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Created by:
Panel 4

Panel 4 Computer Science

Research Assessment Exercise (RAE) 2021,
self-evaluation

Coordinator: Prof. Panos Papadimitratos
Vice-coordinators: Prof. Kristina Höök and Assoc. Prof. Elena Troubitsyna

Organization

Organization schedule

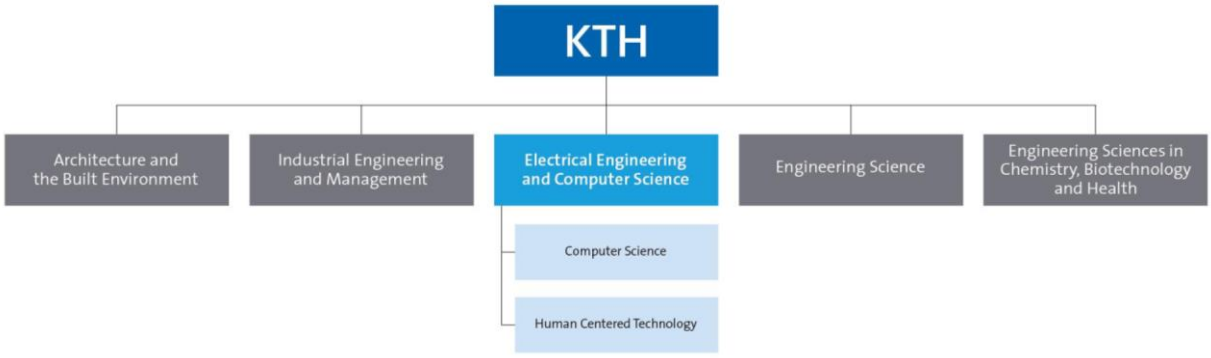

Figure 1. Panel position in the KTH organization.

Involved units

School of Electrical Engineering and Computer Science. Head: Prof. Sonja Berlijn.

Departments

- Computer Science. Head: Thomas Sjöland.
- Human Centered Technologies. Head: Prof. Henrik Artman.

Divisions

- Communication Systems. Head: Assoc. Prof. Anders Vastberg.
- Computational Science and Technology. Head: Prof. Tino Weinkauf.
- Network Systems Engineering. Head: Prof. Rolf Stadler.
- Software and Computer Systems. Head: Thomas Sjöland.
- Theoretical Computer Science. Head: Prof. Karl Meinke.
- Media Technology and Interaction Design. Head: Prof. Henrik Artman.

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List of Abbreviations

AE	Academia Europea
CASTOR	Software Research Center at KTH
CDIS	Center for Cyber Defense and Information Security at KTH
CELTIC PLUS	European Cluster Collaboration Platform
COS	Division of Communication Systems at CSD
CSD	Computer Science Department
CST	Division of Computational Science and Technology at CSD
DF	Digital Futures center
EDA	European Defense Agency
EECS	School of Electrical Engineering and Computer Science
EIT Digital (EIT ICT)	European Digital Innovation and Entrepreneurial Education Organization (formerly known as European Institute of Innovation and Technology in Information Communication Technologies)
ERC	The European Research Council
EU FP6 and FP7	Sixth and Seventh European Union framework programs for research and development
EU H2020	European Union Framework Program for Research and Innovation
HCTD	Department of Human-Centered Technology
ITRL	Integrated Transport Research Lab
ITEA	Transnational and industry-driven research, development and innovation program in the domain of software innovation
IVA	The Royal Swedish Academy of Engineering Sciences
KAW	The Knut and Alice Wallenberg Foundation
KVA	The Royal Swedish Academy of Sciences
MID	Division of Media Technology and Interaction Design at HCTD
NSE	Division of Network Systems Engineering at CSD
PDC	Center for High Performance Computing
SCS	Division of Software and Computer Systems at CSD
SNIC	Swedish National Infrastructure for Computing
SSF	The Swedish Strategic Research Council
STINT	Swedish Foundation for International Cooperation in Research and Higher Education
SUA	The Swedish Young Academy
TCS	Division of Theoretical Computer Science at CSD
VINNOVA	The Swedish Innovation Agency
VR	The Swedish Research Council
VS	Visualisation Studio
WASP	The Wallenberg AI, Autonomous Systems and Software Program
WASP-HS	The Wallenberg AI, Autonomous Systems and Software Program – Humanities and Society
YAE	Young Academy of Europe

Part A: Introduction of panel

Description of the research field of the departments included in the research panel

The research Panel 4, namely, “Computer Science,” covers a significant part of the School of Electrical Engineering and Computer Science (EECS). There are four Departments within EECS: Computer Science (CSD), Electrical Engineering (EED), Intelligent Systems (ISD), and Human Centered Technology (HCTD). The Computer Science Panel covers two departments: CSD and HCTD.

CSD comprises five divisions and HCTD is the only single-division department in EECS. Together, these two departments are responsible for a large part of the EECS research (and education). Their six divisions cover a broad gamut of research topics, with diverse activities in CSD, in alphabetical order: Communication Systems (COS), Computational Science and Technology (CST), Network Systems Engineering (NSE), Software and Computer Systems (SCS), and Theoretical Computer Science (TCS). In HCTD, Media Technology and Interaction Design (MID).

The panel covers research activities, undertaken in the 2012-2020 period, covering a wide variety of subjects: networks, wireless and mobile systems, software engineering and verification, distributed and parallel systems, computer engineering, algorithms, data science, machine learning, security and privacy, modelling of physical and biological systems, natural language tools, media technology, and interaction design. The vast majority of members of faculty and researchers, except some in HCTD-MID, are active in areas that pertain to different parts of Computer Science; thus, the choice of the Panel name.

Description of the self-evaluation process for the research panel

The effort was organized based on the detailed input by the team put together by the Rector and the extensive discussions among all panel coordinators. Within the panel, initially, input was received by all Divisions via the CSD Prefekt, on potential experts to join the panel. Among those, prominent experts were selected towards achieving the broadest coverage of the aforementioned areas of research within CSD and HCTD.

Each Division within the Panel was represented by its Head and at least one more representative, all having access to a shared collaboration space. Information on the evaluation template and the process to collect the related inputs was communicated and discussed among the coordination team and the division representatives. Additional input, notably data pertaining to education, finances, personnel, etc., was provided by the Rector’s team.

The creation of the self-evaluation report was a distributed effort, with contributions by all Divisions. A schedule was set, with meetings to harmonize the inputs and decide on the presentation approach; concerning both the exposition within the report (Part B) and the type and extent of the appendix (Part C).

The extent of the contributions for Part B is proportional to the size of the two departments (CSD is much larger than HCTD), while the impact cases were selected independently of the relative size of the two departments. The contributions were integrated by the coordinating team, and revisions continued; by providing comments to the Divisions, harmonizing inputs and then by requesting, receiving, and addressing remarks from the Divisions; by aligning the report to the quantitative data report created by the Rector’s RAE team; by requesting input and addressing feedback by the Heads of the Departments.

An early version of the report was discussed internally, through an initiative led by the Dean of KTH Faculty in the summer of 2020. Through this and the continuation of the RAE 2021 process in 2020 and in the spring of 2021, a number of meetings and discussions, as well as renewed data and feedback by the Rector's RAE team, led to the refinement of this report.

Identified research panel synergies

We highlight the following key synergies:

- Collaboration of faculty from both Departments in large-scale and large-scope initiatives and centers, including, notably, the recently formed Digital Futures Center. Building on the diverse expertise onboard, collaborations among researchers as well as with strategic industrial partners and stakeholders, seek to address societal challenges.
- Enhancements on teaching practices, now harmonized with Departments responsible for all teaching matters within their areas.
- Common research interests and converging visions, to identify key research areas for further development and organizational improvements.
- Participation in or running of numerous infrastructures, including makerspaces and a well-equipped visualization studio, which have served as fertile ground for collaborations.
- Prioritization of creation of interdisciplinary research facilities and workspaces (workshops, studio spaces), aiming at a campus that is less of an office space and more of a space to build novel constellations.

Part B: Report for each department

Department of Computer Science (CSD)

Self-evaluation

Head of Department: Thomas Sjöland

Division of Communication Systems (COS)
Division of Computational Science and Technology (CST)
Division of Network Systems Engineering (NSE)
Division of Software and Computer Systems (SCS)
Division of Theoretical Computer Science (TCS)

Department of CSD

1. Overall analysis and conclusion; strengths and development areas

Limited SWOT-analysis

	Strengths	Weaknesses
Research	Bulleted list, in order of magnitude 1. Diverse research portfolio of research in areas of high importance, nationally and internationally, addressing societal concerns. 2. World class research, faculty reputation, impactful results, international visibility and collaborations, and industry collaborations. 3. Leadership and researcher quality, reflected on numerous awards and prizes, strong citation records, Fellow grades, Academy memberships, highly selective individual grants, leading roles in international communities, and other distinctions. 4. Very strong record in attracting national and international external funding and participation or leadership in research centers.	Bulleted list, in order of magnitude 1. Some divisions have diverse research and education portfolios, in some cases overlapping with those of other EECS departments or other KTH Schools. Thus, the need for convincing visions within and across Divisions and for considering, possibly, radical changes. 2. Some important CS areas are not covered in CSD. 3. External funding unevenly obtained across CSD and Divisions. Perhaps, too strong dependence on external funding. 4. Publication approaches (e.g., choice of perhaps not very visible journals and conferences) may result in reduced impact.
Organization	Bulleted list, in order of magnitude 1. Research groups with well-defined research and education profiles, nationally or internationally recognized. 2. Research groups running own research infrastructures locally, making use of cloud providers. Excellently performing KTH networking infrastructure. 3. Several senior faculty members being world-leading experts in their fields; surrounded by strong teams of younger researchers. 4. Research groups co-located mostly at the same campus. Groups of the same division in different locations if needed. Lack of barriers to co-operation across research groups. 5. Systems-oriented research that resulted in widely adopted software platforms, standardization contributions, several start-ups, and excellent alumni. 6. Research connected with undergraduate education. Popular courses, MSc theses and advanced courses leading to publications, MSc theses in close collaboration with the industry. 7. Presence in the national media, on numerous topics and occasions.	Bulleted list, in order of magnitude 1. Increasing demand for office space, need for more flexible types of (shared) office space, especially as CS faculty is spread in three campi; transportation connections and improved accessibility. 2. Need for improved access to national infrastructures, external and KTH-wide testbeds and facilities. 3. Divergent group sizes, with small groups having potential difficult to balance research and education agendas. 4. Need for faculty renewal, improved gender balance. Weakness in hiring of top-tier faculty. Need for improved support, faster and well-planned processes. 5. Weak connection to undergraduate first cycle education, with the exception of BSc thesis projects.

Summary statement on contributions of department on impact, infrastructure and sustainable development

Impact

- Participation and leading roles in research centers with continuing activities, including newly formed ones. Centers are in close collaboration with industrial and government partners, pursuing research, education, innovation, towards addressing societal needs.
- Active centers: (i) KTH Center for Software Technology Research (CASTOR), (ii) the center for Cyber Defense and Information Security (CDIS), (iii) KTH Innovative Center for Embedded Systems (ICES), (iv) Security Link, and (v) KTH Digital Futures (DF).
- Collaborations with industry and influence of standards.
- Start-ups and spin-offs, building on research results.

Infrastructure

- Visualization Studio; Neurocomputing Laboratory; FEniCS Project platform for solving partial differential equations (PDEs); Hopsworks platform for end-to-end machine learning pipeline. Contributions to and collaborations with: Science for Life Laboratory; PDC Center for High Performance Computing; SNIC; ITRL.

Sustainable development

Most of the research conducted in CSD has an indirect impact on sustainability goals. Many research activities are directly related. Highlights:

- Projects on energy efficiency, affordable and clean energy, responsible consumption.
- Program for newly arriving immigrants' education.
- Good health and well-being; promoted by multiple projects across CSD.

2. Research profile

General information of the department

The CS Department (CSD) was recently established by including five divisions (formerly termed 'departments'). Since the creation of CSD, significant efforts are dedicated to the integration of educational and administrative processes. An integration of research efforts has just been initiated. Some research inter-division clusters started to form but, overall, this may take several years to achieve. Hence, in this report, we first outline research topics per division, naming members of faculty actively researching each topic; then, we present main research themes across CSD.

CSD has a diverse portfolio of research in areas of high importance, nationally and internationally. Research achievements range from computer vision and software engineering, to networked systems and cyber-security and privacy. Overall, good coverage of Computer Science, with complementary and related areas across CSD, from theory and basic technologies, to systems and applications. Interdisciplinary research. Coverage from fundamentals to contemporary and emerging applications, as well as interdisciplinary activities (e.g., computational brain science). We present next research topics and the corresponding members of the faculty, per division:

COS Division of Communication Systems performs research in the broad area of communications systems with special focus on wireless communications and networking, internet-of-things (IoT), and energy-efficient networks.

Wireless network design and optimization: energy-efficient radio resource management, aerial networks, distributed learning for wireless network optimization (Cicek Cavdar); millimeter-wave networks (Marina Petrova); energy-efficient network design, machine learning for communications (Emil Björnson); techno-economic network design, IoT (Jan Ingemar Markendahl); energy-efficient wireless systems, ultra-dense networks (Ki Won Sung); radio resource management, energy-efficient networking, ultra-dense networks (Jens Zander); energy-efficient networking (Anders Västberg).

Radio systems: antenna array design, wireless communications for moving vehicles (Claes Beckman); multi-antenna communications (Emil Björnson); aerial networks (Mats Nilsson); radio electronics (Håkan Olsson); spectrum sharing and co-existence (Marina Petrova and Ki Won Sung).

Network protocols and services: edge computing, energy-efficient protocols, autonomous management (Cicek Cavdar); joint communication and computation (Marina Petrova); IoT and device-to-device communications (Slimane Ben Slimane).

Software defined networks and network virtualization: energy-efficient networking, virtualization, IOT sensor networking (Markus Hidell); energy-efficient networking, virtualization, IOT sensor networking (Peter Sjödin); radio access virtualization (Marina Petrova).

CST Division of Computational Science and Technology. Research at CST is aimed at understanding and modelling of the dynamics and behavior of complex physical systems (e.g., climate, turbulence in air flow), biological systems (e.g., the brain, heart, cancer genomics) and social systems (e.g., crowd behavior). Most of the pertinent research questions associated with these systems are not amenable to conventional approaches and require high-performance computing and numerical simulations. Therefore, to advance the study of these complex systems we are not only addressing scientific questions but also developing new analytical methods, simulations tools, high-performance computing tools, and algorithms to visualize high-dimensional and multi-scale data.

Computational Biology and Machine Learning in Biomedicine: machine learning, computational biology, cancer (Jens Lagergren); computer vision, biomedical image analysis, machine learning (Kevin Smith).

Biological Physics and Systems Biology: biological physics, quantum thermodynamics, quantum science for life sciences (Erik Aurell).

Computational Brain Science: neurorobotics, real-time neuronal computation, neuromorphic hardware (Jörg Conradt); computational vision, theoretical neuroscience, deep learning (Tony Lindeberg); computational neuroscience/cognition, brain-like computing, neural networks (Anders Lansner (emeritus)); computational neuroscience/cognition, brain-like computing, neural networks (Pawel Herman); computational neuroscience, computational systems biology, kinetic modeling (Jeanette Hellgren-Kotaleski); computational neuroscience, computational biomedicine, machine learning (Erik Fransén); computational neuroscience, brain dynamics, biological neural networks (Arvind Kumar).

Numerical Methods: computational science and engineering, scientific computing, computational biomedicine (Johan Hoffman); scientific computing, digital math, unified computational modelling of aerodynamics and multiphysics (Johan Jansson).

Parallel Computing: high-performance, parallel, scientific computing, computational plasma physics, and space physics (Stefano Markidis); high-performance computing, co-design of HPC technology, performance modelling (Dirk Pleiter).

Visualization: visualization, data science, topological data analysis (Tino Weinkauf); embodied virtual agents, multiagent systems, social robotics, human-machine interaction (Christopher Peters); visualization, human-computer interaction, interactive computer graphics (Mario Romero Vega).

NSE Division of Network and Systems Engineering performs research in the areas of networked system design and optimization, wireless and computing resource management, system security and privacy, enterprise IT and technology management.

*Network and Systems Engineering***:** mobile services, quality of service, educational technologies (Gunnar Karlsson); network management, distributed systems, machine learning (Rolf Stadler); stochastic modelling, communication networks, distributed systems (Viktoria Fodor); optimization, wireless networks and systems, Internet of Things, machine learning over networks (Carlo Fischione); game theory, mobile edge computing, cyber physical systems security, resilience (György Dán).

Cybersecurity, Enterprise computing: cyber security, enterprise computing, probabilistic modelling (Pontus Johnson); information and cyber security, software architecture, industrial control systems (Mathias Ekstedt); secure enterprise architecture, threat modelling & attack simulations, software system complexity (Robert Lagerström).

Technology management: project management, product development, digitalization (Joakim Lilliesköld); project management, quality management in product development, organizational challenges (Liv Gingnell).

SCS Division of Software and Computer Systems conducts research and education on fundamental aspects of software technology and computer systems focusing on cloud computing, service computing, model-based computing systems, social networks, time aware systems, data science and applied artificial intelligence (AI), software engineering, networked systems, internetworking and security and privacy.

Distributed systems: parallel and distributed computing, peer-to-peer computing, streaming analytics, programming systems (Seif Haridi); data intensive computing, stream processing, distributed and parallel computing (Vladimir Vlassov); large-scale distributed computer systems, software systems (Jim Dowling); distributed systems, data intensive computing, deep learning (Amir Payberah); distributed data management systems (Paris Carbone).

Software construction and analysis: software engineering, software testing, software diversity, DevOps (a set of practices that combines software development (Dev) and information-technology operations (Ops) (Benoit Baudry); programming and modelling languages, cyber-physical systems, model-based computing systems, compilers, machine learning (David Broman); software engineering, software technology (Mihhail Matskin); software engineering (Mira Kajko Mattson).

Data science: computational epidemiology, learning machines (Magnus Boman); ensemble learning, conformal prediction, interpretable machine learning (Henrik Boström); decentralized machine learning, gossip learning, information network analytics, graph mining, online social networks (Sarunas Girdzijauskas); artificial intelligence, multi-agent systems, knowledge management (Anne Håkansson).

*Networked systems***:** data centers, geo-distributed storage systems, software-defined networking, network functions virtualization (Dejan Kostic); secure routing, secure communication, credential management, IoT security (Gerald Q. Maguire Jr., Panagiotis Papadimitratos).

Internetworking: Internet routing, software-defined networking, network resilience, network performance (Marco Chiesa, Gerald Q. Maguire Jr., Panagiotis Papadimitratos).

Security and Privacy: networked systems security, privacy enhancing technologies, information-theoretic and physical layer security, secure localization (Panagiotis Papadimitratos).

TCS Division of Theoretical Computer Science is responsible for teaching and research in areas of fundamental computer science. Areas of responsibility include programming and programming languages, software engineering, embedded and distributed systems, formal methods, computer security, cryptography and privacy, data science and computer science education. Research within the TCS division mainly focuses on problems having a foundational or mathematical nature. There is a strong mathematical culture within the TCS division that allows diverse researchers to collaborate and share knowledge in new ways to address emerging scientific problems.

Computational complexity: algorithms for NP-hard problems, analytic methods in algorithms & complexity, hardness of approximation (Per Austrin); general algorithm theory, algorithms for matching problems, algorithms in game theory (Johan Karlander); graph algorithms, distributed algorithms, dynamic algorithms, optimization, fine-grained complexity (Danupon Na Nongkai).

Computer security: software Security, web and IoT application security, foundations of computer security (Musard Balliu); privacy-enhancing technologies, applied cryptography, decentralized systems security (Sonja Buchegger); provably secure systems, intelligence and security informatics (Mika Cohen); high assurance, low level security, security models, security verification (Mads Dam); security of low-level software, security of hardware architecture, virtualization (Roberto Guanciale); security, cryptography, quantum computation (Douglas Wikström).

Computer science education: learning analytics, technology-enhanced learning (Richard Glassey); program coherence, assessment, theoretical computer science education (Viggo Kann); project-based learning (Stefan Nilsson); narrative intelligence, AI and creativity, applied AI (Mats Nordahl).

Data science: repository mining, ML for software engineering, visual analytics (Cyrille Artho); synthetic data generation, privacy-preserving data analysis, adversarial learning (Sonja Buchegger); combinatorial optimization, knowledge discovery, graph mining, social-network analysis (Aristides Gionis); natural language quality analysis, language policy, terminology (Viggo Kann); programming models for data science, large-scale distributed programming (Philipp Haller); automaton learning, ML for software engineering, ML for digital pathology (Karl Meinke); massive graph algorithms and mining, learning-based online and dynamic algorithms (Danupon Na Nongkai); autonomous systems (Elena Troubitsyna).

Software construction and analysis: software testing, formal modeling, software analysis, runtime monitoring (Cyrille Artho); programming language technology, software model checking, program analysis and verification (Musard Balliu); program logics, system modeling, low level verification, information flow analysis (Mads Dam); binary code verification, interactive theorem provers, choreography models (Roberto Guanciale); software verification, multi-agent strategic planning (Dilian Gurov); programming languages, type systems, concurrency (Philipp Haller); bit-based algorithms, application programming interface (API) design (Stefan Nilsson); software testing, cyber-physical systems, autonomous systems (Karl Meinke); automated program repair, chaos engineering, code analysis, software testing (Martin Monperrus); formal modelling and verification of dependable and secure systems (Elena Troubitsyna).

