1, \dots, g_n$? Surprisingly, there is a wide variety of finitely generated infinite groups with uniformly definable subgroups. Such questions are part of a much bigger problem about the expressive power of the first-order logic in groups (or rings, or arbitrary structures). I will discuss this problem and its connections with the weak second order logic and bi-interpretability.

3.15 Non-deterministic automata and group theory

Volodia Nekrashevych (Texas A&M University – College Station, US)

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The class of groups generated by synchronous deterministic automata has been studied for a long time (see, for example, the extensive literature on the Grigorchuk group and its analogs). It was recently discovered that non-deterministic versions of such automata also generate interesting groups, and provide substantially new properties. For example, the author has constructed examples of simple torsion groups of intermediate growth using such automata. We will discuss algorithmic problems related to non-deterministic synchronous automata-transducers, their applications to dynamical systems (for example they appear naturally in the study of hyperbolic dynamical systems) and to group theory.

3.16 Reachability problems in matrix semigroups

Igor Potapov (University of Liverpool, GB)

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A large number of naturally defined decision problems on matrices are still unanswered despite the long history of matrix theory. Originally in Arthur Cayley's "A Memoir on the Theory of Matrices" in 1858, the notion of a matrix arises naturally from abbreviated notations for a set of linear equations where he also defined associated operation of multiplication,

notions of determinant, inverse matrices, etc. Nowadays questions on matrices and matrix problems emerge in much larger context as they appear in the analysis of various digital processes, verification problems [18], in the context of control theory questions [2]. Moreover problems on matrix products have been associated with several long standing open problems in algebraic number theory and transcendence theory, Nash equilibria, in the theory of joint spectral radius and its applications [9, 14, 18, 19].

Many simply formulated and elementary problems for matrices are inherently difficult to solve even in dimension two, and most of these problems become undecidable in general starting from dimension three or four [6, 4, 7, 9, 10, 20]. Only few decidability results are known so far, see for example [1, 12, 5, 11, 13, 21, 22, 23].

Let us given a finite set of square matrices (known as a generator) which is forming a multiplicative semigroup S . The classical computational problems for matrix semigroups are:

- Membership (Decide whether a given matrix M belong to a semigroup S) and two special cases such as: Identity (i.e. if M is the identity matrix) and Mortality (i.e. if M is the zero matrix) problems
- Vector reachability (Decide for a given vectors u and v whether exist a matrix M in S such that $M \cdot u = v$)
- Scalar reachability (Decide for a given vectors u, v and a scalar L whether exist a matrix M in S such that $u^T \cdot M \cdot v = L$)
- Freeness (Decide whether every matrix product in S is unique, i.e. whether it is a code) and some variants of the freeness such as finite freeness problem, the recurrent matrix problem, the unique
- factorizability problem, vector freeness problem, vector ambiguity problems, etc.

The undecidability proofs in matrix semigroups are mainly based on various techniques and methods for embedding universal computations into matrix products. The case of dimension two is the most intriguing since there is some evidence that if these problems are undecidable, then this cannot be proved directly using previously known constructions. Due to a severe lack of methods and techniques the status of decision problems for 2×2 matrices (like membership, vector reachability, freeness) is remaining to be a long standing open problem not only for matrices over algebraic, complex, rational numbers but also for integer matrices.

Recently, a new approach of translating numerical problems of 2×2 integer matrices into variety of combinatorial and computational problems on words and automata over group alphabet and studying their transformations as specific rewriting systems [11, 13] have led to a few results on decidability and complexity for some subclasses:

- The membership problem for 2×2 nonsingular integer matrices is decidable [23]. The algorithm relies on a translation of numerical problems on matrices into combinatorial problems on words. It also makes use of some algebraic properties of well-known subgroups of $GL(2, \mathbb{Z})$ and various new techniques and constructions that help to convert matrix equations into the emptiness problem for intersection of regular languages.
- The Identity problem in $SL(2, \mathbb{Z})$ is **NP**-complete [8, 5]. Our **NP** algorithm is based on various new techniques that allow us to operate with compressed word representations of matrices without explicit exponential expansion.
- The vector reachability problem over a finitely generated semigroup of matrices from $SL(2, \mathbb{Z})$ and the point to point reachability (over rational numbers) for fractional linear transformations, where associated matrices are from $SL(2, \mathbb{Z})$ are decidable [21].

Similar techniques have been applied to show that the freeness problem is co-NP-hard [16] as well as to study the complexity of other freeness problems such as finite freeness problem, the recurrent matrix problem, the unique factorizability problem, vector freeness problem, vector ambiguity problems, etc [15].

There are still many open problems in special cases of dimension three where in general many problems become undecidable. In the seminal paper of Paterson in 1970 [20], an injective morphism from pairs of words into 3×3 integral matrices was used to prove the undecidability of the mortality problem, and later led to many undecidability results of matrix problems in dimension three. In [17] it was shown that there is no embedding from pairs of words into 3×3 integral matrices with determinant one, i.e., into $SL(3, \mathbb{Z})$, which provides strong evidence that computational problems in $SL(3, \mathbb{Z})$ may be decidable, as all known undecidability techniques for low-dimensional matrices are based on encoding of Turing machine computations via Post's Correspondence Problem (PCP), which cannot be applied in $SL(3, \mathbb{Z})$ following the results of [17]. In the case of the PCP encoding, matrix products extended by right multiplication correspond to a Turing machine simulation, and the only known proof alternatives rely on recursively enumerable sets and Hilbert's Tenth Problem, but provide undecidability for matrix equations of very high dimensions. [3].

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3.17 Conjugator length

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Joint work of Martin Bridson, Timothy Riley, Andrew Sale

The conjugator length function of a finitely generated group G maps a natural number n to the minimal N such that if u and v are words representing conjugate elements of G with the sum of their lengths at most n , then there is a word w of length at most N such that $uw = wv$ in G . I will explore why this function is important, will describe some recent results with Martin Bridson and Andrew Sale on how it can behave, and will highlight some of the many open questions about conjugator length.

3.18 Unconditionally secure public key transport (with possible errors)

Vladimir Shpilrain (*City University of New York, US*)

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Joint work of Mariya Bessonov, Dima Grigoriev, Vladimir Shpilrain

We offer what seems to be the first public key transport scheme whose security is not based on any computational assumptions but rather on the presence of several “decoy” keys that cannot be positively distinguished from the real key even by a computationally unbounded (passive) adversary. More specifically, we consider a scenario where one party wants to transmit a secret key to another party in the presence of a computationally unbounded (passive) adversary. The legitimate parties succeed with probability close to 1 (although strictly less than 1), while a computationally unbounded passive adversary succeeds in correctly recovering the secret key with significantly lower probability.

3.19 On the group of automorphisms of a context-free graph.

Géraud Sénizergues (*University of Bordeaux, FR*)

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Joint work of Géraud Sénizergues, Armin Weiß

Context. A famous theorem from [Muller-Schupp, JCSS 1983] establishes that a group G has a *context-free* word-problem if and only if it is *virtually-free* of finite type. A key-notion emerging from this work on the links between groups and formal languages, is the notion of *context-free graph*, which generalizes the Cayley-graphs of context-free groups. This notion and its links with second-order monadic logics was studied in [Muller-Schupp, TCS 1985]. Later on, it was shown by [L. Pelecq, TCS 1995] that the automorphism-group of a deterministic context-free graph is a context-free group. We discuss here two problems about the automorphism-groups of context-free graphs (thus skipping the hypothesis about determinism).

Problems. Let Γ be a *context-free* graph.

- Problem 1: What is the algebraic structure of the group $G := \text{Aut}(\Gamma)$?
- Problem 2: Describe the equivalence $\sim_G$ over the vertices of Γ . Is this relation, in general, a *rational* relation?

(Problem 2 was raised in [G. Sénizergues, ICALP 1996]).

Results. A recent proof of Muller and Schupp’s theorem was given by [Diekert and Weiß, 2017] and consists in showing that, if the Cayley-graph of a group G is context-free, then the equivalence classes of its “optimal cuts” (in some adequate technical sense) are the vertices of a simplicial tree T , endowed with a natural action of the group G , whose vertex-stabilizers are finite.

From Bass-Serre theory of group-actions on trees, it follows that G is virtually-free.

1. We give a variant of this proof by constructing, from the tree T , a *tiling* of the Cayley-graph of G , with only one elementary tile P , which is finite, and a tiling group $H < G$. By some version of the “combination lemma” (originating in a work of [F. Klein 1883]), we conclude that H is free and $[G : H] = \text{card}(P) < \infty$.

2. We adapt the above proof to the situation where Γ is a context-free graph and G is a group acting transitively on Γ (possibly with infinite stabilizers). In this case G has a *three-fold decomposition* as

$$G = H \cdot F \cdot S$$

where H is a free group of finite type, F is a finite subset and S is the stabilizer of some vertex (hence a profinite group). We show that the equivalence $\sim_G$ over Γ is a rational relation.

3. We sketch an extension to the case where Γ is a context-free graph and G is its group of automorphisms. In this case G has again a three-fold decomposition as

$$G = H \cdot F \cdot S$$

where H is a free group of finite type, F is a finite subset and S is the stabilizer of some vertex.

We are currently working on the proof that the equivalence $\sim_G$ over Γ is a rational relation.

3.20 Coarse computability and closures of Turing degrees

Paul E. Schupp (University of Illinois – Urbana Champaign, US)

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Coarse computability studies how well arbitrary sets can be approximated in terms of computable sets. Computability theory studies Turing degrees. We use coarse computability to put the study of some questions about Turing degrees into a complete metric space. We consider only subsets of the natural numbers $\mathbb{N}$ so asymptotic density is classical asymptotic density from number theory. Define two sets A and B to be *coarsely similar* if their symmetric difference $A \Delta B$ has density 0. This relation is an equivalence relation, so we consider the space $\mathcal{S}$ of coarse similarity classes. There is a pseudo-metric defined on $\mathcal{P}(\mathbb{N})$ by setting $\delta(A, B)$ to be the upper density of their symmetric difference. Then δ is a metric on the space $\mathcal{S}$. This metric was introduced by Besicovitch in studying almost periodic functions.

Although the space $\mathcal{S}$ is very nonseparable and noncompact, it turns out to be both complete and contractible, two very useful properties. Define the *core*, $\kappa(\mathbf{d})$, of a Turing degree $\mathbf{d}$ to be the family $\{[A]\}$ of all classes such that A is coarsely computable from $\mathbf{d}$. That is, given total information about a set in $\mathbf{d}$ we can compute a set which is coarsely equivalent to A . The closure $\overline{\mathbf{d}}$ of the degree $\mathbf{d}$ is the closure of $\kappa(\mathbf{d})$ in the metric topology. There are now some very interesting interactions between computability ideas and the metric topology.

3.21 Homological finiteness in one-relator monoids

Benjamin Steinberg (City University of New York, US)

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Joint work of Benjamin Steinberg, Robert Gray

Motivated by the longstanding open problem of deciding the word problem for one-relator monoids, Kobayashi asked in 2000 whether all one-relator monoids are of type FP_∞ . This is a necessary condition for admitting a finite complete rewriting system (Kobayashi was interested in whether all one-relator monoids admit finite complete rewriting systems). In this talk, we discuss recent progress by the speaker and Robert Gray on solving Kobayashi's problem using topological methods. Note that Lyndon proved in the fifties that all one-relator groups are of type FP_∞ .

3.22 A primer of low-depth circuit complexity

Howard Straubing (Boston College, US)

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Howard Straubing presented a survey on low-depth circuit complexity and its connection with finite groups and semigroups. The key result, dating back to work of Barrington and Thérien in the 1980's and 1990's, is essentially this: A circuit family belonging to the classes AC^0 (resp. CC^0 , ACC^0 , NC^1) can be replaced by a family of circuits, each with a SINGLE gate and polynomially many wires, that computes products in an aperiodic finite monoid (resp. solvable group, monoid containing only solvable groups, non-solvable finite group). Questions of strict inclusions between these complexity classes, and various subclasses thereof, are therefore equivalent to establishing the relative computing power of different families of finite groups and semigroups. In spite of a surge of progress some 30 years ago, most of these remain open problems.

3.23 Ramanujan cubical complexes and non-residually finite CAT(0) groups in any dimension

Alina Vdovina (Newcastle University, GB)

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Ramanujan graphs were first considered by Lubotzky, Phillips, Sarnak to get graphs with optimal spectral properties. In our days the theory of expander graphs and, in particular, Ramanujan graphs is well developed, but the questions is what is the best definition of a higher-dimensional expander is still wide open. There are several approaches, suggested by Gromov, Lubotzky, Alon and others, but the cubical complexes were not much investigated from this point of view. In this talk I will give new explicit examples of cubical Ramanujan complexes and discuss possible developments.

3.24 How to compute the stable image of an endomorphism?

Enric Ventura Capell (UPC – Barcelona Tech, ES)

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Let F be a finitely generated free group and let g be an endomorphism of F , given by the images of a free basis of F . The stable image of g , denoted $\text{Im}(g^\infty)$, is defined as the intersection of $\text{Im}(g^n)$ for all $n > 0$. It is known that this stable image is always finitely generated (in fact, with rank bounded by that of F), invariant under g , and that the restriction of g on it is always bijective (I'll give short proofs for these facts). The question (open as far as I know) is “can you compute generators for $\text{Im}(g^\infty)$?” This is interesting because a positive answer would have as a consequence the computability of the fixed subgroup of g , a (hard?) open problem. Note that the computability of $\text{Fix}(g)$ in the case when g is an automorphism has been resolved by strongly using the train-track machinery; in presence of non-trivial kernel this approach doesn't work (unless further developments of the train track techniques allow) and so computation of the fixed subgroup of an endomorphism is an open problem.

3.25 `stallings_graphs`, a Sagemath package to experiment with subgroups of free groups

Pascal Weil (CNRS & University of Bordeaux, FR)

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URL <http://www.labri.fr/perso/weil/software/>

Pascal Weil presented a SageMath package to compute with finitely generated subgroups of free groups. SageMath is an open source free non-commercial mathematical software system. This package, `stallings_graphs`, is available on Pascal's webpage. In this package, the internal representation of a finitely generated subgroup is a tuple of partial injections on some set of the form $[0, \dots, n]$, one for each generator of the ambient free group; which is to say that a finitely generated subgroup is represented by its Stallings graph.

The literature abounds in efficient algorithms using this representation, and many are already part of the package: computation of the rank, of a basis, of the intersection of two subgroups, of conjugates; as well as decision of the finite index property, conjugacy, malnormality. Future work will involve automorphism-related algorithms, including the decision of the free factor property.

3.26 The power word problem in free groups

Armin Weiß (Universität Stuttgart, DE)

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Joint work of Markus Lohrey, Armin Weiß

Main reference Markus Lohrey, Armin Weiß: “The power word problem”, CoRR, Vol. abs/1904.08343, 2019.

URL <https://arxiv.org/abs/1904.08343>

We introduce a new succinct variant of the word problem in a finitely generated group G , which we call the power word problem: the input word may contain powers p^x , where p is a finite word over generators of G and x is a binary encoded integer. While being more general than the ordinary word problem, the power word problem is a restriction of the compressed word problem, where the input word is represented by a straight-line program (i.e., an algebraic circuit over G). The main result states that the power word problem for a finitely generated free group F is $\mathbf{AC}^0$ -Turing-reducible to the word problem for F . Moreover, for a wreath product $G \wr \mathbb{Z}$, where G is either free of rank at least two or finite non-solvable, the power word problem is complete for $\mathbf{coNP}$. This contrasts with the situation where G is abelian: then the power word problem is shown to be in $\mathbf{TC}^0$.

In the talk, first an introduction into circuit complexity and its relation to group theory is given. The second part of the talk outlines the proof of the above mentioned main result.

3.27 Regular subsets of wreath products

Georg Zetsche (MPI-SWS – Kaiserslautern, DE)

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In theoretical computer science, an immensely popular concept for algorithmically working with sets of finite words is that of *regular languages*, which can be characterized in terms of finite automata, finite monoids, and monadic second-order logic (MSO). This popularity stems from an abundance of closure and decidability properties: For example, they are closed under Boolean operations and contain every finitely generated submonoid.

There have been several attempts at finding analogous concepts in infinite groups. Examples include the recognizable subsets and the rational subsets [1]. Let G be a finitely generated group. A subset $S \subseteq G$ is called *recognizable* if it is a union of cosets with respect to some finite-index normal subgroup of G . The class of *rational subsets* of G is the smallest class of subsets that (i) contains the empty set, (ii) contains every singleton $\{g\}$ with $g \in G$, (iii) is closed under finite unions: if $A, B \subseteq G$ are rational, then so is $A \cup B$, and (iv) is closed under the Minkowski product: if $A, B \subseteq G$ are rational, then so is $AB = \{ab \mid a \in A, b \in B\}$, and (iv) is closed under taking finitely generated submonoids: if $A \subseteq G$ is rational, then so is the submonoid of G generated by A .

In the case of free groups or abelian groups, rational subsets have similarly nice properties as regular languages of finite words: For free groups, their automata representation naturally generalizes Stallings graphs and for abelian groups, they coincide with the first-order definable sets. However, in general, both the recognizable sets and the rational subsets lack important features: While the recognizable subsets are closed under Boolean operations and have decidable membership for every G , they have limited expressiveness (e.g. not every singleton is recognizable). Rational subsets, on the other hand, are in general not closed under the

Boolean operations. However, they are expressive in the sense that they encompass all finitely generated subsemigroups.

In this talk, I describe a class of subsets of groups $H \wr F$, where H is finite and F is free. This class of subsets, which are dubbed *regular subsets*, has several appealing properties:

- Every rational subset of $H \wr F$ is regular.
- Emptiness and membership are decidable for regular subsets.
- The regular subsets are closed under Boolean operations.
- Regular subsets can be characterized using MSO over the Cayley graph of the free group. Via Rabin's theorem, this yields decidability of a number of properties. For example, it is decidable whether a given regular subset is recognizable. In particular, it is decidable whether a given finitely generated subgroup of $H \wr F$ has finite index.

Moreover, these constructions yield an elementary algorithm to decide membership in a given rational subset of $H \wr F$. This answers an open problem from [2]: Therein, it was shown that membership in rational subsets of $H \wr F$ is decidable, but it was left open whether this problem is primitive recursive. Another consequence is that not only membership in rational subsets is decidable, but emptiness of any given Boolean combination.

Note that such a notion of regular subsets is unlikely to exist for much more general wreath products $K \wr G$: In order for membership in rational subsets of $K \wr G$ to be decidable, either K or G has to be a torsion group [2] and there is evidence that G has to be virtually free [2].

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4 Open problems

4.1 Asymptotics of words in partially commutative groups

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Find methods of estimating the size of naturally occurring subsets of elements of partially commutative groups (e.g. cyclically reduced; with no left divisor in a given parabolic subgroup).

Articles containing examples of existing results along these lines are listed in the bibliography below. These all apply to the class of partially commutative groups which map canonically onto braid groups.

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4.2 Open problems for integral matrix groups

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Problem 1. Let $(T_1, \dots, T_m)$ and $(T'_1, \dots, T'_m)$ be two lists of rational matrices. The *multiple integral conjugacy problem* asks to decide if there exists $g \in \mathrm{GL}(n, \mathbb{Z})$ satisfying $g^{-1}T_i g = T'_i$ for $1 \leq i \leq m$ and, if so, then to determine one such g . Sarkisyan (1979) proved that this problem is decidable, but no practical or efficient algorithm is known.

Problem 2. Let $U, V \leq \mathrm{GL}(n, \mathbb{Z})$ be two unitriangular groups. The *subgroup integral conjugacy problem* asks to decide if there exists $g \in \mathrm{GL}(n, \mathbb{Z})$ satisfying $g^{-1}Ug = V$ and, if so, then to determine one such g . Grunewald & Segal (1980) proved that this problem is decidable. Still open is the problem to determine a practical or efficient algorithm for this purpose.

Problem 3. Let T be an invertible rational matrix. Eick, Hofmann and O'Brien (2019) exhibited a practical algorithm to compute a finite set of generators for the centralizer $C_{\mathrm{GL}(n, \mathbb{Z})}(T)$. As this centralizer is an arithmetic group, it follows that it is finitely presented. Develop a practical method to determine such a finite presentation.

4.3 Deciding whether a finitely generated subgroup has finite index

Ilya Kapovich (City University of New York, US)

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Problem. Let $\mathcal{G}$ be a “reasonable” class of finitely presented groups with solvable word problem. [E.g. RAAGs, mapping class groups, toral relatively hyperbolic groups, limit groups, 3-manifold groups, $C(4) - T(4)$ small cancellation groups, etc]

Let $G \in \mathcal{G}$ be a group given by a finite presentation $G = \langle X | R \rangle$.

1. Is there an algorithm that, given a finite set of words $v_1, \dots, v_k \in F(X)$ generating a subgroup $H = \langle v_1, \dots, v_k \rangle \leq G$, decides whether or not $[G : H] < \infty$?
2. A variation of the same problem: Is there an algorithm that, given a finite set of words $v_1, \dots, v_k \in F(X)$ generating a subgroup $H = \langle v_1, \dots, v_k \rangle \leq G$ such that it is known that H is quasi-isometrically embedded in G , decides whether or not $[G : H] < \infty$?

Note. It is known that for $\mathcal{G}$ being the class of word-hyperbolic groups, problem (1) is in general undecidable (because of counter-examples given by the Rips construction) but problem (2) is decidable.

4.4 Distinct Baumslag-Solitar groups in the same one-relator group

Olga Kharlampovich (The City University of New York, US)

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Let p, q, r, s be different prime numbers. Can a one-relator group contain $BS(p, q)$ and $BS(r, s)$ at the same time?

4.5 Membership problems for groups of unitriangular matrices

Markus Lohrey (Universität Siegen, DE)

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In a recent paper, Colcombet, Ouaknine, Semukhin and Worrell [On reachability problems for low-dimensional matrix semigroups, arXiv 2019. <https://arxiv.org/abs/1902.09597>] proved that the subsemigroup membership problem for Heisenberg groups is decidable. The n -dimensional Heisenberg group consists of all integer matrices where all entries on the main diagonal are one, and all entries that do not belong to the main diagonal, to the first row, or to the last column are zero. This result leads to the question whether the following two problems are decidable as well.

- the subsemigroup membership problems for groups $UT_n(\mathbb{Z})$ of n -dimensional unitriangular integer matrices (matrices where all entries on the main diagonal are one, and all entries below the main diagonal are zero),
- the rational subset membership problem for Heisenberg groups (it is known that the rational subset membership problem for $UT_n(\mathbb{Z})$ is undecidable if n is sufficiently large).

4.6 Is there an algorithm to compute the stable image of an endomorphism of a free group?

Enric Ventura Capell (UPC – Barcelona Tech, ES)

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Problem. Is there an algorithm to compute the stable image of an endomorphism of a free group?

Discussion. Let F be a finitely generated free group and let g be an endomorphism of F , given by the images of a free basis of F . The stable image of g , denoted $\text{Im}(g^\infty)$, is defined as the intersection of $\text{Im}(g^n)$ for all $n > 0$. It is known that this stable image is always finitely generated (in fact, with rank bounded by that of F). The problem consists on computing a free basis for $\text{Im}(g^\infty)$ from the given g .

One can easily compute recursively the Stallings graph (and so a free basis) for $\text{Im}(g)$, $\text{Im}(g^2)$, $\text{Im}(g^3)$, etc. And it is not difficult to see that the Stallings graph for $\text{Im}(g^\infty)$ is a subgraph of $\text{Im}(g^n)$ for some big enough n . What remains is to be able to decide how tall must we go up this tower of graphs and, whence there, how to choose the appropriate subgraph (out of the finitely many ones).

Inspecting the example $a \mapsto a^2$, $b \mapsto b$, (with $\text{Im}(g^\infty) = \langle b \rangle$), it seems that the problem is about detecting which parts of the graph grow to infinite, and cut them in finite time. Maybe the problem is related to the following question: can we define a dynamic notion of stable image including the points at infinity? (in the previous example, this extended stable image should be something like “ $\langle b, a^\infty \rangle$ ”).