Central research questions and themes, knowledge gaps addressed, main research activities

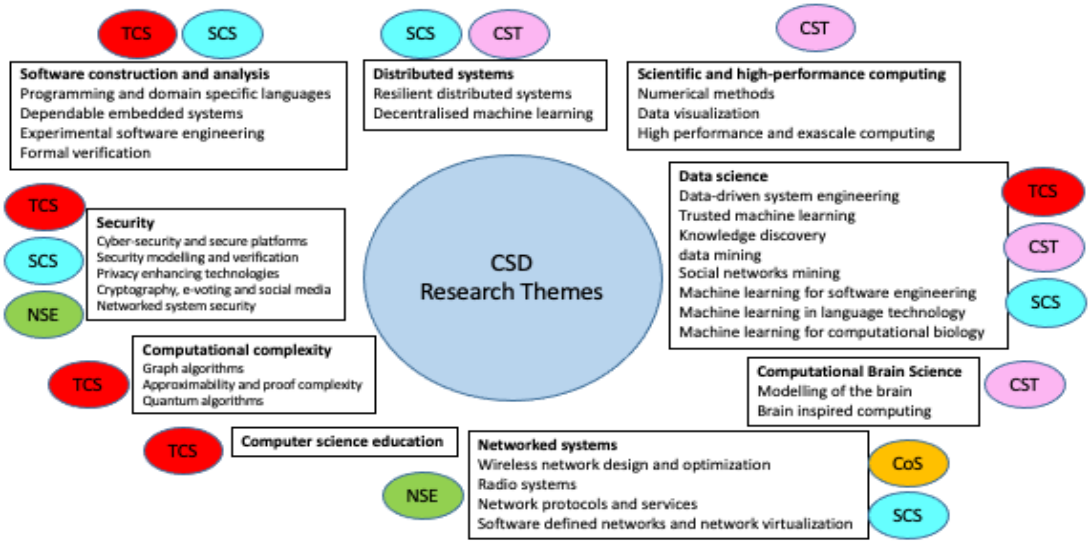


Figure 2. Research Themes at the Computer Science Department.

An overview of research topics is presented in Figure 2. The research carried by the CS department is multidisciplinary in nature and addresses a wide range of topics of fundamental and applied computer science and software engineering. Our research has also a strong interdisciplinary aspect with a wide variety of fields including biology, physics, electrical engineering, psychology etc. Interdisciplinarity has a positive impact on the research. It allows us to identify the new problem domain where our methods and techniques can be applied. Moreover, it facilitates finding scientific or methodological similarities among diverse problems. Furthermore, our interdisciplinary research contributes to addressing societal and sustainability challenges of society. Below we identify the main knowledge gaps and research questions addressed by the strands of research in CSD.

Computational complexity
How to achieve time improvement in graph algorithms? How can machines compute without too much communication? How to resolve basic open problems in proof complexity? How to improve the state of the art for quantum algorithms for factoring and discrete algorithms?

These challenges are addressed by the deep theoretical work on classical complexity problems with the significant advancements in the state of the art in this area. There are many central questions about algorithmic primitives that have not been well-understood for a long time. The first progress in many decades, and sometimes solutions, have been found for some of these notoriously hard problems. Some of these results lead to understanding the limits of computation via connections to deep mathematics. Some others lead to new theoretical techniques for designing efficient algorithms, which can potentially lead to better software, computing devices, etc.

Software construction and analysis
Research on software construction and analysis addresses a wide variety of topics associated with technologies for development and verification of software systems. The main research questions are:

What are the principles and techniques for constructing efficient and sound language environments and compilers for domain-specific modelling languages?

We address this research challenge by developing formal semantics and new algorithms, utilizing both mathematical formalizations and machine learning. Specifically, we focus on composable language

systems and self-learning compilers. Key target areas are modelling languages for cyber-physical systems, probabilistic programming, and differentiable programming. Application areas include, but are not limited to, satellites, digitalized industry, evolutionary biology, and public health. This research spans the research areas of software engineering and machine learning.

How to improve dependability of software-intensive systems by using formal and integrated techniques for software development and verification?

This research question is addressed by developing various model-driven and formal techniques as well as integrating them with various simulation and applied AI approaches. The challenge is to improve scalability and enable highly automated reasoning about various system properties. Among the studied aspects are dependability of embedded software, power-efficiency and real-time properties.

What are the principles and techniques enabling an efficient use of development artefacts for software quality improvement?

This question is addressed along the following directions: code analysis with a strong emphasis on dynamic analysis and code transformation; program repair: how to automatically fix software bugs and generate patches that fix incorrect behavior; software diversification: software monoculture is widely acknowledged as a crucial problem, and we are researching for counter-measures based on natural, amplified or synthetic software diversity; software testing: both program repair and software diversification require actionable oracles, having profound relations with software testing. We contribute to filling knowledge gaps in software testing related to oracles.

How to strengthen formal modelling and verification techniques and amplify their benefits for verification of software correctness, security, safety as well as real-time and other functional and non-functional properties?

This research challenge is addressed by extending capabilities and scalability of model checkers and theorem provers and integrating them. A strong research theme is the development of formal approaches addressing the problems of safety and security verification, supporting model-based testing and integrating the techniques used for the verification of functional correctness with simulation, machine learning and domain-specific techniques.

Security

How to ensure cyber-security of complex networked systems and critical infrastructures and develop secure execution platforms?

With the overall trend of digitalization in society cyber security has emerged as an increasingly important topic. From a system's engineering viewpoint, the key cyber security challenge originates from the increased complexity of interconnected systems and components. It is so far unclear how to assess the level of security and resilience in systems of interconnected systems, how to reason about the interplay between safety and security, and how to identify and ensure an adequate level of security and resilience. The research on cyber-security of critical infrastructures and the industrial control systems plays a significant role in this area. Another important challenge to be addressed in this strand of research is how to develop provably secure execution platforms. The experiments with theorem provers and verification of security of hypervisors for ARM platforms have played a significant role in addressing this challenge.

How to develop the viable techniques for end-to-end security modelling and verification?

The demand for security verification is steadily growing. To address this challenge, there has been a significant amount of research efforts invested in developing new as well as tailoring general-purpose verification techniques. The pursued research directions include modelling and verification of security

requirements, security testing, binary code verification as well as modelling security properties of different architectures.

How to support privacy-preserving communication while enabling data sharing, learning and privacy in the social networks?

This research question is addressed by defining mechanisms based on metadata privacy, deniable messaging and data anonymization.

How to enable secure e-voting and social media?

The research questions addressed in this line of research are centered around the idea of building an e-voting system that follows cryptographic theory and at the same, adopt the best practices from contemporary software engineering. The work on secure social media focuses on studying anonymity-preserving techniques.

How to design trustworthy networked systems, addressing both security of the networked systems and protection of their users' privacy?

Interested in open, dynamic, and decentralized networked systems, with foci on wireless networks, embedded, cyber-physical, and mobile systems, this research theme has strong systems character, implementing and evaluating solutions, while paying close attention to theoretical methods, including, notably, formal protocol analysis and information-theoretic results. Characteristic lines of research include: Secure communication: secure neighbor discovery, secure route discovery and data communication; Security for vehicular communication/intelligent transportation systems (ITS): protocols and security architectures; Security for wireless sensor networks: confidentiality, aggregation, key management; Secure ranging and localization: security for ultra-wideband (UWB) and Global Navigation Satellite System (GNSS), distance bounding, position verification; Privacy enhancing technologies for: ITS, location based services, online social networks, smart spaces; Physical layer and information-theoretic security: secure and reliable communication in a multitude of settings, scaling laws for secure communication; Security and privacy for participatory sensing systems; Security for the Internet of Things (IoT).

Distributed systems

What are the principles and techniques to build resilient distributed software systems?

We address this research question from various perspectives: the definition of algorithms that formally ensure the consistency of distributed systems; the construction of scalable tools that can consolidate the resilience of existing systems; the development of sound experimental methodology to demonstrate the relevance of our techniques for actual software systems. This research spans the areas of distributed systems, programming languages and software engineering.

What are the principles and techniques to build decentralized machine learning/AI?

We address this research question by studying and designing algorithms and methods for decentralized machine learning and information network/graph analytics for decentralized (peer-to-peer) and semi-centralized (federated, super-peer) systems. In particular, we design machine learning algorithms that can operate under highly heterogeneous and asynchronous environments, network churn as well as malicious behavior of the participating nodes. Furthermore, we focus on learning on linked data (graph data) whereby we produce state of the art algorithms for graph and information network mining/ analytics. We also investigate energy-efficient blockchain technologies. This work spans the research areas of distributed systems, data science, graph theory and blockchain technologies.

Networked systems

How to develop a theory of cross-layer adaptation?

We have advanced the state of the art in modelling and optimization of wireless networks. We developed a new theory for distributed optimization that could work with wireless devices with limited computation and communication resources. The central idea was showing that for a class of optimization problems, the computation can be based on the theory of contraction mappings without using Lagrangian duality. We have extended methodologies in the areas of stochastic geometry and Bayesian modelling, and we applied the theoretical frameworks to cognitive wireless networks and to full-duplex communication. We have also brought in energy- and cost-efficiency as optimization criteria, alongside conventional throughput-based criteria. We were among the first to address issues in milli-meter wave wireless communication, through modelling and assessing the impact of interference on network protocol design. We have been advancing the mathematical modelling of wireless protocols for medium access control, and the joint modelling and design of wireless protocols and process controllers. We have developed a formal definition of the Machine Learning over Network (MLoN) problem as a fundamentally new co-design problem between networking protocols and ML principles, methods, and algorithms. We were among the first to address the issue of joint wireless and computing resource management for visual sensor networks and for edge computing and developed a framework for decentralized management based on game theoretical principles.

How to create new wireless network architecture paradigms beyond 5G and achieve energy-efficiency, scalability and interoperability?

To address this challenge, the research has focused on several themes: (i) design of energy-efficient wireless systems, (ii) understanding the fundamental limits of network densification and new wireless network architecture paradigms beyond 5G, (iii) design of spectrum sharing and spectrum coexistence mechanisms for more efficient and affordable spectrum use, (iv) aerial wireless networks and integration of satellite, aircraft, UAV communications with terrestrial networks, (v) wireless network economics, analysis of cost structure, scalability and spectrum value, and (vi) analysis of complex multi-actor business networks for mobile communications and IoT services.

How to holistically realize network protocols and services that fully exploit the underlying hardware, software, and network infrastructure?

This research challenge is addressed by (a) identifying and understanding undocumented aspects of processors in order to exploit existing hardware features for improved performance (in contrast, to the usual focus elsewhere of exploiting this knowledge for security attacks); (b) understanding the temporal patterns in streams of packets and how these can be exploited or modified to increase locality in order to achieve network performance at 100 gigabits per second (Gbps) and greater; (c) how to decompose services to properly distribute the computation and communication over both local and remote resources; (d) scaling services to support the new patterns of communication and demands due to IoT and 5G wireless communications; and (e) how to realize all of these services in a both secure and high performance way.

To address the emerging networking trends as well as their interaction with traditional legacy-deployed Internet-routing systems, our goal is to understand: (1) how today's network routing protocols can be made more performant and robust using expressive packet processing pipelines and automated network management, (2) how one can devise a model for understanding equivalence between different packet processing pipeline implementations, (3) how today's network can launch and defend from devastating Internet routing attacks, and (4) how can we leverage recently-proposed transport protocols to improve load balancing services in core and edge data centers.

The research on mobile services has focused on three central research themes: (1) Quality of Experienced centric mobile networks, (2) Immersive mobile media such as virtual reality (VR)/augmented reality (AR), and (3) new verticals for connected industries such as automotive and smart production. While this has been researched in part elsewhere, there is currently a lack of a holistic approach.

How to achieve reliability and resource efficiency in software defined networking and through network virtualization?

This challenge can be addressed from multiple directions. In the deployment phase, resource efficiency is achieved by making use of common general-purpose computing resources that can virtualize different tasks, instead of dedicated hardware for every task. In the operational phase, high reliability and efficiency is achieved by the improved monitoring and resource management enabled by network virtualization. This question was tackled at KTH by the research on (1) reliability in software defined networking and (2) resource allocation in cloud environments and in edge computing environments considering energy efficiency and resilience as key performance metrics, (3) energy-efficiency in networking, (4) network virtualization and softwarization, and (5) scalable and reliable sensor networking for IoT.

Data science

How to efficiently and reliably utilize the potentials of data-driven approaches to develop reliable and self-managing networked systems?

Over the last five years, we have developed concepts for the efficient prediction and forecasting of end-to-end performance metrics. Using methods from statistical learning, we measure device-level metrics in the infrastructure and predict service-level end-to-end metrics in real-time. Specifically, from measuring metrics like CPU utilization on servers and packet counters on network devices, we predict quality-of-service parameters like video frame rates for a VoD service and query response times for a key-value (KV) service on our testbed. Our solutions manage a very large number of data sources in real time and can quantify the uncertainty of predictions. Currently, we are studying so-called self-driving systems, which dynamically configure to meet management objectives and adjust configuration parameters to changes in the environment. Our solution approach combines various concepts from statistical learning and reinforcement learning.

What are the principles and techniques for enabling trust in machine learning models?

We address this question by developing and evaluating techniques and tools for quantifying uncertainty in predictions of machine learning models and investigating techniques for generating human-interpretable models and explaining predictions of black-box models. Application areas include analysis of biomedical and healthcare data, predictive maintenance, and economic forecasting.

How to develop and apply Machine learning methodologies so that crucial problems in computational biology can be solved, such as the problems related novel experimental techniques and evolution, e.g., somatic evolution in cancer?

Several research topics have been explored to answer this research question. For instance, the use of tumor tree reconstruction tools can reveal, through analysis of single-cell data, how individual tumors have evolved, in particular revealing the order in which mutations have occurred and the timing of metastasis. The development of models and tools allowed to analyze the interaction between cancer cell subpopulations, each having its unique genotype and fitness, and the immune cell subpopulations, especially uncovering how cancer cells evade the immune defense.

Computational Brain Science
How to design and build computational models that integrate biological evidence and brain computational theories for deeper understanding brain function and dynamics?

The research challenge has been addressed by the development of an experimental infrastructure and simulation environment about multiscale interactions in the brain. The problem has also been addressed by developing analytical tools to study dynamics of inhomogeneous system far from equilibrium

How to design and apply energy efficient neurocomputing systems for real-time control?

The long-term challenge is to create better theories, methods and algorithms for perceptual and intelligent systems that perform brain-like functions. We investigate the brain across different spatial and temporal scales from the fine scale level of molecular mechanisms to the coarse system level of brain function.

Scientific and High-Performance computing
How to develop powerful methods enabling studying complex systems by simulation and numerical methods?

This research challenge is addressed by developing simulation and numerical methods for complex dynamic problems such as turbulence and the stability of Navier-Stokes equations, reliable patient-specific simulations of the human heart, its diseases and clinical interventions as well as leveraging the emerging high-performance computing platforms. The research in this area has addressed such problems as modelling blood flow in the heart and turbulence over aircraft wings. This research challenge has also been addressed by developing equilibrium and non-equilibrium classical and quantum physics as well as applying non-equilibrium physics to biological phenomena.

How to deal with noise and uncertainty in data, communicate the trustworthiness or lack thereof of a visualization, and efficiently handle very large data?

The challenge has been addressed by the development of feature-based methods for visualization and analysis of high-dimensional data, interactive graphics/visualization over diverse media, development of topological methods, simulation of real-time social behavior and generation of artificial social and mobile behavior.

How to develop efficient computing and memory technologies as well as high-performance algorithms supporting scientific computing?

The challenge to high-performance computing is to enable an effective utilization of new emerging technologies of supercomputers to such scientific applications as weather forecast simulation, computational fluid dynamics codes etc. The research question is addressed by experimenting with emerging technologies such as non-volatile memories, graphical processing units (GPU), and field-programmable gate arrays (FPGA).

Computer science education
How to facilitate learning and practicing hard concepts of computer science?

The question is addressed by experimenting with novel pedagogical approaches as well as creating open-source tools facilitating mastering of various abstract concepts. For example, we use automatically tested computer labs to illustrate the concept of reduction and quizzes to make the students understand the concept of definition. We also develop open-source tools to help teachers integrate version control into their courses so that students can practice collaborative development skills as they learn computing concepts.

Contributions to the advancement of the state of the art within the research fields of the department

In this section, we present an integrated overview of the main contributions into advancing the state of the art per the identified topics. We give the general references to the groups within the corresponding divisions rather than to individual researchers.

Computational complexity

In *algorithms*, TCS researchers have resolved several long-standing open problems in graph algorithms and related areas. The work pertaining to graph algorithms resulted in 19 papers published in the two flagship conferences of theoretical computer science, IEEE Symposium on Foundations of Computer Science (FOCS) and Symposium on Theory of Computing (STOC). These include breakthrough results on classic problems such as Vertex Connectivity, Minimum Cut, Dynamic Connectivity, and Dynamic Shortest Paths. The results in papers published in STOC 2019 and SODA 2020 lead to a near-linear time algorithm for computing vertex connectivity when the connectivity is small, improving the result from 50 years ago. The result appeared in STOC 2020 gave the first logarithmic time improvement over the celebrated near-linear time algorithm for the minimum cut problem from 1994. The series of results in the recent manuscript have achieved a deterministic dynamic connectivity algorithm with sub-polynomial update time, resolving one of the most central problems in the field of dynamic graph algorithms and improving a classic result in the field from 1985. Another result is settling the decremental shortest path problem, which has been actively considered since 1981. In several cases, achieving the results involved new connections to areas such as fast matrix multiplication, communication complexity, and sub-linear time algorithms. Recently, the first progress in 30 years for solving a linear program deterministically has also been achieved.

In *approximability and proof complexity*, we have improved our understanding of computation in many ways. The group within TCS has obtained a near-optimal approximation algorithm for the classic Max-Bisection problem (published in SODA), and in subsequent work obtained sharp hardness of approximation for several related problems (published in APPROX). Another remarkable result is obtaining strong lower bounds on the size of linear programming relaxations for almost all constraint satisfaction problems. The complexity theory group at TCS has initiated the study of Promise Constraint Satisfaction Problems which has since quickly become a growing area of interest in computational complexity (for instance, there exist at least two ongoing research grants solely focused on further investigation of promise constraint satisfaction (PCSP)). The group obtained the first strong lower bounds for the powerful bounded-depth Frege proof system. The group has published a number of top-ranked papers resolving basic open problems in proof complexity, as well as several publications related to connections between proof complexity and efficient Sat solving. The developed pseudo-Boolean Sat solver achieved state of the art results in the Pseudo-Boolean Competition 2015 and 2016.

In *quantum algorithms*, we have improved the state of the art for quantum algorithms for factoring and discrete logarithms. In collaboration with Google AI, the group has presented improved algorithms along with full-stack cost estimates for running them on scaled-up versions of existing quantum architectures, showing that these improvements lead to almost a factor 100 savings in the quantum spacetime volume used.

Software construction and analysis

An investigation of the novel concept of *automatic test amplification* within SCS has resulted in a significant contribution to the field of software testing. This research has resulted in a number of significant achievements: publications in the top software technology journals Journal of Systems and Software and Empirical Software Engineering Journal; the successful defense of two doctoral theses; the development of two mature tools that were experimented on various industrial settings; and the successful completion of the EU Horizon 2020 STAMP project.

The research within model-based computing systems (SCS) has contributed with several publicly available open-source systems, including Modelyze – a meta programming language for the development of domain-specific languages, Gecode (see above), Timed C and the KTC compiler - a language and tool for real-time programming (used in the MIST satellite project) and UNISON – a code generation system based on constraint models (developed together with Ericsson).

In *experimental software engineering* innovations have been achieved in particular within automated software repair and program hardening. First ever automatic bug fixing bot (Repairnator) has been developed (TCS). Another notable achievement was code analysis technology used by companies and research labs (Spoon). There has been a strong pursue of using machine learning methods for requirements testing of autonomous systems-of-systems (e.g., vehicle platoons) using new model checkers for spatio-temporal logic. Successful industrial case studies with Scania, Qamcom and Zenuity have been conducted. In software testing, a new approach developed within TCS was developed allowing for the use of model checking to compute witness traces for model-based testing concurrent servers. This work found a complex defect in the widely used cloud computing component “Apache ZooKeeper”.

In *programming language systems*, TCS has contributed the first typed core language formalizing fault-tolerant distributed computation based on lineage, including a type soundness proof, which is a major step towards providing provable fault-tolerance properties for distributed programming languages. Within TCS, theoretical and empirical results on improving implementation correctness and resource management of systems for executing message-passing programs in decentralized networks have been achieved.

In dependable *embedded software and systems*, there have been several contributions within TCS in the techniques for the formal specification and verification of safety of autonomous systems, and integrated formal safety-security co-engineering. A practical approach for the Deductive Verification of Safety-Critical Embedded C-Code has been developed within a collaboration with Scania. Several integrating approaches proposed within TCS enabled a consideration of power-aware allocation of fault-tolerant multi-rate AUTOSAR (www.autosar.org) applications as well as formal analysis and verification of Simulink models.

In *formal verification*, a number of techniques focusing on verification of security and dependability have been proposed within TCS. Additionally, within TCS h a novel theory and practical tools for optimization of regression proving in large program verification projects have been developed. It allows avoiding unnecessary machine time to verify evolving programs. Moreover, TCS has developed a method and tool for the procedure-modular verification of temporal specifications, as well as a method and tool for the provably correct extraction of control flow graphs from Java bytecode programs.

Security

Threat modeling and attack simulation: A core topic of NSE cyber security research is to develop methods for modelling and assessment of the security of large, heterogeneous systems of systems. This is done by combining software and systems engineering modelling methods with probabilistic attack and defense graphs. This approach pioneers the area of automatic attack graph generation and simulation based on software system model specifications, and relies on the development of domain specific modelling languages for various ICT infrastructures such as industrial control systems, vehicles, cloud infrastructures (see mal-lang.org). To support this probabilistic approach, data-driven and empirical research on the complexity of attack vectors is performed. To assess the effectiveness of various security controls, tools and frameworks are developed for ethical hacking, for automated observation of third parties in cyber ranges, as well as expert elicitation techniques. In addition, state of the art is advanced in machine learning-based game-theoretical modelling of attacker-defender interactions, with the objective of identifying optimal attack strategies and corresponding defenses,

focusing on algorithmic mitigation schemes in critical infrastructures. The work on threat modelling and attack simulation has been published in multiple fora including IEEE Transactions on Dependable and Secure Computing, Computers & Security, and IEEE Systems Journal. This research has also laid ground for the establishment of the spin-off company Foreseeti, currently valued at over 100 million SEK and awarded and listed by organizations such as Dagens Industri, Ny Teknik, the Royal Academy of Engineering Sciences, and others.

Security modelling and verification: The group within TCS has developed a broad and thriving range of activities in the security and privacy area. The group proposed a new symbolic approach to information flow security for low level code (CCS publication). The work has demonstrated the close connections between logics of knowledge and language-based models of information flow. Another contribution in this area is a new monitoring approach for data processing policies based on tree automata and the TaintDroid framework (CCS). The work in this area has also allowed the group to give the first comprehensive account of security monitoring for multithreaded Java programs (published in Mathematical Structures in Computer Science (MSCS)).

The TCS security group has also developed a series of verified hypervisors for the ARMv7 and ARMv8 platforms. This work included: a) the first binary level isolation proof for a functional ARMv7 based separation kernel, end-to-end verified for both privileged and user mode execution, and implemented in the HOL4 theorem prover (CCS), b) the first formally verified Linux capable ARMv7 based hypervisor, extended with provable protection against code injection attacks, c) verified interrupt handling in the High Assurance Security Products On COTS platforms (HASPOC) hypervisor for an ARMv8 multicore platform. For use in isolation proofs, we also developed a fully automated proof-producing information flow analysis tool for HOL4-based processor models. Together with the external collaborators, the group has also developed a system with provably secure guarantees for applications that interact with databases.

The work on security testing resulted in a novel methodology to assess the soundness of abstract side-channel models in computer architectures based on grey-box testing, symbolic execution and satisfiability modulo theories (SMT) solvers. The tool has been successfully used to discover various microarchitectural vulnerabilities and a serious bug in a widely used higher-order logic (HOL) formalization of the ARMv8-A architecture.

The work on proof-based security verification has also led to the development of a new platform HolBA for binary verification. The platform is tightly integrated with the HOL4 theorem prover and applicable to MIPS and ARM family processor architectures. This platform is likely to play an important role for the future research of the TCS security group.

The work on the analysis of architectural security has allowed the group to identify new cache-based storage side channels capable of violating both confidentiality and integrity of virtualized systems and formally verified several countermeasures. Recently the group proposed the first processor pipeline model capable of reflecting all known microarchitectural attacks in the Spectre family. Three new vulnerabilities were identified and the effectiveness of existing countermeasures including constant time and serializing instructions were analyzed.

Privacy-enhancing technologies. The TCS privacy research team developed building blocks for privacy-preserving decentralized communications including metadata privacy, deniable messaging, and different mechanisms for provider-independent online social networks. We also evaluated uses and limitations of synthetic data for privacy-preserving data analysis and developed machine-learning based techniques for anonymization of facial images. We developed distance-bounding protocols that allow for attribute-based credentials; i.e., proofs of proximity and credentials without, for example, revealing one's identity. Another contribution of the group is privacy-enhancing technology for IoT

apps by discovering and fixing privacy vulnerabilities in popular IoT app platforms like IFTTT, Zapier, and Microsoft Flow, and context-derived privacy protection after ownership changes of IoT devices.

The SCS Networked Systems Security (NSS) group has developed, implemented and evaluated credential management for pseudonymous authentication in large-scale mobile systems, demonstrating scalable infrastructures. Developed hybrid approaches, with anonymous authentication. Use cases and protocols for connected vehicles and location-based services (LBS). Architecture and protocols for cooperative Location Based Services (LBS) privacy protection, along with security. Protocols for: location privacy, revisiting the mix-zone approach; scalable secure and privacy preserving communication. Architecture and protocols for secure and privacy-preserving participatory sensing; achieving strong protection, in this and the aforementioned results, from honest but curious infrastructure entities and service providers.

Cryptography, e-voting and social media. An important milestone in e-voting was the open-source release of the Verificatum mix-net (VMN) – a result of 10 years of development efforts. VMN is unique in several respects: It is completely faithful to cryptographic theory while at the same time adopting best practices from real world software engineering. VMN has had a major impact in the e-voting community: it remains the only mix-net implementation produced by a research community considered to be fit for use by national election authorities. For instance, it was deployed in the Norwegian parliamentary election in 2013. Other crypto-related research is the work on post-quantum cryptography, reported as part of work of the TCS complexity theory group.

In cooperation with Swedish Defense Research Agency FOI the group has identified best practices for informing crisis alerts using social media and studied the effects and use of AI by both benign and malicious actors in terms of information and cyber security management. They combined traditional military gaming with game theory to experimentally study strategic thinking in defense and security populations, providing the studied populations a deeper understanding of their own strategic thinking.

Networked systems security and privacy. Pioneering results on secure and fault tolerant mobile ad hoc networks, with more than 4300 combined citations for 15 papers (1st/2nd author) with at least 50 citations each. Recent related outcomes: (i) “Secure Wireless Communications: Bridging theory and practice,” keynote at European Symposium on Research in Computer Security (ESORICS) 2016; (ii) Secure Communication in Wireless Networks,” invited talk at the ACM MobiHoc Workshop on Frontiers of Networks: Theory and Algorithms, 2016, (iii) “Secure communication in ad hoc networks,” keynote at IEEE/IFIP Med-Hoc-Net 2014.

Seminal contributions on security and privacy for vehicular communication and large-scale mobile systems, with more than 4500 combined citations of 15 papers (1st/2nd author) with at least 50 citations each. Representative recent related outcomes: (i)“Buckle-up: Connected cars could face privacy bumps in the road ahead,” panel at Computers, Privacy and Data Protection conference (CPDP) 2016; “Security on Wheels: Security and Privacy for Vehicular Communication Systems,” tutorial at ACM Conference on Computer and Communications Security (CCS) 2016, (iii) 2018 Internet Engineering Task Force (IETF) Applied Networking Research Prize (ANRP) award, citation on “SECMACE: Scalable and Robust Identity and Credential Management Infrastructure in Vehicular Communication Systems,” in IEEE Transactions on ITS 2018, (iv) 2014 ACM WiSec Best Paper Award on “SPPEAR: Security & Privacy-Preserving Architecture for Participatory-Sensing Applications”. Early significant results are obtained in secure ranging, distance bounding, and secure positioning; recent results include: VR young researcher award on this topic (2012); US patent (2012); bilateral project with European Space Agency (ESA) (2019).

Networked systems
NSE has progressed the state of the art in modelling and optimization of wireless networks, considering the interplay of networking and application design and with a strong focus on theoretical foundations.

Optimization techniques for wireless networks: We developed a new theory for distributed optimization that could work with wireless devices with limited computation and communication resources. The central idea was showing that for a class of optimization problems, the computation can be based on the theory of contraction mappings without using Lagrangian duality. We have extended methodologies in the areas of stochastic geometry and Bayesian modelling, and we applied the theoretical frameworks to cognitive wireless networks and to full-duplex communication.

Milli-meter wave and industrial communication: We were among the first worldwide to address link layer issues in milli-meter wave wireless communication, through modelling and assessing the impact of interference on network protocol design. We have been advancing the mathematical modelling of wireless protocols for medium access control, and the joint modelling and design of wireless protocols and process controllers.

Joint wireless and computing resource management: We were among the first to address the issue of joint wireless and computing resource management for visual sensor networks and for edge computing, with the tools of stochastic network calculus and age of information, and developed a framework for decentralized management based on game theoretical principles.

Opportunistic communication: We have major contributions in the area of opportunistic communication, where wireless networks are formed without infrastructure support. We contributed to this area with system design, demonstrators as well as with stochastic modeling-based performance evaluation.

Wireless networks and machine learning: We have developed a formal definition of the Machine Learning over Network (MLoN) problem as a fundamentally new co-design problem between networking protocols and ML principles, methods, and algorithms.

The COS division has contributed with adding radio specific aspects, and has also added the business and regulatory perspective to the scientific design of wireless networks, to develop future technology that can enable a digitalized and wirelessly connected society in an economically viable manner. Trade-offs that different deployment strategies (e.g., cell density, frequency band, active/passive antennas) strike in terms of high capacity, low energy consumption, spectrum licenses and co-existence, and short/long-term deployments costs have been studied. The contribution consists of both scientific theory and input to stakeholders.

Radio systems: The COS division has tackled a wide range of fundamental and applied problems in the design of radio communication systems, from propagation and antennas, via the physical, control, and network layers to the business modelling. One major contribution in this area is the design of energy-efficient architectures, including the topology of radio access points, the physical layer technology, the resource management, energy-aware routing, and uncoordinated link power savings. The division has also contributed to the state-of-the-art in aerial (airborne) communication systems, where the key problem has been to enable air-to-ground backhaul links with a capacity of Gbps per aircraft. Fundamental theory has been developed to connect the number of ground stations, antenna array sizes, transmission power, and bandwidth. A strategic partnership with Airbus has enabled direct impact on the industry.

Spectrum policy: The COS division has performed research on novel spectrum sharing techniques supporting policy makers in drafting new spectrum strategies and policies. In particular, the division

has studied technologies, business models and applications for secondary spectrum sharing, sometimes labelled as “cognitive radio”. These techniques are of paramount importance due to the rapidly growing interest for local, indoor communication in dense urban environments, where currently Wi-Fi is the dominating solution. Currently, KTH in cooperation with Swedish industry and the Swedish telecom regulator are running a feasibility study on use of local (5G) spectrum for industrial applications.

Network protocols and services: A central research challenge at the COS division has been to evolve the state-of-the-art related to the deployment and scaling of mobile services. Instead of following the traditional quality of service (QoS) metrics of network performance, the user perceived service quality has been introduced, which can enable 90% resource reductions without affecting the perceived quality. Important contributions have been made to enhancing the resilience of packet-switched Internet networks, enhancing the reactiveness of networks, as well as the scalability, performance, robustness, and flexibility of load balancer services. Contributions have been made to traffic-engineering problems in a variety of different networks (e.g., wide area networks, data centers), with focus on optimizing the traffic flow of traffic in a scalable and robust manner. Improvements and testing of the OpenFlow controller programs have been carried out and been highly cited. Integrated solutions for environmental sensing systems and application platforms have been developed.

Software defined networks and network virtualization: The COS division has contributed to the design of modular and flexible design of wireless medium access protocols that can be implemented on software defined radio platforms. Pioneering work has been made on light-weight network virtualization as an enabler for cloud networking and open platforms for software-defined networking. A novel synthesis framework of service chains has been developed to enable partitioning of processing across network switches and processors, capable of providing very high performance (above 100 Gbps per user) at nearly zero latency. The delay variance is an important criterion when satisfying service level objectives, thus methodologies for satisfying such requirements have been developed, including the exploitation of geo-distributed data centers and deep understanding of the interaction between network interfaces, processors, and caches. 4 patent applications have been filed together with industrial partners. One key use case is virtualized Cloud-Radio Access Networks (CRAN), which are now utilized within 5G.

Distributed Systems

The research within distributed systems at SCS has resulted in the Hopsworks platform, which is a next-generation distribution of Apache Hadoop, with a heavily adapted implementation of the Hadoop Filesystem (HDFS), called HopsFS. HopsFS won the IEEE Scale Prize 2017 as the most scalable HDFS filesystem, and Hopsworks won the award for European Data Science Technology Innovation 2019. Moreover, researchers at SCS have been actively contributing to developing Apache Flink, which is an efficient, distributed, and general-purpose data processing platform. It features powerful programming abstractions in Java and Scala, a high-performance runtime, and automatic program optimization. It has native support for iterations, incremental iterations, and programs consisting of large directed acyclic graphs of operations.

Data Science

Data-driven system engineering: Over the last five years, the researchers at NSE have developed concepts for the efficient prediction and forecasting of end-to-end performance metrics and KPIs. Using methods from statistical learning, we measure device-level metrics in the infrastructure and predict service-level end-to-end metrics in real-time. Specifically, from measuring metrics like CPU utilization on servers and packet counters on network devices we predict quality-of-service parameters like video frame rates for a video on demand (VoD) service and query response times for a KV service on our testbed. Our results scale to a very large number of data sources and quantify the uncertainty of predictions. Currently, we are studying so-called self-driving systems, which dynamically configure to

meet management objectives and adjust their configuration to changes in the environment. The solution approach combines various concepts from statistical learning and reinforcement learning.

Foundations of data science: The past decades have witnessed significant progress in the development of intelligent methods for analyzing large volumes of data and performing challenging tasks with success that matches, or in many cases exceeds, the performance of human experts. In their majority, however, the developed methods are opaque and non-interpretable. In addition, they suffer from data biases and produce models that are not fair. The research community has recognized these issues and a lot of recent work has been devoted to design models that are fair, accountable, and transparent. Most of the work, however, focuses on supervised learning. One challenge that has received relatively less attention is to address the problems of explainability and fairness in unsupervised learning. Our goal in TCS is to develop methods that produce an interpretable clustering along a small number of data dimensions, or provide simple and comprehensible explanations for a given clustering produced by a black-box method. In the topic of fairness, we will investigate different notions of fairness in unsupervised learning, for problem settings in clustering, nearest neighbor, and matrix decomposition.

Social network analysis: Social media play a critical role in today's information society, not only by connecting people with their friends, but also by providing a medium where information is disseminated and public opinion is shaped. Initially it seemed that giving ordinary citizens the means to create content of their own and share their opinion publicly can have only positive effects: increase the exposure to diverse ideas and improve the democratic process. However, during the past few years we have witnessed that the rise of online media has led to a series of undesirable phenomena, such as creation of information silos and increased polarization. In this context, one important challenge is to address the deficiencies of today's online platforms and create environments in which social-media users are encouraged to exchange alternative views and engage in constructive deliberation. With the ERC project REBOUND at TCS we aim to develop theoretical foundations and algorithmic techniques to address this challenge. We aim to develop methods to discover structure and patterns of segregation, conflict, and closeness in social-media systems. We will address the issues of reducing bias and polarization, breaking information silos, and creating awareness of users to explore alternative viewpoints.

Trusted machine learning: The research within data science at SCS has resulted in new techniques and algorithms for quantifying uncertainty, primarily within the frameworks of conformal and Venn prediction, allowing predictions to be made with user-specified confidence under mild assumptions. The research has also contributed with techniques for generating interpretable models and explaining black-box predictions with statistical guarantees.

Machine learning for software engineering. TCS has contributed to developing a general mathematical theory and designing efficient machine-learning algorithms for learning-based testing of reactive systems. The TCS research team has successfully applied machine learning to reverse-engineer dynamic models of multi-vehicle use-cases from software-in-the-loop (SIL) and hardware-in-the-loop (HIL) vehicle simulations.

Machine learning in language technology: In the area of language technology, TCS has studied applications of natural language processing (NLP) in the clinical domain, using electronic health records. For example, NLP techniques, combined with entity-recognition models and temporal information, are used to extract likely disease onsets in patients, or to identify suicide-related information. The group has also focused on non-topical analysis of naturally-occurring text at scale, including sentiment analysis, stylistic analysis, author profiling, and learning semantic models, among others.

In the area of data science, a new group was established at the end of 2019 by Professor Gionis. The focus of the group is in the foundations of data science and social-network analysis. The group has initiated research in the area of interpretable machine learning. A new result appeared in the ACM KDD 2020 conference, for the problem of inferring a small set of interpretable rules that describes a dataset. In the area of social-network analysis the group has built on its ongoing research on the study of polarization phenomena on social graphs. Two new results appeared in the NeurIPS 2020 conference. The first work develops spectral methods for detecting polarized communities in signed networks with provable guarantees. The second work develops efficient approximation methods to maximize co-exposure of two conflicting topics on a social network, and thus, to maximize the diversity of the content seen by the users of the network.

Machine learning in computational biology and bio-image processing: Within CST, machine learning methodology is developed and applied to problems in computational biology. We develop both Bayesian methods and deep-learning methods. The Bayesian methods are based on inference techniques such as MCMC, SMC, and VI. We develop deep-learning methods, e.g., based on GANs and Variational Autoencoders, and apply these both for medical image analysis and for analysis of omics data, i.e., genomics and transcriptomics. An earlier research line focused on how genes evolve relative to the evolution of the species they belong to has been replaced by one focused on somatic evolution in cancer. How genes evolve is crucial to transforming results from model organisms, such as mice and Drosophila, to knowledge about human biology. However, evolutionary events such as lateral gene transfers are also vital for the development of antibiotic resistance in bacteria. That cancer tumors evolve constitutes the fundamental principle explaining many of this disease's most challenging properties, including common disease relapse following initially promising therapy response. Modern data types such as single-cell sequencing and spatial transcriptomics give rise to challenging data integration problems. In particular, to fully exploit spatial transcriptomics data, integration of image and transcriptomics data is required.

Modelling brain functions and study of brain diseases: The research conducted within CST has resulted in a deeper understanding of the computational mechanisms underlying biological brain functions. The group has contributed to advancing the state of the art in understanding principles governing multi-scale interactions in the brain, from molecules to behavior. Over the range of brain levels, we have developed models of the basal ganglia, a forebrain structure involved in selection of behavior and reward learning, cortical memory including short- and long-term functional aspects and olfactory perceptual system. The models are built at different levels of biological detail, from subcellular signaling models, over detailed cellular level models to systems level simplified models. The group is furthermore studying the dynamical and information processing properties of biological neuronal networks. Specifically, we are investigating how neuron and synapse properties shape the large-scale network function and neural coding. We have been instrumental in developing a theory to explain communication of information across the brain. We have also revealed mechanisms underlying the observed statistical properties of brain activity. Furthermore, with collaborators, we developed a biophysical model of a peripheral nerve which is used to address questions in chronic pain. We are furthermore a contributor to the computational pipeline that is used to analyze synapse protein data. The analysis tools enable integration of data over multiple spatial scales and comparisons of data distributions to identify regions of interest in memory, aging and psychiatric diseases.

The CST group has also contributed to creating a theory of brain function, sensory and higher cognitive functions. The group uses spiking simulation models including long- and short-term forms of Hebbian and non-Hebbian synaptic plasticity to model cortical associative memory systems and function. Synaptic working memory is in focus and they study interactions between long- and short-term memory in cortex models comprising multiple connected cortical patches. We have further developed an axiomatically determined framework of visual receptive fields, which leads to predictions about spatial and spatio-temporal receptive field profiles with close similarity to receptive fields in biological

vision. These receptive fields can also be used as an efficient basis for the first layers in computer vision algorithms. We have devoted special efforts on handling multiple spatial and temporal scales in a time-causal and time-recursive context for video analysis and developed mechanisms for automatically selecting salient spatial and temporal scales in spatial, temporal and spatio-temporal data.

Moreover, CST has also focused on studying the theory of brain diseases. Based on the theoretical understanding of biological neuronal networks, the computational brain science group has also developed computational models of brain diseases (Parkinson's disease, Alzheimer's diseases, Epilepsy and drug abuse) and algorithms to control brain activity dynamics using external brain stimulation.

Brain-like computing: The group within CST have been investigating key principles by which information processing in brains works and apply those to real-world interacting technical systems. Examples include neuromorphic computing in dedicated hardware and spiking algorithms for real-time motor control of portable neuroprosthetic devices. In an independent line of research, the groups investigate efficient low-power visual information processing of event-based (spiking) input, which allows low latency understanding of visual input. Based on competence in theoretical brain science, we are developing parallel algorithms and architectures for temporal sequence learning and unsupervised learning of sparse distributed internal representation. We have moreover developed bio-inspired models of deep networks based on functional models of biological complex cells coupled in cascade and explored their ability to solve visual tasks.

Scientific and high-performance computing

Numerical methods: Research of CST group has focused on the development of numerical methods for partial differential equations and adaptive algorithms for massively parallel computing systems, with a specific focus on computational mechanics and in silico medicine. Numerical methods enable scientists and engineers through computer simulation to study complex systems which are hard or impossible to investigate by physical experiments. Simulation also forms the foundation for virtual prototyping and digital twins in industries from manufacturing to drug discovery, and patient-specific simulations open for new strategies in personalized medicine. Specifically, at the division, novel simulation technology has been developed for computational fluid dynamics, fluid-structure interaction and diffusion-MRI, with applications to aerodynamics, renewable energy, medical imaging and cardiovascular disease. The impact of this research is manifested in a number of scientific publications in the leading journals and conferences of the respective fields, plenary and invited presentations to the main conferences, community recognition of developed open-source software, industrial use, and successful creation of spinoff companies.

In the area of statistical physics and open quantum physics, the CST group has made significant contributions into developing higher-order Feynman-Vernon theories and applications to fermionic bath, and other bath such as spin baths, which do not have equivalent bosonic baths. The CST group has also studied the large deviations of heat and work, especially beyond non-interacting blip approximation (NIBA) approximation in spin-boson problems. Moreover, we also worked on extensions of Kimura-Neher-Shraiman theory of the quasi-linkage equilibrium state to low recombination rates and as a tool to predict epistatic components of fitness from population-wide genomic data.