The answer to this problem has a direct application: the computability of the fixed subgroup of arbitrary endomorphisms (the corresponding problem for automorphisms has been solved making strong use of train track techniques).

4.7 Rational subsets of Baumslag-Solitar groups $\text{BS}(1, q)$

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Background. The motivation for my problem comes from rational subsets of Baumslag-Solitar groups $\text{BS}(1, q)$ (see abstract 3.27 for a definition of rational subsets): If the answer to the problem is *yes*, then this yields a notion of regular subsets of $\text{BS}(1, q)$ that has similar properties as the regular subsets of wreath products $H \wr F$ as described in abstract 3.27. In particular, a positive answer would imply that membership in rational subsets of $\text{BS}(1, q)$ is decidable. Even more: Emptiness of given Boolean combinations of rational subsets would be decidable.

Setting. Consider the ring $\mathbb{Z}[\frac{1}{q}]$ and its additive submonoid $\mathbb{N}[\frac{1}{q}]$, which consists of all numbers $a = \sum_{i=-m}^n a_i q^i$ for some $m, n \in \mathbb{N}$ and $a_{-m}, a_{-m+1}, \dots, a_n \in \{0, \dots, q-1\}$. This representation is unique if we require that $a_{-m} > 0$ or $m = 0$ and also $a_n > 0$ or $n = 0$. In this situation, we represent the number $\sum_{i=-m}^n a_i q^i$ by the word

$$a_{-m} a_{-m+1} \cdots a_{-1} \bullet a_0 \cdots a_n$$

over the finite alphabet $\Sigma = \{0, \dots, q-1, \bullet\}$. Here, the symbol $\bullet$ can be thought of as the radix point. Let $\iota: \mathbb{N}[\frac{1}{q}] \rightarrow \Sigma^*$ be the map that yields the word representation of each number. We call a subset $A \subseteq \mathbb{N}[\frac{1}{q}]$ *automatic* if $\iota(A)$ is a regular language.

Problem. Suppose $A \subseteq \mathbb{N}[\frac{1}{q}]$ is automatic. Is then A^* , the submonoid generated by A , effectively automatic? Here, *effectively* means that given an automaton for $\iota(A)$, one can compute an automaton for $\iota(A^*)$.

Discussion. If A is in fact a subset of $\mathbb{N}$ (meaning only non-negative powers of q have non-zero coefficients), then this is well-known to be true: Every submonoid of $\mathbb{N}$ is ultimately periodic and thus automatic (and if given an automaton for $\iota(A)$, standard methods yield an automaton for $\iota(A^*)$). This means, if $A \subseteq \mathbb{N}$, then even the assumption that A be automatic is not needed for automaticity of $\iota(A^*)$. In the general case $A \subseteq \mathbb{N}[\frac{1}{q}]$, this assumption cannot be dropped: There exists a submonoid of $\mathbb{N}[\frac{1}{q}]$ that has an undecidable membership problem and is thus not automatic.

5 Discussion on future directions

5.1 Results of the plenary discussion

On the last day, there was a plenary discussion, moderated by Alexei Myasnikov, on future topics of research on Algorithmic Problems in Group Theory. This section provides a (somewhat restructured) short summary on the directions suggested by the participants.

1. Properties of algorithms
 - a. What is the *complexity* of problems that are known to be decidable?
 - b. A currently active field in algorithmics is *fine-grained complexity*, which studies the degrees of polynomials in polynomial time algorithms.
 - c. Which problems have *practical* algorithms?
2. Equations: Solvability & estimates on solutions
 - a. Diophantine problem for braid groups
 - b. Diophantine problem for the Grigorchuk group
 - c. Diophantine problem for $B(n, m)$ (Burnside groups)
 - d. Linear groups:
 - i. Particular equations
 - ii. Knapsack problem (and other parametric equations)
 - e. Word equations with length constraints (which are examples of non-regular constraints)
3. Isomorphism problems
 - a. Isomorphism problem for f.g. nilpotent groups.
 - b. Isomorphism problem for f.g. polycyclic groups.
 - c. What about quasi-isomorphism?
4. Reachability problems
 - a. Post-Correspondence Problem for free groups: Given $(u_1, \dots, u_n)$ and $(v_1, \dots, v_n)$ in F , does there exist a word $w(x_1, \dots, x_n) \neq 1$ so that $w(u_1, \dots, u_n) = w(v_1, \dots, v_n)$?
5. Reductions between problems
 - a. For each group G , study reductions between decision problems: Which problems can be reduced to which, and with which kinds of reductions?
6. Formal languages
 - a. Word problems: Alexei Myasnikov suggested that rather than formal language classes strictly from computer science (regular, context-free, context-sensitive, etc.), one should consider classes arising from algebra.
 Murray Elder pointed out that people had done work on this. An example is the notion of G -automata [3], where G is a group acting like a “counter”. For instance, if $G = \mathbb{Z}^d$, then one obtains blind d -counter automata; if G is a free group of rank ≥ 2 , G -automata are equivalent to pushdown automata. In a G -automaton, each transition is labeled by a letter from the alphabet to read, and a group element to multiply the counter by. A run of the automaton is valid if the product of its group elements is $1 \in G$. The resulting language classes have appealing closure properties: For instance, whether the word problem of a group H is accepted by some G -automaton does not depend on the chosen generating set for H .
 These automata have also been generalized to monoids and have been studied under the name *valence automata* [2].

- b. Word problem via multiplication tables: Gilman proved a group G has a context-free multiplication table if and only if G is word hyperbolic [1].

Here, a *multiplication table* (MT) is a language of triples of group elements written in some regular normal form. A triple (u, v, w) belongs to the language if $uvw = 1$ in the group. In other words, the entry in row u and column v is w . So we can ask: Which groups have a regular MT (the finite ones) or an indexed MT (many groups do, the Heisenberg group, solvable Baumslag-Solitar groups, etc.), a poly-context-free MT, or an MT accepted by a G -automaton?

- c. Rename EDT0L: Should we find a different term for EDT0L languages? It was suggested to call them “rationally endomorphic” and to call ET0L “non-deterministic rationally endomorphic”.

7. Probabilistic aspects

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Users and automated driving systems: How will we interact with tomorrow's vehicles?

Edited by

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Abstract

In today's vehicles, the driving task is increasingly often shared between the driver and the vehicle. It is expected that this will become the norm rather than the exception in the foreseeable future: on some road segments the driving task will be automated, and drivers will become passengers. Thus, we need to design automotive user interfaces with partial automation, and even full automation, in mind. This was the underlying motivation to propose and run this seminar. In the Dagstuhl seminar, six inter-related key research questions were addressed: First, “how to design user interfaces to support the driver's transition back from the role of passenger to the role of driver?”. Second, “how user interfaces can support work and play for drivers while the vehicle is controlled by automation?” and third “how we can support communication between all transportation users, from drivers, to pedestrians, to bicyclists?”. Furthermore, we explored “how the design of automotive user interfaces affects trust in automation?” and finally discussed “how novel technologies, such as augmented reality displays or advanced spoken dialogue systems can support drivers, and others, in and around partially-, and fully-automated vehicles?”. As an umbrella topic, the question “how all of these questions relate to the legal aspects of deploying automotive user interfaces?” received also high attention and lively discussions amongst participants. Dagstuhl seminar 19132 is a follow-up of the 2016 Dagstuhl seminar 16262 “Automotive User Interfaces in the Age of Automation” and brought (again) together researchers from HCI, psychology, cognitive science, human factors, automotive industry/OEMs and people active in the standardization process to discuss critical problems on the way to automated driving.

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1 Executive Summary

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For much of the time since the invention of the automobile, human-machine interaction (HMI) in vehicles was reasonably clear: drivers controlled the vehicle by manipulating the steering wheel, pedals, and a few levers, buttons, or similar mechanical input devices [2]. They received information about the state of the vehicle through dials, warning lights, and sounds. And, they interacted with a relatively simple in-vehicle entertainment device: the radio, or perhaps the cassette- or CD player.

It is true that the number of input and output devices increased dramatically over the years — for example in the late 1950s, the Ford Edsel was described as a “devilish assemblage of gadgets” [5]. The Edsel was soon out of production, but the number of gadgets kept climbing. It is also true that drivers sometimes operated the vehicle when they were tired, and fell asleep at the wheel. Other times they consumed too much alcohol, and were not able to safely control their vehicle. Yet, the basic concepts of human-machine interactions in the vehicle were well-defined for research and development purposes. The driver’s primary task was to drive: keep the vehicle on the road, avoid crashes, maneuver through traffic, and ultimately reach a destination. The driver also engaged in secondary tasks, such as manipulating the radio, as well as other non-driving-related tasks, such as talking to passengers, and eating. Creating good human-machine interfaces meant supporting the driver in these primary and secondary tasks, while assuring safety for everyone on the road.

Then, with the introduction of mobile computing devices, engagement in secondary tasks, such as talking to remote conversants, as well as sending text messages, and manipulating the interfaces of various mobile applications, became a significant issue in cars. In a sense these distractions were the same as those that drivers faced with the myriad buttons in the Ford Edsel. But, there were differences too: the Edsel did not allow the driver to communicate to remote conversants, nor did it have a touch-screen with ever-changing content.

Today, we again find ourselves at a crossroads. Our cars have myriad buttons, as well as different mobile technologies, both for drivers and for passengers. But, additionally, the primary task of driving is often shared between the driver and the vehicle [9]. Most studies in distracted driving tend to focus on how non-driving activities serve as a distraction from the primary task of vehicle control. In the context of highly automated vehicles (HAV), driving will be the distraction from non-driving activities [6]. Sometimes, the vehicle can effectively take over the driving task, and we can expect that this will become the norm rather than the exception in the foreseeable future: the driving task will be automated, at least on some road segments, and the driver will become a passenger. Yet, in this same foreseeable future we can also expect that the vehicle will sometimes hand the driving task back to the driver, who will have to transition back from the role of passenger to the role of the driver [14], [18]. This is the new landscape of in-vehicle human-machine interaction, and it presents a number of research questions that we addressed in this Dagstuhl seminar. In the rest of this report, we introduce pre-workshop tasks and summarize the activities and outcome of the seminar. Automated traffic is a challenge not limited to the interaction between a human driver and an automated vehicle. Automated vehicles will be part of a mixed traffic with other traffic



■ **Figure 1** Traditional group picture of participants of seminar no. 19132 on the stairs of Dagstuhl castle.

participants of less or no automation. Also further traffic participants such as pedestrian and bicycles are part of this and requires a certain level of communication and recognition of the vehicles intention and actions among vehicles and the surrounding traffic participants.

Research questions tackled in Dagstuhl seminar 19132

1. **Handover:** One of the key questions in designing in-vehicle human-machine interaction for partially automated vehicles is, how can the vehicle safely hand back the task of controlling the vehicle to the driver. In the short term this is one of the most important questions for those designing vehicles with automation, because in the short term such vehicles will have to hand control back to the driver relatively often [14], [15]. We need to understand how the modality, conveyed information, and reliability of take-over requests (TORs), engagement in non-driving tasks, and motion perception can influence drivers performance in task switching in highly automated driving context [6].
2. **Trust:** Drivers must trust the automation features in order to take advantage of them [19]. We need to individually understand the trust in the individual actions of the vehicle starting out from assistance systems [21] to more automated functions [13], [20].
3. **Creating a place for work and play:** One important benefit of automation would be that drivers can become passengers, and thus use the time in the vehicle to either be productive (work), or relax (play). How can human-machine interaction for automated vehicles be designed, such that drivers can take advantage of their newfound freedom from driving [9], [12]? How can we do this, taking into account the physical and computational characteristics of the vehicle, as well as the potential for motion sickness?

4. **Communication between all traffic participants:** With the advent of automation, the transportation environment will include partially and fully automated vehicles. Yet, manually driven vehicles will remain for the foreseeable future, as will pedestrians, bicyclists, and other transportation users. For safe driving, all of these transportation users will have to communicate, but it is not yet clear how this can best be accomplished [16].
5. **Advanced technologies for in-vehicle HMI:** The technologies that are available for human-machine interaction are continuously improving. Two exciting technologies that will be worth examining in the context of automated vehicles are speech interaction (e. g. [8]), and augmented reality e. g. [11] and [10].
6. **Legal aspects of in-vehicle interfaces:** Automation, as well as the user interfaces built for partially and fully automated vehicles, will have to fit into the legal structures of the countries where the vehicles are used [7]. What are these structures, what do designers need to know about them, and how can they help develop the future legal structures?

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3 Pre-Workshop Tasks

In advance to the seminar we asked the participants some fundamental questions in the area of the seminar to be able to better prepare the Dagstuhl seminar and to ensure it is a valuable experience for all the participants. The following three questions were sent-out to participants and responses collected.

Suggested Readings

Question 1: “What is some publicly available work (e.g., a paper, an app, a prototype, etc.) created by someone else that you find very inspirational in your work related to the interaction with automated driving technology? Please send us one or two PDFs or references/links.”

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Work Authored by Seminar Participants

Question 2: “What is one (publicly available) work of yours (e.g., a paper, an app, a prototype, etc.) related to the seminar topic that you would like to share with fellow Dagstuhl seminar participants? Please send us a PDF or reference/link (two are also ok).”

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Research Questions

Question 3: “What do you consider to be the most challenging/interesting research question related to interaction with tomorrow’s vehicles? (If you have more than one question, that’s great, send them all..)”

The following list of categorized research questions (no particular order otherwise) was used to structure the seminar and initiate discussions in the field.

■ Trust calibration

- How can calibrated trust into automated vehicles’ capabilities be achieved by HMI design? (M. Baumann)
- What influences long-term trust development into and interaction behavior with automated vehicles? (M. Baumann)
- How to establish a purposeful user understanding of the usefulness and boundaries of the (semi-) autonomous driving system? (I. Pettersson)
- What are suitable strategies for long-term trust development? (J. Ziegler)
- How can you measure trust objectively? (G. Burnett)
- What is an appropriate level of trust? (G. Burnett)
- What HMIs can help in the development of calibrated trust? (G. Burnett)
- What factors will affect trust in automation? (B. Walker)

■ AV-driver/passenger interaction

- How can automated vehicles made cooperative team players for the drivers? (M. Baumann)
- How can automated vehicles interact smoothly with surrounding non-automated traffic? (M. Baumann)

- How to make sure that both are aware of the other in a correct way, also if there are changes over time? (C. Janssen)
 - If they can't "sit back and relax", how do we keep them alert and awake in an appropriate way? (C. Janssen)
 - Collaboration metaphor as a concept of driver-vehicle interaction in an autonomous vehicle. (J. Sodnik)
- **Ethical/legal issues**
 - What right do vehicles have to judge the competencies and limitations of their users? (L. Chuang)
 - What should go to ISO? (J. Krems)
- **System transparency, Explainable UI**
 - Should vehicles communicate their limitations to their users? How often, which, and how? (L. Chuang)
 - If things do go wrong and human assistance is needed: How can the driver be informed/warned correctly and timely? (C. Janssen)
 - Future vehicles will be equipped with a wide variety of automation features that provide differing degrees of automation of the dynamic driving task within different operational design domains. Individual vehicles are likely to be equipped with several such features, each with its own driver interface. How will the driver of the future be able to understand the capabilities and limitations of these systems? (S. Shladover)
 - Should automated vehicles be able to explain their behavior and if yes, at which level and how? (J. Ziegler)
 - How can the user be informed about decisions of the autonomous system? (N. Rußwinkel)
 - Implicit or explicit signals? (J. Krems)
- **User state assessment**
 - How to correctly assess both the human's and the systems attention, understanding of system functioning, situational awareness? (C. Janssen)
 - How to evolve driver/car sensing & communication? (I. Pettersson)
 - How important is it to correctly detect driver's state (physical and mental)? (J. Sodnik)
 - How can/should the driver be made aware of the status of the world and the state of the (automated) vehicle? (B. Walker)
 - The need for new types of information means that we need new technological approaches: Driver Monitoring to determine driver state for decision making concerning driver ability, availability, receptivity and what we do with that information? (J. Harbluk)
- **User experience**
 - How to balance "safety" with "pleasure" and being relaxed. That is: if cars get better, at what stages can people truly "sit back and relax"? (C. Janssen)
 - How to balance between branding vs. consistency? (I. Pettersson)
 - What is an acceptable level of notifying drivers with ads or location-based recommendations (POIs, activities, services etc.) and how should they be presented? (J. Ziegler)
 - Can automated vehicles be „creepy“ and for whom? (J. Ziegler)
 - In a shared economy with no individual car ownership, what is the concept of a car manufacturer to gain customer loyalty? (A. Riener)

■ Mode confusion

- How to prevent mode confusion & misuse? (I. Pettersson)
- How can the driver interfaces be designed to support safe and proper usage of these systems (while also deterring or preventing improper usage)? (S. Shladover)

■ Driving safety

- Is driving behavior safer when using automated functionalities in the vehicle? (J. Sodnik)
- How different is driving distraction between automated and conventional vehicles? (J. Sodnik)
- Safer road traffic, especially for young people. (C. Sutter)
- Traffic safety issues in traffic 5.0. (C. Sutter)
- How to make sure that AI works in automated vehicles as designated? (... will not have seen many situations/scenarios in training data before; how to identify edge cases?) (A. Riener)
- How do we assess safety? How will we evaluate this? How will we know when we have accomplished this goal? (J. Harbluk)

■ Human individuality, user preferences

- HMI concepts for urgent take-over situations – can one concept fit all driver groups (age, gender, experiences)? (J. Sodnik)
- How will different users respond to varying types of monitoring? (G. Burnett)
- How can an HMI adapt accordingly based on user data? (G. Burnett)
- How can we predict the impact of cultural background on UX design? (G. Burnett)
- How can we objectively assess cultural differences for future vehicle designs? (G. Burnett)
- How will automated vehicles help/hinder persons with disabilities (as drivers, passengers, pedestrians, etc.)? (B. Walker)
- How to address human individual preferences (vehicle dynamics, driving speed, overtaking behavior) in (fully) automated vehicles? (A. Riener)
- Will it be possible for the individual to parametrize the driving algorithm? (A. Riener)
- How do we best characterize the mental models of the users and the vehicles so that we can design to support successful and safe interactions? (J. Harbluk)

■ Future research directions

- How do we “accurately” predict the short-term/long-term capabilities/limitations of AV technology so that we can better direct our research efforts? (B. Donmez)
- Predictive policing in traffic safety (cf. DDACTS). (C. Sutter)
- What factors will affect uptake/adoption of automated vehicles? (B. Walker)
- The need for new methods: What to measure, how to measure and the interpretation of new complex & types of data? (J. Harbluk)

■ Transition of control

- What information do people need for transitions in/out control? (G. Burnett)
- What is an acceptable level of human performance in resuming control? (G. Burnett)
- What exactly, is a handoff/takeover request and how the heck will the engineering/design match human capabilities? (B. Walker)
- In what situations should the control be handed to the driver and in what situation the driver would be incapable to take control? (N. Rußwinkel)
- What are the relationships between usability and inadvertent operation for transition HMIs? (G. Burnett)

■ Motion sickness

- What HMIs can alleviate motion sickness? (G. Burnett)
- How can we predict motion sickness? (G. Burnett)
- Is yawning an accurate predictor for motion sickness? (A. Riener)

■ Situation awareness

- What role can multimodal interfaces play in automated vehicles, especially related to situation awareness? (B. Walker)

■ Remote operation, teleoperation

- Teleoperation has the potential to employ L5 functionality already at L3+. What needs to be done in order for the passenger to accept remote operation by a human (instead of an automated driving function)? (A. Riener)
- How to design the user interface for the remote operator to get full awareness of the situation? (A. Riener)
- Will there be a bi-directional communication between passenger and remote operator to enhance operation quality and improve on trust/acceptance? (A. Riener)

4 Overview of Talks

4.1 Striving Towards Safe Collaborative Interactions in Automated Driving

Ignacio J. Alvarez (Intel – Hillsboro, US)

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I am excited to take part in this seminar because it aligns with my user-centered philosophy to automated driving. I see the purpose of automation in augmenting the human driving potential to achieve safer and more enjoyable driving experiences. And I am a firm believer that intelligent connected automated vehicles is the solution to provide safer and more effective means of transportation to fulfill society needs. My work is focused on the development of intelligent automated driving systems and the development of tools to create human – system collaboration which include simulation environments, HMI prototyping, and research processes. Some of the biggest challenges we currently face are how to design automation systems that understand humans in all their complex needs but also how can we design interfaces that allow users to understand automated driving systems, their decisions and operational envelopes. The reconciliation of human vs system judgment is a first step to solve the human-in-the-loop conundrum. The next step is to develop vehicles that adapt to the particular user needs while at the same time guaranteeing societal needs which might come at the expense of the individual. The first and most important interaction challenge in partial or full automation we need to solve is safety and the calibrated trust interactions it requires to work collaboratively. To this end Intel has released an open-source library on responsibility sensitive safety that will enable researchers to integrate it into automated driving systems and simulators to study the required user experience needs from the human end. I expect the seminar will help us share tools, methods and results. I see the time here as critical to define a common strategy that through collaboration in our next research phases will give us the answers and solutions we need to influence the future of the transportation industry.

4.2 Vehicle Automation as Team Player

Martin Baumann (Universität Ulm, DE)

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The technological progress in recent years makes the vision of fully automated vehicles in the near future plausible. These vehicles will change the driver's role dramatically. They will take over many if not all of driving tasks for some or even all the trip time. By definition these vehicles are able perceive their environment, assess the situation and the possible actions and carry out the actions on their own. Consequently, these vehicles constitute a second autonomously acting intelligent agent next to the human. This creates the danger of so called automation surprises, that is the human in the vehicle does not understand, what the automation is currently doing, why it is doing this, and what it is going to do next. Such a lack of understanding may lead to safety critical interventions by the human, to low trust into and low acceptance of such systems. This in turn will significantly reduce the possible positive impact such systems can have on traffic safety, efficiency and the human drivers' comfort. To avoid such problems it is of pivotal importance that the vehicle can act as a team player to the driver. For this it is necessary that the automation possesses the ability to communicate with the human inside the vehicle to achieve a shared situation representation between human and machine agent. On this basis the human driver is able to predict the automation's action and to direct the automation in case the situational characteristics require it. This provides the basis for successful trust calibration and in the end a successful, efficient and satisfying driver-vehicle cooperation.

4.3 Social Interaction of Vulnerable Road Users with Automated Cars

Susanne Boll (Universität Oldenburg, DE)

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We currently see the advent of automated driving. In the near future there will be mixed traffic scenarios in which vehicles with no, partial, and full automation will coexist and have to cooperate with traffic participants, including pedestrians and cyclists. Road traffic appears to be a highly regulated system in which agents act according to traffic code rather than their normative beliefs and values. Many interactions in urban traffic, however, are not or only weakly legally regulated and observed. They base on established social practices by social norms. There are many traffic situations (e.g., flashing when turning, overtaking or leaving a roundabout, narrow places where a lane ends on a multi-lane road, e.g., due to construction sites or obstacles) in which cooperative, reciprocal behavior is needed to avoid conflict.

Hence, we need to understand the effect that automated vehicles might have on the established interaction between traffic participants in urban traffic. How will automated and autonomous vehicles change social practices of cooperating in urban traffic scenario? How is social behavior changing in traffic with increasing numbers of automated vehicles? How much social behavior should an automated vehicle show for a successful cooperation in mixed traffic scenarios.

We aim to understand how the interaction between human and automated traffic participants changes social norms. We investigate in which way trust and respect among traffic participants change and a “dehumanized” traffic participant maybe be treated with less respect or forgiving as a human traffic partner. We are developing paradigms of interaction for a social signal for relevant traffic scenarios. The result of this part of our research will be intuitive and unambiguous cues that automated vehicles can give to surrounding traffic participants, such as pedestrians, cyclists, and drivers of non-automated vehicles.