Visualization: We shaped the transition from continuous to combinatorial methods in topology-based visualization. Combinatorial methods for topological data analysis are parameter-free, robust against noise, and provide consistent results. Weinkauf's results extend persistent homology to the separatrices of the Morse-Smalecomplex, which has a high practical value in the analysis of data with line-like or surface-like features in a wide range of applications from vortex core lines in fluid dynamics to dendritic spines in computational biology. Further applications of this theory led to novel algorithms for detecting similarity and tracking features in time-dependent data sets. Weinkauf's group provided

the only topological denoising method with guarantees on the topology and the level of smoothness in the resulting data.

In flow visualization, Weinkauf's group developed ground-breaking views on the description of characteristic curves in unsteady flows, picked up by other research groups around the world to study unsteady vortex cores. Several contributions apply pattern matching to flow and scalar field visualization in order to allow the user to define a feature via example and let the system find similar occurrences. In multi-dimensional visualization, Weinkauf's group developed the first perceptual optimization method for scatter plots aiming at making visualization methods more accessible to all people. This work is accompanied by online tools for everyone's use.

High-performance computing: The group at CST have been working on tools and programming environments for High-Performance Computing with a focus on Exascale technologies. With the ever-increasing performance of HPC systems, expecting to reach the Exascale (that is 1019 floating point operation per second) it is getting increasingly difficult to understand application performance, particularly what aspects limit the performance of certain applications, and to program them in an efficient way. More heterogeneous and complex hardware show the limits of today's approaches. Our group works on programming environments that allow efficient use of heterogeneous hardware (particularly CPUs and GPUs) and help manage the complexity of modern memory and I/O hierarchies. We also work on approaches combining HPC simulations with analytics activities, such as in-situ visualization. Our approaches are applied and field tested in a variety of application domains, including space physics, molecular dynamics, and *Computational fluid dynamics* (CFD): In addition, we work on more dynamic performance tools that can efficiently capture the performance characteristics of extremely large applications and provide on-line information of the running application. Much of our work is performed in large international collaborations, particularly H2020 projects.

Computer science education
The group within TCS has conducted research on understanding of students' learning of hard concepts in theoretical computer science, and improved practice in courses in algorithms and complexity. It has considered implementation and effects of a program integrating courses for students of computer science and engineering, including reflection, self-regulated learning, study skills, quality enhancement, program development, studies of student competencies and student stress. It has increased understanding of how teaching assistants (TAs) in computer science courses experience their role and what the faculty can do to support their TAs, in order for them to make fair and equal assessments and to facilitate learning among the students. It has advanced the integration of version control as a basic skill for CS1 level students, developing open-source tools to support other teachers in their courses, and utilizing repository data mining for learning analytics. The group has developed accelerated learning techniques that benefit traditional, specialized and life-long learning educational contexts. CS Education research is discussed and partly carried out in the Cerise group, a local group where all teachers interested in computer science education are welcome, regardless of title or organizational belonging.

Quality and quantity of contributions to the body of scientific knowledge

CSD members of faculty have had numerous important roles in research communities: leading roles in conference organization (Steering Committee Memberships, Advisory Board Memberships, General Chair roles), program committees, notably leading roles as Technical Program Committee Chairs, and leading journal editorial board memberships. Overall, the CSD faculty has increased reputation and sustained international and national collaborations. For example, visits and exchanges, with KTH faculty in prestigious universities abroad, as well as regularly hosting renowned researchers in

Stockholm and numerous joint projects. The CSD diversity can be seen as an advantage, allowing to engage across domains and research fields, towards addressing societal concerns.

The quality of the research work of CSD faculty members, including world class research, is reflected on their leadership and international and national recognition and visibility, impactful results, including notably strong citation records, awards, and highly competitive grants. Characteristic examples: Institute of Electrical and Electronics Engineers (IEEE) Fellows (Prof. G. Maguire and Prof. P. Papadimitratos); Academia Europea members (Prof. G. Maguire and Prof. J. Håstad); a Knuth Prize (Prof. J. Håstad); an Association for Computing Machinery (ACM) Distinguished Scientist (Prof. P. Papadimitratos); a European Data Science Technology Innovation award (group of Prof. S. Haridi); Applied Networking Research Prizes (groups of Prof. R. Stadler and Prof. P. Papadimitratos); a Royal Society of Medicine Fellow (Prof. M. Boman); Royal Swedish Academy of Engineering Science fellows (Prof. J. Zander, Prof. P. Johnson, Dr. M. Frodigh); an IEEE Computer Society Helmholtz Prize (Prof. T. Lindeberg); numerous best paper awards for journal and conference papers.

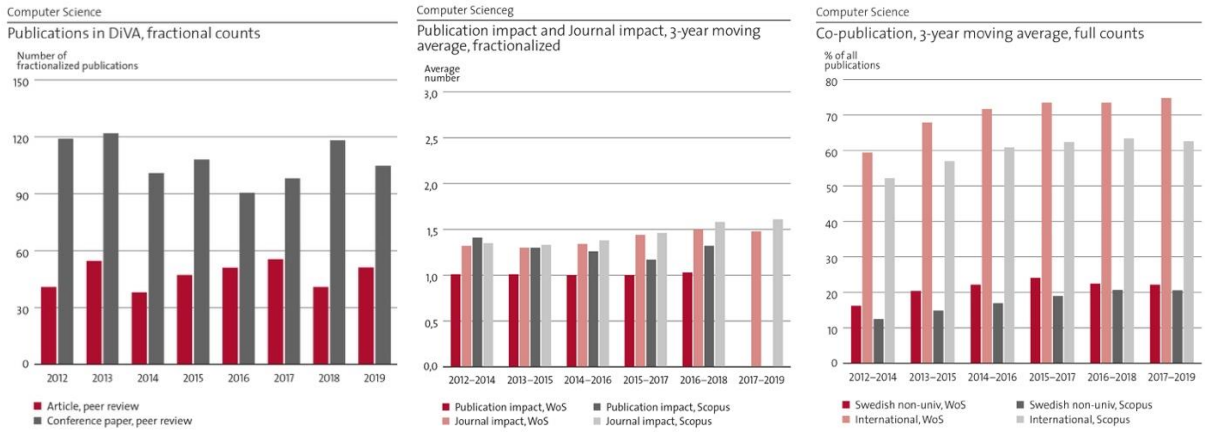
Researchers currently with CSD are the most cited in their respective areas in Sweden; e.g., Prof. G. Maguire in computer communications, Prof. P. Papadimitratos in security and privacy, Prof. B. Baudry in Software Engineering, Prof. S. Haridi in Distributed Systems, Prof. T. Lindberg in Computer Vision, Prof. A. Gionis in Data Mining; several other very highly cited faculty members, among the top at KTH. Furthermore, individual research grants with particular distinction (e.g., ERC Consolidator to Prof. D. Kostic, ERC Proof of concept to Prof. Hoffman; KAW Academy fellowships to Prof. P. Papadimitratos, Assoc. Prof. Marina Petrova, and Prof. Emil Björnson; SSF Future Research Leader awarded to Assoc. Prof. Marina Petrova, Assoc. Prof. David Broman, and Prof. Emil Björnson). Moreover: Young Academy Members (Assoc. Prof. R. Lagerström (Swedish Young Academy), Prof. P. Papadimitratos (Young Academy of Europe); Honorary Doctorate (Prof. J. Zander, Aalto University, Finland); Board member National Telecom Regulator (Prof. J. Zander); IVA 100 list (Prof. M. Monperrus, Prof. M. Ekstedt, Assoc. Prof. R. Lagerström, Prof. P. Johnsson, Prof. P. Papadimitratos).

Bibliometric data for CSD collected in the Web of Science platform are presented in Figure 3. A steady output (Fig. 3a) and impact (Fig. 3b, c) are visible over the years, with an upwards trend for journals. This, on the one hand, reflects the approach of a part of the researchers to write journal papers, following up on their conference/workshop papers (short or long). On the other hand, the trend reflects the content of Web of Science (WoS) and Scopus, which cover more broadly journal publications rather than conferences/workshops. Scopus has a broader coverage compared to WoS, yet it does not offer a wide representative coverage of all peer-reviewed events the ensemble of CSD researchers publishes to.

In order to further reflect the quality and quantity as well as impact of the CSD research, we collected citation data from Google Scholar (GS). The appendix to this self-evaluation report provides a list of faculty and research associates and their GS indices, citation count, H-index and i10 index. Being cognizant of its limitations, we consider GS because it is widely used as a bibliometric tool in Computer Science, covering conference publications, the most common way to publish in the field. Moreover, GS is often used by a variety of funding agencies. Based on GS, for each Division, we provide indices, highlights, and selected papers, with bold font for authors employed by KTH at the time of publication. Each representative publication is accompanied with a brief motivation, typically a distinction. Authors in bold font were KTH employees at the time of the publication.

COS: Citation indices for the presently employed COS staff are below. Six additional faculty members and researchers do not have Google Scholar pages. Their citation counts are low and this reflects the bimodal nature of the research output in the division.

h-index: 1-10: 1 people; 11-20: 4 people; 21-40: 7 people; 41-80: 1 people
i10-index: 1-10: 1 people; 11-20: 0 people; 21-40: 3 people; 41-80: 5 people; 81-160: 5 people



(a) (b) (c)

Figure 3. Bibliometric indices for CSD

Most cited publications:

1. E. Björnson, J. Hoydis, M. Kountouris, M. Debbah, “Massive MIMO systems with non-ideal hardware: Energy efficiency, estimation, and capacity limits,” IEEE Transactions on Information Theory, vol. 60, no. 11, pp. 7112-7139, 2014 (103 citations per year, 726 total).
2. G. Miao, **J. Zander,** K. W. Sung, **S. B. Slimane**, “Fundamentals of mobile data networks,” Cambridge University Press, 2016. (42 citations per year, 212 total)
3. B. Ahlgren, **M. Hidell**, E. C-H Ngai, “Internet of Things for Smart Cities: Interoperability and Open Data”, IEEE Internet Computing, Vol 20, No 06, Nov-Dec 2016. (42 citations per year, 209 total)
4. M. A Lema, A. Laya, T. Mahmoodi, M. Cuevas, J. Sachs, **J. Markendahl**, M. Dohler, “Business case and technology analysis for 5G low latency applications,” IEEE Access, vol. 5, 5917-5935, 2017. (32 citations per year, 127 total)

CST: *h-index*: 1-10: 2 people; 11-20: 3 people; 21-40: 14 people; 41-80: 2 people
i10-index: 1-10: 2 people; 11-20: 1 person; 21-40: 6 people; 41-80: 6 people; 81-120: 4 people

Most cited publications:

1. R. Achanta, A. Shaji, **K. Smith,** A. Lucchi, P. Fua and S. Süsstrunk, "SLIC Superpixels Compared to State-of-the-Art Superpixel Methods," in IEEE Transactions on Pattern Analysis and Machine Intelligence, vol. 34, no. 11, pp. 2274-2282, Nov. 2012. (7819 citations)
2. M. Ekeberg, C. Lövkvist, Y. Lan, M. Weigt, and **E. Aurell**, Improved contact prediction in proteins: Using pseudolikelihoods to infer Potts models, Phys. Rev. E 87, 012707 – Published 11 January 2013. (468 citations)
3. **A. Kumar,** S. Rotter, and A. Aertsen. Spiking activity propagation in neuronal networks: reconciling different perspectives on neural coding. *Nat Rev Neurosci* 11, 615–627 (2010). (394 citations)
4. J. Eriksson, E. K. Vogel, **A. Lansner**, F. Bergström, L. Nyberg, Neurocognitive Architecture of Working Memory, Neuron, Volume 88, Issue 1, pp. 33-46, 2015. (377 citations)
5. M. Lundqvist, J. Rose, **P. Herman**, S.L. Brincat, T.J. Buschman, E.K. Miller, Gamma and Beta Bursts Underlie Working Memory, Neuron, Volume 90, Issue 1, pp. 152-164, 2016. (370 citations)

Tony Lindeberg is a highly cited researcher (more than 23 000 citations) and received the Helmholtz Prize in 2017 by IEEE Computer Society Technical Committee on Pattern Analysis and Machine Intelligence.

NSE: The quality and quantity of contributions by the division are high. Between 2012-2018, some 10 publications from the division received best paper awards from major IEEE conferences and journals (notably the best paper award of the IEEE Transaction on Communications of 2018), the average impact factor of publications has been 86, and the field normalized citation index is 23.

h-index: 1-10: 0 people; 11-20: 1 person; 21-40: 8 people;
i10-index: 1-10: 0 people; 11-20: 1 person; 21-40: 1 person; 41-80: 3 people; 81-100: 4 people

The following are examples of publications from the division:

1. **H. Shokri-Ghadikolaei**, **C. Fischione**, G. Fodor, P. Popovski, M. Zorzi, "Millimeter wave cellular networks: A MAC layer perspective", IEEE Transactions on Communications, 63 (10), 3437-3458 (Best paper award of IEEE Transactions on Communications, in 2018, namely the "O. Rice" Award. This paper is arguably the first to pose a systematic design and investigation of medium access control issues in cellular wireless networks. In fact, it received the "O. Rice" Award of 2018.)
2. P. Park, S.C. Ergen, **C. Fischione**, et al., "Wireless network design for control systems: A survey", IEEE Communications Surveys & Tutorials 20 (2), 978-1013. (This paper overviews a line of research on wireless communications to support control applications, which C. Fischione initiated at KTH shortly after joining, as a natural continuation of his research at University of California at Berkeley. The paper is receiving considerable attention.)
3. L. Wang, **V. Fodor**, "On the gain of primary exclusion region and vertical cooperation in spectrum sharing wireless networks," IEEE Transactions on Vehicular Technology 61 (8), 3746-3758. (The paper represents well the methodology we follow in the area of wireless networks research, which is interdisciplinary in the sense that it combines tools of communication theory as well as teletraffic theory.)
4. **S. T. Kouyoumdjieva**, P. Danielis, **G. Karlsson**, "Survey of Non-Image-Based Approaches for Counting People," IEEE Communications Surveys & Tutorials 22 (2), 1305-1336, 2019
5. S. Trifunovic, **S. T. Kouyoumdjieva**, B. Distl, **L. Pajevic**, **G. Karlsson**, B. Plattner, "A decade of research in opportunistic networks: challenges, relevance, and future directions," IEEE Communications Magazine 55 (1), 168-173, 2017 (Citations: 82)
6. **S. Jošilo**, **G. Dán**, "Selfish decentralized computation offloading for mobile cloud computing in dense wireless networks", IEEE Transactions on Mobile Computing 18 (1), 207-220. (The conference version of the paper, which appeared in IEEE Infocom 2017, received the 2018 IEEE Sweden Joint VT-COM-IT Chapter Best Student Conference Paper award.)
7. **Ó. R. Helgason**, **S. T. Kouyoumdjieva**, **G. Karlsson**, "Opportunistic communication and human mobility," IEEE Transactions on Mobile Computing 13 (7), 1597-1610, 2013
8. B. Jennings, **R. Stadler**, "Resource management in clouds: Survey and research challenges," Journal of Network and Systems Management 23, no. 3 (2015): 567-619. (This has become an influential paper on how to model and approach resource management in cloud environments. It has more than 520 citations to date in Google Scholar.)

Cybersecurity

9. H. Holm, K Shahzad, M. Buschle, **M Ekstedt**, " P2CySeMoL: Predictive, Probabilistic Cyber Security Modeling Language," IEEE Transactions on Dependable and Secure Computing, vol. 12, no. 6, s. 626-639, 2015. (The paper represents the research group's model-based approach to cyber security research.)
10. **P. Johnson**, **R. Lagerström**, and **M. Ekstedt**, "A Meta Language for Threat Modeling and Attack Simulations," in Proc. of the International Conference on Availability, Reliability and Security (ARES 2018) and the joint International Workshop on Cyber Threat Intelligence (WCTI

2018), 2018. (The paper represents the research group's cornerstone to model-based approach to cyber security. Extended version of this work is currently under review in a journal.)
11. **P. Johnson**, **R. Lagerström**, **M. Ekstedt**, and Ulrik Franke, "Can the Common Vulnerability Scoring System be Trusted? A Bayesian Analysis," IEEE Transactions on Dependable and Secure Computing, vol. 15, no. 6, pp. 1002-1015, 2018. (The paper represents the research group strive to populate security models with empirical data.)
12. A. Vernotte, M. Välja, M. Korman, G. Björkman, **M. Ekstedt**, and R. **Lagerström**, "Load Balancing of Renewable Energy: A Cyber Security Analysis," in Energy Informatics, vol. 1, no. 1, Springer Open, 2018.

SCS: The following statistics are based on 13 research active SCS faculty members (not including doctoral students). Total number of SCS publications in period (conference, journal, book chapters) = 872. Total number of SCS citations in period (source Google Scholar) = 81343. Citation indices for all researchers and active SCS staff:

h-index: 1-10: 3 people; 11-20: 6 people; 21-40: 10 people; 41-80: 3 people
i10-index: 1-10: 2 people; 11-20: 1 person; 21-40: 6 people; 41-80: 9 people; 81-160: 4 people

Highlight: P. Papadimitratos has had in the 2012-2020 period on the average 1000 citations per year (GS). In 2021, based on citation count (approx. 14960) he ranks 24th for all KTH and 7th among all EECS faculty. Indicatively: in his broad areas, globally, he is 85th among those in "security" as one of their research areas; and 46th globally among those in "privacy".

Distinguished publications, per area - in no particular order:

Distributed systems

1. **P. Carbone**, S. Ewen, **S. Haridi**, A. Katsifodimos, V. Markl, K. Tzoumas, "Apache Flink™: Stream and Batch Processing in a Single Engine", 2015 Bulletin of the IEEE Computer Society Technical Committee on Data Engineering. (Highly influential paper with more than 750 citations.)
2. M. Ismail, S. Niazi, M. Ronström, **S. Haridi**, and **J. Dowling**, "Scaling HDFS to More than 1 Million Operations Per Second with HopsFS", 17th IEEE/ACM International Symposium on Cluster, Cloud and Grid Computing (CCGRID), 2017 *Winner of 10th IEEE International Scalable Computing Challenge (SCALE 2017)*

Software construction and analysis

3. O.L. Vera-Pérez, B. Danglot, **M. Monperrus**, **B. Baudry**, "A comprehensive study of pseudo-tested methods", Empirical Software Engineering, 2019. (This paper is a major result of the STAMP H2020 project, coordinated by SCS; it is published in one of the best journals in software engineering (The Empirical Software Engineering journal is ranked number 7 for software research venues and number 3 among journals); the experimental protocol is original; the tool presented in this paper (Descartes) has been transferred into the pipeline of major software projects.)
4. S. Natarajan and **D. Broman**. "Timed C: An Extension to the C Programming Language for Real-Time Systems." In the Proceedings of IEEE Real-Time and Embedded Technology and Applications Symposium, 2018. (Outstanding paper award)

Data science

5. **Z. Kefato**, N. Sheikh, **L. Bahri**, A. Soliman, A. Montresor, **S. Girdzijauskas**. "Cas2vec: Network-agnostic cascade prediction in online social networks", 2018 Fifth International Conference on Social Networks Analysis, Management and Security (SNAMS) (Best paper award)
6. N. Safinianaini, **H. Boström,** and V. Kaldo, "Gated Hidden Markov Models for Early Prediction of Outcome of Internet-Based Cognitive Behavioral Therapy", Artificial Intelligence in Medicine (AIME) 2019: 160-169. (Mario Stefanelli award for the best student paper)

Networked Systems Security and Privacy

7. **M. Khodaei**, **H. Jin**, and **P. Papadimitratos**, "SECMACE: Scalable and Robust Identity and Credential Management Infrastructure in Vehicular Communication Systems," *IEEE Transactions on Intelligent Transportation Systems (IEEE TITS)*, vol. 19, no. 5, pp. 1430--1444, May 2018. (IRTF ISOC Applied Networking Research Prize (ANRP) 2018)
8. **S. Gisdakis**, **T. Giannetsos** and **P. Papadimitratos**, "SPPEAR: Security & Privacy-Preserving Architecture for Mobile Crowd-Sensing Applications," *ACM Conference on Security and Privacy in Wireless and Mobile Networks (ACM WiSec)*, Oxford, UK, July 2014. (ACM WiSec best paper award)

Networked Systems

9. M. Kuzniar, P. Perešíni, and **D. Kostić**, "What You Need to Know About SDN Flow Tables", Proceedings of the Passive and Active Measurement Conference (PAM), March 2015. (41 citations per year, 205 total)
10. G. P. Katsikas, **T. Barbette**, **D. Kostić**, R. Steinert, and **G. Q. Maguire Jr**, 'Metron: NFV Service Chains at the True Speed of the Underlying Hardware', in 15th USENIX Symposium on Networked Systems Design and Implementation (NSDI 18), Renton, WA, 2018, pp. 171–186. (*Top Networked Systems Conference*)

TCS: TCS members have published at many top (A*) conferences (e.g., FOCS, STOC, S&P, CCS) and many top journals (e.g. Journal of the ACM (JACM), Society for Industrial and Applied Mathematics (SIAM)) in their field of specialization.

Johan Håstad was awarded the Knuth Prize in 2018. He has been elected Fellow of the American Mathematical Society and Fellow of the ACM during the assessment period. Håstad, Na Nongkai, and Nordström have all been recipients of ERC grants.

The following statistics are based on 20 currently employed and research active TCS faculty members (not including doctoral students): Total number of TCS publications in period (conference, journal, book chapters) = 508; Total number of TCS citations in period (source Google Scholar) = 22662.