4.4 The Future of Research in Autonomous Vehicles

Linda Ng Boyle (University of Washington – Seattle, US)

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Technology continues to revolutionize the way we travel. While a truly driverless society will most likely not occur in our lifetime, it is the promise of our future. As research moves forward, the limitations of the technology, the infrastructure and the human user will need to be considered for some time to ensure appropriate design, training and policies. Research in autonomous vehicles (ground transportation) benefit from insights from other domains that include manufacturing, health-care and aerospace. For example, in aviation, extensive work has been conducted in supervisory control [1], shared control [2], shared perception of risks, and shared understanding ([3], [4]). This includes interactions with the human pilot, co-pilot, traffic controller, and automation. Research questions need to take into account the context and the human operator’s goals when traveling (work, play or relax) as these will impact the operator’s ability to interact, trust, accept and use their transport system [5]. Qualitative as well as quantitative approaches are needed to account for “hand off” as well as “take over” issues [6], this needs to be considered from the system as well as the human’s perspective. Along with this, comparable test scenarios and test cases are needed to ensure that research is reproducible and repeatable.

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4.5 Designing New User Interfaces for Cars and Passengers

Stephen Brewster (*University of Glasgow, GB*)

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The amount of time spent traveling is on the rise: 3.7 million workers in the UK alone travel for two hours or longer every weekday [1], and this situation is mirrored across Europe, with 8.1 % of commuters traveling to different regions and 0.9 % commuting across borders [2]. The proportion of this time spent as passengers is increasing, thanks to new technologies such as driverless cars [3], a market expected to reach \$42 billion by 2022 [4]. Consequently, more people will be passengers wanting to fill their travel time usefully. The potential for technology to help passengers reclaim this lost time is impeded by 3 significant challenges:

- Confined spaces – These limit our interactions and force us to use small displays such as phones, tablets, dashboards, and seat-back/rear-seat systems [5].
- Social acceptability – We may be sharing the space with others, whom we may or may not know, inducing a pressure to conform which inhibits technology usage.
- Motion sickness – Many people get sick when they read or play games when in motion. Once experienced, it can take hours for symptoms to resolve and productive time is lost.

VR/AR Head Mounted Displays (HMDs) have the unique possibility to overcome these challenges in ways no other technology can, but only if bold new research is undertaken to unlock their potential. ViAJeRo will perform the breakthrough research needed in HCI and neuroscience to enable passenger usage of XR HMDs, with the underlying goal of making more effective, comfortable and productive use of travel time. If people are productive during their commutes, a better work-life balance can be achieved (e.g. spending less time at work); if they can consume media then they can support the creative industries and the content they produce. Our research at Glasgow will expand the XR market, allowing for new applications, services and peripherals to be developed, and provide the tools and techniques to allow European developers to lead the way in passenger experiences.

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4.6 Why do we Travel? On the Importance of Understanding the Drivers of Human Mobility

Duncan Brumby (University College London, GB)

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Humans have a deep and intrinsic need for mobility. We travel great distances to gather for work and leisure. We run errands for daily essentials, but sometimes just for something to do. We eagerly await the next vacation to a distant shore as a reward for our toil. We quickly become bored and restless staying in the same place, so much so that being locked up in prison has long been used as a punishment for committing crime.

Over the past 100 years, the car ushered in an era that has given many people the freedom to travel great distances in a relatively comfortable and private space. This personal mobility comes at the cost of requiring a trained, alert and responsible driver. Mass public transportation systems on the other hand delegate this responsibility to a single professional driver, freeing the passengers to sit back and enjoy the ride. This is all well and good but is often seen as both inconvenient for people because of the constraints imposed by an inflexible travel schedule as well as being undesirable because of travelling in a shared space surrounded by strangers.

Self-driving cars are appealing because they promise a way to break this trade-off between driving a car and riding public transportation: the freedom of personalised mobility in a comfortable private space without the need to take responsibility for the actual driving. A privilege once reserved for the elite few becomes accessible to the many – a chauffeur for everyone!

A fantastical future is imagined by the arrival of self-driving cars. Personal mobility will be enabled among those previously excluded from driving: from children and teenagers, to the elderly and people with disabilities. Self-driving cars will reduce the cognitive, attentional and emotional demands of driving. This will free drivers from the monotony of the road so that they can focus on more valuable activities instead, whether that be work, rest, or play. The number of accidents on the road will be cut and there will be substantially improved traffic flow that will rid populated areas of the scourge of traffic congestion. Drink driving, driver distraction, road rage, and driver fatigue, all of these things will become problems of the past, or so we are told.

This technological utopianism is mirrored by a dystopian vision of the future. Once liberated from driving, will this bring just yet more time to be filled in the day looking at a screen; is this really more interesting and rewarding than driving? What of the people who make a living out of driving, the taxi drivers and truckers, what opportunities will be made for new and interesting work to do instead? Which journeys will remain necessary in the future?

The Internet has already begun to have an impact on human mobility. The rise of remote work, and greater flexibility over when and where work is done means people do not need to travel to the office everyday when a virtual meeting will do just as well instead.

So, just as the arrival of the car 100 years ago changed the way that we lived in the past, the arrival of self-driving cars has the potential to have a profound impact on the way that we live in the future. As a first step, it is important to understand why we travel and what drives human mobility. Without understanding this there is a real risk that people will simply fail to adopt and use this new technology because it is not needed or wanted.

4.7 Navigate, Automate, Levitate: Human-Machine Interface Design for Future Vehicles

Gary Burnett (*University of Nottingham, GB*)

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A modern vehicle has been likened to a 'computer on wheels' utilizing a wide range of computing and communications-based technologies aiming to improve safety, efficiency, inclusivity, and the comfort/experience of users. It is commonly predicted that future vehicles will include more automation functionality with some researchers now anticipating the science fiction vision of flying cars. Users of such cars will demand fundamentally different experiences compared with the drivers and passengers of today. In this respect, a plethora of Human Factors issues will be central to defining what that experience will be, including fundamental topics such as trust, motion sickness, user-system transitions, behavior change, etc. At the University of Nottingham, we have conducted many studies since the 1990s investigating how people can and could/should interact with future vehicles. Initially, the focus of research was on distraction issues for the now ubiquitous in-vehicle navigation systems – and many of our experimental studies have had a direct influence on the development of the interfaces we now take for granted (e.g. [2]). More recent work has considered the design and evaluation of the Human-Machine Interface (HMI), often in the context of a vehicle which is not always being human-driven – including the use of natural language interfaces [4], augmented reality [1] and gesture-based interaction [3]. A particularly important study [5] we have recently conducted with 52 people who experienced a SAE Level 3 vehicle for a week demonstrated the myriad of problems associated with the resumption of the driving task following a long period of automation.

As for 2016 when I was here, I have benefited immensely from the in-depth and extended conversations with colleagues on human-centered design issues for future vehicles. I have learnt about many interesting theories, methods, studies that can inform our work and look forward to working closely with my Dagstuhl friends in years to come.

Keywords: Driving, Automation, Human-Machine Interface

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4.8 From Control to Partnership: Challenges of User-Vehicle Communication

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With increasing vehicle automation, our interaction with vehicles is steadily transitioning from controlling them to partnering them. More interestingly, this represents a directionality shift in communication. In a control relationship, information flows primarily in one direction. The human is responsible for perception, which proceeds cognition, resulting in fine motor limb actions that are communicated to the vehicle in order to generate powerful joint outputs. The vehicle primarily communicates to the user in terms of its actions and the user is responsible for determining how compatible this is to their intent. Automation means that the vehicle assumes the responsibility for setting intent for vehicle operations, especially at the levels of control and tactical. If the vehicle sets intent, it too determines what constitutes an error that must be corrected. All of this can proceed, so long as vehicle automation is capable of estimating error and correct for it accordingly. An automated vehicle could be incapable for correcting an error that it has accurately discerned. We could choose to put such instances aside because it is debatable as to whether users can, themselves, correct for such errors even if they were in control.

Instead, I raise for study the following instance, namely where vehicle automation realizes its incapability to perceiving/estimating error and communicates this inability to the human. This could occur either because the vehicle's sensors are unreliable, or the vehicle is incapable of setting intent or does not own the prerogative to do so. In the first case, the vehicle should submit a request to rely on the user's sensors. This request might not be noticed, either because the user is especially engaged in what they are doing [1], [2] or because they do not expect a request in the first place [3]. The latter could be mitigated by providing a compelling cue that sustains redirected attention for longer than usual durations [4]. The complexity, however, lies in that we have to develop two-way communications from the vehicle to the user and from the user to the vehicle, whereas, it used to be a simple and unambiguous one-way communication system. Furthermore, aspects of system reliability might have to be effectively communicated to the user to instill a sense of authority and perceived responsibility [5]. Without communicating uncertainty or reliability, it is possible for the user to assume that vehicle automation is assuming the responsibility of estimating error for a given aspect of driving when it is no longer doing so [6].

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4.9 Driver Mental Models of Automation

Birsen Donmez (University of Toronto, CA)

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With vehicles becoming highly automated, the driver’s role is changing from one of direct control to one of coordination with and supervision of automation. These new driver tasks are arguably more cognitively complex than tasks associated with direct vehicle control. Mental models allow people to explain how a system works, predict the outcomes of their actions, hypothesize where certain features might be accessed within the system, and interact with the system in general. Supporting the development of accurate driver mental models becomes increasingly important as more complex automation systems are being introduced or are planned to be introduced to the vehicle.

In order to support accurate driver mental-model formation, the research and the design community need a better understanding of how different automated systems function currently and will function in the future. For example, unexpected failure events occur when the automation turns off, or acts in an unforeseen manner, thereby requiring the driver to regain manual control from the automation. Some of these events may be predictable by the driver (i. e. through external cues indicating that a failure may occur) or unpredictable. Our research focuses on how these two different failure types affect driver monitoring and take-over quality. In general, researchers and designers need a complete understanding of how and why vehicle automation failures may occur in order to design interfaces that can support driver mental models.

We also need to understand what driver behaviors can be considered appropriate and safe in an automated vehicle context. There are no commonly accepted standards or metrics to assess the risks associated with different driver behaviors in automated vehicles. For example, two seconds is the threshold adopted by government agencies for risky off-road glances [1], but this threshold is based on research conducted in non-automated vehicles.

Keywords: mental models, automation failures, standards, vehicle displays

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4.10 Cooperative, Highly Automated Systems to Bridge the Unsafe Valley of Automation

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After over 40 years of intense and increasingly interdisciplinary research, the incremental revolution towards automated traffic systems has successfully started, but is far from finished. Partially automated systems are successfully on the road, but in low numbers. A hype towards autonomous systems has created some progress in the abilities of vehicle automation, but has also created false expectations which can lead developers and drivers into an unsafe and potentially deadly valley of automation. The Tesla and Uber accidents might only be a forerunner to a major series of safety problems, which will slow down or even stop the incremental revolution. To solve this problem, partially and highly automated systems should be designed not for maximum autonomy, but for a maximum of cooperativity between machines and humans, between the machines and not to forget, between humans and humans. This has to include traffic participants without automation or other technological support. In addition to cooperativity and performance, a maximum of safety, resilience, usability and joy of use should be designed, built and tested into these complex traffic systems.

Key challenges regarding the users, vehicles and infrastructure will be:

- Safe, resilient and human-compatible automation and V2X capabilities, which have a SIL level (Safety Integrity Level) high enough for partially, highly and fully automated driving.
- Clear modes of automation, which combine the (SAE- and BAST)-levels of automation with the scientific stages of automation and with layers of cooperation, providing a good inner and outer compatibility leading to an intuitive understanding and interacting with the automation. Open questions here are, whether 2, 3 or 4 different modes satisfy the balance between performance, flexibility, controllability and usability.
- Good HMI design for those modes, which combine
 - The need of the OEMs to differentiate themselves.
 - The need of users and the public to have standardized pattern, that allow a safe operation and change of vehicles.

The key challenges for the community are:

- In over 40 years of research, a tremendous amount of knowledge and wisdom has been generated, of which the first 30 years are not so easy to access. To avoid that the wheel has to be re-invented all the time, and all the errors and mistakes replicated with them, the more experienced colleagues should make the old papers available also online, and report not only their successes, but also their failures. The younger colleagues should not only do a Google search with a cut-off-line of a few years, but root themselves a bit deeper into history, and patiently encourage their older colleagues to discuss the past successes and failures.
- As the traffic systems get more complex, more people are needed to handle the depth of the details, but also more people are needed to handle the width of complexity in a systematic way. Interdisciplinary and system thinking have a good chance to be the key to success, which needs a certain openness and willingness to go beyond the “own” community and integrate technology, people and organizations. In Dagstuhl, there was

already a good openness, and especially a good mixture of technical, human factors and design expertise. The next disciplines that should be integrated are the colleagues understanding the legal system, the infrastructure and the business models.

4.11 Human-Automated Driving System Interaction: New Roles, New Models, New Methods

Joanne Harbluk (Transport Canada – Ottawa, CA)

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The relationship between the user and the vehicle is very much changed from what it was only a short time ago. As a society, we are now asking questions about what it means to be a driver/user/human and what it means to be a vehicle. The vehicle/human relationship is now characterized as a cooperative one rather than the vehicle merely being a tool used by humans. This new relationship leads us to ask new questions of both humans and vehicles. And of course, we face many new challenges. How do we design for mutual cooperation and safety during complex interactions such as requests to intervene (for handover or shared control) when requested by the vehicle or the human? How does this interaction change over the various forms of automated driving? How do we support these?

New challenges:

- The need for new types of information means that we need new technological approaches: Driver Monitoring to determine driver state for decision making concerning driver ability, availability, receptivity and what we do with that information?
- How do we best characterize the mental models of the users and the vehicles so that we can design to support successful and safe interactions?
- The need for new methods: What to measure, how to measure, and the interpretation of new complex & types of data?
- Safety: How do we assess safety? How will we evaluate this? How will we know when we have accomplished this goal?

Thank you to our organizers, Susanne, Andreas, Andrew & David, for this amazing opportunity to gather with old and new friends, to think deeply, and to consider these important issues from many perspectives. And thank you to Schloss Dagstuhl for taking such good care of us all this week making this a wonderful experience.

Joanne Harbluk

4.12 Dynamic Humans, Machines, and Contexts in Human-Automation Interaction

Christian P. Janssen (Utrecht University, NL)

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Different types of (semi-)automated vehicles have different abilities and technological features, such as adaptive cruise control and lane assist. The ability to use these features depends

on the context and the user. The contexts of driving can change dynamically, for example due to weather or roadworks, and limit the ability of the vehicle to use automated features (e.g. lane assist). The correctness of the user's understanding of the system can also change dynamically, for example they might miss an alert that tells them that a system goes off ([1], [2]). These dynamics of context, user and vehicle make it hard to predict over time what the exact system state is, and requires formal models and frameworks to do so [3].

My perspective is therefore that it is important that these dynamics are taken into account in the design and evaluation of new technologies. To minimize accidents, stake holders should not make the incorrect assumption that users/drivers know exactly what the system does at all times. Human user and non-human automated system have a need to understand each other's perspective. For the non-human automated system in particular, this would require maintaining some sort of user model of the person.

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4.13 Cross-Cultural Driving Styles

Wendy Ju (Cornell Tech – New York, US)

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As we consider future interactions with automation, it is important to consider how we will co-construct how interactions should work with real users in real environments facing real constraints. This requires novel design and simulation methods, which allow us to observe how people will behave in various alternative futures. The Future Autonomy Lab at Cornell Tech is looking at how to design interaction with autonomous systems, novel simulation methods, cross cultural issues in driving, field research techniques for human-vehicle interaction, and dataset generation for machine learning.

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4.14 Human Factor Issues for Vehicle Automation

Josef Krems (TU Chemnitz, DE)

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Prototypes of highly automated cars are already being tested on public roads in Europe, Japan and the United States. Automated driving promises several benefits such as improved safety, reduced congestions and emissions, higher comfort as well as economic competitiveness and enhanced mobility in the context of demographic changes. These benefits are often claimed on the basis of a technology-centered perspective of vehicle automation, emphasizing technical advances. However, to exploit the potential of vehicle automation, human-machine-related issues are considered a key question, shifting the perspective towards a human-centered view on automation. Research on human-automation interaction pointed out already “ironies of automation” that can undermine the expected benefits. Relevant issues mainly relate to the role change in various levels of automation, i.e. mode awareness and transitions from manual to automated control, reduced vigilance due to the monotony of supervising tasks in partially automated driving, changes in attention allocation and engagement in non-driving tasks, out-of-the-loop unfamiliarity resulting in reduced situation awareness, mental models of automation, trust calibration as well as misuse and overreliance. For reducing negative automation effects and enabling successful human-automation interaction, feedback on automation states and behaviors is considered a key factor. The focus of our own research is on take-over-requests, communication between highly automated cars and other road users, and on comfort and acceptance. For example, we try to identify pedestrians intentions by analyzing micro-trajectories based on motion-tracker data. Another open issue is to identify cues that indicate intentions of highly automated vehicles (e.g. give way) to VRU. It also has to be discussed to which extent these results can be used for defining regulations through the ISO process.

4.15 Interfaces for Work-Related Tasks in Automated Vehicles

Andrew Kun (University of New Hampshire – Durham, US)

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Automated vehicles hold out a number of great promises for the future ([1],[2]). Critically, they should make driving much safer than today. They should also free up time for their users to engage in non-driving tasks, including tasks related to work. However, we do not yet know how to best design in-vehicle human-computer interaction for work-related tasks. This is an important problem, especially in the context of cars that are not fully autonomous, and the driver periodically needs to take over the responsibility of controlling the vehicle [3]. Which types of work tasks should the interface support so that users can safely return to the driving task? Which tasks would be of greatest use for different workers, from engineers, to managers, to technicians? How can we design interactions so that they do not result in motion sickness? Which interface modalities are the best match for the tasks to be performed in the relatively small vehicle cockpit? These are some of the questions that we need to answer as we work towards enabling users to engage in work-related tasks in automated vehicles.

Keywords: automated driving, future of work

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4.16 How to Make the Driver Aware of the Role he has to Play?

Sabine Langlois (IRT SystemX and Renault, FR)

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The topics I would like to discuss at Dagstuhl are related to the different levels of automation, because our future vehicles will be equipped with systems partially or highly automated. One of our challenges is to make clear for the driver which role he has to play so that the team “system + driver” can manage a safe and pleasant drive.

With a Level 2 system (ACC+ Lane centering), the driver must continuously supervise: is it OK for humans to assume this role for a long duration? How can the system and its HMI support the driver in this role?

With a Level 3 system, the car takes the responsibility of the driving task, but the driver must stay “receptive” (term as used in [1]) because he will have at some point to take over. Even if the car performs a minimum risk maneuver in case the driver does not hand over, the maneuver could be under his responsibility. Does this mean the driver should stay in the loop? If yes, how can the car persuade him to do so because it is contradictory to his expectations? At some point, the compatibility between the system performance and driver’s response (to perceive, analyze, decide and act) could be lost. We should also consider that the driver may lose confidence in his own capacity to correctly intervene. According to Captain Chesley “Sully” Sullenberger, “we need to make sure we’re assigning the proper roles to the human and the technological components” Could an answer to the problem be to display system uncertainty level? If yes, could it be used as an alternative or in conjunction with a takeover request?

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4.17 The Environment, Standards and Vehicle Occupant Experiences

Roderick McCall (Luxembourg Inst. of Science & Technology, LU)

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The emergence of the semi and fully autonomous vehicle coupled with the desire to be greener either through government policies or vehicle buying patterns presents challenges for researchers and industry. The vehicles of the future must provide radically new in vehicle experience which offer a driving, work and play space in order to remain desirable. The challenge is further amplified by the emergence of car sharing schemes, which potentially mean that the “driver” will not necessarily be able to specify exactly the vehicle they want. This necessitates the needs for interaction standards across manufacturers, so that a driver can get into any vehicle and know how they expect any (semi-) autonomous system to behave. A positive challenge is now how to create driving experiences in (semi-) autonomous vehicles which have the aim of reducing carbon footprint and congestion.

4.18 Automated Vehicles and Novel Forms of User Experiences

Alexander Meschtscherjakov (Universität Salzburg, AT)

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We live in a time of tremendous change due to the increasing automation in many areas of our lives. May it be industry, home or the mobile context. This increase in automation brings many challenges for the design of interaction with automated systems, that seem to act autonomously in a certain way. This is especially true for automated vehicles due to the fact that they will be objects of our daily lives, across all cultures, across all social strata.

The notion of usability and user experience will change when there is no “user” of a vehicle anymore in the traditional sense acting as a driver, but more as an operator or the supporter of the automated driving vehicle. Since the transition of manual driving to assisted driving to automated driving will not run smoothly the design of interaction and cooperation between the vehicle and the user (i. e. driver) as well as other (vulnerable) road users (VRUs) will become one of the most important question in the next decade.

How can we design the interaction of a system that changes its behavior between being purely reactive (i. e. manual driving), to assistive (e. g. adaptive cruise control, lane change support) to (semi-)automated. Questions such as how to design safe and convenient hand-over-situations [1], driver de-skilling [2], or how not to fall into a trolley-dilemma [3] needs to be resolved. Another big issue will be the transformation of VRUs interaction with driverless vehicles. When we have solved these issues, we can think about other sensible tasks in a moving vehicle and how to fight motion sickness.

I argue that we need more real live data, and that the scientific community, politics, as well as the economic stakeholders need to work tightly together to make automated driving a long-lasting success.

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4.19 Reflection Statement by Ingrid Pettersson

Ingrid Pettersson (Volvo – Goeteborg, SE)

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 Ingrid Pettersson

Automated cars come with many possibilities and promises, but also pose many hard development challenges. The vehicles need to be developed in line with human needs and capabilities, and I strongly believe in early incorporation of users in the development process and seek to address user experiences (UX) of automated driving in my research (e.g.[1], [2]). User research should be deployed from early stages of development and ideation, to evaluation and iteration of ongoing concepts, addressing the various sorts challenges and possibilities of autonomous cars (e.g. [3], [4]).

I am especially interested on how we best approach user experience research from early stages of development [5], and techniques that allow us to study user interaction in as natural conditions as possible are important [6]. I see the need for extensive further research regarding for example:

- How to establish a purposeful user understanding of the usefulness and boundaries of the (semi-) autonomous driving system.
- How to prevent mode confusion & misuse.
- How to evolve driver/car sensing & communication.
- How to balance between branding vs consistency.

I look forward to learning from the very experienced researchers present, and to possibly start up new research collaborations, especially within tools and methods to address user research in the field of interfaces for autonomous driving.

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4.20 Mobility of the 21st Century – Automated Driving and Future Mobility Concepts

Bastian Pfleging (TU Eindhoven, NL)

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Before the inventions of trains and the automobile, transportation was a very challenging, expensive, and potentially dangerous activity – especially over longer distances. This heavily influenced how people lived: Especially home and workplace were often at the same location or close to each other. Once mobility became affordable – especially in form of cars, motorcycles, bicycles, trains, and busses – this led to a massive change for many people in large parts of the world, since they gained the opportunity to easily reach a remote location. Today, people spend a considerable amount of time in their cars, be it for the daily commute, for shopping, business trips, or to go on vacation.

With assisted and automated driving, we hope to not only increase driving safety and reduce road fatalities. At the same time, we hope to enable the drivers to make use of the time in their cars and convert their cars into a new space for (non-driving-related) activities: One of my current research goals is therefore to understand how we can adapt the design of the car to accommodate for these activities and make the automated ride (again) an enjoyable comfortable activity.

Once driving time becomes time for other activities, this may have huge societal effects: For instance, this can influence how we perceive our daily commute: If we already can start with our daily work when entering the car (or have breakfast during the commute), we might care less about the length and duration of our commute. This can in turn impact the decision where we want to have and, thus, have an influence on future urban planning.

Beyond the interaction in the automated car, we also need to understand how these cars interact with the outside world, especially other road users such as pedestrians, bicyclists, and drivers of manual cars. Our current research also addresses these questions.

With automated (and potentially electric) vehicles, the way how we use the car potentially may change: Already today, we see that car sharing and ride hailing are novel forms of transportation whose acceptance seem to rise. With automated vehicles, we expect that this trend will continue towards using mobility as a service: Similar to using a music streaming service instead of buying, and playing CDs or music files, we might pay for the access and use of shared cars. We can imagine that this increases the user's flexibility: While using only a small “bubble”, like a car for individual use during the morning commute or on the way to the train station, we might use a different (bigger) car when returning from the grocery store. In the evening, we might invite the partner in a sporty car to the theater, while a spacious and comfortable vehicle offers flexibility when going on vacation. In combination with a better link between different modes of transportation, this could drastically change the patterns how we use mobility in the future.

For all the cases explained above, we see challenging and inspiring research questions with regard to human-computer and especially human-vehicle interaction. The Dagstuhl Seminar on “Users and automated driving systems: How will we interact with tomorrow’s vehicles?” therefore is a timely seminar to identify and discuss these research questions and shape the roadmap for (joint) future research in this area with the goal to improve our mobility.

4.21 Level 0, Level 1, ... High ... 3.78 ...Autonomous?

Andreas Riener (TH Ingolstadt, DE)

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After having organized the predecessor seminar in 2016, we came back to Dagstuhl to see how research (and industry) has evolved/progressed since then and what new challenges have been identified (have arisen). Interestingly, many topics in 2019 are similar to the ones identified in the previous seminar, but are discussed in much more details, with much more enthusiasm and flavors, and arguments brought-up are well underpinned with recently published related work (partly co-authored by Dagstuhl seminar 16262 participants). The big topics identified in 2019 are 1) conflicting mental models – an interface issue in human-machine interaction around for quite a while and 2) the levels of automation. There was a long debate on the appropriateness of subdividing automated driving systems (ADS) into 5 subclasses. Quite a few people argued that the classification should be more fine grained (i. e., level x.y), others provided arguments to abolish the levels at all. Already in today’s automated vehicles, it is sometimes hard to discriminate between levels, as a car model is likely to have automated driving functions on different levels while one function can also come in variants on different levels (for example a parking assistant). It is rather intransparent for the driver/passenger, which “mode” is currently on and how (if allowed at all) to interact with the vehicle in that mode or with the function currently engaged. This problem domain was an ideal starting point for the seminar 19132 with the underlying question “how to interact with tomorrow’s vehicles”? 31 participants tried hard to come-up with solutions by applying different creativity methods, such as brainstorming rounds, break-out groups, prototyping sessions, amongst others. Even though we have not solved concrete problems, it was (again) a fun week and we (=co-organizers) are pretty certain that the discussions will have an influence on the future work of our participants. We’ve been already asked to propose another follow-up seminar in 2 years time for the next round of interaction. We will definitely consider!

Thanks for the warm hospitality,

Andreas

4.22 Understanding and Designing Plausibility and Self-Awareness into Automated Systems

Maria Rimini-Doering (Robert Bosch GmbH – Stuttgart, DE)

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As a Senior Expert in Human-Machine Interaction within Corporate Research of Robert Bosch GmbH, I coordinate publicly funded projects for the division of Software intensive Systems (e.g. Embedded Systems, User Interaction Technologies, Consumer IoT).

As I prepared for the present workshop, the news about problems (and terrible crashes) of the Boeing 737 MAX were in the news. This inspired me to propose the following questions that I felt would be interesting to explore:

1. How do we learn and teach to plan, program, realize and test highly automated systems with “situational awareness” or better self-awareness and dialog capabilities?
2. What are the probable actual errors in a system, e. g.:
 - Only one sensor taken as input (no check on consistency)
 - No check on plausibility
 - Repeated unquestioned onset of the control system after several manual turn-off commands
3. How can we utilize the contribution of the workshop at the Driving Assessment Conference 2017: “Control Transfer Challenges for Automated Driving Systems”?
4. What has been done, what is still to do?

I am looking forward to discussing these and other questions at this Dagstuhl seminar.

4.23 Understanding and Anticipating the User in Semi-Autonomous Driving

Nele Rußwinkel (TU Berlin, DE)

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To enable anticipation of the user by an autonomous system, we need to give the technical system the ability to understand the cognitive state of the user. For takeover situations in semi-autonomous driving it is necessary to understand what information the driver already has processed (e. g., surrounding vehicles, or cause of takeover) and what information is still missing to enable a safe take over and/or deliberate decision by the user.

Such an ability could be achieved by the method of cognitive modeling. In previous work we were able to predict how quickly a user would be able to learn how to handle a new application and how quickly different system upgrades could be integrated into the user’s mental model [1].

In some other work [4], we developed an intelligent cognitive system that is able to anticipate the actions of the pilot and to identify inadequacies and possible future mistake. For autonomous driving there is the need of a more details modeling approach that can also anticipating the visual processing of the environment including other vehicles, special road conditions and other relevant information.

Depending on the complexity of the environment the takeover process could be supported by additional information. The time needed for a safe take over would also depend on such processing mechanisms and could be predicted [5, 2].

Having such an intelligent cognitive system would not just help to provide an optimal take over procedure but also provides an understanding of the context to the technical system. This would be the foundation of a communication between User and system.

Questions that should also be addressed are: In what situations should the control be handed to the driver and in what situation the driver would be incapable to take control? How can the user be informed about decisions of the autonomous system?

For all these questions we need a way to provide a model of the dynamic cognitive state of the user.

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4.24 Amplification of the Human Mind and Intervention User Interfaces

Albrecht Schmidt (LMU München, DE)

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My group at the Ludwig Maximilians Universität, München, is heavily involved in exploring human use of automated systems. Our guiding principle is that human-machine systems can outperform humans, as well as machines that act alone. This is important, because we believe that a large class of automated and autonomous systems allow for joint control, where the majority of decisions are automated but where users can intervene. Thus, the opportunity for creating useful systems is quite significant.

In our work we are guided by the following ideas:

- Human-computer interaction is the key discipline for creating intelligent systems
- Intuitive cooperation between humans and computers is the key challenge
- Machine learning and automation are only components in a solution

Starting with these ideas we have developed the following design principles for what we call ?intervention user interfaces? [1] ? interfaces that can help support joint user-machine work on problems and tasks:

- Ensure expectability and predictability.
- Communicate options for interventions.
- Allow easy exploration of interventions.
- Easy reversal of automated and intervention actions.
- Minimize required attention.
- Communicate how control is shared.

I am looking forward to discussing these ideas with workshop participants. Even more importantly, I am looking forward to the discussions at the workshop reassuring me that research in the area of ?users and automated driving systems? is still relevant, and not overtaken by broader research themes.

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4.25 Intention-Aware Cooperative Driving Behaviour Model for Automated Vehicles

Ronald Schroeter (*Queensland University of Technology – Brisbane, AU*)

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The modeling of drivers in vehicles has been motivated by a desire to understand, predict and improve the driver's driving performance and safety. With AVs, the driving task will dramatically morph towards a supervisory role that cooperates with the AV, and render existing driving behavior models obsolete. New driving models are needed to capture the notion of a cooperative task between human and machine as its foundation. AVs call for a shift towards a more elaborate understanding of in-vehicle interactions, and new ways to address the pressing challenges that this transition towards cooperation raises. Theoretical constructs need to support novel cooperative principles such as negotiating activities, communicating and reconciling disparate perceptions of the environment, anticipating actions, and sharing intention, to be able to effectively (co)operate (with) AVs and other autonomous systems.

We found Intention Awareness (IA) to be a useful investigative lens to explore driving as a cooperative task. It has not been explored with the view of increasing the human's awareness of the system's intentions or in the context of improving cooperation with AVs. Our human-centric approach that explores cooperative Intention Awareness (IA) between human driver and machine may profoundly influence existing research on Situational Awareness, safety, predictability, trust, and usability in AVs. Our hypothesis is that sharing the vehicle's intention improves certainty, latency and cognitive workload in reconciling disparate SA because it focuses on the SA's high level meaning (semantics) rather than syntax.

Building on the Wendy Ju's Husband-metaphor to illustrate this: the driver signals their awareness of the driving situation (the syntax) by communicating their intention to slow down (semantics) with ostensible intentional cues, e.g. taking the foot off the accelerator and hovering it over the brake pedal. This puts the co-driver or passenger at ease, and vice versa the driver. Intentions are inferred from past individual subtle, intuitive, or direct reciprocated interaction experiences. This project seeks to understand the context-dependent interactions and chains of transactional cues between two humans in the car to inform future interfaces.

4.26 Challenges to Making Automated Driving Systems Understandable to Users

Steven E. Shladover (*University of California at Berkeley, US*)

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I have been researching multiple aspects of road vehicle automation since the early 1970s and have seen many changes in the attitudes and expectations surrounding automation since that time. My research has addressed topics such as:

- the design, implementation and testing of prototype automation systems on cars, buses and heavy trucks to assess their technical performance and the reactions of people driving and riding in the vehicles;
- using traffic microsimulations to assess the transportation system impacts of automated driving systems at various market penetration levels;
- developing the terminology, technical standards, and regulatory frameworks needed to enable safe deployment of the more highly automated driving systems.

Based on my experience in this field, I expect that many years of additional research effort will be needed to satisfactorily address the large technological challenges that remain in the fields of environment perception and safety assurance for software-intensive automation systems. In parallel with this work, much work also remains to be done on the human user interfaces of the Automated Driving Systems (SAE Level 3 and above). Among other challenges, future vehicles will be equipped with a wide variety of automation features that provide differing degrees of automation of the dynamic driving task within different operational design domains. Individual vehicles are likely to be equipped with several such features, each with its own driver interface requirements and implementations. How will the driver of the future be able to understand the capabilities and limitations of these systems, and how can the driver interfaces be designed to support safe and proper usage of these systems (while also deterring or preventing improper usage)? How can this be done with sufficient consistency across the industry to minimize user confusion, without unduly violating the natural desire of each company to differentiate their products from those of their competitors?

4.27 Assessing Driving Performance and Driving Style of Autonomous Vehicles

Jaka Sodnik (University of Ljubljana, SI)

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Driving a vehicle is a complex task requiring drivers to make accurate perceptions and cognitions about the environment, their own driving skills, their psychophysical state as well as vehicle performance and surrounding traffic. All this information has to be processed and interpreted at a high rate of speed leading to correct decisions and actions. Although all drivers have in common the task of safe driving, as individuals, they are all unique. We can study this driver's uniqueness and skills in a simulated driving environment by observing their reactions to different critical situations, unexpected traffic and weather conditions and their attitude towards other traffic participants. The final result is individual's personal driving profile and risk assessment score which can be used to predict future behavior and potential hazardous reactions in real traffic. Automation of driving task on the other hand is progressing fast and different forms of (semi-)automated vehicles (AVs) have been in operation for quite some time. There are many challenges accompanying this transition, ranging from technical and safety related issues, to the issues related to driving style and driving behavior in relation to other traffic participants. This high level performance of AVs should also be assessed in order to operate in a way that nobody is harmed, endangered and not even hindered or bothered unnecessarily. There is a need to find certain quantifications for this assessment by taking into account human behavior and capabilities to handle different traffic

situations. We therefore propose the same approach and similar driving style assessment system as for human drivers. It should incorporate rules and testable guidelines for one vehicle as well as all other traffic participants and should be included as a mandatory part of AVs verification and certification.

4.28 Road Traffic Safety and Human Errors in Automated Driving

Christine Sutter (Deutsche Hochschule der Polizei – Münster-Hiltrup, DE)

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What are we talking about?

More than 1.3 million road users die of road traffic accidents every year [1] and an even higher number of road users are severely injured per year worldwide. In children and young adults, aged between 5 and 29 years, road traffic injury is the leading cause of death [1]. This is a depressing fact, with fatalities mostly rising in low-income countries and stagnating or only slowly decreasing in higher-income countries [1].

How to improve road traffic safety?

Pillar 3 of the Decade of Action for Road Safety aims at providing safer cars [1]. Driver support features (SAE level 0-2, [2]), and automated driving features (SAE level 3-5, [2]) increasingly support or even substitute the human driver. Using those features is helpful to reduce human errors in driving, so they have the potential to decrease the risk of road traffic accidents.

From a psychological point of view, I am not convinced that this will be the case. Systems operating on level 3 automation and the take-over procedure are complicated to handle for human drivers. The switch between manual or assisted driving to supervising the system during automation and the take-over on request is highly demanding for the human information processing system. The critical part is the successful take-over, and the troubleshooting in case the system malfunctions. One might suspect that circumstances even increase human errors with level 3 automation. I also question that human errors decrease with level 4 automation, as we increasingly trust in human capabilities in software development and teleoperation. In my opinion, it remains unclear if vehicle automation solves the problem of human errors in driving, and maybe we can reach the same goal with alternative concepts of mobility.

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4.29 Reflection Statement by Bruce N. Walker

Bruce N. Walker (Georgia Institute of Technology – Atlanta, US)

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Bruce N. Walker (Georgia Tech Sonification Lab) has a broad range of research interests, including Human-Technology Interaction, Sensation & Perception, Multimodal User Interfaces

& Sonification, Human-Automation Interaction, Trust in Automation, Technology/Automation Acceptance, and Assistive Technology.

Some interesting questions in the realm of automated vehicles include:

- What factors will affect uptake / adoption of automated vehicles?
- What factors will affect trust in automation?
- What, exactly, is a handoff / takeover request, and how the heck will the engineering/design match human capabilities?
- How can/should the driver be made aware of the status of the world, and the state of the (automated) vehicle?
- What role can multimodal interfaces play in automated vehicles, especially related to situation awareness?
- How will automated vehicles help / hinder persons with disabilities (as drivers, passengers, pedestrians, etc.)?

Prof. Walker's goals for the Dagstuhl seminar include:

- Community Building: Connecting us all, a little more formally.
- Learning: What are all of you working on?
- Friend Raising: Collaborators for potential research projects.
- Planning Some Projects.
- Fund Raising: Finding support to do research.

4.30 Designing Automated Vehicles for All Road Users

C. Y. David Yang (AAA Foundation for Traffic Safety – District of Columbia, US)

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As more advanced technologies are being introduced into the vehicle fleet to assist drivers with the ultimate goal of automated driving systems, it is important to also examine and assess how future vehicle technologies will impacts other road users such as pedestrians, cyclists, and people with special needs to ensure safe and efficient transportation operations. Research needs to be carried out to establish a comprehensive and fundamental understanding of the interactions and dynamics between automated vehicles and vulnerable road users.

As a group, vulnerable road users could constituted high variability and individual differences. Consequently, understanding variability within this group and their individual needs must be considered in the design and functionality of automated vehicles. Some of research questions that need to be looked into are listed below:

- How can human-machine interface (HMI) be made intuitive for vulnerable road users?
- How can automated vehicle mode be communicated to different vulnerable road users?
- What system functionality and information feedback is most important for different road user groups?
- What kinds of pedestrian/cyclist behaviors represent the most problematic for automated vehicles and drivers?
- What design guidelines/principles should be considered for elderly drivers or those with other needs?

Main Research Fields: Human-Machine Interface, Vulnerable Road Users

References

- 1 AAA Foundation for Traffic Safety. *2018 Forum on the Impact of Vehicle Technologies and Automation on Vulnerable Road Users and Driver Behavior and Performance: A Summary Report*. AAA Foundation for Traffic Safety, Washington, DC, USA, 2019
- 2 AAA Foundation for Traffic Safety. *2017 Forum on the Impact of Vehicle Technologies and Automation on Users: A Summary Report*. AAA Foundation for Traffic Safety, Washington, DC, USA, 2018

4.31 Transparency and Explanations for Automated Behaviors in Future Vehicles

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Automated vehicles use a range of machine learning techniques which for the user act essentially as black boxes. Our group's current research addresses the problem of increasing transparency and user control for recommender systems which so far mainly function as black boxes. We have developed several methods that let users influence the predictions of statistical models of recommending, and are currently working on system-generated explanations for recommended items based on user reviews. My aim for this seminar is to discover new connections between our current research focus on interactive recommender systems and user-related aspects of automated vehicle. In line with the emerging research field of explainable AI, we aim at developing methods for explaining the behavior and decisions of intelligent systems also in the field of automated vehicles. Such explanations should be constructed and presented in a way that can be easily perceived and understood by the human driver without increasing cognitive load. Furthermore, we see various options for integrating recommender functions into future vehicles, be that at the level of setting appropriate parameters for the driving behavior, for recommending routes, or for providing commercial and other services to the driver or passenger of an automated vehicle.

5 Seminar Activities: Break-Out Groups, World Cafe, Discussions, and Prototyping Sessions

5.1 Intro Presentations, Brainstorming Wall, and Clustering

After an introduction to the seminar by the co-organizers Susanne Boll, Andrew Kun, Andreas Riener, and David Yang, most of the first day was spent with short intro presentations by the participants followed by discussions and Q&A. Figure 2 represents a quick overview of research areas presented/discussed during the intro presentations on day 1. In total, 170 terms/research questions/issues were collected during day 1 and used to generate this word cloud.

To make the sure that the rest of the week fits the seminar participants' actual research interests, the co-organizers did not choose to define topics for the break out groups on the remaining days in advance, but to find topics worth being discussed in form of a "brainstorming wall". During the introduction rounds (that were already opened for short discussions with the whole group), most-often mentioned topics were collected on PostIts,



Figure 2 Word cloud from the intro presentations on day 1 (Source: A. Riener).

organized into associated groups and pinned them on a pin board visible to all participants. In the afternoon of the first day, each participant was invited to vote for his favorite topics of interest using self-adhesive colored dots. The result, after re-organization by the workshop organizers on Monday evening, is shown in Figure 3. The identified “blobs” were finally selected as the topics for the break out groups on Tuesday and the WorldCafé on Thursday as well as for the prototyping session on Wednesday.

5.2 Tuesday: Break-Out Groups

After clustering and reorganizing, the top 4 topics from Monday (see Figure 4): “Models”, “Levels”, “Disruption”, and “Teamplayer”, were used for the Tuesday break-out groups (4). The other clusters identified during the brainstorming (e. g., “Safety”, “Transparency”, “Individualization vs. Standards”, “Tools and Methods”, “Social Interaction”, “Teleoperation”, and “Inclusivity”) (see Figure 10) were used for prototyping (Wednesday) or World Café (Thursday).

5.2.1 Models – Driver-Automation Cooperation: Modes, Models, and Modeling

Summary of the group discussion as outlined in Figure 5: Models are simplified representations of the real world, and should be as simple as possible depending on the purpose but not any simpler than that. They are relevant and even essential to Automated Vehicles (AVs) because

- users have them (i.e., mental models guide their behavior),
- AVs are designed to have them (e.g., vehicle models, environment models, and user models), and
- different stakeholders can use them to guide design including the design of UX, journey experience, safety-relevant interventions, infrastructure, policy, and user mental models.

Driver mental models can form naturally or can be influenced purposefully through design. Stakeholders may use different modeling techniques to create other models related to AVs. These models can be predictive, descriptive, conceptual, prescriptive. They can be



■ **Figure 3** Result of day 1: Brainstorming wall including results of the voting by participants.

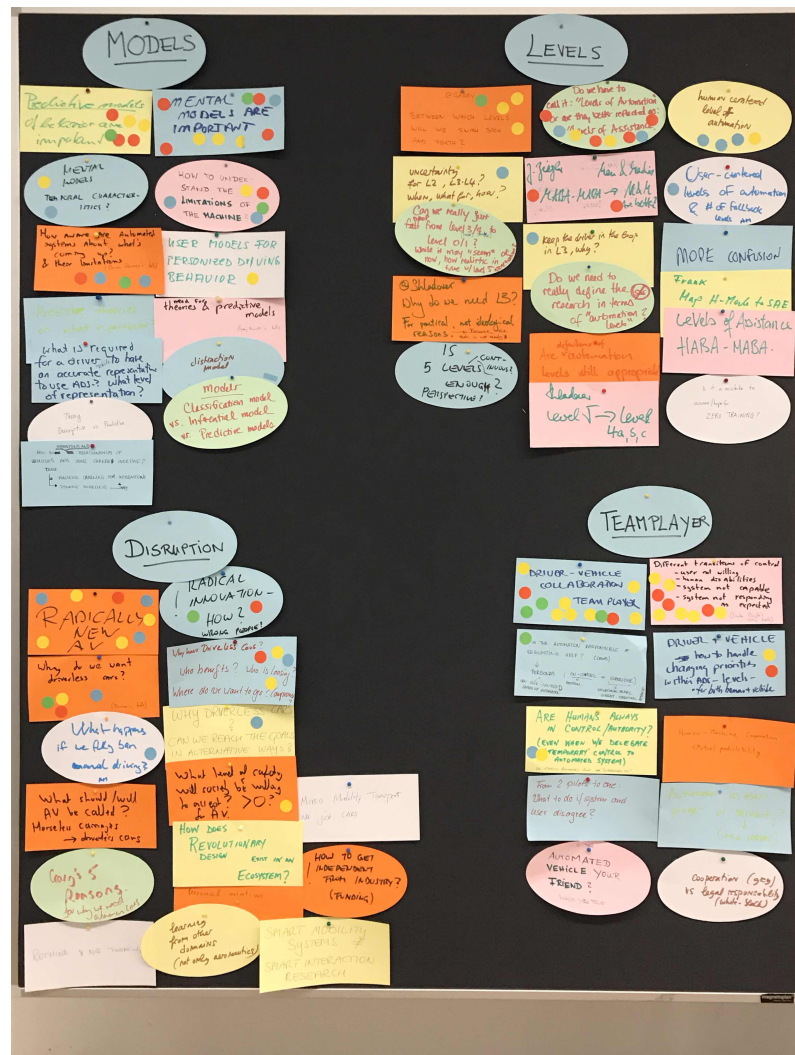
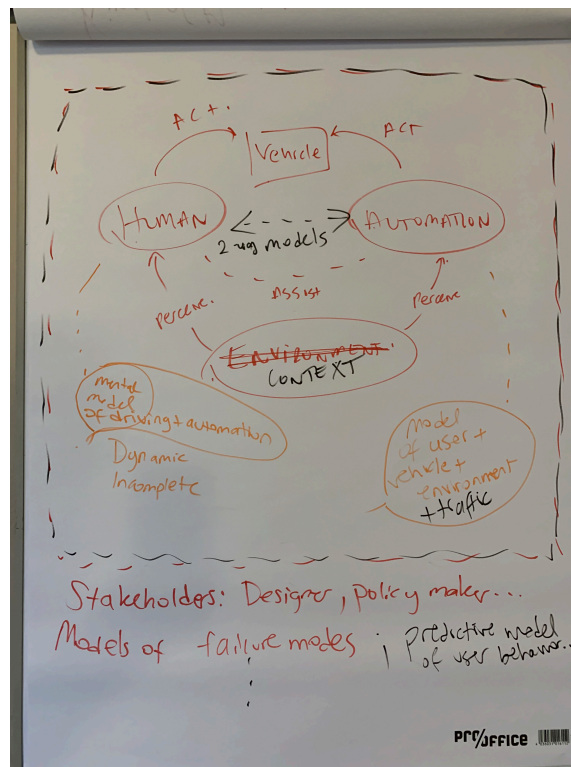


Figure 4 Result of day 1 after clustering and reorganizing by the seminar co-organizers: The 4 top topics “Models”, “Levels”, “Disruption”, and “Teamplayer” were used in the Tuesday break-out groups.



■ **Figure 5** Brainstorming in the “Models” group.

deterministic or stochastic. They can describe cognitive architectures. Different modeling techniques have different advantages and disadvantages and a combination of them may have to be used in practice. Further, the validity of different techniques may change across different applications.

Finally, given that the behavior of different agents can change over time in the complex AV-human system (e.g., over the air updates for automation), both user mental models and stakeholder built models may have to be updated.

5.2.2 Levels of automation

The SAE levels of automation are written with limited use, but they are not as insightful for researchers when attempting to conduct comparable studies. A new framework is needed to better reflect the context that the automation can be used. The paper [3] initially discussed and structured during the break-out group focuses on the researcher’s perspective which considers the operational design domain and the distribution of control. A final version was compiled the two weeks after the Dagstuhl seminar and submitted as full paper to AutoUI 2019.