Citation indices for 20 research active TCS staff:

h-index: 1-10: 0 people; 11-20: 8 people; 21-40: 7 people; 41-80: 2 people
i10-index: 1-10: 0 people; 11-20: 3 people; 21-40: 6 people; 41-80: 5 people; 81-160: 3 people

Most impactful papers:

Security

1. U. Franke and **J. Brynielsson**. Cyber situational awareness – A systematic review of the literature. Computers & Security, 46:18–31, October 2014. (Citations 254).
2. **M.Dam**, **R. Guanciale**, N. Khakpour, **H. Nemati**, and **O. Schwarz**. (2013, November). Formal verification of information flow security for a simple ARM-based separation kernel. In Proceedings of the 2013 ACM Special Interest Group on Security, Audit and Control (SIGSAC) conference on Computer & communications security (pp. 223-234). (Citations 81)

Software construction and analysis

3. **M. Monperrus**, Automatic Software Repair: A Bibliography, ACM Computing Surveys (CSUR), January 2018, Article No.: 17 (Citations 219)
4. A. Bennaceur, R. Hähnle, **K. Meinke**, Machine Learning for Dynamic Software Analysis: Potentials and Limits, International Dagstuhl Seminar 16172, Dagstuhl Castle, Germany, April 24-27, 2016, Revised Papers, Springer Verlag, LNCS 11026, 2018. (8300 downloads).

Computational complexity

5. M. Henzinger, S. Krinninger, **D. Nanongkai**, T. Saranurak: Unifying and Strengthening Hardness for Dynamic Problems via the Online Matrix-Vector Multiplication Conjecture. STOC 2015: 21-30. (Citations 179).
6. **P. Austrin**, V. Guruswami, **J. Håstad**, (2+eps)-Sat Is NP-hard, SIAM Journal on Computing 46 (5), 1554-1573, 2017. (Citations 45)

Engagement in national and international research collaboration within academia and its outcomes

CSD has built a large network of collaboration by regularly participating in joint projects funded by EU H2020, EU FP7, ERC, CELTIC PLUS, EIT ICT, EIT Digital, ITEA, EDA, SSF, KAW, MSB, VR, Vinnova, WASP, Wallenbergs Stiftelse, STINT (please a list of abbreviations on p.6, with more details in the presentation of the funding profile).There is participation or leadership in research centers: participation on many fronts of the Digital Futures (DF) center; leading the CASTOR software research center; leading the center for Cyber Defense and Information Security (CDIS); leading industrial competence groups in the Innovative Centre for Embedded Systems (ICES); SecurityLink center Steering Committee; led the Wireless@KTH center; led thematic areas in the Autonomic Complex Communication nEtworks, Signals and Systems (ACCESS) Linnaeus Centre. Furthermore, there is strong presence in national or international collaborative projects and programs. For example, the Human Brain Flagship project at a European level; or at a national level, CDIS with funding from the Swedish Armed Forces; or leading two out of three projects awarded and currently running within the SSF Big Data and Cybersecurity Programs.

COS: The division has a large network of academic collaborators in Sweden and abroad, including Linköping University, Lund University, University of Oulu, Aalto University, Aalborg University, Polytechnic Institute of Castelo Branco, Polytechnical Institute of Lisbon, Delft University of Technology, Technische Universität RWTH Aachen University, Dresden University of Technology, King's College London, Yonsei University, and KAIST. Two of the professors of the division, Marina Petrova and Emil Björnson, are even sharing their time between KTH and other universities. The major outcomes of these collaborations are joint European projects, such as the Horizon 2020 project “Virtual Presence in Moving Objects through 5G (PriMO-5G)”, the EIT Digital projects “5GrEEn: Towards Green 5G Mobile Networks” and “Seamless Direct Air to Ground Communications (DA2GC) in Europe-ICARO-EU”, EU Celtic Plus projects SooGREEN “Service Oriented Optimization of Green Mobile Networks” and AI4Green “Artificial Intelligence for Green Mobile Networks”. There are also collaborations with WASP, including the Expedition project “ICARUS—Intelligent Cell-free Access for wiReless Ubiquitous Services”.

CST: The division has an extensive network of academic collaborations in Sweden, in Europe and worldwide, for example, Karolinska Institute, Danderyd Hospital, Karolinska Hospital, Nordita, Stockholm University, Chalmers, Uppsala University, Lund University, Linköping University, Aalto University, Magdeburg University, NTNU, Ulm University, Max Planck Institute for Intelligent Systems, University of Tubingen, ETH Zurich, MIT, Cambridge University (international), Fred Hutchinson Cancer Research Center in Seattle, Universitätsklinikum Giessen und Marburg, Edinburgh University, Department of Molecular Oncology, BC Cancer, Vancouver, University of British Columbia, Vancouver, Kiev University, Lesya Ukrainka Volyn National University (Lutsk, Ukraine), Beritashvili Institute of Physiology and Caucasus University in Tbilisi (Georgia), Lawrence Livermore National Lab, Los Alamos National lab, and Pacific National Lab, Chinese Academy of Sciences, Ecole Normale Supérieure Paris, CNRS Paris, King’s College London, University of Michigan.

These collaborations often take place within international research projects sponsored by the European Union within the H2020 framework or Swedish funding agencies. Outcomes include joint publications in the most reputed journals and conferences of the division’s research areas, but also extended periods

of visiting to and from these universities. One example is that Erik Fransén conducted a 10-month sabbatical at Edinburgh university during 2017-2018, and he is now a visiting professor at Edinburgh university. Erik Aurell was co-PI of the Finnish Center of Excellence in Computational Inference Research (COIN) (Aalto University and University of Helsinki, 2012-2017), engaged in the Chinese Academy of Sciences' President's International Fellowship Initiative (2016), and held a Chaire Joliot, ESPCI (2018) (Paris, France). Arvind Kumar was a visiting associate prof. At university of Tokyo in 2020. Johan Hoffman conducted a 6 months sabbatical at the Auckland Bioengineering Institute in 2011-2012, and was an external scientific member at Basque Center for Applied Mathematics (BCAM) in 2014-2016. Johan Jansson has been affiliated with BCAM since 2013, where he was a co-PI for the Severo Ochoa Center of Excellence.

A large number of CST faculty members collaborate closely with other Swedish universities in the Swedish e-Science Research Center (SeRC), which is funded by the Swedish government Strategic Research Area (SRA) Initiative since 2010. CST researchers are also engaged in the SRA for Neuroscience (StratNeuro). CST researchers are engaged in several international open-source projects with high impact, including the visualization software Inviwo, and the computing platform FEniCS for solving partial differential equations.

Some example of European Union projects: the three H2020 Marie-Curie (MSCA ITN) projects CONTRA, ANIMATAS and CLIPE, each of which involves training 15 early-stage researchers (PhDs) and involve substantial training and secondment activities (usually 2-3 months) at host institutions, which include academia and industry.

The research in high performance computing strongly relies on international collaboration with leading supercomputing centers in Europe (e.g., BSC in Spain, CEA in France, CINECA in Italy, CSCS in Switzerland) and outside of Europe (e.g., Oak Ridge National Lab in US) as well as engagements with leading providers of HPC Technologies like Arm, Atos, HPE/Cray, Huawei, IBM and NVIDIA.

We also regularly appear as program committee members at the top conference, for example, Supercomputing conference, ISC High Performance, International Conference for High Performance Computing (SC), IIJCN or ICANN, RECOMB, ISMB, ICML, Computational Neuroscience Society, International Conference on Scale Space and Variational Methods in Computer Vision (SSVM), International Conference on Pattern Recognition (ICPR), European Conference on Artificial Intelligence (ECAI), International Conference on Autonomous Agents and Multiagent Systems (AAMAS), Intelligent Virtual Agents (IVA), IEEE Vis, EuroVis, CVPR, ICCV, ECCV, ICML, NeurIPS, ICLR, AAAI, MICCAI; and we have members on the editorial board of several top journals and book series, such as, SIAM book series Computational Science and Engineering, Computers and Fluids, Frontiers in Neuroinformatics, IEEE Transactions on Visualization and Computer Graphics (TVCG), Plos One, Journal Network Neuroscience (eNEURO), PlOS journal, PlOS Computational Biology, Neural Computation, and a review panelist for NASA.

Erik Aurell is the main organizer of the Nobel Symposium in Physics "Predictability in Science in the Age of AI (NS183)" (upcoming, scheduled for 2022).

NSE: The division has an extensive network of academic collaborations in Sweden, in Europe and worldwide, including UC Berkeley, MIT, Harvard, EPFL, University of Illinois Urbana-Champaign (UIUC), TU Munich, CNR, IIT Madras, Shanghai Jiao Tong University, Tsinghua University, TNO, and Totalförsvarets forskningsinstitut (FOI), RISE, and Linköping University in Sweden. These collaborations often take place within international research projects sponsored by the European Union within the H2020 framework or the Swedish Research Council. Outcomes include joint publications in the most reputed journals and conferences of the division’s research areas, but also extended periods of visiting to and from these universities. For example, Robert Lagerström and Carlo

Fischione spent sabbatical years at Harvard University and MIT and György Dán at UIUC and at EPFL. Several doctoral students of the division have spent extended research visits in the above institutions. Such visits of NSE researchers in these international top reputed institutions have contributed to the appointment of NSE's doctoral graduates and postdocs as faculty in reputed international universities, broadening the career perspectives for young researchers. A recent example includes Dr. Luca Turchet (NSE Postdoc) now Assistant Professor at Trento University, Italy (arguably the best Italian University within Computer Science). Within teaching close to research, the outcomes of these international collaborations include also Master's thesis projects and Master's student exchange. Moreover, several joint conference and workshop organization, and top ranked journal special issues are organized between NSE researchers and international collaborators. Examples include several special issues of the IEEE Journal on Selected Areas on Communications, or conferences such as IEEE SmartGridComm and IEEE ICDCS.

SCS: The division has extensive national and international collaboration with universities, research organizations and companies. Some of the major recent collaborations include:

Karolinska Institutet (KI). Researchers at SCS have a long-standing collaboration with Karolinska Institutet (KI), one of the most prestigious medical universities in the world. Prof Magnus Boman has a leading role in these collaborations, which include projects on Internet-based cognitive behavioral therapy (CBT) for depression, social phobia, and anxiety, with support from Erling-Persson Family Foundation, Forte, and the Swedish Research Council. KI is currently supporting a researcher exchange with KTH, funded directly by the Rector of KI, to conduct a maturity- and gap analysis of AI at KI as well as hospital clinics, the outcome being a report directed towards intensifying cooperation between KTH and KI on AI. This initiative is a step towards realizing "Stockholm Trio", an advanced research collaboration between KI, KTH and Stockholm University (SU), as already implemented for a directed international joint consortium with University of Tokyo, and to be expanded, as it is supported by rectors of all three universities. The Computer Science department at KTH is here playing a pivotal role.

WASP. B. Baudry has a WASP Professor chair, the division also has two WASP Expedition projects, 4 regular doctoral students and 5+ industrial doctoral students funded by WASP.

H2020 STAMP project (2016 – 2019). This project was coordinated by B. Baudry. It gathered 4 research groups and 6 software companies. The innovative software technology produced in the context of STAMP has been published in top academic venues (International Conference on Software Engineering (ICSE), IEEE/ACM International Conference on Automated Software Engineering (ASE), International Symposium on Empirical Software Engineering and Measurement (EMSE)) and have been demonstrated in the most important industry conferences (Devoxx, FOSDEM).

H2020 EU project "ExtremeEarth: From Copernicus Big Data to Extreme Earth Analytics" (2019-2021) This project is coordinated by V. Vlassov. The project develops AI and Big Data technologies that scale to the petabytes of Copernicus data, and applies these technologies in two of the thematic exploitation platforms of the European Space Agency: Food Security and Polar regions. The project gathered an international consortium of 11 partners from 6 countries including 4 universities, 5 companies and 2 research institutes.

SSF "Continuous Deep Analytics (CDA)" (2018-2022). Modern end-to-end data pipelines are highly complex and unoptimized. They combine code from different frontends (e.g., SQL, Beam, Keras), declared in different programming languages (e.g., Python, Scala) and execute across many backend runtimes (e.g., Spark, Flink, Tensorflow). Data and intermediate results take a long and slow path through excessive materialization, conversions down to different partially supported hardware accelerators. End-to-End guarantees are typically complex to reason due to the mismatch of processing

semantics across runtimes. The Continuous Deep Analytics (CDA) project aims to shape the next-generation software for scalable, data-driven applications and pipelines. Our work binds state of the art mechanisms in compiler and database technology together with hardware-accelerated machine learning and distributed stream processing.

SSF Framework grant: Automating System SpEcific Model-Based Learning (ASSEMBLE) is a 5-year research project that is financially supported by the Swedish Foundation for Strategic Research (SSF). The project started in July 2016 and has a total funding of 29 million SEK. The objective of the project is to develop a new probabilistic modelling language together with new machine learning inference algorithms to enable fast and complex development of smart systems. The project team consists of four researchers: From KTH: David Broman and Joakim Jaldén. From Uppsala University: Thomas Schön (main PI) and David Black-Schaffer.

SSF Framework grant: Secure and private connectivity in smart environments (SURPRISE) is a 5-year multi-university project that started in 2018 and will be completed in 2023, with a 33 MSEK budget. The PI is Prof. P. Papadimitratos; co-PIs are Prof. M. Skoglund (KTH), Erik G. Larsson (Linkoping Univ.), Simone Fischer-Hübner (Karlstad Univ.), and Thomas Johansson (Lund Univ.). SURPRISE provides an advanced yet pragmatic approach for practical security and privacy for smart environments: solutions that catalyze a broad set of applications and services, relying on well-understood and rigorously evaluated components that significantly advance the state of the art. Its advisory board includes representatives from the industry (SAAB, ABB, Combitech, ATEA) and the Swedish Defense University.

TCS: All groups have participated in multiple nationally funded projects. *Computational complexity*: Members of the complexity group regularly make long-term (several months) visits to the Simons Institute for the Theory of Computing in Berkeley. The majority of our publications are joint with international collaborators from all across the world. We also regularly appear as program committee members at the top conferences in algorithms and complexity and we have members on the editorial board of several top journals such as SIAM Journal on Computing. Since 2014, the complexity group has run the Swedish Summer School in Computer Science (S3CS), a yearly summer school on selected topics in theoretical computer science which has consistently attracted top researchers as speakers. Na Nongkai has a visiting professorship at École Normale Supérieure, Paris and is a member of the Interest Group on Algorithmic Foundations of Information Technology (IGAFIT).

Computer Security: Dam has participated in the EU-FP7 Commission 7th Framework program (FP7), UaESMC - Usable and efficient secure multiparty computation (UaESMC), 2012-2015. Brynielsson has been a member of MIRROR. European Union Horizon 2020 project, Agile Cooperative working using Knowledge of Social network Information Systems (ACKSIS). European Defense Agency (EDA), CONTAIN. EU FP7, Alert4All.

Computer science education: The group collaborates with the UpCERG research group at Uppsala University. One collaboration, which also included researchers from the USA and UK, led to a journal article in 2018 on modelling competencies for computing education. We have collaborated with the University of Florence on teaching NP-completeness, which led to improvements of courses at both universities, a completed doctoral project, conference and journal articles.

Several teachers in the group have been awarded Swedish Foundation for International Cooperation in Research and Higher Education (STINT) stipends for 5-month sabbaticals to the USA and Singapore. Ric Glassey planned a visit to National University of Singapore (NUS), in Fall 2020 (postponed). He has also been on two 1-month exchange trips to Northeastern University, Liaoning Province, China (2015, 2016). STINT sabbaticals have led to course improvements and new research studies at KTH.

Data Science: Karlgren was a member of European Commission Sixth Framework Program (FP6), PROMISE Network of Excellence, 2010 - 2013, and European Commission Horizon 2020, Ground Truth 2.0, Environmental knowledge discovery of human sensed data, 2016 - 2019. Vellupillai has been a member of VR/Marie Curie project MeDESTO, 2016-2019 and U.K. Engineering and Physical Sciences Research Council (EPSRC) project, Healtex, 2016-2020. Gionis is an ISI Foundation Fellow in Torino. Gionis is participating in the European Horizon Research Innovation and Action project SoBigData. Meinke organized a Dagstuhl Workshop on Machine Learning for Software Analysis in 2016.

Software construction and analysis: Monperrus is co-PI of H2020 project STAMP and co-Organizer of the 2020 workshop on automated program repair as well as leader of the cluster for software technology within the WASP program. Meinke has been a member of the EU projects ARTEMIS MBAT, SafeCOP, and Testomat. Artho has been a recipient of Japan Science and Technology Agency (JST), A-step start-up research grant, 2014-2016 Japanese Society for the Promotion of Science (JSPS) kaken-hi grant, 2014-2016 Japan Science and Technology Agency (JST), and member of MMSD center, 2019 (ongoing). Troubitsyna participates in EU Joint Undertaking Shift to Rail within X2Rail2 and X2Rail3 projects: “Advanced Signaling, Automation and Communication Systems”. Dam, Gurov and Meinke participated in EU-FP7, Highly Adaptable and Trustworthy Systems (HATS), 2009-2013.

Follow up from previous evaluations

The last research assessment exercise was carried out in 2012 (RAE 2012). The recommendations covered formally a different part of KTH, across three schools then, with input from three panels being relevant and overlapping with the activities now covered by the RAE 2021 Panel 4. We outline below recommendations and responses.

It was recommended, overall for KTH, to create a more rational organizational structure that avoids duplication of programs/competences and enhances the potential for cooperation through appropriate environments. More specifically, for CSD, it was recommended to bridge theoretical and applied research, encourage and support faculty members to obtain external funding and collaborate more.

A major shift towards addressing these recommendations was the creation of CSD itself, within the recently formed EECS. CSD integrated five divisions (former departments) and undertook the responsibility for all education as well as research coordination. The result is already visible, with more streamlined educational programs at all levels. There is also strong encouragement of tighter cross-division collaborations, with examples being the creation and involvement in joint research centers, research projects as well as joint doctoral student supervision.

Also following recommendations from the last evaluation: All divisions worked on increasing their research publication impact; targeting venues and periodicals with a high(er) impact factors, as well as promoting visibility through tutorials, invited seminars and keynote lectures.

There were concerted efforts to intensify international collaborations; this was indeed so and collaborations widened geographically. The research cooperation via research visits and joint projects made a positive impact on research. Interdisciplinary collaborations intensified as well, with further efforts to be involved in large-scale international or national projects that involve industrial stakeholders.

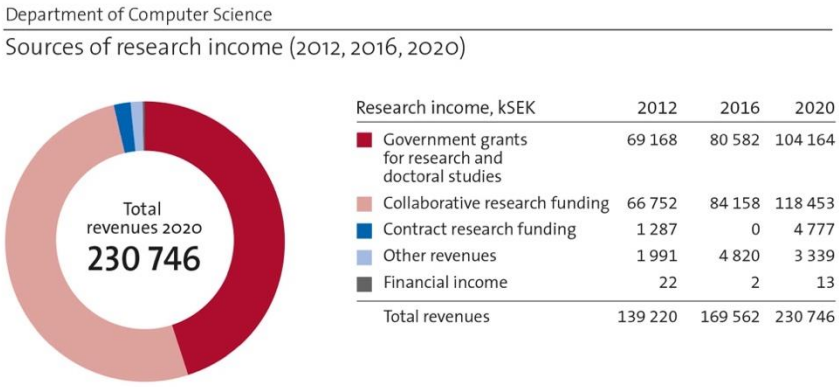
A broad effort was made on hiring: first, towards hiring both top young talents and prominent established professors, e.g., through the WASP program. Significant efforts have also been made in achieving better gender balance via hiring female researchers in traditionally male-dominated

disciplines, e.g., theoretical computer science. Last but not least, new positions to be opened are discussed within CSD, involving all divisions jointly.

3. Viability

Funding; internal and external

CSD has a very strong record in attracting national and international external funding. We have a diverse funding profile, including highly selective grants. Notably, European Research Council (ERC) grants, Knut and Alice Wallenberg (KAW) Academy Fellowships, as well as Swedish Science Foundation (VR) and Strategic Research Foundation (SSF) grants. Furthermore, a diverse set of European Union Framework Program and Horizon 2020 projects, as well as Wallenberg Autonomous Systems (WASP) projects and faculty positions, and funding by VINNOVA. The overall funding for the CSD has been constantly increasing for the assessment period, as summarized in *Figure 4*.



Research income, kSEK	2012	2016	2020
Government grants for research and doctoral studies	69 168	80 582	104 164
Collaborative research funding	66 752	84 158	118 453
Contract research funding	1 287	0	4 777
Other revenues	1 991	4 820	3 339
Financial income	22	2	13
Total revenues	139 220	169 562	230 746

Figure 4. CSD research income.

The main external sources of funding include: (i) *FP7 and H2020*: European Union research framework programs, past and current. (ii) *VR*, which focuses on fundamental research. (iii) *SSF*, focusing on applied research of strategic relevance for Sweden. (iv) *STINT*, the Swedish Foundation for International Cooperation in Research and Higher Education. (v) *VINNOVA*, the Swedish agency sponsoring technological innovation. (vi) *KAW Foundation*: it funds Academy Fellows, in conjunction with the Swedish Academies, as well as a gamut of (collaborative) projects. (vii) *WASP*: the Wallenberg Artificial Intelligence, Autonomous Systems and Software Programs, focusing on fundamental research in these three main areas. Moreover, *WASP-HS* focuses on humanities and society. (vii) *Digital Futures*: A program of the Swedish government focusing on ICT and mobile systems, the successor of the Information and Communication Technology - The Next Generation (Strategic Research Areas (SRA) ICT TNG) platform. (viii) *EIT Digital*: The European Institute of Technology and innovation, sponsoring pre-commercial research. (ix) The Swedish Energy Agency. (x) *MSB*: The Swedish Civil Contingencies Agency.