References

- 1 Linda Boyle, Christian P. Janssen, Wendy Ju, Andreas Riener, Steven E Shladover, Christine Sutter, Frank Flemisch. *Clarifying variations in vehicle automation: Beyond levels of automation*. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI’2019), Utrecht, 2019. (submitted)

Clarifying variations in vehicle automation: Beyond levels of automation

Anonymous Author(s)*

ABSTRACT

Human operators of vehicles with automated capabilities often infer a linear progression of automation, which is often based on the Society of Automotive Engineers (SAE) Levels of Automation. The SAE levels were designed to provide a common language for use by industry and government and to promote joint understanding of the relative roles of humans and driving automation systems. However, research centered on these discrete levels of automation are not necessarily comparable as driving automation systems can vary based on the operational design domains and the distribution of control. The operational design domain (ODD) provides the dimensions (e.g., environment, traffic, other road users) and driving scenarios in which the automation can operate properly. The variations in ODD can impact the abilities, comprehension, responsibilities and intended actions of the system and the human, and thereby the overall understanding regarding who is in control when. This paper discusses steps towards a common framework that can be used by researchers to design, test, and evaluate vehicle automation given differences in the operational design domain and the distribution of control actions.

CCS CONCEPTS

• Human-centered computing → HCI theory, concepts and models; Interaction design theory, concepts and paradigms; • Applied computing → Transportation.

KEYWORDS

Vehicle automation, Automated driving, Operational design domain, Control distribution, SAE J3016

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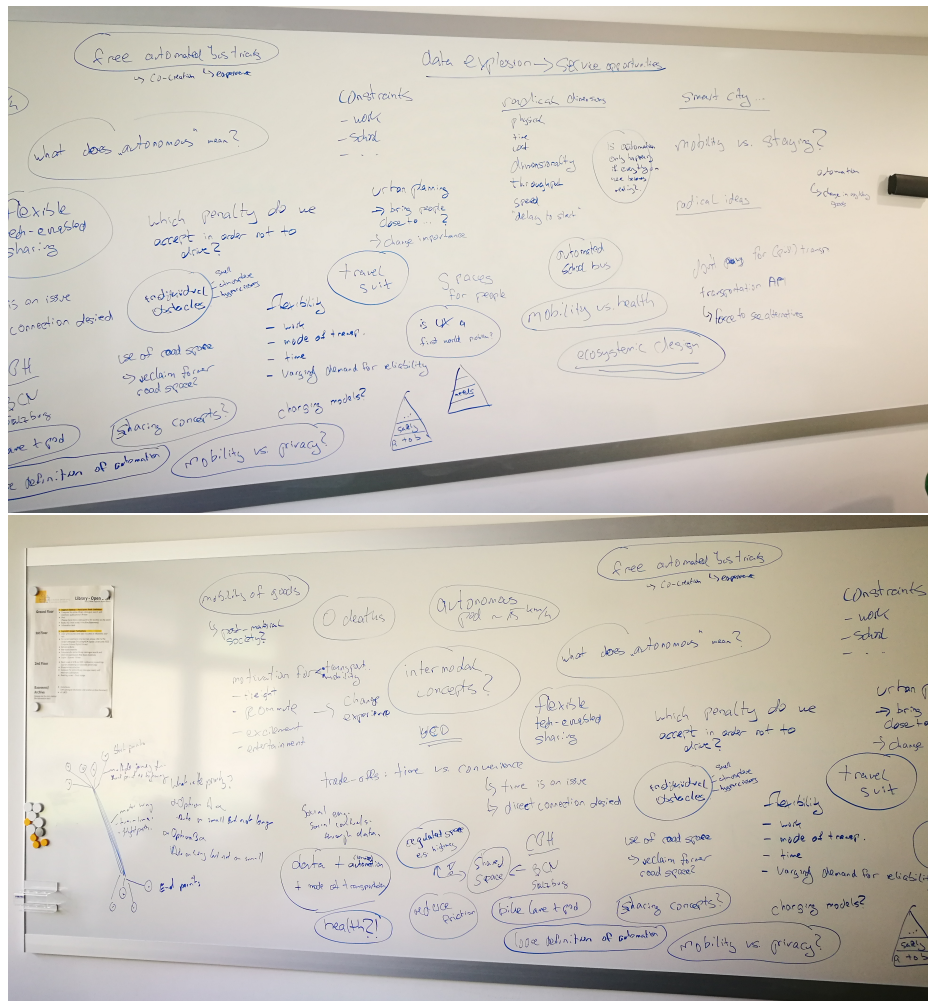
1 INTRODUCTION

There are many assumptions associated with the operational capabilities related to various vehicle automation technologies. These assumptions are fostered by popular media, who often use terms such as “self-driving,” “autonomous cars” and “automated vehicles” interchangeably. The Society of Automotive Engineers (SAE) created a matrix that grouped the levels of automation into six categories from 0 for fully manual to 5 for fully automated. Researchers, regulators, car manufacturers, and others have adopted these levels as a way to communicate to one another on the automation capabilities of the vehicles they are testing, evaluating, designing and developing policies. However, even those in the automotive user interface (Auto-UI) community fail to use the SAE levels appropriately, often mistaking the levels for modes, and conflating what people could, should or would do within that automation level.

This paper proposes to resolve some of these issues by presenting a framework that goes beyond levels of automation such that we consider the *operational design domains* (ODD), which are the contexts in which different automated vehicles are intended to be used, and on *distributions of control* which address the ability, comprehension, responsibility and intended action in different automated scenarios. By considering vehicle automation applications in this broader framework, we can create more comparable studies on human interaction with vehicle automation. This can then inform discussion with other stakeholders such as manufacturers, designers, and end users.

Our framework provides a more user-centered perspective, which is important for the Auto-UI community to converge research efforts and to identify gaps in our understanding of human-automated vehicle interactions. It balances out the more technical perspective described in SAE J3016 [13] and the extension SAE J3114 [19].

■ **Figure 6** Paper of the “Levels of Automation” group submitted to AutoUI 2019 conference.



■ **Figure 7** Brainstorming result of group “Disruptive innovation”.

5.2.3 Disruptive innovation

The group work started with brainstorming (Figure 7). Below is a summary of the topics discussed.

- New opportunities
 - Data+services/”automation”+mode of transportation as design material & opportunities
 - Sharing concepts
- Many aspects related to urban planning
 - Convert(traffic) space into widely shared spaces(e.g., with pedestrians)
 - Service provisioning
 - Context-aware vehicles
 - Design AVs to operate in pedestrian-/bike-prioritized areas
- Is UX for AV region-specific (a first-world problem)?
 - Do we need to focus on regions other than Europe/US?
- Transition phase manual car to AV vs. making people mobile

- More ecosystemic design approach
 - Flexibility
 - Intermodal approaches
 - Separation of personal mobility and luggage/goods (see also corresponding video in Wednesday prototyping session)
- Mobility vs. health
- Dimensions of radical invention
 - Dimensionality: Use of vertical space
 - Time
 - Cost/payments
 - Physical
 - Throughput/speed
 - “Delay to start”

5.2.4 Teamplayers

Definition of team-player collaboration:

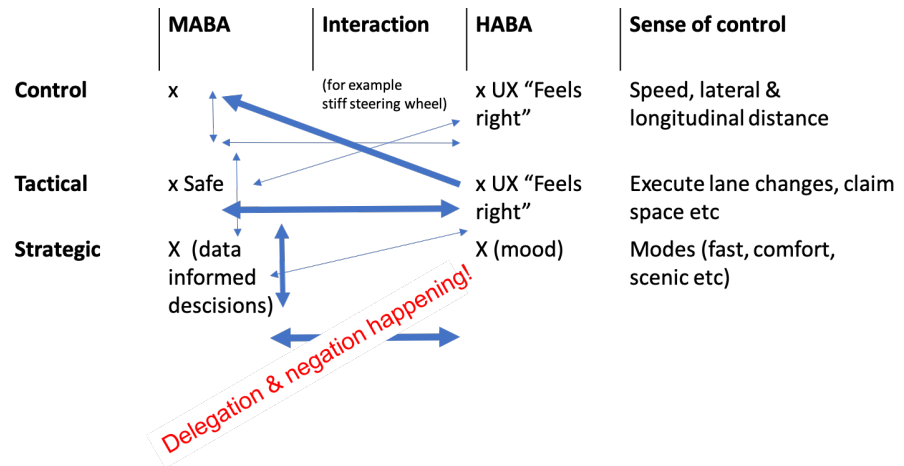
1. Interference by two agents
2. Interference solved by actions facilitating goal achievement of both agents working (towards a common goal)

Description of this type of collaboration

- Shared task between two agents
- Continuous or discrete involvement (from user perspective)
- Joined cognitive system
- Distribution of tasks is more flexible (human is supporting the automation)
- Collaborative system (mutual control, soft transition modes)
- User in control
- User impairment support
- Collaboration on higher level
- On strategic level (deciding on the destination), solving tasks together

Problems and challenges

- Problems with expectations
- Over trust/no trust at all
- Different use cases/edge cases for different metaphors
- How can users get correct understanding
- Exchange of information/the car should let the driver know it is in control
- What kind of messages to use to communicate this

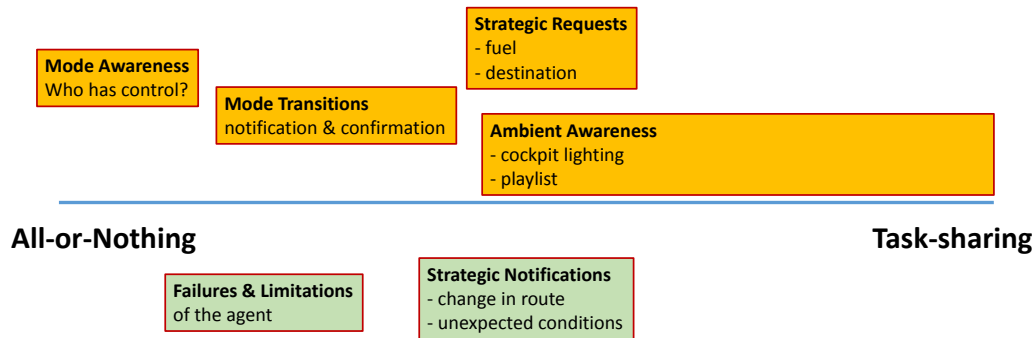


		Mutual	Vehicle	Driver
	Operational levels	"Horse" metaphor	"Guardian angel" metaphor	"Chauffeur" metaphor
Meta-level (Recommendation system)	Strategic	Stop for refueling Stop for rest/food	Avoid traffic jam	Find best route to work on / finish my task
	Tactical	Overtake Follow another vehicle	Avoid risky overtake	Speed up (Drive over the speed limit)
	Control		Avoid discomfort	

Teamplayers – Classification by Collaboration Type

Meta	Level	Synchronous Cooperation	Delegation	Assistance/ Supervision	Co-Evolution
	Connection /Relational	Social communication between diff. vehicles, advise on shopping opportunities	Drive me to meet friends at 7pm	Alert other entity of medical condition	Learn about preferred co-drivers
Recommender/Advisor functions	Strategic	Jointly define route,	Find points of interest and bring me there	Avoid congested roads,	Learning preferred routes, destinations
	Tactical	acceleration in overtake maneuver	Take-over, drive in traffic jam, cross intersection, platooon	Stop for refueling	C: learn user preference for safe overtaking
	Control	Joint steering, Reenforced braking...	ACC, Lane-keeping	Observe speed limits	adapt to driving style

■ Figure 8 Discussion result of group “Teamplayers” (part 1).



■ **Figure 9** Discussion result of group “Teamplayers” (part 2).

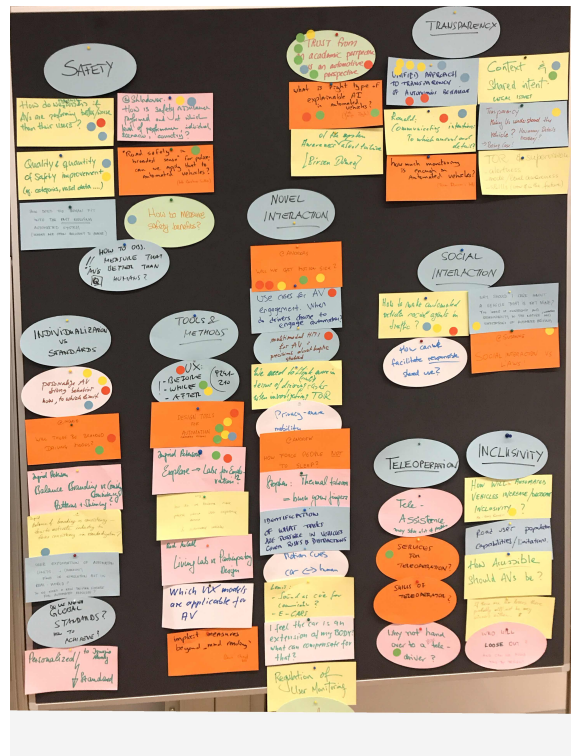
Research questions:

- How does the user adapt the priorities of the system according to current goals?
- How to reconcile different perceptions & priorities in a situation?
- What are the mechanisms that can be used in the negotiation?
- How should metaphors be used – as design guidelines or as a tool to communicate technology to the user?
- Do different metaphors exclude or complement each other?
- Which modalities are appropriate for which type of communications (notifications and information)?

5.3 Wednesday: Prototyping Session

Before starting with the prototyping session on Wednesday, Susanne Boll gave a short overview talk how to prototype and what the expected output is (see Figure 11). She introduced the method of “Quick and Dirty” prototyping and presented the available prototyping material (Figure 12) and showed examples of previous prototyping sessions. Based on the results of day 1 and the subsequent clustering (see Figure 10), initial topics for the prototype session were set. In addition, seminar participants were invited to “pitch” new ideas (Figure 13) they want to work on during the next hours and try to attract supporters for their ideas.

Participants voted for the favorite topics and then organized themselves into small breakout groups and worked on creating prototypes of interfaces. All of the groups were productive and some also reported on their prototypes – these brief reports are included below.



■ **Figure 10** Result of day 1 after clustering and reorganizing by the seminar co-organizers: 4 top topics (upper chart) and other clusters (lower chart) were used in further sessions.

Procedure

Introduction 09:30

- Introduction into Quick and Dirty Prototyping

Quick'N'Dirty Prototyping in your groups 09:45 – 12:15

- Collect ideas and be creative
- Get weird ideas ☺
- Don't think in technological boundaries
- Build one or more prototypes that address the requirements of your project
- Find ideas how to interact with the prototypes
- Take pictures/videos of your prototypes and its evolution

Finalize Prototype and Generate Prototype Video Thursday 9 – 10h

- Create a 3-5 min video illustrating your idea and vision

Presentation Thursday 10-11h

- Each group presents their prototypes (Video+3mins plus Discussion)
- Everyone can comment, discuss and give further ideas

■ **Figure 11** Overview and schedule for the prototyping session.

5.3.1 Prototype: Teamplayers

(Prototype by Nele Russwinkel, Ronald Schroeter, Josef Krems, Jurgen Ziegler, David Yang, Birsen Donmez, Joanne Harbluk, Frank Flemisch, Martin Baumann, Jaka Sodnik)

The teamplayers group from Tuesday worked on a video prototype to convey their concept presented two days before. Scenario description: “We are on the way to the meeting, running late. We are approaching the roundabout with very intense traffic which contains several critical points for AV system. Therefore the system proposes collaboration with the driver (team work) to resolve the issue more efficiently.”

Storyboard:

- PART 1
 1. Vehicle is approaching to the roundabout, driving in autonomous mode
 2. Driver is relaxing, exchanging some information with the IVIS
 3. Suddenly ambient light in the vehicle changes and informs the driver about the changed conditions
 - The vehicle changes its confidence state to red
 - It invites the driver to take over the control
 4. The driver takes over but it requires additional information
 5. The cyclist joins the roundabout
 - Vehicle enters to guardian angel mode
 - Vehicle performs the emergency braking maneuver
- PART 2
 1. Vehicle is capable of taking back the control and informs the driver about that
 - It changes its confidence state back to blue
 2. Suddenly the vehicle notices the unknown object and it doesn't understand the situation
 - It is a police officer indicating the vehicle to stop
 - Vehicle requests some information from the driver and changes its confidence state to red
 - Driver takes over and performs the stop maneuver
 3. Vehicle learns about this situation and remembers it
 4. Vehicle is capable of taking back the control and informs the driver about that
 - The vehicle changes its confidence state back to blue
- PART 3
 1. There is an accident (fire) on the right lane of the exit
 - Vehicle requests some information about this from the driver and changes its confidence state to red
 - The driver takes over the control again and avoids the fire by performing wider maneuver with bigger radius
 2. Conflict is resolved and the vehicle exits the roundabout successfully
 - The vehicle changes its confidence state back to blue



■ **Figure 14** Teamplayer prototype (Martin Baumann, Ronald Schroeter).

5.3.2 Prototype: Novel Human-Machine Interfaces for the Management of User-Vehicle Transitions in Automated Driving

(Prototype by Gary Burnett, Wendy Ju, Sabine Langlois, Andreas Riener, Steven Shladover)
 For automated vehicles operating at SAE Level 4 capability, control could feasibly be passed from machine to human and vice versa -regardless of whether minimal risk condition exists as a fallback solution. We propose two Human-Machine Interfaces (HMIs) to assist in the management of these transitions: 1) A “Responsibility Panel” providing the necessary feedback for a user to understand who must undertake different driving related activities (look, brake, throttle, steer) and who might be liable if a fault arises (user or car company); 2) A “Readiness to Drive” testing HMI that only allows a human to retake control when a certain level of competency is demonstrated. Future work should evaluate the effectiveness of our HMIs.

Video link: <http://www.andreasriener.com/Dagstuhl19132/Dagstuhl-Brexit2-mediumquality.mov>



■ **Figure 15** Video prototype “Novel Human-Machine Interfaces for the Management of User-Vehicle Transitions in Automated Driving”, also submitted to AutoUI Video track [4].

References

- 1 Gary Burnett, Wendy Ju, Sabine Langlois, Andreas Riener, Steven E Shladover. *Novel Human-Machine Interfaces for the Management of User-Vehicle Transitions in Automated Driving*. Adjunct proceedings (Video track) of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019. (*submitted*)

5.3.3 Prototype: The (future) mobile office

(Prototype by Andrew Kun, Linda Boyle, Stephen Brewster, Christan Janssen, Duncan Brumby, Lewis Chuang)

Video link: [http://www.andreasriener.com/Dagstuhl19132/The\(future\)MobileOffice.mp4](http://www.andreasriener.com/Dagstuhl19132/The(future)MobileOffice.mp4)

Camera-ready version: <https://youtu.be/HrZmSb8NvBg>



■ **Figure 16** Presentation of the video prototype for concept “The (future) mobile office”.

We created a video that shows a concept of a future mobile office in a semi-automated vehicle that uses augmented reality [6]. People perform non-driving tasks in current, non-automated vehicles even though that is unsafe. Moreover, even for passengers there is limited space, it is not social, and there can be motion sickness. In future cars, technology such as augmented reality might alleviate some of these issues. Our concept shows how augmented reality can project a remote conversant onto the dashboard. Thereby, the driver can keep an occasional eye on the road while the automated vehicle drives, and might experience less motion sickness. Potentially, this concept might even be used for group calls or for group activities such as karaoke, thereby creating a social setting. We also demonstrate how integration with an intelligent assistant (through speech and gesture analysis) might save the driver from having to grab a calendar to write things down, again allowing them to focus on the road.

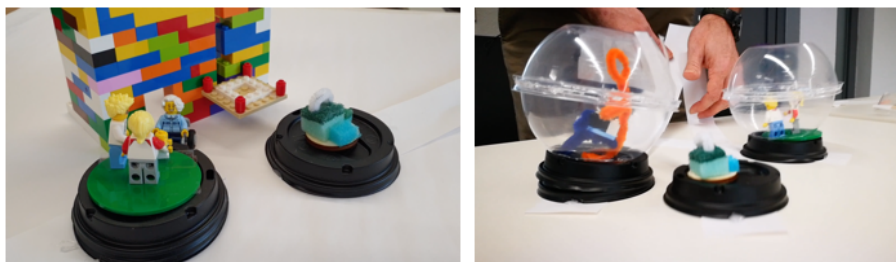
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- 1 Christian P. Janssen, Andrew L. Kun, Stephen Brewster, Linda Boyle, Duncan Brumby, Lewis L. Chuang. *Exploring the Concept of the (Future) Mobile Office*. Adjunct proceedings (Video track) of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019.

5.3.4 DiscHover – Next generation mobility platform

(Prototype by Susanne Boll, Alexander Meschtscherjakov, Bastian Pfleging, Bruce Walker, Maria Rimini-Döring, Christine Sutter)

In DiscHover we discussed and explore new forms of mobility and how the separation of mobility of individuals and goods could be solved by DiscHover, a hovering disc which can transport individuals but also goods such as the grocery shopping or luggage. We imagined a world in which this transportation device would allow us to freely move around along and in the company of friends without having to use a car. We prototyped very nice forms of DiscHovers, for work and for leisure, some that involve privacy such that one could even play the drums or listen to music during the ride. With DiscHovers one travel alone but also in company and different DiscHovers can join, just depending on the current transportation need.



■ **Figure 17** Snapshot from prototype concept for DiskHover

5.3.5 Prototype: T.R.A.V.I.S

(Prototype by Ingrid Pettersson and Ignacio Alvarez)

Ingrid Pettersson and Ignacio Alvarez presenting their video concept outlining several different scenarios.



■ **Figure 18** Presentation of prototype concept for T.R.A.V.I.S.

5.4 Wednesday afternoon: Excursion “Baumwipfelpfad Saarschleife, Mettlacher Abteibrauerei”

After 2 1/2 days of intensive work, Wednesday afternoon was reserved for a nice excursion with a relaxing hike. This time, we went to the “Baumwipfelpfad Saarschleife”, had an enjoyable walk around and finally visited Mettlacher Abteibrauerei. There, we learned how to brew (and of course drink) beer and we also enjoyed dinner at their great restaurant. The bus brought us back to Dagstuhl right-in-time for the cheese platter in the wine cellar ;-).



■ **Figure 19** Excursion to Saarschleife and Mettlacher Abteibrauerei on Wednesday afternoon.

5.5 Thursday: World Café

5.5.1 Transparency and trust (facilitator: Sabine Langlois)

The topic concerns the trust towards a system (often also called robot) that allows the driving task to be automated, and the degree of transparency the human-machine interface (HMI) should have to help the user be trustful. The following three entities should be considered: a) the user inside the car, b) the automated driving system (ADS; or robot), and c) the persons outside the car (also called outside world). Two types of relationships among these entities can be described: monitoring and communication. Pedestrians (outside world) should be able to identify who is responsible for the driving task, either the human inside the car or the robot (monitoring). The robot should be able to monitor the user and should also be aware of its own limitations (self-awareness of the robot, thus able to monitor itself). The transparency of HMI supports communication from robot to user, and from robot to outside world. The user should have a way to interact with the robot and the outside world, but also the pedestrians (outside world) need to have a way to convey their intention of crossing to the robot.

Transparency has to be calibrated to support trust: There is an optimal amount of information to convey, otherwise trust decreases. This optimal transparency depends on different factors:

- **Usage duration:** first HMI should display what the robot detects (e.g. Tesla instrument cluster), then information should be provided only if there is a problem. Therefore, the threshold between what is a problem and what is not, needs to be defined.
- **User characteristics:** Two types should be considered: 1. The propensity to trust (is the user sceptic or compliant), 2. Cognitive style (is the user information seeker or avoider).
- **Level of automation:** As defined in SAE J3016 [1]



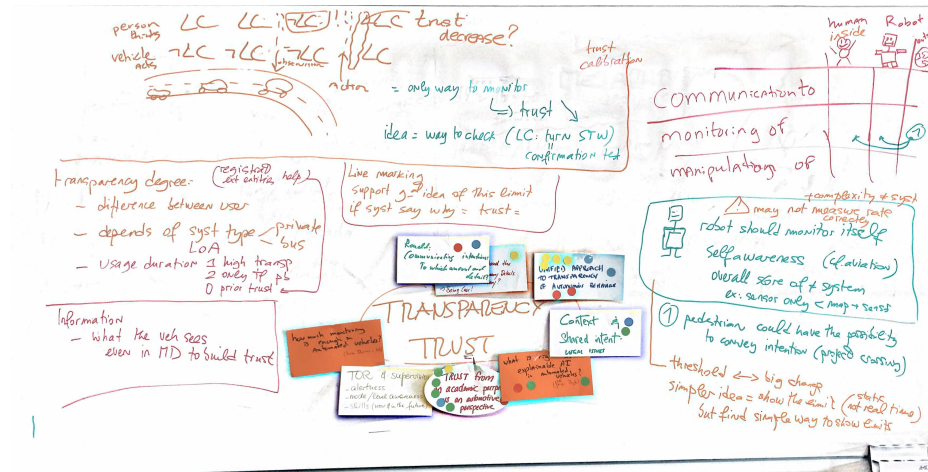
■ **Figure 20** Discussions at the four World Café “tables” 1) Transparency and Trust, 2) Novel Interactions, 3) Tools and Methods, and 4) Remote Operation.