COS: The amount of funding has been mostly steady. The COS division is funded about one third by teaching (including commissioned education) and the rest by research. The external part of the research funding is slightly more than half of the total research funding.

The COS division is being reorganized in 2021, as a subset of the faculty and students moved to the SCS division. The total budget has decreased accordingly but a recent increase in external funding is enabling new recruitments of PhD students and postdocs. In 2012-2019, COS has obtained more than 110 MSEK of external funding from EU FP7 and H2020, CELTIC PLUS, EIT ICT and EIT Digital, Vinnova , SSF, Internet foundations, IoT Sweden, Viable cities, Swedish International Development Cooperation Agency (SIDA), Trafikverket, STINT and WASP.

CST: Internal sources constitute Research and postgraduate education (Swedish: Forskning och forskarutbildning (FoFU)) funds provided to the department via the school and KTH. These are relatively stable however only provide a minor part to the research budget.

As of January 2020, external funding is distributed as follows: VR (12, 55MSEK), VINNOVA (2, 2.3MSEK), Wallenberg (3, 6.2MSEK), STINT (1, 0.8MSEK), STEM (4, 5.6MSEK), SSF (2, 53MSEK), Swedish Research Council for Sustainable Development (FORMAS) (1, 0.88MSEK), EU (10, 63MSEK). Total 187MSEK.

Developments: The breadth of the department is a strength in this respect, as it allows us to apply for funds from a range of providers and a variety of calls.

Critical factors: Overhead coverage of funds from providers who do not comply with the full cost model is a continuing problem. Cost sharing by using FoFU funds is the only viable option which thus leads to "lock-in" of internal funds to projects funded by external providers.

NSE: The NSE division is well-funded with roughly 20% from teaching and 80% from research. Research funding is about one third from internal sources (KTH FOFU, TNG, etc.) and two thirds from external sources. External funding comes from Swedish organization (VR, SSF, Vinnova, FM, etc.) as well as from European funding sources and programs (H2020, EIT, ITEA, etc.). There is some direct industry funding, for instance from Huawei.

The internal funding mostly comes from teaching activities of large courses, such as Internetworking, Ethical hacking, Introduction to computing systems, and Project management, all of which have more than 150 students each.

The external funding is substantial, with individual research projects often having a budget larger than 10 MSEK. Moreover, the external funding of the division exhibits a good mix between basic and applied research, which greatly contributes to the development of ground-breaking results.

A critical factor of the NSE division, common to most of the EECS divisions, is that the external funding covers more than 50% of the division's operations. Moreover, such external funding always has a limited time duration, from three to five years (in exceptional cases ten years). Thus, the sustainability of the division's operations greatly relies on the ability of the faculty to attract such external funding.

SCS: The SCS division is well-funded, with internal funding coming from both teaching and internal research funding. A better balance between internal and external funding should be aimed for, with internal funding to be used mainly for supporting permanent staff, while non-permanent staff (post-docs, doctoral students) preferably should be funded by external funds due to the more uncertain nature of the latter.

The research at SCS is funded by e.g., SSF Trustfull; SSF Continuous Deep Analytics (CDA); CELTIC Internet of Devops; H2020 STAMP; WASP chair; WASP Expedition; WASP Industrial doctoral students; Vinnova CODA; and Vinnova Resultaten i Staten.

FP7 Marie Curie iSocial (2012-2017, EUR 3.6 million (MEUR) total, approximately 1MEUR for KTH), H2020 Marie Curie Real-time Analytics for Internet of Sports (RAIS) (2019-2022, 3.6MEUR total, approx. 1MEUR for KTH), H2020 ExtremeEarth (2019-2021, 6MEUR total, 0.621MEUR for KTH).

Vinnova: Smart Sustainable Cities of the Future (1M, 2019), VR: Learning Machines for Internet-Based Psychiatry (>5M, 2019-2021), Erling-Persson Family Foundation: (similar topic) (>4M, 2018-2021),

MMW: Multimodal emotion expressions using machine learning (>6.5M, 2019-2024), Karolinska (Rektor): AI@KI (2020). Development: AI for healthcare becoming mature; Critical factors: incredible push from clinics to improve outcomes and patient health using machine learning.

SSF individual grant for future leaders (David Broman, FFL 6) (12MSEK), SSF Framework grant (29MSEK split on 4 PIs, main PI at Uppsala University), VR Project grant (4.2MSEK), WASP Expedition grant (2 postdocs), WASP Collaboration project (1 doctoral student)

NSS (Papadimitratos): Three projects funded by the European Commission (EU FP7); four by the EIT ICT Labs/EIT Digital; a Young Researcher Project award, a framework grant, and a project grant funded by VR; and a KAW Academy Fellowship and its prolongation, covering a total of 10 years. Additional external funding: KAW WASP, SRA ICT TNG, VINNOVA, Viktoria Swedish ICT, and SecurityLink. A framework grant by SSF, which involves 5 Swedish Universities and 4 industrial partners. Approximately, in the covered period, 52MSEK (own shares for collaborative projects).

NSLab (Kostic): in this period 46MSEK own funding (2 ERCs, SSF framework grant, EU project, WASP).

TCS: The submitted data shows that combined internal and external research funding for TCS has increased from 29.7MSEK (2012) to 48.2MSEK (2020). There has been a period of falling or flat research funding from 2012 to 2016, but the situation has improved since 2016.

A detailed analysis of the sources of funding for TCS indicates substantial changes. For example, funding for pure science research from VR has fallen dramatically from 9.9MSEK (2012) to 0.3MSEK (2020). Funding from the EU (including ERC grants) has fallen (almost steadily) from 7.2MSEK (2012) to 4.7MSEK (2020). Funding for applied science research from Vinnova has increased from 0MSEK (2012) to 4.7MSEK (2020). Funding for large-scale science projects has increased dramatically, e.g., from the Wallenberg Foundation from 0MSEK (2012) to 9.6MSEK (2020) and from SSF 2.2MSEK (2012) to 9.0MSEK (2020).

The funding shift towards applied science and away from pure science, as well as towards groups and away from individuals, seems to have affected TCS somewhat negatively and in ways that we have tried to adjust to, e.g., by new hiring. Finally, TCS internal co-funding of publicly funded projects is becoming increasingly common, and in larger amounts, which consumes scarce internal research funding (FoFU).

Academic culture

CSD has well-defined groups in terms of own research and education profile, nationally or internationally recognized. Typically, Divisions have all teams co-located at the same campi. In some cases, groups of the same division are at different locations. This allows for close interactions with the relevant research environment. Overall, there are no barriers to co-operation across research groups.

The nature of research culture varies across divisions but has many common features. All divisions run regular thematic or cross-disciplinary seminars where doctoral students present their progress, faculty members discuss their on-going research as well as invite external visitors to talk about their research. Regular individual supervisor-doctoral student meetings are run by all the divisions. Many faculty members are part of strategic research platforms at KTH, which provide additional fora and venues for discussing research matters. Suitable examples are the Swedish e-Science Research Center (SeRC), the emerging KTH Digital Futures initiative, KTH Railways group etc. Shared externally funded projects are increasingly common, and staff sometimes mentor each other in funding calls.

We have special office space for organizing regular meetings, discussions and seminars. Larger research groups increasingly occupy larger dedicated lab spaces. Across all the divisions, we make active use of teleconferencing facilities such as Zoom or Skype Business. At CST there is also an opportunity to exploit a large screen to facilitate communication in larger groups in the Visualization Studio - VIC. KTH also provides support to exchange and share research documents within KTH.

At COS and NSE, there is also a tradition of annual "planning retreats", where the entire academic staff discuss the results and research strategies as well as plan the division's activities for the coming year. The external speakers give inspiring seminars on selected topics (e.g., career development paths, popular science public speaking, research impact in the society, or innovation).

At TCS, the academic culture is for the most part based on personal collaboration, often without the need for specific equipment or infrastructure. There is a strong "whiteboard culture" in open spaces, such as corridors and coffee rooms. There is strong upward pressure on TCS office accommodation. Several small meeting rooms are maintained by TCS, but these compete with guest and part-timer accommodation.

At CST, the research culture is diverse reflecting the breadth of scientific disciplines represented by the faculty. To jointly discuss matters of importance, CST has established a board of the division, which currently comprises the majority of the professors and one junior faculty representative. CST also provides seed funding for novel, short-term high-risk high-gain interdisciplinary projects and joint workshops facilitating research exchange within the division. These initiatives led to successful applications for research funding at national and international levels, and publications by members of different research environments at CST.

The NSE nourishes a mix of the cultural traditions of basic research, which rewards the development of basic principles, with the applied research, which rewards the understanding and building of complex systems. Such a mix is particularly beneficial, because it allows the young researchers to put greater emphasis on the impact and the holistic view of their research agendas.

Current faculty situation

Figure 5 summarizes the faculty and research personnel for CSD. In several divisions, there are several senior staff (especially professors) that are world-leading experts in their fields, surrounded by strong teams of younger researchers. The recruitment across both departments has emphasized equality. A Computer Science faculty member was the first Head of the School of EECS. Division-specific information follows.

COS: We have an alarmingly large fraction of professors retiring soon. These retirements are as follows: 2 to 3 professors and 1 associate professor. Given the upcoming retirements of the top faculty members, it is vital that we are allowed to open one position at a higher level (professor or associate professor) and at least two assistant professor positions. In the meantime, we have employed a visiting professor from Linköping University at 80%. Getting to the balance point for faculty members will take time, but we hope to overcome the deficiency of female full professors in a future promotion. The only assistant professor in the division is female and will be promoted to associate professor in early 2021. Despite the clear gender imbalance, the division is performing fairly well compared to similar research groups at other universities.

CST: In terms of age distribution, professors at CST are centered around 56, associate professors and lecturers around 48 and 35, and researchers cover a wider range. Note, all who originally were employed as assistant professors are now associate professors. In the nearest few years, we expect 3-4

of the associate professors to be eligible for promotion to full professors. Given the current retirement age of 67, in 12 years' time 6 of the professors will retire.

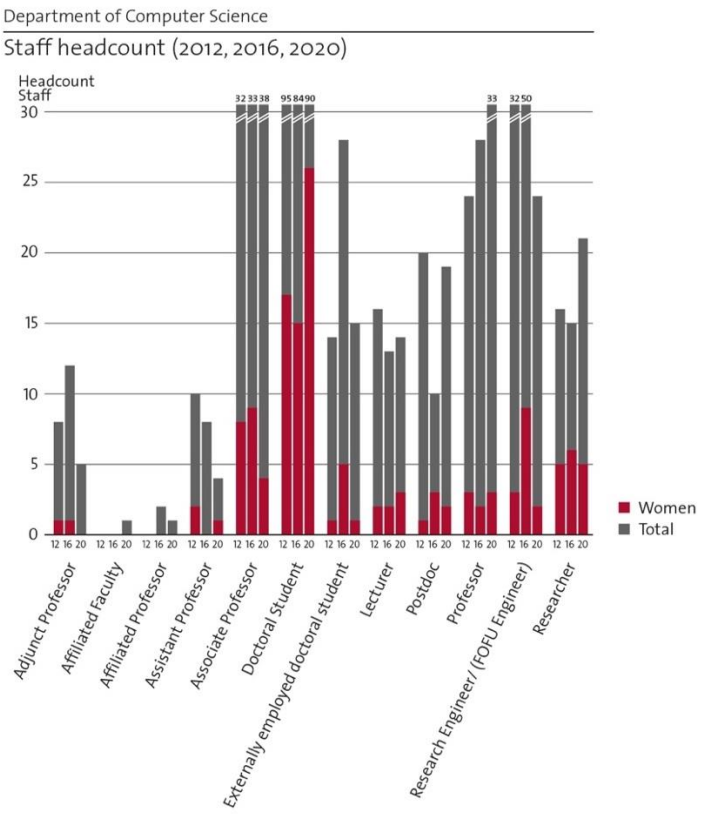


Figure 5. Faculty and research personnel at CSD.

NSE: Currently, the Division has a faculty composition which is balanced toward the prominence of full professors (7 out of 10 faculty), each older than 40. Such a composition is not uncommon among the current school's divisions. There are two women among the faculty (a full professor and a lecturer). Two associate professors are on the career track toward the full professorship expected within the next 3-5 years. The next steps to achieve a sound balance within the next 5 years will be hiring at least two faculty members, hopefully at least one female, in the division's strategic research areas.

SCS: SCS needs faculty renewal within 1-5 years; five junior faculty positions within the next three years, including at least one full time lecturer, and five additional positions within the following five years, including one full time lecturer. New positions are expected in the areas of systems for data science, modelling, distributed systems, computer systems, and machine learning. With these actions, the number of full professors is expected to stay the same over time, provided that three of the associate professors are promoted to full professor within five years, and the number of associate professors is expected to stay the same provided that new assistant professors are recruited. Special attention to recruiting female faculty is required to obtain a desired gender balance over time. E.g. one of the two current female associate professors is on leave of absence to uphold a professorship in Norway.

TCS: With respect to the submitted data, TCS faculty (non-doctoral and non-teaching assistant positions) consists of 23 men and 3 women (11%). Among doctoral students, we have 19 men and 5 women (20%). During the assessment period TCS has improved the gender imbalance by hiring 3 women faculty. In further addressing the gender imbalance we follow the guidelines and principles provided by KTH and the EECS school, as well as proactive job advertising on social media. TCS has the following age distribution of faculty: 20-30 years (0), 31-40 years (3), 41-50 years (11), 51-60 years (10), 61+ years (2). Thus, simply to keep teaching resources stable, TCS will need to hire at least 5 staff over the next 5-10 years.

Recruitment strategies

COS: The recruitment has previously focused on postdocs, due to their ability to directly contribute to research in external projects and since there is less risk involved when the employment contracts are shorter than the period of the grants that have been obtained at the time of employment. However, thanks to the track-record of steady funding and the acquisition of several new five-year-long grants, a more ambitious and somewhat more risky approach will be taken where focus is shifted towards recruiting doctoral students. The new leadership at COS believes that the education of doctors is an important aspect of the activities, in addition to the research results that are produced, thus it is worth the risk.

The focus on tenure track recruiting is to recruit the most competent people possible as faculty members, while – there should be near zero hiring of research staff (other than for specific projects and for only limited periods of time). As mentioned above, the retirement of professors and associate professors create a need for renewing the faculty and to focus will be to attract top talent and give them a platform to build new activities that can benefit the division in the long-run. Equal opportunity and diversity are natural aspects in the recruitment strategy.

CST: As can be deduced from the current faculty situation in the division, we recognize an urgent need to increase the number of assistant professors and post-docs. It is particularly important for the development of the division to strengthen the competence in the field of Data Science, Computational Science and High-Performance Computing. Our recruitment strategy is multifarious and largely dependent on the type of a position. In the recent past we succeeded in recruiting an associate professor in Neurocomputing Systems as part of a strategic initiative at the school level. To that end, we actively searched and encouraged suitable candidates, females and males, to submit their applications. We intend to continue to promote our division and its diverse research environment through rich networks of academic collaborators with the aim of attracting promising candidates. It is particularly felt that this approach holds the potential for drawing attention of prospective female faculty candidates. Regarding calls at the school level with a broad profile, such as “Computer science”, one of the key challenges for the division, as one of the more interdisciplinary units in the school, is to holistically enhance our visibility to be able to attract potential applicants. Furthermore, given the new policy for faculty employment adopted at the school level, we need to ensure that there are clear teaching needs that a prospective candidate would be able to address. We work on this by steadily increasing our involvement in education, particularly in fast growing domains relevant to our broad research profile such as high-performance and exa-scale computing, data visualization, statistical physics and open quantum systems, computational brain science, computational biology and bio-image processing, as well as large-scale fluid dynamics simulations.

From an economic perspective we recognize the difficulty of securing suitable funding (e.g., faculty funding) that allows for long-term commitment of the division to new faculty members. To this end, one of the priorities and key challenges in this regard is to obtain support from Rektor for strategic hiring in the aforementioned domains. With respect to the recruitment of doctoral students and postdoctoral researchers, the main platform for attracting candidates are open advertisements at suitable webpages governed by the central KTH administration as well as dedicated global-scale channels such as scientific organization career pages and mailing lists. A number of the current doctoral students have also been recruited with the support of our individual networks of national and international collaborators.

Equal opportunities in the employment process are safeguarded by the university policy, particularly at the level of faculty recruitment. There are no clear instruments however to enforce equal opportunities in the recruitment of non-faculty members of academic staff. However, at the school and KTH level, workshops for faculty on recruitment, equal opportunities and norm-critical thinking have been given.

NSE: The recruitment strategies regarding faculty aim at promoting excellent international research quality and very high teaching quality, by attracting first and foremost young talents. However, the division suffers from the common problem of the School that faculty members lack basic funding and thus talented young researchers may choose other international academic environments.

The recruitment of post-docs and researchers usually follows the acceptance of research projects and is based on the needs that the project demands. However, the top-quality candidates, as evidenced by their CV and university transcripts, is the primary criterion for recruitment. Although the recruitment of doctoral students follows the acceptance of research projects, many faculty members do not attach a doctoral student to a specific project, thus allowing much intellectual freedom in their research. This is one of the reasons for the world-class research that they contribute to maintain. The division exhibits an excellent balance between national and international doctoral students. Moreover, the academic culture of the division positively favors the recruitment of female doctoral students with excellent CVs.

SCS tries to recruit faculty on all levels based on an organic growth of the already strong research areas and an attempt to retain the historically strong commitment to KTH education on all levels. Using support from different sources inside and outside KTH the division tries to create a stimulating environment for internationally oriented young faculty with an interest in contributing significantly also to the Swedish speaking student population who are needed for supplying the surrounding industry with competitive engineers. In the coming five years the division needs to replace five full professors and three to four associate professors as well as two to three lecturers. In order to accomplish that goal, an aggressive recruitment strategy for positions on all levels as well as promotion of the strongest younger faculty and assistant faculty will be needed. Looking ahead ten years, another similarly sized group of faculty members will need to be replaced. An effort to integrate the faculty better with the faculty of the other four divisions in the newly formed CS department and also with faculty with similar or complementary interests and competences from all other departments of the school is crucial as well as securing strong external funding as a base of the research of this division. Recruiting also faculty that primarily teach will be necessary in order to support especially the basic level of education. This can be achieved with attractive positions as a lecturer. A strategy is to endorse cooperation rather than competition inside KTH in order to be competitive with respect to the outside world. Postdocs and doctoral students as well as research engineers will be recruited on temporary contracts to further strengthen the impact of the division's research and education. The gender balance aspects must be addressed by a combination of attempting to attract good candidates to our positions and considering expanding in a direction where it can be expected that the gender bias towards men will be reduced or even broken. A synchronization of the opening of positions with international seasonal variations in recruitment will be strived for. By announcing several positions at once we hope to achieve better visibility, and by attracting stronger support from KTH, SSF, various private funding agencies such as Wallenberg, we hope to create the basis to attract and retain strong faculty in the future.

TCS: The recruited faculty at TCS during 2012-2019 is very international. The division has benefited from two high profile WASP Professor appointments (Gionis - Finland and Monperrus - France) with generously endowed positions funded by the Wallenberg Foundation. These Professors have quickly established large productive research groups, with mainly international hiring. Only a few internal candidates have been recruited, (excluding the category of adjunct professors). The reason is that we have announced the positions broadly and actively approached potential candidates. Theoretical computer science is a male-dominated area, but we have managed to recruit three women (Sonja Buchegger, Elena Troubitsyna and Sumithra Velupillai).

Since TCS is responsible for a large number of first and second cycle courses, we have a significant need for teachers, not matching KTH's predominantly static and history-driven faculty funding distribution

model. As a result, three pure teaching track lecturers (Lecturer) have been recruited during the period (two starting in 2020). These lecturers have a Ph.D., but do not bring in faculty funding for research.

Doctoral positions have been advertised through the KTH channels. In addition, many researchers use community websites and portals to advertise. Typically, a doctoral advertisement attracts a high number of applicants (e.g., 80-100 applicants per position), which seems to reflect the attractive nature of the positions internationally. Judging non-Swedish academic qualifications, and shortlisting from a large number of applicants have been seen as challenging tasks that currently lack KTH or School guidelines and support. Gender equality is safeguarded by the requirement for mandatory candidates of both genders in the shortlist for interviews.

Infrastructure and facilities

COS operates a teaching and research laboratory related to the design of radio transceivers, wireless communication links, software defined radios (SDRs), and network systems, the "COS RF Labs". These are used in research projects and for lab exercises in courses for the engineering students. The facilities have been developed over several decades and the latest addition is the development of an SDR research lab. The lab facilities have mainly been enabled by:

- A large donation of general RF instruments from Telia (including mm wave equipment);
- a complete RF electronics lab moved to COS by Prof. Håkan Olsson (from a previous research center);
- own recent investments of an SDR lab sourced by Wireless@KTH.

The COS RF labs enable RF measurements, IoT and sensor design, construction of demonstrators, low-energy investigations, network design (protocols, operating systems, cloud services, etc.) and IRL SDR designs. RF equipment has also been made available to other parts of KTH, such as the mmWave test setup used by the DSP group at IS (15Gig for 5G) and a set of units delivered to Mentorspace in Electrum. The labs have network infrastructure with dedicated fiber links to the Internet, where COS is operating its own Autonomous System (AS 8973). Furthermore, through the deployment of 6LoWPAN border routers, the labs provide IoT infrastructure in the premises. The COS RF labs are situated in three places in COS offices, room 2432, room 4476 and room 4481. The latter is available for education, such as student projects and exam thesis studies, and there is also a dedicated fiber link to the student lab facilities in room 203.