To evaluate trust towards an ADS, it is first useful to study the definition of trust. A first question to answer is: is trust considered as a noun or a verb? As already stated, trust depends on usage duration: trust-building starts prior usage, because of following factors: experience of ADAS/AD of the user; his propensity to trust; regulation toward AD; branding. During the learning phase, one idea to help trust-building is to refer to animal metaphor (e.g. trust building between a human and a dog). When the user encounters his first problem with the system, two types of trust evolutions can be observed: for the compliant user, trust will drop significantly (he was over-trusting the system), whereas for the skeptic user, trust will increase because the skeptic user is waiting for a problem to better understand the system (he was under-trusting the system). If an explanation is provided when the problem occurs, trust will drop less for the compliant user; an agent representing the artificial intelligence of the system could be a good way to convey this information.

Self-awareness is not an easy feature to give to the system, because there is the risk of negative and positive alarms. The self-awareness level (also called confidence level) should be an overall score of the different subsystems. It should not be too complex to understand, as such it should not be too dynamic. Two different use cases have been described: the case where confidence level fluctuates a lot, and the case where confidence level slowly drops down. Shouldn't the fluctuation, even if above threshold, be warned about? (whereas a low fluctuating level for sure should not). The following question was asked: wouldn't be easier to show the limits instead of providing a score? A simple way to show limits should then be found. The threshold should also be defined (see above: after some usage, the threshold should be modified to just to show problems).

References

- 1 SAE International. *Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles J3016_201806*. 2018



■ **Figure 21** Final result of the World Café on “Transparency and Trust” (facilitated by Sabine Langlois) (part 1).

5.5.2 Novel interactions (facilitator: Stephen Brewster)

In this group, we discussed a wide range of topics around interaction in the car. In the area of user sensing, we discussed how we might collect data about the user (e.g. BCI, emotion, driver state, seat settings) that would be used for input into the driving system. This could be used for shared awareness between the car and driver, and also between the driver and other passengers. This could also be shared with other cars. An important issue of privacy came up with sharing this information.

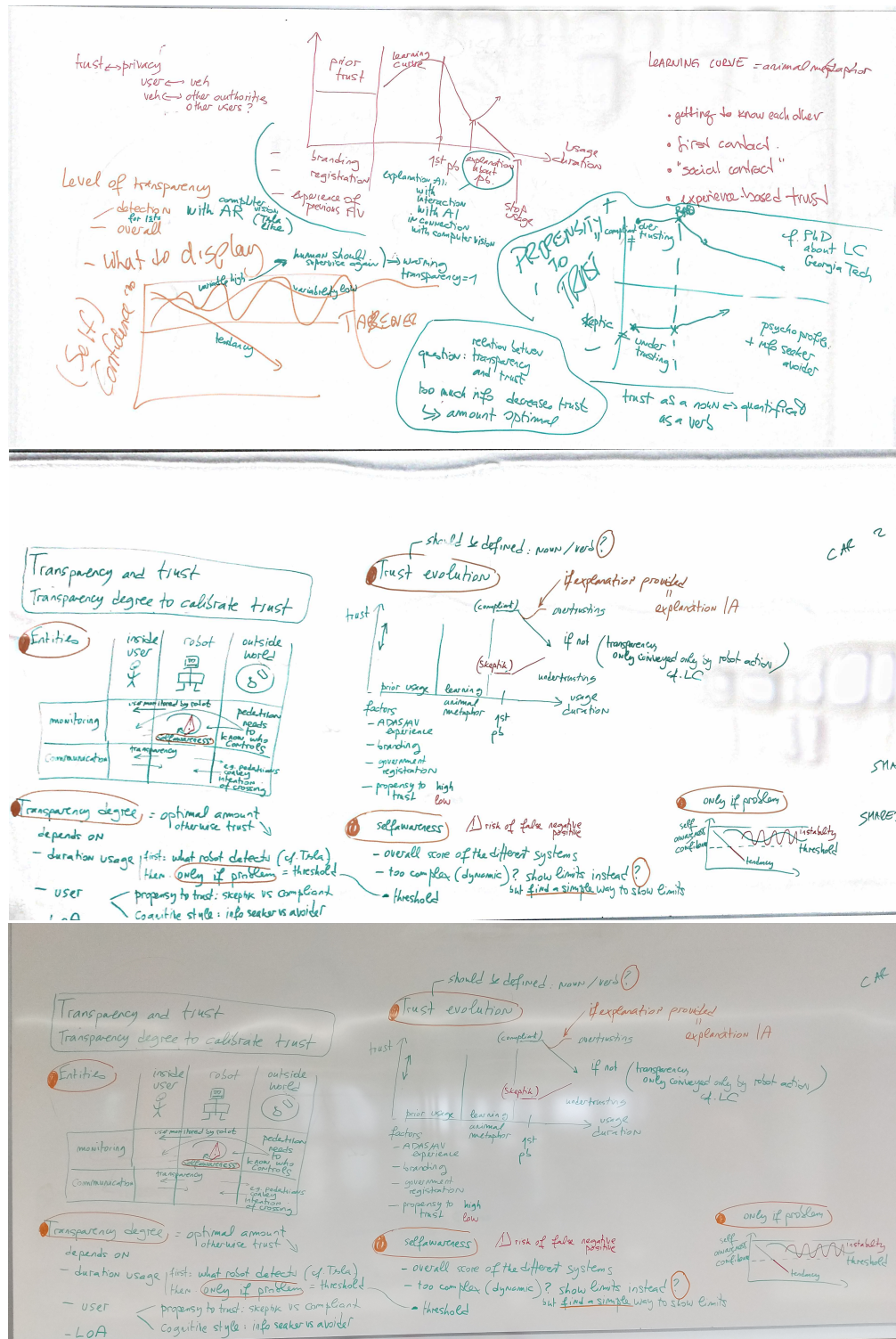
Other discussion topics included knowing what the capabilities of the car were, especially for new drivers or rental situations. How learnable is a new car, and how transferable are the skills learned in one to another. There are issues of standardization here. There are also issues of updates – the car might change from one day to the next with a software update. We also discussed personalization and how the setup of your car might follow you to a new car, perhaps through your phone or profile.

We discussed “out of car interaction” or things that happen outside the car, for example how to exit the car, external lighting, other road users, summoning the car. Important issues occur with users with disabilities as how does a blind person find their Uber, for example.

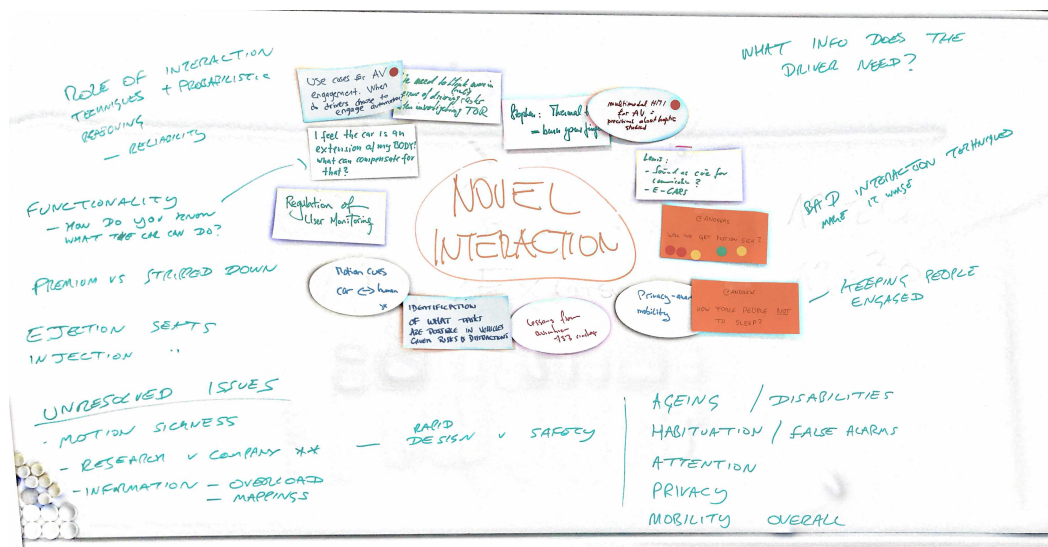
Finally we discussed more unresolved issues. For example, dealing with motion sickness is still important. Information overload for the driver. Rapid design iterations vs. safety. Privacy was a big topic that came up throughout the discussions. How might data that could be used to make driving safer be collected and used in ways that preserved privacy.

5.5.3 Tools and methods (facilitator: Wendy Ju)

As a research community, we would like to share methods, protocols, scenarios, tools, and datasets. This will facilitate the practice of research and enable us to more directly compare results. One major area for this discussion is the research environments; we would like to share



■ **Figure 22** Final result of the World Café on “Transparency and Trust” (facilitated by Sabine Langlois) (part 2).



■ **Figure 23** World Café on “Novel interactions” (part 1).

commonalities of simulators, theater/improved environments, tracks, in-vivo environments and living labs. Another major area has to do with methods. Much of the community focuses on controlled experiments in driving simulators. However, additional methods, for example, on-line video prototype experiments, or methods for creating realistic sense of risk in simulation would benefit the whole community. (A survey of methods for UX & Design is being generated by Anna-Katharina Frison, e.g., [1], [2].)

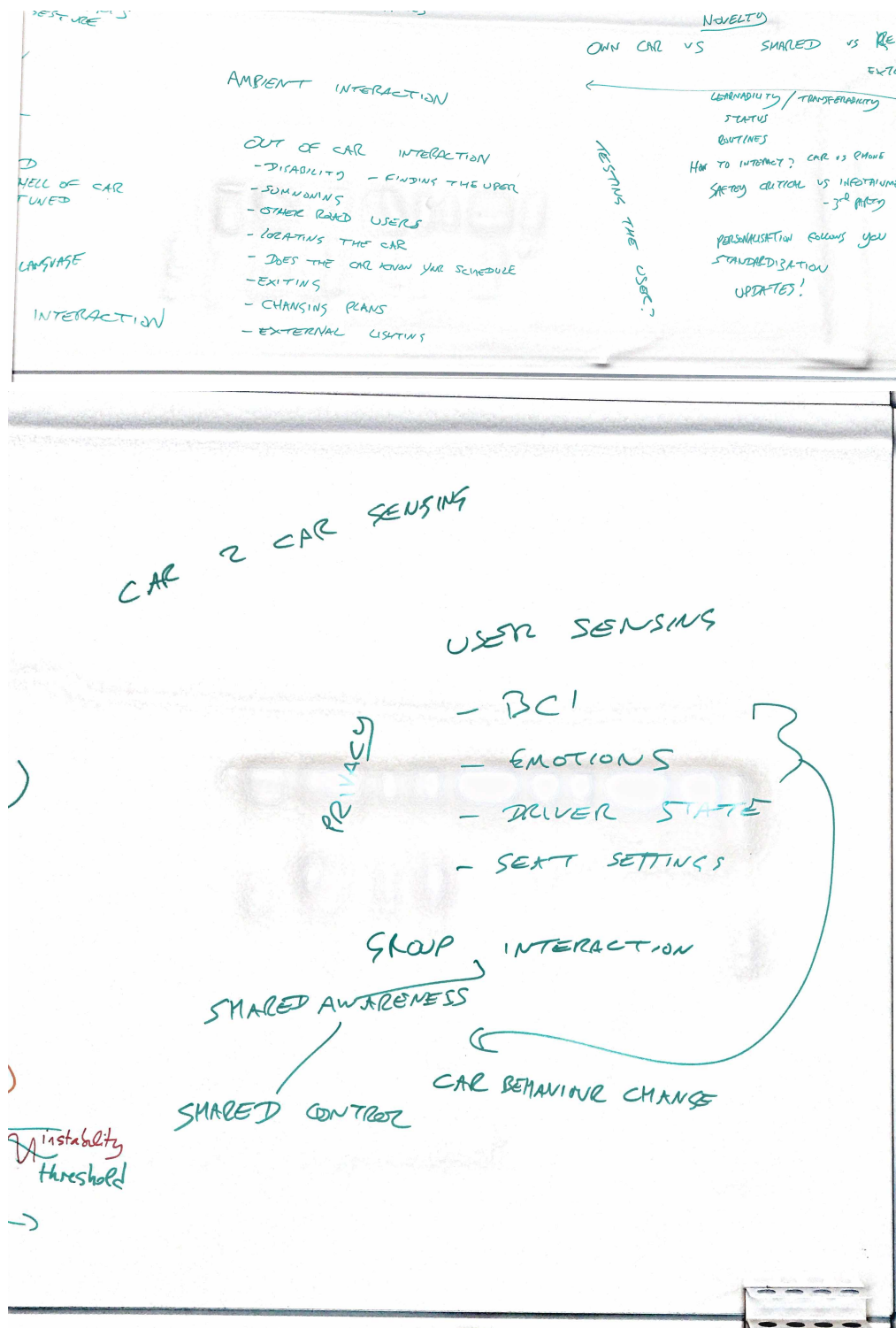
Measures and benchmarks are an important area for research community agreement. In Driving simulation, this community would like to come to agreement on measures for AV interactions. Beyond the measures and metrics inherited from traditional driving simulation experiments, trust, situation awareness and shared situation awareness are emerging as common measures. However, there is a need in this space to understand tasks, scenarios, roles, or control structures to understand what situation awareness means in the AV space. When we look at more naturalistic or observational experiments, it would be good to develop common ways of capturing and labelling naturalistic and behavioral responses. Common methods for collecting, cleaning, analyzing and validating and replicating data from studies would make for greater robustness, credibility and comparability within our field.

On the subject of data, we would all like to learn more about how to generate and share data. Physiological measurement, eye tracking tools, or CAN BUS sniffers might be particularly useful to understand behaviors in more uncontrolled environments. Methods for integrating data streams are also something we all need.

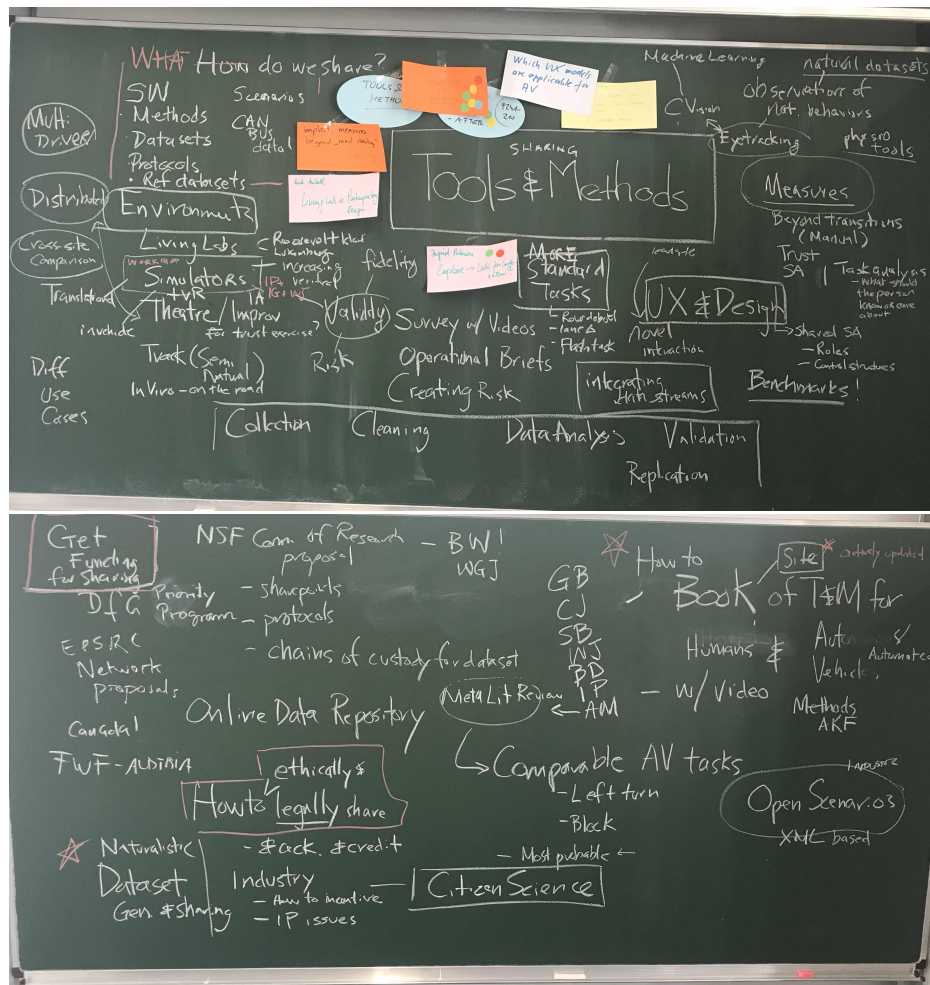
In terms of concrete next steps, we proposed to organize a how-to book/website of tools and methods for researching human-autonomous vehicle interaction. We plan to write proposals to fund communities of research that would help to establish sharepoints for the methods, protocols, software or datasets the community should share.

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- 2 Yannick Forster, Anna-Katharina Frison, Philipp Wintersberger, Viktoria Geisel, Sebastian



■ Figure 24 World Café on “Novel interactions” (part 2).



■ Figure 25 Summary of the World Café of group 4 "Tools and Methods".

Hergeth, Andreas Riener, Josef F. Krems. *Where We Come from and Where We Are Going: A Systematic Review of Automated Driving Studies*. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019. *submitted*

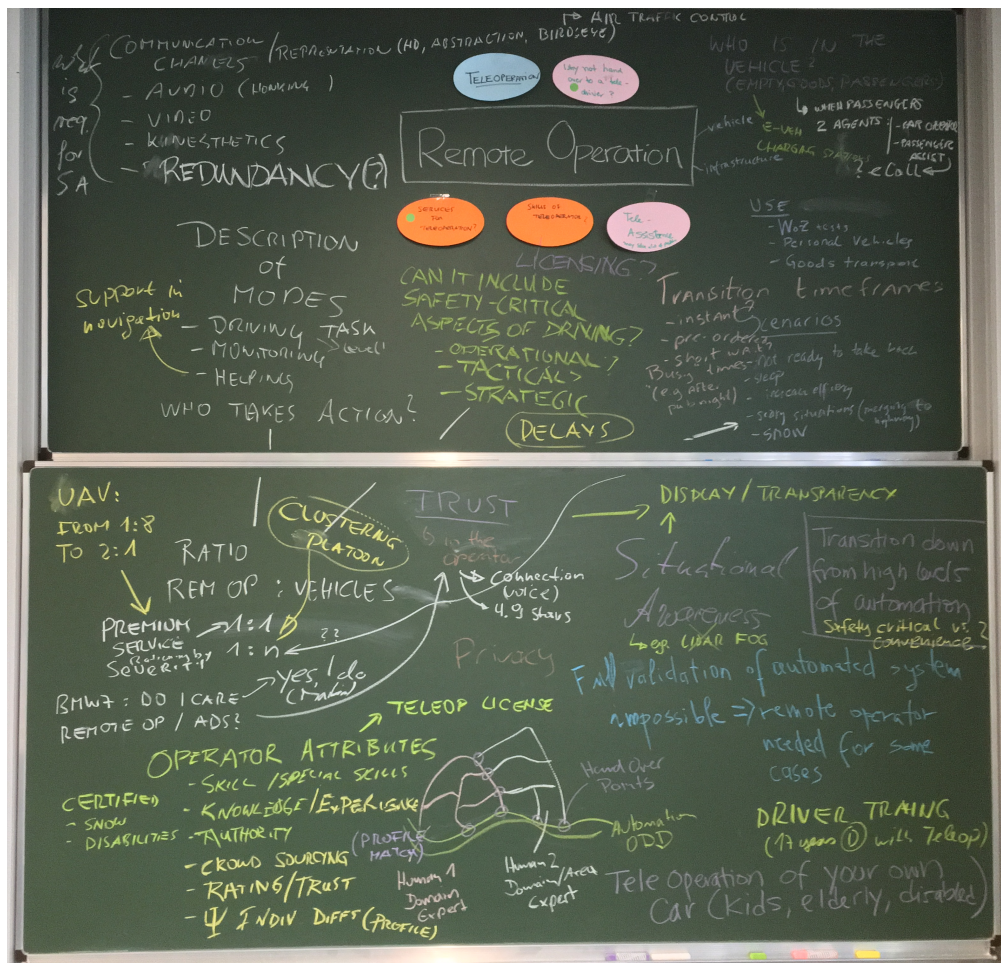
5.5.4 Remote operation/Teleoperated driving (facilitator: Andreas Riener)

In the domain of automated driving, numerous (technological) problems have been solved in recent years, but still many limitations are around that could eventually prevent the deployment of automated driving systems (ADS) beyond SAE L3. A remote operating fallback authority might be a promising solution. In this group, we were discussing challenges and opportunities related to the tele-operation of vehicles. (With this term, we understand the hand-over of control from an ADS to an operator located in an external control room. In the discussion, we found out that there are many similarities to Unmanned Aerial Vehicles (UAV), for example related to the ratio of operators : vehicles (1:1 vs m:n). We further discovered that the skills and occupational conditions required for a teleoperator including tele-op licensing are not defined yet and discovered it rather important to inform the driver about an external take-over (transparency display). As for the situation awareness of the operator in the remote control room, we agreed that there is a need for multi-modal communication including visual information (traffic scenario, either as videos, abstractions, bird eye's view, amongst others), auditory cues (environmental perception, e. g. a honking car in the back or overtaking emergency vehicle), and kinesthetics to avoid motion sickness. We also talked about potential use cases/scenarios and classified them based on three general categories: Remote operation of a) empty cars only (send to parking garage, etc.), b) transporting goods, and c) assisting human drivers (from low "switching on windshield wiper" to high "take over the driving task"). For the latter category, trust (in the operator) is another important issue to consider.

Follow-up readings:

References

- 1 Alex Davies. *The War to Remotely Control Self-Driving Cars Heats Up*. online: <https://www.wired.com/story/designated-driver-teleoperations-self-driving-cars/>, March 26, 2019
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■ **Figure 26** Summary of the World Café of group 4 “Remote operation”.

5.6 Friday: Wrap-Up and Planning of Follow-Up Activities

In the closing session on Friday, all participants discussed together joint follow-up activities to that seminar. The participants identified numerous possibilities for future cooperation, collaboration, and communication to a broader audience. These include, among others:

- Videos from the prototyping session will be finalized and submitted to AutoUI 2019, e.g. [4, 2]
- Videos will also be shared amongst participants and used for educational purposes
- Several subgroups (e.g. of break-out groups) plan to write papers for conferences or journal articles, e.g., [2, 3]
- NSF, DFG, EPSRC, NFR, FWF, COST/ITN: Joint grant proposals planned for community building (driven by World Café “Methods and Tools”)
- Participants also suggested to compile a “handbook of research methods” in the broader field of the seminar
- Follow-up workshops or a panel discussion planned are for AutoUI 2020 and similar conferences
- Tuesday group “Disruption/Radical innovation”: Q: are we the right persons? Organize a panel session with Urban planner, geologist, sociologist, legal, pedestrian/bicyclists

association, etc. related to automated driving

- Panel on governmental perspective on automated driving planned for AutoUI 2019
- Follow-up Dagstuhl seminar proposal planned (maybe more than one?)
- As a community, we should encourage people to provide open data using OSF, Github, link in the paper, etc.
- “Mobile office” NSF project (L. Boyle & A. Kun) discuss to collaborate with A. Riener on a similar project (staff exchange, workshop)
- Some participants think about special issues in journals, such as IEEE PC or Ubiquitous Computing or IJHCS journal

In another session, Frank Flemisch presented the brand new 2019 edition of the “VDA¹ Normungs-Roadmap zum automatisierten Fahren” (VDA standardization roadmap for automated driving), see Figure 27.