CST operates the Visualization studio, VIC, a facility used across KTH for advanced visualization purposes in research as well as undergraduate education. The studio is a research environment with technology for visualization and interaction where students, researchers and industry meet. The technology in the studio includes among other things: interfaces for movement and gesture control, eye-tracking and gaze tracking, haptics and stereoscopic viewing systems (passive, active, as well as auto-stereoscopic). It also has computational capabilities for advanced graphics rendering, including a direct connection to the Center for High Performance Computing (PDC).

CST operates a research and teaching laboratory for the design and implementation of neuro-computing systems. Examples of developed neuro-computing systems include indoor autonomous mobile robots, neuro-prosthetic interfaces, and low-latency and low-power spiking computing modules for wearables. The laboratory includes an open-space robotic area with motion capture setup.

The FEniCS Project is a computing platform for solving partial differential equations which is developed and maintained as a freely available, open-source project by a global community of scientists and software developers, with CST faculty at key positions. FEniCS is selected as one of the six reference codes in the EXCELLERAT European Center of Excellence.

The department also collaborates closely with two national infrastructures, the Science for Life Laboratory (www.scilifelab.se), Sweden's main center for high-throughput biology and the PDC Center for High Performance Computing (HPC)[2], the leading HPC center in Sweden.

The Director of PDC is Professor Dirk Pleiter, also a member of faculty at CST, who will oversee the introduction of the new HPE Cray EX supercomputer at PDC.

Thanks to an infrastructure grant from SciLifeLab/KTH, researchers at CST have installed a state-of-the-art system for deep learning, the DGX-1 at SciLifeLab. The DGX-1 offers 1 petaFLOP of compute power through 8X Tesla V100 graphical processing units (GPUs) and dual 20-core Intel Xeon E5-2698 v4 2.2 GHz CPUs. The DGX-1 has been installed in the Alpha-6 server room and is available to SciLifeLab researchers.

NSE: The division has a modest research infrastructure, which is perceived to be a constraint for systems research. At the same time, the division has access to larger infrastructure and research facilities present at KTH and offered by collaborating institutions (e.g., RISE and FOI) or industry partners (e.g., Ericsson or ABB). To build and operate large research facilities and infrastructures, significant long-term investments would be needed, which are difficult to obtain, since the Swedish academic system favors relatively short-term projects (2-5) years which need to show high research productivity, whereas experimental research often has associated heavy coordination and maintenance efforts that reduce the research output. To make an infrastructure internationally competitive, a strategy could be to join efforts with other divisions of the school/KTH. Good examples are the research areas of intelligent transport systems (KTH ITRL lab), and smart buildings (KTH Live-in lab).

SCS: The current existing infrastructure is used mainly for data-intensive computing. In this respect SCS cooperates with RISE SICS to use their data center facility ICE at Luleå. The research group of distributed systems in cooperation with a spin-off, LogicalClocks, operates Hopsworks on ICE for data-intensive research and education, where it is used for Master's courses on scalable analytics and machine learning. Several research projects use cloud services (Amazon and Google) for specific research projects. The division has also initiated the procurement of a GPU cluster to be installed at PDC. Additional capabilities include a static automotive testbed, experimentation with GNSS security, mobile security, and credential management servers.

Hopsworks was developed by the distributed systems research group, which led to the spin-off LogicalClocks (CEO Jim Dowling). Hopsworks is a multi-user open-source platform for designing and operating end-to-end machine learning (ML) pipelines at scale. Hopsworks supports popular open-source frameworks for data engineering and data science, including ScikitLearn, Spark, Beam/Flink, TensorFlow, PyTorch. Hopsworks makes it easier for Data Scientists to write production-ready code, by supporting a Feature Store to ensure data quality and clean training data for ML models, and also by making Jupyter notebooks first-class citizens on the platform. Notebooks can be used to write production code that is run directly in ML pipelines. Airflow can be used to orchestrate and operate the different stages in ML pipelines, while Hopsworks also provides support for HopsFS, the world's most scalable HDFS-compatible filesystem, with unique support for small files and high throughput.

TCS: By the nature of our field, TCS infrastructure needs are lower than for some other EECS fields (e.g., robotics, vision). Therefore, basic infrastructure needs become more important. Adequate office space with low occupancy rates, communal discussion spaces (preferably with whiteboards), effective basic IT infrastructure including support and access to quality online digital tools are shared basic needs. In recent years, KTH and Swedish supercomputing resources are being used (e.g., EECS-PDC and Swedish National Infrastructure for Computing (SNIC)). Commercial cloud solutions such as Google Cloud or Microsoft's Azure are also becoming more used (at cost to researchers). For TCS Data

Science, there is an increasing and as yet unmet need for adequate GPU computing facilities and data storage. This need will probably grow rapidly in the next few years.

During the assessment period, TCS has moved from a local IT-support to a centralized IT-support. This change negatively affected the quality of service (QoS) during the assessment period (e.g., e-mail). However, currently many TCS staff are happy with the level of IT-support. Support requests usually get fixed within a day. Still, management of some tools and platforms (e.g., KTH-Ubuntu) is not transparent, and the quality of many KTH web-based administrative tools is poor and difficult to influence. IT Service Level Agreements (SLAs) need to be clearer and adhered to centrally.

At present, TCS has very little flexibility when it comes to desks/rooms. By March 2020 TCS accommodation will already become overcrowded. When it comes to longer-term accommodation needs, it is not easy to estimate more than 2 years ahead. However, we expect the TCS division to continue to grow, especially in terms of temporary research staff and students.

4. Strategies and organization

Goals for development 5–10 years ahead

Vision: In 5-10 years, CSD is the premiere research, education and innovation environment in the area of CS in Sweden, and one of the leading environments in Europe.

COS: The COS division is restructuring in 2021 with renewed focus on wireless communications and the underlying fixed infrastructure. In this process, several key faculty members are moving to other divisions and among the remaining faculty, at least three members are retiring within the next 5 years. Hence, looking 5-10 years ahead, a key goal is to recruit and then support new faculty members in building new successful research careers at the COS division. The plan is to recruit an experienced professor that can lead the division in the short-term and several young assistant or associate professors that can develop over the next five years and then take leading roles by securing major research grants from Swedish and European funding agencies, as well as graduating doctoral students that support the industry. The fact that two younger faculty at the COS division have recently received SSF Future Research Leader grants and Wallenberg Academy Fellow appointments demonstrate that there are opportunities for COS to acquire further major grants in the future. Since the research activities at COS are highly reliant on external funding, the division must develop a strategy to sustain the ability to obtain such funding. COS is also a leader and participant in several consortia behind major EU funded projects, which have a track-record of renewing their funding. The division must continue taking a leading role in such projects to ensure further renewal and participation.

The COS division created the Wireless@KTH center, which was a leading voice and meeting place for the telecommunication industry in Sweden for several decades. These activities have been slumbering in recent years, but the goal for next 5-10 years is to renew this center, on its own or as an integral part of the KTH Digital Futures center, and re-establish KTH as a leading research institution in developing theory and applications for the 6G wireless technology. 6G is expected to be standardized and released towards the end of this decade, which is well aligned with this development plan. KTH has a long reputation in the wireless area but must continue making excellent research, also after new faculty members have been recruited. This can be achieved through careful recruitment and active mentoring of new faculty members, as well as deeper collaboration with other KTH divisions that have expertise in the wireless area. The funding situation is bright since telecommunication continues to be a prioritized research area by Swedish government, as a key enabler of a digitalization of society, but it calls for more multidisciplinary research where the connection between technology and application is strong from the outset. The goals of the COS division can be achieved by continuing and renewing the collaboration with the Swedish industry, dissemination of research through publications in top-level journals,

increased visibility via videos and social media activity, and international collaborations and exchanges with other top institutions.

CST: We research fundamental and relevant questions in our specific fields. Our strategic goals are defined as follows:

We publish in journals and conferences of the highest standard in our fields. We are recognized leaders in our fields: researchers are highly visible and in high demand as experts, as participants in multidisciplinary research programs, as invited speakers, giving tutorials at international conferences, in program committees for conferences, editors and reviewers for scientific journals and grant applications as well as academic opponents for doctoral theses. Our impact on industry and society is strong and we are highly visible. Innovation plays an important role in our research output. Researchers and students start spin-offs on a regular basis, and entrepreneurship is held in high regard. The research environment is dynamic and attractive to visitors and doctoral students. Guest researchers and postdocs invigorate the research environment, create international bonds and form an important base for recruitment to faculty positions. We leverage and intensify transdisciplinary initiatives within CST: we have potential to build new subfields by cross-disciplinary collaborations (e.g., HPC for brain-like computing paradigm).

Means identified to reach the goals: The researchers, research groups and divisions are encouraged to not only participate in project phases, but to engage in research program design activities. This includes (but is not limited to) national and international research platforms, research agendas, and consultation activities. The aim is to volunteer our expertise to influence research programs during their design phases, not the least with respect to the EU programs. Identify top visiting senior researchers. Identify top-talent to recruit to our faculty. Develop strategies for alumni relations as well as life-long learning. Improve the visibility of our research output -not only in the form of publications, but also for research impact and innovations.

NSE: We plan to make significant contributions to and become a leading group in *data-driven analysis, design, and operation of networked systems* for critical infrastructures including telecommunication systems, energy distribution systems, water distribution systems, and transportation systems. The focus will be on enabling automation, reducing energy consumption, and achieving high reliability, security, and resilience. The efforts will be complemented by professional activities including organizing events and editorship in leading journals, e.g., IEEE Journal on Selected Areas in Communications (J-SAC) or the Proceedings of the IEEE. We plan to further expand the Data Science Micro Degree Program in 2020, a large-scale example of commissioned education in the EECS School and which is attracting researchers from leading companies worldwide, such as Ericsson, ABB-Hitachi, Scania, and SAAB. Furthermore, we aim to ensure that the research results are well formed for further innovation and exploitation for practical use.

In addition, the division aims to develop existing research and education in the field of cyber security. Activities in this field are boosted by the new Center for cyber defense and information security (CDIS), which is likely to expand significantly in the coming years. Research contributions are expected in the areas of cyber-attack simulation, AI cyber operations, secure IoT, self-learning systems, and game-theoretic approaches. The division will expand its contract teaching offering, in particular in the field of cyber defense that was commenced in the fall of 2020.

On the KTH and national level, NSE faculty will contribute to research centers including *CASTOR* and KTH *Digital Futures*, as well as to the WASP and WASP-AI doctoral programs. On the European stage, the focus will be on collaborative EU projects and ERC grants. Globally, NSE plans are to strengthen and possibly extend our collaborations with academic groups at MIT, Harvard, Princeton, UC Berkeley, UIUC, Korea Advanced Institute of Science & Technology (KAIST), and Hong Kong University of

Science and Technology (HKUST), as well as with industry partners, such as Cisco, IBM Research, ABB, Ericsson, and KDDI.

SCS: Goals related to main research areas at SCS division:

Distributed systems: Every day, tremendous amounts of data are generated through online services, social networks, and IoT devices. This massive data is distributed by nature and cannot be centrally controlled and managed. It is, thus, crucial to develop platforms, computation/programming models, and algorithms that enable distributed processing of data for highly scalable applications. In general, our aim is to develop computing capabilities for a highly distributed, reliable, secure, energy-efficient, and real-time end-to-end analytics of various data types (e.g., batch, streaming, and graph data), across different environments, such as edge devices and wireless networking infrastructure. To this end, we contribute on variety of distributed systems domains, including (i) data intensive computing platforms to shape the next-generation software for scalable, data-driven applications by binding state-of-the-art mechanisms in compiler and database technology together with hardware-accelerated machine learning and distributed stream processing, (ii) federated and distributed learning to develop new technologies on big data analytics on edge, data stream processing, and graph streaming, as well as distributed and decentralized privacy preserving data analytics algorithms, and (iii) automated building of end-to-end analytics systems to auto-configure distributed data-driven applications and enable automated code generation from high-level user specification (e.g., using a declarative language or domain specific language).

Data science: As systems employed in industry and society at large today frequently are depending on models developed using techniques and tools from the area of data science/machine learning, the emphasis on Fairness, Accountability, and Transparency (FAT) and explainable AI (XAI) has increased dramatically during the last few years. The research at SCS will contribute to these areas by developing techniques for explaining black-box predictions and for approximating strong, opaque, models with transparent ones. The research will further contribute to the area of accountability by developing techniques for uncertainty quantification, where point predictions are complemented with valid prediction regions and predictive distributions, to provide effective support for decision making. The research will also contribute to the area of fairness, for example, through techniques to guarantee the error levels for specific categories.

A significant threat to our societies and democracies today is the concentration of personal data in the hands of a small number of IT giants. They thrive by providing the users with “free” centralized AI-based services, by consolidating and monetizing private data and effectively establishing “digital dictatorships”. The main challenge for disrupting this trend will be focused around developing new technologies for decentralized and distributed ML and data analytics, assuring that high-quality AI services can be provided not only by current IT giants but also in a collaborative fashion. We expect major contributions from the research at SCS in the fields of decentralized information network analytics, federated learning and privacy preservation. In particular, we plan to develop new technologies for decentralized learning on decentralized data that can offer the same functionality and user experience as mainstream services.

*Software Construction and Analysis***:** Correct and efficient design and implementation of software systems are crucial in today’s society. The number of software engineers in Sweden has increased significantly over the past decades. As a consequence, there is a strong need for enhanced software and system development tools, as well as improved development processes, to meet future needs of reliable and efficient software systems. Within the SCS division, the model-based computing system group focuses on the development of new domain-specific modelling languages and tools, targeting cyber-physical systems (for domains such as autonomous vehicles and digitalized industry), as well as probabilistic languages for biological systems (especially targeting phylogenetics and public health

systems). The goal is to be world-leading in the area of languages and tools for domain-specific languages, with the focus on (i) languages for probabilistic and equation-based reasoning using so called differentiable probabilistic programs, and (ii) to offer open-source compiler environments that have state-of-the-art performance. Furthermore, the aim is to develop tools of production quality, which can be used directly by the industry and other scientists.

Networking: A major aim is developing ultra-low latency Internet services. This is a logical continuation of a large SSF grant and is the focus of an ERC Consolidator Grant in the division. As witnessed in the COVID-19 pandemic, it is crucial for Internet services to be able to quickly scale up tenfold or more, while maintaining excellent efficiency levels that keep energy consumption under control. All this has to be done while maintaining tight bounds on the latency of packet processing within mobile networks, data centers, and geo-distributed storage systems.

Networked Systems Security: A major goal is to develop building blocks for a trustworthy, secure and privacy preserving, and the Internet of Things. One KAW Academy Fellowship and its continuation, one SSF Framework and one VR grant, and involvement in SecurityLink (steering committee), and other projects address this challenge. Security and privacy are fundamental towards acceptance and deployment of emerging IoT technologies. Even more so in a post-COVID-19 environment that necessitates rich data collection, reliably without erosion of privacy. A gamut of our systems already addresses this multifaceted challenge. Trustworthy IoT technologies can be pivotal for broad gamut of interdisciplinary initiatives.

TCS: During the reporting period TCS has expanded to cover a much larger range of core CS topics in much greater depth, in areas like software construction, security, and data science. For the coming 5-10-year period our main objective is to consolidate progress through strategic recruitments, and to open up for expansion into neighboring core CS areas such as: operating systems, computer architecture, parallel and distributed computing, dependable systems, quantum computing. Following on from our recent integration in the EECS Computer Science Department, TCS will strive for further cross-divisional research collaboration and synergies within CS. However, many divisional goals represent personal or group goals which are described below.

In *algorithms*, the ongoing trend of discoveries of improved algorithms for classic graph problems (like Connectivity and Shortest Paths) will continue over the next 5 years, and new techniques will be invented that let us better understand these fundamental problems. Within 10 years, entirely new paradigms for designing and analyzing graph algorithms will be discovered, completely changing the way we think about these problems. TCS is at the forefront of this ongoing trend and will make key contributions.

In *complexity theory*, our understanding of the powerful “Sum-of-Squares” algorithm (with connections to diverse fields such as convex optimization, machine learning, and proof complexity) will improve. Within the next 5-10 years we will obtain a much clearer picture of the powers and limitations of this algorithm. Furthermore, using this knowledge, we will be able to shed some light on the mathematical foundations and limitations of machine learning, for instance when and why the classic “method of moments” works.

In *quantum algorithms and cryptography*, within 5-10 years we will be able to run error-correcting programs on small quantum computers, paving the way in the longer term for actual quantum computers able to solve cryptographically relevant problem instances. TCS will continue its work on efficient quantum algorithms for factoring and related problems, including investigating possible weaknesses in the newly proposed potentially quantum-secure cryptographic protocols.

Strong and provable security: The security research community, including at KTH, is currently experiencing a markedly increased demand for strong security solutions from government, industry, defense, and civil services, in areas like privacy, verified execution platforms, secure supply chains, web and IoT security, e-voting, critical infrastructure, and others. As the major tech companies, HW vendors, and open-source initiatives like RISC-V are beginning to take security verification more seriously we are likely to see a larger scope for integrated kernel- and network-type verification. In the longer perspective we will see better support in tooling and technologies for application security and privacy, mainly driven by the needs of society for trustworthy, secure, and privacy-enhanced technologies. Rigorously verified end-to-end secure systems will be developed for critical applications, and for large scale applications we are likely to see an increased use of principled security solutions in emerging technologies as well as in security and privacy critical applications like web browsers.

Privacy-enhanced technologies: Privacy-preserving communications, learning, and sharing of data can lead to a plethora of new insights and possibilities without endangering individuals. Health records could be shared for medical research, remote health monitoring or ambient assisted living could be trusted. Vulnerable populations, such as political activists, could communicate while being protected from surveillance. Supported by increasing awareness of privacy, also thanks to recent legislation such as the EU General Data Protection Regulation (GDPR), it is to be expected that privacy-enhancing technologies see wider adoption.

Intelligence and security informatics: In the near to medium term, we are likely to see research results in this area increasingly inform working procedures and procurement of new technical systems. Work in this direction may improve security engineering and operations with badly needed well-founded measures and metrics to be used for evaluation and development of new systems and procedures within the field of intelligence and security informatics.

Computer Security: Within the provable security domain we will develop new theories, tools, and tool frameworks that will allow us to better scale and automate code and proof generation, for instance through increased use of automated, synthesis-oriented methods. We will also further develop our experimental work designed for information flow aware compliance testing, continue the development of tools and deploy them in a wider variety of contexts to better automate the search for vulnerabilities. We will demonstrate our platforms on key applications, for instance e-voting and critical networks.

In terms of *computer science education*, we see the field increasingly leveraging advanced technologies like AI and data science to progress towards evidence-based, data-driven learning that adapts to learner needs, abilities and expectations. Based on the progress mentioned above, it is probable that we in 10 years have to find ways to move beyond traditional university-based education models towards higher goals of sustainable education for all varieties of people in all stages of their lives. Learning technology will play a vital role in this mission, and computer science education will continue to be a key innovator in this effort. Our research aims to move forward our understanding of what is possible in terms of data-driven learning, developing tools and technologies that increase educational opportunities and abilities, whilst ensuring an empirical and evidence-based approach. Important is also the spreading of so-called Scholarship of Teaching and Learning (SoTL), where teachers undertake systematic inquiry about student learning and disseminate the results. In 5-10 years, we hope that most teachers of the division are applying SoTL.

Data science: We anticipate that the adoption of AI, machine learning, and data science in our society will bring into the spotlight new needs and new requirements, and important new areas will emerge, bringing the human into the picture and considering societal impact. Examples include polarization and misinformation in social media, as well as interpretability and fairness in machine learning. The academic field of developing machine-learning technologies for software engineering is still in its infancy. We expect some major contributions to safety and security analysis. Our goal is to contribute

with fundamental research to solving large-scale software-engineering problems with machine learning.

In the field of language technology, we expect significant progress in developing methods that can be used to accommodate aspects of content that have less to do with factual topical features and more to do with mood, tenor, stance, and other less conventional dimensions. We will contribute in this research direction by studying how human information processing makes use of contextual and non-conventional factors to interpret content of information items. With respect to research in clinical NLP, we expect to see progress in incorporating new learning-learning techniques and addressing the issues of generalization and reproducibility in current state-of-the-art.

Software Construction and Analysis: Experimental software engineering will continue to revolutionize the way software is being built and maintained. Major scientific breakthroughs will be made as well as disruptive start-up technologies. In 10 years, because of the massive presence of automated bots, much research effort will be spent to coordinate human and bot contributions. Commercial uptake of ML technologies for software engineering will be well established. Scalable and easy to use ML-based tools will be available.

In programming language systems, a key breakthrough will be the development of programming models for large-scale distributed programming that enable compositional development with static reliability guarantees including liveness and fault-tolerance. In embedded software and systems, a main research challenge is to achieve safety and trustworthiness of autonomous systems. This requires development of: (1) scalable rigorous techniques for verification of complex systems based on safety-critical AI-based components; and (2) powerful security-protection mechanisms for networked safety-critical systems. Main breakthroughs are expected in the use of data-driven and AI based approaches for scalable verification.