References

- 1 Philipp Niermann. *Normungs-Roadmap zum automatisierten Fahren*. Verband der Automobilindustrie e.V. (VDA), DIN-Normenausschuss Automobiltechnik (NAAutomobil), Behrenstraße 35, 10117 Berlin. 2019. pp. 29. online <https://www.vda.de/de/services/Publikationen/normungs-roadmap-zum-automatisierten-fahren.html>

¹ Association of the Automotive Industry



■ **Figure 27** 2019 edition of the standardization roadmap for automated driving (VDA, pp. 29).

6 Publications inspired by Dagstuhl seminar 19132

The following list summarizes publications inspired by the seminar (as of September 10, 2019).

References

- 1 Stefan Neumeier, Philipp Wintersberger, Anna-Katharina Frison, Armin Becher, Christian Facchi, Andreas Riener. *Teleoperation: The Holy Grail to Solve Problems of Automated Driving? Sure, but Latency Matters*. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019.
- 2 Christian P. Janssen, Linda Boyle, Wendy Ju, Andreas Riener, Ignacio Alvarez. *Agents, Environments, Scenarios: A Framework for studying Human-Vehicle Interaction*. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019. (*submitted*)
- 3 Linda Boyle, Christian P. Janssen, Wendy Ju, Andreas Riener, Steven E Shladover, Christine Sutter, Frank Flemisch. *Clarifying variations in vehicle automation: Beyond levels of automation*. Proceedings of the 11th International Conference on Automotive User Interfaces and Interactive Vehicular Applications (AutomotiveUI'2019), Utrecht, 2019. (*submitted*)
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7 Conclusion

Dagstuhl seminar 19132 brought together 31 experts in the field of in-vehicle human-machine interaction in order to discuss how our field can contribute to the success of future automated vehicles.

Workshop participants contributed to the discussion in a variety of ways. They started their efforts with pre-workshop activities: they helped us create a list of recommended readings as well as a list of important research questions. At the workshop, participants engaged in lively debates in multiple formats, from formal presentations, to breakout groups, to prototyping sessions, to world cafe-style forums.

The result of these efforts include an intellectually rich week at Dagstuhl, a set of scientific ideas that are already incorporated into documents submitted for review, as well as specific plans for collaborations between participants.

To wrap up this document, as organizers, we would like to express our deep appreciation to all of those people who contributed to the success of this workshop. First and foremost, we

thank the team at Schloss Dagstuhl for their dedication and exceptionally high-quality work, from organizing the meeting, to hosting us at the castle. And of course, we are most grateful to all of the workshop participants who took an entire week out of their busy schedules to join us in order to create new scientific knowledge in the field of human-machine interaction for future vehicles.

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Programmable Network Data Planes

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Abstract

Software-Defined Networking (SDN) started the “softwarization” of networking. By relocating the control plane onto a logically centralized machine, SDN gave programmers the ability to specify the behavior of the network directly in software, unleashing a major transformation both in the networking research community and in industry. However, a key limitation of the original SDN vision was the limited functionality exposed in protocols such as OpenFlow. Recent efforts to develop reconfigurable data planes and high-level network programming languages has made it possible to truly program the data plane – i.e., to change the way packets are processed on network devices. The ability to fully program the network-both control and data plane-is expected have a profound impact on the field of networking in the coming years. In this seminar we discussed the key questions and problems to be addressed in the next 10 years on the area of programmable dataplanes, and how they will potentially shape the future of networking. As an outcome we are now working on a research agenda to serve as the start of a discussion with networking researchers, practitioners, and the industry as a whole. This report is a first step towards that goal.

Seminar March 31–April 5, 2019 – <http://www.dagstuhl.de/19141>

2012 ACM Subject Classification Networks → Network architectures, Networks → Network protocols, Networks → Network components

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1 Executive Summary

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Traditional networks are complex and hard to manage. It is difficult to configure networks according to predefined policies, and to reconfigure them in response to dynamic changes. Traditional networks are also vertically integrated: the control and data planes are bundled



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together. Around 10 years ago, the Software-Defined Networking (SDN) paradigm emerged and began to change this state of affairs. SDN breaks the vertical integration, separating the network's control logic from the underlying routers and switches (by means of a protocol such as OpenFlow) and promoting the (logical) centralization of network control. As such, it enabled the introduction of new abstractions in networking giving the ability to program the control plane of networks. Modern data center networks employ SDN-based techniques to simplify network management and operate at very large scale, and new networking services are now made possible – prominent examples are VMware's Network Virtualization Platform, Google's Andromeda and Microsoft's AccelNet.

Despite offering programmatic control to network operators, the original SDN data plane was limited to the protocols supported by OpenFlow. Over time, the OpenFlow specification evolved to support operator requirements, growing from 12 header fields in the original version to nearly 50 protocols in recent versions. The primary reason that OpenFlow is limited to specific “baked in” protocols is that the capabilities of switching chips are fixed at fabrication time. However, recent chip designs have demonstrated that it is possible to increase the flexibility of switch ASICs while still maintaining the terabit speeds required of networking hardware. In addition, as programming these chips is difficult – they expose their own low-level interface, akin to microcode programming – a domain-specific language, P4, was recently proposed to program network data planes (see p4.org). These advances are leading to a growing understanding of the inherent challenges related to data plane programming, resulting in further changes that promote future advances. For example, P4 was originally based on a simple architectural model, but has evolved to allow different switch architectures, aiming for stability of the language while increasing the flexibility to switch designers.

At the same time as programmable switches and programming languages such as P4 were being developed, a different group of researchers within the networking community has explored an alternative approach in which advanced data plane functionality is implemented on end hosts. This approach is often known as Network Function Virtualization (NFV). Platforms such as OpenVSwitch and Intel's DPDK framework make it possible to implement sophisticated packet-processing functions on end hosts rather than network switches, at line rates up to 10Gb/s and beyond. A key advantage of using CPUs is their flexibility, which makes it easy to adapt as requirements evolve. For example, it is straightforward to implement fine-grained monitoring of network flows or cryptographic operations – two pieces of functionality that are difficult to implement on standard switch ASICs.

In this context, the seminar on programmable data planes brought together leading practitioners from the areas of networking, systems, programming languages, verification, and hardware, to exchange ideas about important problems and possible solutions, and to begin the task of developing a research agenda related to programmable data planes. We have discussed several topics, including data plane architectures; programming languages, compilers and targets; use cases and applications; verification tools and formal methods; and end-system issues.

In the seminar we discussed questions including where packet-processing functionality should reside, how programmable data planes should evolve, how networks can benefit from these new elements, and how they can cope with the new challenges that arise. The focus was on the key challenges of the field and on the most fundamental problems to look at in the next 10 years, together with an aim to identify the “right” steps to take to move forward and the key problems to tackle next.

We have made some progress toward answering the following synergistic research questions during the seminar: What is the right division of labor between control and data plane? What are the right high-level language abstractions for programming networks, and what guarantees could we expect a compiler to provide reachability, security, or even properties as detailed as the correct use of cryptography? What is the trade-off between making more intelligent data plane architectures and the resulting network performances? Can we enhance current methods adopted to check network configuration errors with new solutions that automatically assure the absence of misconfiguration?

In the rest of the report we summarise the outcome of the most relevant discussions we had during the seminar.

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3 Seminar structure

The organizers designed the seminar to be highly interactive. Most of the seminar was organized around sessions in which each participant was encouraged to actively contribute. For instance, on the first day, we did several rounds of “speed dating” to break the ice and quickly exchange information about technical ideas related to programmable data planes. In the same vein, “change my view” debates drew out issues for which there were a range of opinions in a constructive way. Breakout sessions were used to make progress on identifying open questions and possible directions for future research. The agenda also included several conventional talks including: two keynotes, six invited “cross-pollination” talks, as well as talks by each of the PhD students and several tool demos.

4 Overview of talks

4.1 Keynote

Nick McKeown (Stanford University, US)

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In his keynote Prof. Nick McKeown (Stanford University) shared his views on why we are where we are with programmable data planes and the P4 language. The keynote started with the question of why network programmability didn’t happen before. The reason presented was three-fold. First, there was a vested interest in the status quo. The second reason is the split between hardware and software researchers. Third, the fact that adding programmability to hardware is indeed a hard problem. So the next natural question was on why this (unstoppable) change is happening now? The “desire for programmability” in networking has its roots back in the 1990s, but it was not practical for performance and power efficiency reasons. But with respect to the data plane the assumption that held until very recently was that processing packets efficiently and with high performance required fixed-function hardware.

One of the first attempts to change the status quo happened in the late 1990s with Network Processing Units (NPUs). The focus was on parallelizing packet processing. Several research projects were started and many scientific papers were written on packet processing using multiple RISC cores. This improved the situation, but still at limited scale and performance. It seemed clear that applying the performance-enhancement techniques from computing directly into networking was not enough.

The community then started an introspection to answer the question: what type of processing is done networks? At the same time, OpenFlow was being proposed, and has been a learning experience to start to answer the question. While OpenFlow was limited, too fixed, and the abstraction was not right, it gave a good idea of the basic operation of network equipment. For packet processing, switches and routers look on headers and perform actions based on these fields: the match+action abstraction.

The community has followed observing this as a generalised abstraction, and asked itself whether there is a simple instruction set that allows us to describe on a high level language the desired packet processing to enable it to be compile it down to hardware targets? The question is complicated, as it is hard to figure out an instruction set for most domains, because parallelism needs to be taken into account. However, networks is a relatively easier

case, at least for the most common functions, due to the stateless and parallel nature of how switches process packets. Stateful functionality is a much harder problem, as it can break parallelism. There was anyway a feeling that programmability must come at a cost (more energy, slower processing, larger tables).

But turns out this is not really true, as most switching elements have no relation to programmability, so there is in fact no penalty. In practice, there is slightly lower power for the programmable part, while retaining the same performance. The die size is the same (because of the serial IO), and hence the cost is the same. Programmability represents a relatively small fraction of the chip: the wiring part is big and the size does not change, memory also uses a lot of space and is growing, and the ALUs, the programmable bit, is relatively small. As a result, while CPUs struggle to reach 100Gbps, the fastest switches can now process data at Tbps (Barefoot Tofino can switch 6.5Tbps, or 10 billion packets per second).

While we now have programmable data planes, building them is hard. The example of Barefoot Tofino, the first programmable switch, is illustrative. Tofino has 10 billion transistors, and the new version will have 21 billions. The Tofino team had around 150 people working, divided into compiler, applications, and chip design. To overall cost to design and develop a new chip is of between 150 to 250 million dollars, as the processing technology is extremely expensive and complicated. From an investor perspective this may not be very attractive because of the costs and risk.

To close, the question of inevitability was made: was programmability inevitable? The consensus was that SDN was inevitable. Big companies such as Google wanted to build cheaper networks to scale better, wanted more control, which required disaggregation, so it basically changed the scenario, and in consequence the industry. The same trend seems to be true with programmable data planes today. One of the important questions in the next 10 years is on which is the right hardware architecture for programmability.

4.2 Keynote

David L. Tennenhouse (VMware – Palo Alto, US)

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In the second keynote, David Tennenhouse, VMware’s Chief Research Officer, has drawn a big picture of where we are in programmable networks as a result of 4 decades of introducing software into the field. A common theme was the idea of putting Computer Science into networking, as well as the role of virtualization as an enabler for innovation. An important point was the need to understand what is programmable, as this determines who can innovate and where.

David started with some historical background on the Internet, ATM and active networks. Several important concepts for programmability and virtualization were highlighted, including multiplexing (virtualizing links), the granularity of computation (per byte, per flow), virtual switching and datagrams, etc. Active networks, in particular, are very relevant as they can be considered a first instance of data plane programmability. The goal was similar: to enable innovation in networking. The concept of “network capsules”, for instance, were programs were carried in packets, and the header was in practice used as a dispatch function, with the dispatch parameters in the header. The idea was radical, in order to make room to have others make less wild (but maybe more practical) ideas.

The discussion that ensued included how the concept of active networks affected the end-to-end arguments, and what type of computation we add to the network, and where. There was a general agreement that complex computation will probably stay at the edge. IXPs were also mentioned as a good place to innovate. NFV was also discussed, an effort telcos are leading. It was argued that the problems of NFV are in many cases rooted on a lack of CS principles in addressing the existing challenges.

At closing, some of the opportunities and challenges on the field were discussed, including the need to add support for virtualization in switches, addressing the new security issues that arise in this new context, VNF integration, and the need to focus on declarative approaches and on correctness and verification mechanisms and tools.

4.3 Talk

Gabor Retvari (Budapest University of Technology & Economics, HU)

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Gabor Retvari from Budapest University of Technology & Economics has gave a talk on “The quest for a sane definition of dataplane programming”. Gabor’s hypothesis was that a common understanding of what data plane programmability was largely missing. He presented several examples that could be perceived as such (e.g., changing BGP configurations, changing a protocol in Linux, adding a new ebpf program, etc.) and there was indeed no global agreement.

Gabor presented his personal take, that consisted in distinguishing the semantics from the behaviour. Dataplane programming would require altering the semantics (i.e., parsers/de-parsers, match-action table definitions, action types, queuing disciplines, the control flow), and using a standard interface/API exposed by the network dataplane for this purpose.

The discussion that ensued included the different roles between the data plane and the control plane, and their interactions, and the idea that to be programmable you would need to program the forwarding function of the equipment – something that was rebated with an example: what if you had a huge, but fixed, header, and the program was in the header?

4.4 Talk

Dotan Levi (Mellanox Technologies Ltd. -Yokenam, IL)

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Dotan Levi from Mellanox Technologies has given a view on the common architecture of modern programmable NIC hardware. Besides the expected Ethernet ports, buffers, and a PCIe switch, the architecture includes (R)DMA, QPC (to maintain context of the flow), schedulers, and FPGA-based accelerators for erasure coding, TLS, IPSec, etc. For the latter, there is a queue to access the FPGA, which means that from the point of view of the NIC there is only a queue. The architecture also includes a message channel to allow for disaggregation, which means the FPGA acceleration can be remote.

4.5 FlowBlaze demonstration

Salvatore Pontarelli (University of Rome “Tor Vergata”, IT) and Roberto Bifulco (NEC Laboratories Europe – Heidelberg, DE)

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Programmable NICs allow for better scalability to handle growing network workloads, however, providing an expressive, yet simple, abstraction to program stateful network functions in hardware remains a research challenge. Salvatore Pontarelli (Axbryd/CNIT) and Roberto Bifulco (NEC Laboratories Europe) presented a demonstration of FlowBlaze, an open abstraction for building stateful packet processing functions in hardware. The abstraction is based on Extended Finite State Machines and introduces the explicit definition of flow state, allowing FlowBlaze to leverage flow-level parallelism. FlowBlaze is expressive, supporting a wide range of complex network functions, and easy to use, hiding low-level hardware implementation issues from the programmer. They have shown their implementation of FlowBlaze on a NetFPGA SmartNIC.

4.6 Talk

Eder L. Fernandes (Queen Mary University of London, GB)

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Eder Leao, Research Assistant and PhD candidate at Queen Mary University of London, presented his work “Horse: a Tool for Dynamic and Faster Experimentation of Control Planes”. The starting point is that evaluating new control plane applications or assessing the impact of changes on the network behavior, e.g., new routing protocols or topologies, requires simulation or emulation tools capable of providing results as close as possible to those from a real-world experiment. Large traffic loads and dynamic control-data plane interactions constitute significant challenges to these tools. In addition, the need for ever-increasing computational resources severely limits researchers’ ability to test their ideas at scale. To address these challenges Eder proposed a tool for faster evaluation of both SDN and legacy networks. His approach emulates the network’s control plane and simulates the data plane, to bring realism to control plane testing while being also capable of experimenting for increasing topology sizes and loads. He presented the design and implementation of a proof of concept, and some preliminary results. The discussion centered around some of the challenges of the approach, including control plane convergence, issues with the fluid traffic models used, and the time to setup the control plane.

4.7 Talk

Stephen Ibanez (Stanford University, US)

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The rise of P4 programmable devices has sparked an interest in developing new applications for packet processing data-planes. Unfortunately, the application developers have only met with limited success. The bane of designing data-plane applications is that they must satisfy the strict constraints of the underlying hardware, which makes it difficult to implement complex stateful processing logic. These challenges are exacerbated by the fact that modern programmable data-plane architectures support a very small collection of events. Typically, packet arrivals, packet departures, and recirculation events. In his talk “Event-Driven Packet Processing” Stephen Ibanez, PhD student at Stanford University, shared his observation that network applications are inherently event-driven and as such, programmable data-plane hardware should also be event-driven. By identifying a set of useful data-plane events and outlining a new hardware architecture to support them, he demonstrated how we can achieve an unprecedented level of programmability without sacrificing performance. The discussion centered around some of the potential consistency issues of the solution.

4.8 Talk

Daehyeok Kim (Carnegie Mellon University – Pittsburgh, US)

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Programmable switches have been touted an attractive vantage point to serve various network functions (NFs) such as network address translators, load balancers, and virtual switches because of their in-network location and high packet processing rates. However, the limited memory capacity on programmable switches has been a major stumbling block that has stymied their adoption for supporting many memory-intensive NFs (e.g., datacenter scale NATs and load balancers that maintain millions of flow table entries). While it is theoretically possible for switch ASIC vendors to extend the memory capacity (e.g., adding more SRAM or adding off-chip DRAM), these solutions are not cost-efficient and are fundamentally limited in flexibility and scalability.

In his talk “Generic External Memory for Switch Data Planes”, Daehyeok Kim, PhD student at CMU, presented an alternative approach in which NFs implemented on a programmable switch can make use of DRAM on servers connected to the network. The design is driven by the observation that in data centers, DRAM and network resources are underutilized. This gives an opportunity to leverage those unused resources to extend switches’ memory capacity with low cost. While this low cost solution is appealing, there are several technical challenges before we can realize this in practice. These include performance, load balancing, and fault-tolerance. In the talk, he described the key challenges, how they addressed them, also introduced his prototype implementation and preliminary evaluation results to demonstrate the practicality of the solution.

4.9 Talk

Hugo Sadok (Federal University of Rio de Janeiro, BR)

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The standard approach adopted by software middleboxes to use multiple cores has long been to direct packets to cores at flow granularity. This, however, has significant shortcomings. First, it is inefficient, since it cannot use all cores when there is a small number of concurrent flows—which happens frequently. Second, asymmetry in flow distribution causes unfairness even with a larger number of flows. Yet, the current trend of higher-speed links and core-richer CPUs only aggravates these problems. In his talk “A Case for Spraying Packets in Software Middleboxes”, Hugo Sadok, PhD student at CMU, proposes a natural alternative: that middleboxes should direct packets to cores at a finer granularity. His system, *Sprayer*, solves the fundamental problems of per-flow solutions and addresses the new challenges of handling shared flow state that come with packet spraying. *Sprayer* builds on the observation that most middleboxes only update flow state when connections start or finish; ensuring that all control packets from the same TCP connection are processed in the same core. In the talk he has shown that, when compared to the per-flow alternative, *Sprayer* significantly improves fairness and seamlessly uses the entire capacity, even when there is a single flow. The discussion centered around potential reordering issues from the cumulative effect of chaining network functions.

5 Summary of breakout sessions

5.1 Scalable and stateful in-network computing

Support for stateful packet-processing is an important consideration that differentiates various programmable data planes. Early efforts focused on turning fixed-function switches to programmable switches, maintained the classic separation of control plane and data plane, meaning that table updates can only be performed using the control plane. Furthermore, it assumed that operations within the data plane are stateless or mostly stateless (e.g., support for MAC learning, or packet and byte counters might be provided). However, the development of the PISA architecture, which provides support for general-purpose registers, as well as the emergence of in-network computing generalizes the simple SDN model. However, supporting network functions that require per-flow state such as NAT and load-balancers remains challenging.

Going beyond PISA, there have been several recent attempts to enable stateful operations in the data plane. One such example is *FlowBlaze* [NSDI’19], which uses state machines to enable stateful operations. *P4->NetFPGA* [FPGA’19] enables stateful operations using externs, and supports atomic operations for maintaining and changing state.

Overall, the group concluded that support for stateful operations within the data plane is essential. To achieve this will require introducing new primitives to P4 and related languages that abstracts away the details of the hardware while still supporting mutable state. A key challenge will be adding stateful operations without affecting performance: switches must still support full line rate with only minimal changes to existing hardware designs.

5.2 Is P4 the RISC of Packet Processing?

The discussion started with the evolution of programmable networks, from pre-SDN to programmable data planes and the evolution of the P4 language. In an analogy with the evolution of human societies, before SDN was the hunter-gatherer time period, with hardware architects in charge of networking. The SDN period was the period after the “discovery of fire”, by giving more control to the users, but still with the data plane dictated by the manufacturer: fixed parsers and fixed match-action. The P4_14 period corresponds to the “domestication period, separating planting from harvesting”, introducing programmable parsers, programmable match-action, and primitive actions. Finally, the P4_16 period was the period of a “sophisticated civilization (e.g. roman empire)”, with an enhanced version of the language, and the introduction of the Portable Switch Architecture (PSA) and API generation framework (control plane API, such as P4Runtime).

At the moment, P4 seems to be an ISA-like interface between higher-level applications (L3 router, telemetry, stateful applications) and the underlying target architectures (software switches, FPGA, Tofino, SmartNICs, etc.). The higher level applications are compiled down to the ISA (P4 + PSA) – we could call it RISN (Reduced Instruction Set Networking) – and the target architectures implement the interface.

5.3 Edge packet processing should have a different programming model from core hardware.

While everyone agreed on what constituted a network “core”, the edge became far more contentious. The focus shifted to discussing different granularities of where programmability is inserted at the edge. The group summarize a list of different properties of edge processing tasks, for example:

- those processing aggregates of traffic
- those processing a few flows
- those processing hundreds or thousands of gigabits
- those processing a few megabits
- those that hold entire movies
- those that only hold a few flow table entries
- those that need no state to process packets
- those that need only a fixed amount of per-flow state
- those which reconstruct the entire data in a connection and might need an arbitrary amount of state
- those that use shared state
- those that encrypt packet, or decrypt them, or compress them, or do things one cannot even imagine

Hence the conclusion was that the programming model was more tied to the capabilities required rather than core vs edge. The conclusion hence led to a new question: “What is an appropriate taxonomy of processing capabilities that we might use to derive programming models?”

5.4 Can we bridge the gap between network measurements and application performance?

The group of people participating this breakout session recognises that there is a mismatch between operators' and users' perspective. Such a mismatch results in a non-trivial translation from the data retrieved with network monitoring practices and application needs. On the one side, the collection of monitoring information has been so far a pretty well explored area by the community. Many different approaches have been considered, from flow-level analysis to per-packet measurements using probabilistic data structures, i.e., sketches, or In-band Network Telemetry (INT). On the other side, there is still a lack of consensus on high-level abstractions. The group agreed that although this is somewhat an old problem, network programmability can help in the process of aggregating fine-grained measurements into high-level application-aware metrics. Specifically, bridging the gap between network measurements and application performance can be achieved only through rethinking application development process. Indeed, just capturing and then analysing all the traffic in the network, which is a very challenging problem itself, might not be enough to have a comprehensive understanding of the network/applications ecosystem. This is because the translation to high-level metrics, e.g., service level objectives (SLO), remains still unclear. To bridge this gap, network packets need to be easily associated to specific applications. This can be done by tagging the packets. In this way, applications can "dialogue" with the network and inform which packets are important or which metrics affect mostly the correct behavior, i.e., latency, jitter. As a consequence, there is a need to rethink application development process: developers need to provide information about network metrics they are interested in and subsequently embed those notions in form of tags in the packets. Then, leveraging data plane programmability network operators can use the tags to translate the fine grain measurements taken in the network with the high level objective of an application. Such an approach will also help during the debugging process when an application performance degradation is experienced by quickly locating if the problem relates to the network or the software application itself.

5.5 Data planes: security challenge or opportunity?

In this breakout session we started by discussing the security challenges of programmable data planes. First, software is more bug prone than hardware. Programmers tend to take it more light heartedly, and software is to be written by the end user, that is usually less experienced (and careful) than a vendor. The functionalities will also tend to be more complex, potentially creating new problems. Second, attackers can now change the behavior/semantics of the device. Similarly to SDN, this creates new attack vectors that have to be addressed in a different way from traditional measures. Finally, it becomes important to make sure that countermeasures are applied (e.g., assertions to be added to the program, verification be performed, etc.).

Then, we discussed how it could improve security. First, it allows the development of new verification mechanisms and tools. This requires different objectives than functional verification, and proper security models. In addition, it needs to be updated as we add security functions, potentially at the network level (vs just at the device level). Second, it enables containing effects of attacks ("sandboxing"), for examples by using (micro)segmentation of the network, traffic, code, and of the execution environment. Third, we can now include assertions to be added by security experts (vs programmer), that are not program specific and can possibly be common to multiple programs (e.g., aspect-oriented programming). The expressiveness of the language may need to be restricted for security reasons.

Finally, we addressed opportunities, including rapid remediation or minimizing the number/amount of functions on the device. The fact that assertions and verification are enabled give opportunities for hardening networks. In addition, the end user has now visibility on the program, so it can fix security breaches directly. Open source can also be an opportunity (and a challenge). There are also new opportunities for the network to protect the rest (e.g., in the IoT case), as programmability allows implementation of more sophisticated countermeasures. The biggest challenge is to take advantage of the opportunities.

5.6 Will declarative language for networking ever succeed? Can we map a single program to multiple targets?

Writing code for network devices require a deep understanding of the capabilities supported by the target architecture. The level of functionalities exposed to the programmer, such as supported match types and hash functions, or Read-Modify-Write operations (RMW) that can be performed vary greatly across distinct chips. Considering the fact that the desire of developers for portability not always align with vendor's need for differentiation, we raise some relevant points that should be taken into account on the quest for higher level languages to program data planes.

We first look into stateless packet processing. Because the trade-offs of programmability for stateless header processing are almost nonexistent, it should be feasible and easier to have a well defined minimum set of features that must be supported across different targets (a Portable Switch Architecture). Such definition could enable the development of portable programs without giving performance away.

Stateful packet processing is a more complex problem. The need to store and keep track of network information is different across different applications, what makes it harder to define a standard set of instructions. Such complexity raises questions:

- Is there a minimal set of instructions that could possibly become a standard Instruction Set Architecture (ISA)?
- It is acceptable to exchange performance for generality? Is there an acceptable threshold for most applications?

For the first question, if we think about traditional stateful network applications such as firewalls and NAT, there are some well defined actions needed to implement the applications. However, new applications for in network computing could bring a whole new set of specific instructions. As for the second question, a potential approach would have compilers able to estimate and expose the potential loss of performance and let the customers weigh on the trade-offs.

5.7 Switches should continue to be used as switches

The discussion within this breakout group on “Switches should continue to be used as switches, i.e., as network devices that receive packets, parse them, and then forward them with little or no modification” evolved around the general role of switches in today's networks: whether switches should simply forward packets or also perform more complex operations. Several recent works have shown how programmable switches can be used to improve application performance in two possible ways: i) improving the communication channel through which

applications communicate (i.e., the network/transport layer) or offloading application logic into the network. Through the first approach, network operators can program data plane pipelines to support the delivery of a packet from a source node to its designated destination while guaranteeing some level of performance. For instance, operators rely on load balancers to make efficient utilization of network bandwidth resources, use network telemetry to verify the status of the network communication, implement fast reroute to quickly detour packets upon network failure, and use packet schedulers and congestion control support to implement different level of application performance in the network. Programmable data-planes are clearly a game changer for this type of network applications. Through the second approach, network operators can program part of the application logic within the data plane packet processing pipeline. Some examples of this paradigm include range from key-value storage systems (e.g., NetCache [1]) to coordination services (e.g., NetChain [2]) and beyond. This group believes that in-network computing holds great promise for programmable data planes but it yet has to prove its advantages with convincing use cases, which have been so far limited and debatable. Today's main barriers to move application logic into the network are represented by the limited memory support at data plane speed (e.g., small, no transactional) and lack of transport reliable support, which makes it harder to implement distributed mechanisms. Whether switches will be used in the future to offload application logic clearly depends on a variety of factors including costs, future application requirements, and switches data plane capabilities. We however expect to see extensive research efforts coming from the networking community in the study of in-network computing in the coming years.

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5.8 Virtualization of programmable data planes won't work because current languages are too low level

The discussion of this breakout group started by noticing that there is no such a thing as "too low level language" for virtualisation, i.e., assembly. Then, the discussion has evolved around the meaning of virtualisation itself. In this context, the group has focussed its attention on the problem of sharing switch's resources among different programs. Although enabling composition of different P4 programs has already been tackled by existing literature, i.e., P4Visor [1], the group acknowledged that it is not clear yet how to support performance isolation. One option can be to leverage the multiple pipelines available in current programmable data planes hardware and switch between them by recirculating the packets. This solution has been considered not practical though. Indeed, it was noticed that different pipelines are generally attached to different physical ports, making the switching of pipelines possible only if cables closed in loopback are being adopted, thus wasting precious physical port resources. After some brainstorming around potential solutions and their drawbacks, the group has agreed that the P4 language should not represent a barrier for virtualisation. In contrast, the specifics of a programmable hardware could, although those can reflect back to the language itself. Indeed, a meaningful question seems to be whether the underlying architecture has features that hinder virtualization, e.g., one might want to have multiple

queues that are assigned to different slices and each slice has its own scheduler under the control of one single program. This is a call for a virtualisation-aware hardware architecture that builds upon the PIFO results [2].

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5.9 It’s time to redesign the traditional undergraduate networking course around data-plane programs!

The breakout session started with the question that we need to be clear about what we mean by networking, as there are many aspects (e.g., physical layer, coding theory, etc.). The focus was on Computer Science courses, and they are mainly about the way the Internet works. The reason is probably the Internet ossification, so for an introductory class you want to teach students how sockets work, explain Ethernet, ARP, DHCP, DNS, etc. This ends up as becoming in the awkward middle between theory-style classes and system-style classes.

Given the layered structure of the Internet, several approaches have been tried. The most common today are Kurose and Ross’s top-down approach and Peterson and Davie’s bottom-up, but others (e.g., Scott Shenker) have a different approach: starting from the middle, with routing and reliable transport. And then spreading to the edge. Trying to frame the lecture as a solution to a problem that we can define clearly was seen as an interesting approach. The lecture starts by presenting the students a strawman solution, and then refine it with their help.

With respect to the laboratorial sessions, several practical assignments and group projects were discussed. Some (Jon Crowcroft a while ago) involved writing a new transport protocol and interoperate. Others (Laurent Vanbever at ETH) include each group of students managing their own AS, requiring them to configure their own networks and establishing connectivity with others groups/ASes, using Docker, OVS, Quagga, etc. In Stanford and Cambridge there is also one course on how to build a router that is of interest (currently using P4 which facilitates development). Congestion Control Shootout + ETH Communication Networks seem like three ingredients that get at what I’m looking for. Keith Winstein at Stanford also has a TCP congestion control contest.

P4 can be a game-changer in this respect, and the P4 education group has been making an effort to publicly share curated material in their github page.

5.10 eBPF, DPDK, XDP, FPGA, SmartNIC – what, when, why?

These are very diverse technologies that cannot be compared to each other directly: DPDK is a framework, eBPF is a virtual machine, XDP is a hook, FPGA is hardware, and a SmartNIC can be many different things. However, they can potentially be used to implement similar applications (or parts of them), so we summarize the advantages and disadvantages of each.

DPDK has the advantages of being an industry standard for NFV, and industry backing. Enables good software-level performance with many optimizations such as pre-fetching, memory, caching, vectorization, SIMD for parallel workloads, etc. As disadvantages, it

requires domain specific knowledge, dedicating ports, and rewriting the network stack in userspace, and/or looping back to the kernel.

eBPF's advantages include being integrated with the Linux kernel, can be changed without changing the kernel, although running in the kernel, and good performance if using the right hook. However, it has somewhat limited functionality, it's difficult to implement complex functions (Cilium uses many helper functions in the kernel, for instance), and does not expose low-level code to acceleration, making it hard to take advantage of vector capabilities like SIMD instructions; especially since hooks are called per packet.

XDP is one of the hooks for eBPF, and the recent introduction of AF_XDP allows eBPF to combine user space and kernel packet processing (essentially providing an early branching point between the two). As advantages, it has near DPDK performance without dedicating a NIC like DPDK, and is good if you want to use the Linux kernel to multiplex against different network stacks. As disadvantages, it still needs to do everything to the packet in userspace (like DPDK).

FPGA and SmartNICs are very diverse technologies, with no clear baseline and lots of implementation specific features. The best aspects are that it is not needed to burn a core for performance, and helps in meeting space constraints (i.e., no space to deploy extra servers in some edge deployments). However, it is unclear how to program them (no real standard), platforms are very different, and they often do not have guaranteed performance.

5.11 How can we improve application performance using programmable packet scheduling?

The breakout session started by asking problems does packet scheduling solves? First, bandwidth guarantees, isolating well behaved flows from ill-behaved flows. Then, minimizing delay (latency), FCT (with and without flow size info), offering delay bounds (both local and end-to-end) and delay jitter bounds. It helps minimizing the number of missed deadlines (or deadline violation probability bound), offers bounded loss rate (or buffer overflow probability bound), minimize slowdowns (a.k.a. bit transmission delay) – $\text{delay} / \text{flow_size}$, and allows to simultaneously achieve multiple performance objectives.

Application need to provide some information to the network to help it make scheduling decisions, such as indicating co-flows so that the network can implement policies that minimize co-flow completion times, which packets are more favorable to be dropped, provide back pressure into the network so the network can use that info to make scheduling decisions (e.g., deadline hints). Several efforts exist to achieve this goal, including the TAPS IETF Working group that is discussing ways to change the socket interface so that applications can indicate performance requirements/desires to the network.

Some applications might be improved by enabling custom packet scheduling policies, including network performance isolation (the network could prioritize packets from flows with no downstream congestion in order to avoid sending packets that will be dropped downstream, thus wasting capacity reducing isolation), and Time Sensitive Networking (TSN), that often requires precise synchronization and packet scheduling amongst switches.

6 Summary of panel discussions and debates

To spark active conversation and open-ended discussion, we started the seminar with several semi-structured activities between small groups.

6.1 Speed dating

In the first activity, “Speed Dating”, individual researchers led small group discussions. Each leader proposed a (semi-controversial) thesis statement and gave a short 5 minute “pitch” in favor of their thesis to a small group of 5-7 people. The small group then asked questions or proposed alternative theses and argued against the proposal. After about 10-12 minutes, conversation stopped and each small group member moved to a different leader. The leaders then repeated their “pitch” and led another discussion. This process of 10-12 minute small group discussions repeated until every attendee had visited every leader’s presentation. Some of the presenters and thesis statements were as follows:

Minlan Yu (Harvard University): “Measurement system design should be led by applications not network devices”. Today, many measurement systems (e.g., the latest INT design) are all led by capabilities of network devices, followed by operators who then think about what queries they can ask using the new measurement capabilities. I argue that we should design measurement systems focusing on how to better serve applications directly without worrying about device capabilities. We have entered a stage where we have devices with enough programmability and researchers/engineers who are smart enough to implement what we need if we have a good abstraction that meet application needs.

Justin Pettit (vmWare): “AF_XDP is the right way to do dataplane processing in Linux” Dr. Pettit aimed to focus the conversation on a sequence of questions related to the AF_XDP extension for dataplane processing: What are the security implications, specifically in regards to side-channel attacks? At what point (specifically speed) does it make sense to start offloading some or all to hardware? And if we want to move it to hardware, what does that look like? FPGA? SmartNIC with small general purpose CPUs? NIC with flow offloading?

Timothy Griffin (Cambridge University): “Dynamic Routing Protocols Work!” Dr. Griffin provided the following summary: This was an intentionally provocative assertion. It generated a conversation that continued throughout the week with many people. Gradually, it morphed into this question : “In the future when programmable switches are ubiquitous, what changes will we see in the IETF?” Presumably it will make some kinds of interoperable protocols easier to define, develop, and test. We may see many more network operators and end-users proposing protocols. This may be especially true in the areas of transport and security. However, in the control plane things may be different. What incentives are there now for network operators to worry about interoperability? Inter-domain, OK, sure. But intra-domain? Not clear. Perhaps end-users will force some minimal interoperability so that services can span multiple providers (for example, VPN standards such as VXLAN and other virtual network services). My assertion is that this kind of activity represents a “paradigm for programming the dataplane” – new functionality is introduced in the dataplane (say some kind of tunnel), and distributed protocols are developed and defined to populate the in-switch tables needed to implement the functionality. I don’t think this paradigm is going away any time soon.

Noa Zilberman (Cambridge University): “In-network computing is the way to scale computing” Dr. Zilberman provides the following summary: In network computing is the execution of traditionally host-based applications within the network, e.g., within a switch

or a NIC, as the traffic goes through the network. Network devices process billions of packets a second, and several works have demonstrated their use to achieve billions-of-ops a second throughput (KVS, consensus, data aggregation, network services etc.). While CPUs have improved x27 in performance since they met the end of Moore’s (and Dennard’s) law, network devices have scaled x200, and (so far) continue and scale [2015 numbers]. In-network computing provides a trajectory for continuing and scaling computing, providing the much needed improvement in performance (throughput, latency), alongside better power consumption (10M’s of ops/Watt in a switch, compared with 10K’s of ops/Watt on a server) they are also “low cost” – you already have the device within your network.

6.2 Change my view debate

In the second activity, we conducted a debate style conversation with two individuals leading the conversation and presenting arguments for and against a specific topic.

The first topic was: “Deep Packet Inspection is obsolete. The rise of end-to-end encryption renders DPI useless.”

Aurojit Panda was for, with three arguments. First, that it was unsafe, as there is a lot of TLS interception happening, there is the problem of old cipher suites, and that generally adding boxes is making us worse. Second, it is infeasible, due to the stateful requirement that does not allow it to scale. Finally, it is unnecessary, as we need the DPI to have policy, and content analysis is hard – we should just use meta-data.

Jon Crowcroft was against, as we need tattered ends for latency, energy, and privacy. We need at least a bit of DPI, as serving content from the edge is important.

Others have argued TLS is everywhere, so its feasibility is killing DPI, and software developers are winning because you have it at the edge; there should be active delegation of trust, so things should not be done surreptitiously; and there is a tension between the stakeholders. Would do we trust? Who checks our network? Should anyone take care of security on my behalf?

The second topic was “P4 will stand the test of time. (20 years from now we will all be writing P4v39)”

Robert Soule is for, arguing PISA to be the natural design. Also, P4 is simple, follows well the match-action abstraction, and these fundamental abstractions will stay with us. Sujata Banerjee was against, as she thinks we should be programming at a higher level of abstraction. Also, maybe we won’t be programming data planes in 20 years, as they may have all been written.

Robert rebuttal mentioned programming in P4 to be painful and that we indeed need a higher level abstraction, but we will develop that with time and P4 may be the assembly code and other languages will compile to P4

Others argued that we may not need P4 in 10 years as the network will be so powerful that we will have functions at the edge. Others have said it’s inevitable because it restricts the right way, its extensible, and has clear semantics.

The third topic was “FPGAs and SmartNICs will or should take over the role that x86 plays in software packet processing, e.g., software switching and network functions”

Dotan Levi is for has FPGAs give diversity, and ASICs need to be generic, so there are things the FPGA will not do. Ben Pfaff is against as FPGA was always the “tech of the future”, but has important limitations, such as many customers wanting L4 stateful, with FPGAs helping a little but not enough. Also, above L4 you need to match in URLs, etc., so NetFPGAs also does not help here. Finally, FPGA programming is not portable, and it’s challenging to hire skilled people.

Some have argued FPGA to be good for parallelism, and other mention the problem of not being power efficient. Other mentioned that CPU memory hierarchies can now be written and not reverse engineered which is positive. Finally, new FPGA-based products are not only FPGA anymore (e.g., Xilinx ACAP). There is programmable logic; there is a processor; blocks for ML, etc.

7 Summary of cross-pollination activities

7.1 Data Planes and Control Planes

Laurent Vanbever (ETH Zürich, CH)

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Should network control planes be centralized or distributed? Should they be implemented in software or in hardware? In this talk, Prof. Vanbever presented his recent journey exploring these design dimensions. He first described Fibbing [1] and Netcomplete [2], two frameworks enabling to control distributed network control planes in a centralized manner by synthesizing: (i) the routing announcements; or (ii) the router configurations, respectively. He then described Blink [3] and hardware-accelerated control planes [4], two recent works that show the benefits of offloading pieces of the control plane logic (e.g., detecting failures) to the data plane. Specifically, Fibbing introduces fake nodes and links into an underlying linkstate routing protocol, so that routers compute their own forwarding tables based on the augmented topology. Fibbing is expressive, and readily supports flexible load balancing, traffic engineering, and backup routes. Netcomplete is instead a system that assists operators in modifying existing network-wide configurations to comply with new routing policies. NetComplete takes as input configurations with “holes” that identify the parameters to be completed and “autocompletes” these with concrete values. Finally, the talk showed that programmable data planes are powerful enough to run key control plane tasks including: failure detection and notification, connectivity retrieval, and even policy-based routing protocols. As an example, Blink is a data-driven system exploiting TCP-induced signals to detect failures. The key intuition behind Blink is that a TCP flow exhibits a predictable behavior upon disruption: retransmitting the same packet over and over, at epochs exponentially spaced in time. When compounded over multiple flows, this behavior creates a strong and characteristic failure signal. Blink efficiently analyzes TCP flows, at line rate, to: (i) select flows to track; (ii) reliably and quickly detect major traffic disruptions; and (iii) recover data-plane connectivity, via next-hops compatible with the operator’s policies.

References

- 1 S. Vissicchio et al., “Central Control Over Distributed Routing”, ACM SIGCOMM 2015
- 2 A. El Hassany et al., “Netcomplete: practical network-wide configuration synthesis with autocompletion”, USENIX NSDI 2018
- 3 T. Holterbach et al., “Blink: fast connectivity recovery entirely in the data plane”, USENIX NSDI 2019
- 4 E. Costa Molero et al., “Hardware-Accelerated Network Control Planes”, ACM HotNets 2018

7.2 Programming Languages applied to Networks

Alexandra Silva (University College London, GB)

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Dr. Silva provided an overview of programming languages applied to networks to an audience of 12-16 attendees. Her talk combined principles (e.g., desirable properties for a network programming languages) as well as the presentation of a specific network programming language: NetKAT. She introduced the concepts of semantics (both denotational and operational), expressiveness, verification, and extensions. She then described KAT, “Kleene Algebra with Tests”, and showed how to apply KAT to NetKAT which allows network operators to prove properties such as reachability. The audience discussed how KAT/NetKAT, based in regular expressions, was a straightforward theoretical framework both for systems audiences and for theorists due to the ability to describe the language in terms of finite automata. Dr. Silva then briefly described ProbNetKat and ConcurrentProbNetKet to describe probabilistic events like congestion. The discussion ran over time and led into smaller group Q&A.

7.3 Switch ASICs

Andy Fingerhut (CISCO Systems – San Jose, US)

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Most packet processing devices today are general purpose CPUs, but most of the bits/second pass through specialized devices like NPUs and configurable switch ASICs (a term used to call out that while they have many configuration options, they typically are not programmable in the way a Barefoot Tofino or NPU are). In this cross-pollination session the discussion ensued around these questions: What are some of the reasons for the wide differences in cost per port for different device categories? What can the configurable switch ASICs do? Why are some of them so complex, and why is the control plane software developed by vendors like Cisco so expensive to develop and maintain?

7.4 FPGAs and Smart NICs

Gordon Brebner (Xilinx – San Jose, US)

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In his cross-pollination session, Gordon Brebner from Xilinx Labs has discussed FPGAs and Smart NICs. After an introduction to FPGAs, Gordon has discussed the advantage of the Adaptive Compute Acceleration Platform in modern FPGAs, that drastically reduces the programmability cost. It was made clear that the FPGA is not just the logic gates, including a CPU, Network on chip, an AI Engine array, etc. A discussion ensued on the difficulties of programming an FPGA, namely the need to think like a hardware designer, describing the design in Verilog and VHDL, and having to worry with circuit size and operating at a certain

clock rate. The good news is that today the hardware design experience is less needed, given the emergence of software-side languages and libraries, including domain-specific (e.g., P4) or general-purpose (e.g., C).

Many layers (of hardware, software, and expertise) are needed to build a network program: starting from the chip designer and FPGA hardware programmer, moving to the P4 pipeline architecture and P4 data plane, and ending on the P4 run time programmer and application programmer. This effort is now being used with tools such as the P4 for FPGA compiler (joint work from Xilinx Labs and Stanford University).

Next, Gordon presented some ideas on NICs, from the basic NICs (e.g., from Intel) to smart NICS (both FPGA- and NPU-based), contrasting them with switches. Interestingly, their architectures are pretty similar. The evolution of Xilinx NICs was only presented, starting from NICs with standard network functions, and their evolution to include custom functionality, including acceleration elements (e.g., for transport functions), increasing architecture disaggregation, and moving from packet processing to stream processing.

Gordon closed the session by presenting some of the issues being discussed around the P4 Portable NIC Architecture. These include, first, a discussion on the standard components of the ingress and egress pipeline, whether more variability was needed when compared to the Programmable Switch Architecture (PSA), and the isolation and virtualization mechanisms required. Second, the question of how the host CPU interface can be modelled, how to differentiate between the data plane CPU and the control plane CPU, and the impact on P4Runtime. Third, thinking beyond packet forwarding. For instance, is protocol (e.g., TCP) termination covered? Should we perform payload processing as well as forwarding? Finally, the aim is for a modular specification that has as much in common with PSA as possible.

7.5 Network Verification

Costin Raiciu (University Politehnica of Bucharest, RO)

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Costin Raicu presented an in-depth introduction to verification of stateful data planes. In the first part of the talk, he discussed two verification approaches: one based on symbolic execution and one based on weakest preconditions. Both approaches rely on a first-order solver (e.g., Z3) to check the satisfiability of logical formulas. But they differ in how those formulas are constructed. Symbolic execution traverses the program in the forward direction, while weakest preconditions propagates logical conditions backwards through the program. These approaches perform differently depending on the characteristics of the program.

In many programs, it is important to model assumptions about the control plane to allow verification of the data plane to succeed. Existing tools usually require the programmer to add manual annotations to the program that capture these assumptions. In the second part of the talk, Costin discussed a new approach that can automatically synthesize the necessary preconditions required for executing a given table. In practice, this technique enables verifying properties such as header validity without any manual intervention on the part of the programmer.

7.6 Software Switches

Ben Pfaff (VMware – Palo Alto, US)

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Open vSwitch lacks support for user-configurable protocols: users cannot easily add support for new protocols or fields within existing protocols. The PISCES project [1] from a few years ago showed one way to do this with P4, but PISCES could not be merged into mainstream OVS because it broke backward compatibility, which would not be acceptable to many OVS users. Additionally, it did not support the kernel datapath. In practice, the biggest obstacle to adding P4 or other user-configurable protocol support is the OVS datapath interface. This interface is a frozen ABI because it is implemented in the Linux kernel; it can be extended but not changed. It has a specific idea of what protocols exist, which can similarly be extended but not changed. Extensions can happen only very slowly: they must first be pushed into upstream Linux, which releases a few times a year, and then percolate slowly out to Linux distributions and then to users over a period of years. This is not practical for user-configurable nonstandard protocols. What's the way forward then? One way would be to use an eBPF program instead of a Linux kernel module, since eBPF offers more opportunity for local customization. But eBPF is currently too restrictive and has a performance penalty. Over time, these disadvantages might decline. Another approach would be to use AF_XDP for fast userspace access to packets. With that approach, OVS could drop the datapath interface entirely (as long as some similar approach could be worked out for Hyper-V), which would give OVS much more opportunity to evolve in new and exciting ways.

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- 1 Shahbaz et al., “PISCES: A Programmable, Protocol-Independent Software Switch”, ACM SIGCOMM 2016

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