Congruence with university-level goals for “A leading KTH” as set out in KTH’s “Development Plan 2018-23” (page 5)

CSD follows the general KTH recommendation to publish under Open Access. The CSD research engages with the following parts of the *KTH development plan*:

A leading KTH

- CST: we recruited faculty with high international visibility in the reporting period such as Prof. Weinkauf in Visualization, Assist. Prof Conradt in Neurocomputing, and Professor Dirk Pleiter in high performance computing. In terms of education and striving for a more digitalized world, we provided one of the first MOOCs of KTH in the reporting period and are actively seeking out new technologies to enhance our teaching.
- CST: our researchers are part of the Human Brain Project and many other international collaboration projects.
- COS: the division will retake the leading role in wireless communications that it previously had through recruitment of top-talent faculty members, to replace retiring faculty members, and mentoring of young faculty members. Telecommunications remain one of the few industries where Sweden has a leading role in the world and COS has a key role in supporting them through joint research and educating doctoral students.
- NSE: our track record and plans regarding international collaboration, high visibility in terms of research achievements and professional service, and our commitment to faculty and student exchanges. We also serve society regarding cyber defense and information security competence.
- SCS: the division will continue to be a highly international unit, by attracting researchers and students from all parts of the world, and by continuing the international research collaborations, e.g., in joint research projects and software development efforts.

- TCS has recruited two new Professors with high international visibility (Gionis and Monperrus) and strong bibliometric profiles.

A visible KTH

- CST & HCT: Visualization Studio VIC is our premier platform for interacting with industry and society: Hundreds of guests per year take the opportunity to see and interact with research results from our and other EECS divisions.
- COS: The division was early with using social media to promote its activities. It has recently started a bi-weekly podcast called "Wireless Future" and will continue to grow its social media presence to be visible towards both fellow researchers and the general public. Dissemination of research through videos for different target audiences (latest research as well as popular science).
- TCS holds many projects and contributes many researchers in software construction and analysis, and computer security and analysis to the CASTOR and CDIS centers.
- CDIS has received attention in Sweden for the close collaboration of KTH with the Swedish armed forces both in terms of research and commissioned education in cyber security.

An open KTH

- COS: the division has a long track-record of collaboration with industry and providing support to government agencies, for example, when it comes to frequency spectrum allocation. Most of the Master students that are studying communications are writing their theses in collaboration with the industry. The division plans to take a leading role in the open science direction, particularly, focus on open publishing and reproducibility of research through sharing of simulation code.
- CST: reaches out to many actors in the private and public sectors of the Swedish society. We were awarded the annual EECS award in 2020 for our ability to create impact in society by letting the students solve real problems in projects provided by Swedish organizations. With numerous successful projects reported in Swedish news, it has also drawn positive attention to the educational activities of EECS.
- NSE: we have extensive collaboration with industry and government agencies.
- TCS: apart from the centers, we have also developed other forms of collaboration including joint industry/academia positions and affiliate staff
- TCS: has made big strides during the reporting period, by incorporating new research areas, reorganizing the Master's degree programs including the introduction of new topics and courses with tight connections to the TCS research areas, and involving senior level students in research projects to a larger extent.
- TCS: research spans a far wider range from fundamental theory to practice, in areas such as security and software engineering, and over the coming period also in data science area with the recent recruitment of Gionis.

A KTH for a more digitalized world

- COS: the division has an active role in the KTH center Digital Futures, which focuses on digitalization. The visiting professor Emil Björnson is supported by this center and many of the current and planned research activities are well aligned with the goal of connecting the society and thereby enabling the internet of things and its applications.
- CST: we provided one of the first MOOCs of KTH in the reporting period and are actively seeking out new technologies to enhance our teaching.
- CST: we provide infrastructure for digitalized research collaboration and teaching through the Visualization Studio VIC.

- NSE: the division has an active role in the KTH center Digital Futures, which focuses on digitalization leading two out of seven work groups. NSE faculty Joakim Lilliesköld also leads the digitalization of education at KTH as well as leading the digitalization response due to covid.
- SCS: the main research areas at SCS, distributed systems, data science, software construction and analysis, networking, and security and privacy, all are at the center of digitalization, providing new techniques and tools to support the handling of large-scale, continuously growing data, means to optimize decision-making in organizations and society at large by learning from the data, and making it easier and less-costly to develop correct, fault-tolerant software needed for the digitalization.
- TCS: progress has been made through the creation of the CASTOR and CDIS centers.

A KTH for a more sustainable world

- COS: the previous, current and planned research activities have focused on development of energy- and cost-efficient wireless infrastructure. The activities span the planning of the networks as well as the operation. The experiences from this research are taught to the Master and doctoral students, through textbooks that have been developed locally.
- CSC: of increasing importance is the need for systems that not only maximize throughput and minimize delay, but also take energy efficiency into account, something which is highly related to sustainability. Related to this are also the many important application areas of data-driven approaches to support sustainability, e.g., in climate research.
- CST: researches new algorithms to make computations less energy-consuming and more insightful through research in high-performance computing, brain-like computing as well as visualization and data analysis.
- CST: research simulation methods for virtual prototyping of renewable energy technology
- NSE: our focus is on critical societal infrastructure.
- TCS: considerable progress through the development of new research areas: secure execution platforms, data science and AI, autonomous systems.

An equal opportunity KTH

- COS: The division is working actively to provide equal opportunity to open positions, by ensuring that candidates from underrepresented groups are interviewed at the same or higher level than other candidates. The division has been successful in the recruitment of younger faculty members, with gender balance among those below 45 years old. The more senior faculty is gender imbalanced for historical reasons, but the upcoming retirement of three faculty members will give the opportunity to resolve this situation.
- SCS: This is of high relevance for the division, as significant efforts are needed to obtain a gender balance that better reflects the society at large. This involves ensuring that the research culture is inclusive, in all possible aspects, and that specific efforts are taken to attract female researchers and doctoral students.
- TCS: Professor Viggo Kann was awarded the KTH Rector's Prize for Equality and Diversity in 2020 for introducing these issues into the CS curriculum in an innovative way. The gender balance among staff is an area for future improvement.

Leadership structure and collegial structure

Each division is led by a division head and a vice head. All divisions have a structure consisting of a leadership group comprising the head and deputy head of Division, some (or all of the) professors, and other representatives of the faculty, including doctoral students.

CSD has a director of studies and a director of graduate studies. All divisions have monthly staff meetings and regular faculty meetings. Many divisions make use of video-conferencing tools to make it

easier to participate in the meetings. The doctoral students meet regularly. Most divisions have a regular seminar series where research topics are discussed.

Strategies for high quality

All the divisions have similar quality assurance processes for:

Doctoral students

- Progress is monitored through the Individual Study Plan (eISP).
- All students are required to hold a seminar at 30, 50 and 80% level.
- There is typically a yearly mentor meeting where all students get to see another supervisor than their own.
- All students have at least two, often three supervisors.
- Courses given to doctoral students are evaluated in course evaluations upon which a course analysis is written.
- Each division has a dedicated head of doctoral studies.
- Before sending the thesis for printing, a senior researcher at the division will make an "internal" review of the text.
- At the defense, external experts, often recruited internationally serve on the thesis committee alongside an opponent that leads the defense, asks questions and put a perspective to the research done (but the opponent does not get to vote).
- The quality of the research by the doctoral student is in the normal case also assured by having substantial parts of the work published in peer-reviewed publications prior to the doctoral defense, although this is not a formal requirement.

Research quality

- All the division aim for high quality international conferences and journals, with peer review – often in conference proceedings.
- All publish their papers with open access in OA journals or in the Swedish DiVA database.
- Some divisions practice internal peer review of papers before they are sent, or engaging in writing camps or writing workshops where researchers reads and comments on one-another's drafts
- All the divisions have some form of internal seminar series with internal as well as invited speakers
- Quality is privileged compared to quantity: the publication of few articles of high quality per year is strongly encouraged, whereby the content of the articles is elaborated over longer periods and cultivated to avoid marginal or incremental contributions.
- Collaboration with national and international highly competent researchers is encouraged for what concerns the most forefront topics or high-risk research.

Faculty development

- Promotion to associate professor is seen as the target for all assistant professors and they are coached in this process.
- Promotion to "docent" is encouraged for all full-time faculty.
- Promotions function as reviews and quality assurances of individual researchers, a process which involves both a faculty committee and external experts.
- The promotion to full professor is endorsed by the EECS school only for candidates that effectively drive their own independent research agenda, in a new sufficiently distinct area from the "parent group". The candidates should also have taken an active part in management, development and/or operation of education in the first cycle, second cycle and third cycle. This policy is a recent revision

and here, we believe more could be done to make promotions better suited to our needs, to the needs of faculty to see a path towards independence.

Industrial & societal impact

- As industrial impact is a significant strength of many of our research groups, we should also establish a better way to assess research and innovation impact for future research assessments

In some divisions (CST) the internal funding is given proportionally to ability to pull in external funding. The COS division ensures that the internal funding is first used for co-financing of external projects and then shared between the faculty. In other divisions (HCT) the aim is that everyone should have a certain level of faculty funding as part of their position.

Since a large part of the research in all divisions relies on external funding, efforts are constantly required to stay competitive, in particular with respect to research quality, since this is often the most important criterion for attracting external funding.

At HCT, a senior researcher is supporting the division's PIs in writing grant proposals and in general organizing writing retreats, bringing in best practices for the improving quality of writing, which venues to publish in and similar. In terms of outcome the service seems to be effective as HCT has been endorsed with more external grants during the last couple of years.

5. Interaction between research and teaching at all three levels (BSc, MSc, PhD) of education

Interaction between research and teaching at all three levels (BSc, MSc, PhD) of education

In all divisions, the relationship between research and teaching is strong. Almost all faculty both teach and do research. In most divisions, the relationship is obviously strongest for 3rd cycle, doctoral-studies, and 2nd cycle, MSc-studies, and less for 1st cycle teaching where the subject areas often are well-established computer science topics. This said, Bachelor's and Master's, and (of course) doctoral students often explore research questions with the division's research area– sometimes at such a quality level that they get published in international conferences or journals.

There are several very popular Master's level courses (e.g., data science, distributed systems, hacking), as well as advanced courses (e.g., networked system security) that are project- and research-oriented and can lead to publications with undergraduates. Faculty and researchers serving as examiners and supervisors for numerous Master's theses yearly. Some theses result in publications and patents. Many theses are carried out in close collaboration with the industry

COS: 1st cycle courses – BSc-level: There is limited coupling between research and 1st cycle education. One area where there is coupling is in course projects where students come in contact with research papers and write their own papers; however, in practice only a small fraction actually introduce new ideas. Another coupling between research and courses at this level is the introduction of recent results into the current teaching (typically as examples).

2nd cycle courses – MSc-level: At the Master's level, there is coupling to research starting in the first term with a mandatory course in research methodology and scientific writing, – in which students carry out a small research assignment in a stepwise fashion during the course. Many courses include a research component or explicitly include studying and discussing recent research papers. Many courses are in areas where the involved faculty are doing research and, thus, can share their expertise when evaluating published works and their scientific importance. Several courses utilize the tools and equipment that are being used for research at the 3rd cycle. Finally, all students must complete a degree project course –which involves research and analysis. A large fraction of these is done together

with industry and research institutes, and many students are conducting research and development in the industry after graduation.

3rd cycle courses – Doctoral-level: A very large portion of doctoral education is coupled to research, both directly and indirectly (for example by using research results in courses). A new course on Multiple Antenna Communications is being developed to ensure that the new 5G physical-layer technology is well understood among students that graduate from the doctoral education.

CST: Thesis courses engaging in original research at all three levels (BSc, MSc, Doctoral). In thesis courses at the three levels, students engage in projects defined within CST's research interests. Moreover, in many of the thesis projects, students work on a task defined by an industrial or academic research collaborator. We thereby obtain vital information regarding computational needs of companies and research centers and potential contacts for further research collaborations. Specifically, the Embodied Social Agents Lab, based at CST and VIC, is a hub for connecting research and teaching involving virtual embodied agents, social/mobile robots and urban environments across all three education levels. This includes Bachelor theses (computer science and engineering physics programs) and Master's theses (computer science, human-computer interaction, interactive media technology programs), and at the doctoral level, funding from multiple European projects with stakeholders across academia and industry to support the training of early-stage researchers. ANIMATAS (3.89MEUR, 2018-2021) is a European Horizon 2020 Marie-Curie network training 15 early-stage researchers on the theme of applying artificial systems to real-world pedagogical applications. CST members have central roles as training coordinators and trainees respectively within the network. CST also has an important role in CLIPE (4.2MEUR, 2020-2024), an upcoming Marie-Curie project training a network of a further 15 international doctoral students on the topic of naturalistic, highly interactive virtual characters. CST supports one of eight nodes in CONTRA (Computational Oncology Training Alliance) which is an EU funded Innovative Training Network consisting of KTH and 7 other major European universities as well as partners from pharmaceutical, biotech-start up, and software development companies.

More generally, DD142x, the first-cycle degree project in computer science, engages first-cycle students, supervisors, and examiners at CST as well as other divisions in the Department of Computer Science in original research processes. Selected theses become peer-reviewed publications. Similarly, the second-level degree project courses DA232X through DA258x engage Master's degree students in original research endeavors. Examples of accepted peer reviewed publications from these courses include work towards handling occlusion in mobile outdoors augmented reality, work in collaboration with the Nobel Museum of Stockholm, and interactive ambient visualizations for crowd engagement.

A number of courses introduce current research topics into the projects and lecture material. For example, in the second-cycle course DA2210, Theory of science, the background of teachers as scientists is vital for the discussions during lectures. For the past year the first-cycle course DD1393, Software Engineering, has been employing learning techniques applied in a research project called "Software development academy (SDA)", working with challenge-driven education in an agile framework and self-learning techniques. Outcomes of the research project are in progress for publication. The second cycle DH2321, Information Visualization, has introduced students to interactive virtual reality delivery of lecture content where a team of instructors drive a simulation and 4D visualization of the airflow in hospital operating rooms to analyze the paths of airborne bacteria. This work is the result of the ongoing research project VisBac funded by FORMAS. Similarly, the research project BioViz visualizing simulated neural networks was introduced and advanced through the work of students in DT2140, Multimodal Interaction and Interfaces.

A number of initiatives involve the application of computer graphics and game technologies to supporting the teaching of science, technology, engineering, art and applied mathematics (STEAM)

subjects at the Bachelor's and Master's levels. This includes 0,118 MSEK funding from School of Computer Science in 2013 for the development of the Models and Simulation first-cycle course DD1354, integrating computer graphics research as visualization support for teaching mathematical modelling methods. The course places a strong emphasis on engaging students in active learning of the research skills necessary to specify problems in mathematics in addition to pursuing solutions.

As research on physics-based simulation models and data driven models are merging as a consequence of the surge in computing power and access to data, this needs to be reflected in basic education. The second-cycle DD2363 Methods in Scientific Computing is designed to address these needs and it is a mandatory course within the Scientific Computing track of the Computer Science Master's degree program (CSSC). Similar courses created to address neural networks and machine learning research are the second level courses DD2437, Artificial Neural Networks and Deep Architectures, and its predecessor DD2432, Artificial Neural Networks and Other Learning Systems as well as DD2434, Advanced Machine Learning. The second-level DA2205 course on research methods is mandatory for all doctoral students. Other courses created to address current research interests are DA2210, Introduction to the Philosophy of Science and Research Methodology for Computer Scientists, and DD2423, Image Analysis and Computer Vision. Finally, project-based courses afford the flexibility in learning objectives to encourage the exploration of current research themes. These courses include DH2321, Information Visualization, DH2413, Advanced Graphics and Interaction, DD2402, Advanced Individual Course in Computational Biology, DD2430, Project Course in Data Science, DD2470 Advanced Topics in Visualization and Computer Graphics. These courses range in level between second and third cycles, based on the individual student's interests.

Third-cycle courses dedicated to education through research include: *FDD3434 Advanced Course in Machine Learning, FDD3336 Interactive Entertainment Technologies, FDD3401 Neuroscience, FDD3437 Artificial Neural Networks and deep Architectures, FDD3451 Individual Course in Computational Biology*, and *FDD3435 Graduate Course in Mathematical Modelling of Biological systems*.

Engaging courses in original pedagogical research peer-reviewed and published CST course instructors have led published research in computer graphics education active learning methods based on the pedagogical investigations in *DH2413 Advanced Graphics and Interaction* and in *DH2321 Information Visualization*. Master's theses have also explored the role of interactive and immersive graphics and gamification in the advancement of active learning. Completing the loop between research and teaching, the ProsocialLearn (4.2MEUR, 2015-2018) and ANIMATAS projects are directly concerned with the research and development of pedagogical ICT platforms to support teaching.

NSE: 1st cycle courses – BSc-level: In 2017 a new Bachelor's thesis course was established, which has received considerable attention in terms of students from several programs at the university. The course is conceived as small research projects (15 credits), which for our division are directly inspired by ongoing research by the faculty. Each year, the projects are published in a form inspired by conference proceedings, see here for 2020.

2nd cycle courses – MSc-level: The Master's thesis projects that we propose are directly connected to ongoing research projects, for instance in the cyber-security or in the cyber-physical systems areas. In addition, the thesis projects that are given by external parties need to follow a scientific methodology and are both supervised and examined by our faculty.

The courses we provide on the MSc level are typically connected to the research expertise of the faculty, and address not only technical issues, but also general skills such as scientific writing and oral presentation. We regularly revise the course contents, as well as the course offerings according to the advances of research and development.

For example, the Master's-level project course *EP2420 Network analytics* gives students an introduction to data-driven engineering. They work with various sets of traces from our research testbed. Using methods from data mining and machine learning, the students process and analyze the data and study the effectiveness and overhead of various prediction and forecasting methods.

Two courses in security, namely *EP2790 security analysis of large-scale computer systems* and *EN2720 Ethical hacking*, are both having numerous guest lecturers from industry to inspire the students in their future careers and to give insight into how companies use the methods. These courses are also deeply rooted in the division's security research, letting the students practice methods that NSE is researching. These courses also have instances as doctoral level courses with additional activities that are yet more closely related to the research.

The course *EP2200 Queuing theory and teletraffic systems* focuses on theoretical tools of network design, and includes small projects that are inspired by our research in wireless networking as well as cloud and edge computing.

The *EP2950 Wireless networks* course is partially taught by an adjunct professor from Ericsson research and also includes literature study and poster presentation on recent advances in the wide area of wireless networking.

EH2720 Management of projects having many guest lecturers from industry to inspire the students in their future careers and to give insight into how companies use the methods. The course is also deeply connected to the division's management research, letting the students practice methods that we are researching.

3rd cycle courses – Doctoral-level: Research is directly coupled to teaching in all of our courses for doctoral candidates. We provide courses both on theoretic foundations and within emerging research areas, and most of the courses include projects that can be connected to the students' own research. Examples for the first category are *FEP3360 Algorithms for networks – Complexity and approximations* and *FEP3301 Computational game theory*, while for the second one *FEP3260 Fundamentals of machine learning over networks* and *FEP3370 Advanced ethical hacking*. Furthermore, the courses are attractive: an example is Machine Learning over Networks, which attracted over 100 doctoral students in its first edition in 2019 from all over KTH and other Swedish and international institutions.

The division is also deeply involved in two life-long learning or contract education graduate programs: one in the area of *Data Science* and one in the area of *Cyber Defense*. The programs are directly connected to the most recent research in their respective areas. The programs have received considerable industrial and institutional interest.

SCS: 1st cycle courses – BSc-level**:** Few courses at the bachelor level at SCS, e.g., within 3-year engineering programs, are directly connected to the research at the division. However, some courses at the master level are elective during the third year of the BSc programs. Moreover, the BSc theses are frequently related to the research at the division, e.g., in data science. 1st cycle education at SCS includes courses on object-oriented, functional and logic programming, database management, operating systems, and computer engineering including computer architecture. Some of the courses are given by faculty that mainly teach.

2nd cycle courses – MSc-level: The research activities of SCS have substantially contributed to the Master's level education within the areas of data science and machine learning. The research competence of SCS faculty has resulted in a number of newly developed Master's and doctoral courses in the areas of data science, machine learning and distributed systems. In particular, Master's level

courses in these areas include: “Data Mining, basic” (ID2211) and Data Mining (ID2222), “Programming for data science” (ID2214), “Data-intensive computing” (ID2221), “Scalable Machine Learning and Deep Learning” (ID2223). SCS created and coordinates the “Software Engineering of Distributed Systems” Master’s degree program. Since its start, at least 20 students from the program have moved on and have obtained a doctoral degree, in KTH or elsewhere.

EP2520 Building Networked Systems Security is an entirely team-project oriented course that exposes students to design and implementation of real-world, contemporary security solutions for wired and wireless networks. It provides equipment and access to its own infrastructure. *EP2510 Advanced Networked Systems Security (ANSS),* a ‘paper-chasing’ and research-oriented course, coaching undergraduate students to perform targeted research. Numerous students move on with MSc thesis. Most importantly, ANSS project work has repeatedly led to full-length conference papers, short conference papers and demos (notably, ACM WiSec’18 best demo award), and, on one occasion, to a journal publication.

SCS coordinates several research-related tracks within the EIT/KTH Master’s degree program ICT Innovation: “Cloud Computing and Services”, “Data Science” and “Autonomous Systems”. These tracks on a regular basis provide a substantial number of doctoral students to SCS and other divisions of KTH.

The key courses in all Master’s programs, which also are given within five-year civil engineering programs, are taught only by the faculty who are active researchers in the corresponding fields.

3rd cycle courses – Doctoral-level: Doctoral level courses at SCS often mirror Master’s level courses, but with more extensive examination requirements. Doctoral courses at SCS include “Systems for Scalable Machine Learning” (FID3024), “Programming for Data Science” (FID3214), “Advanced Course in Data Mining and Analytics” (FID3018), “Advanced course in Data-Intensive Computing” (FID3019), “Blockchain Fundamentals: Technology and Applications” (FID3022), “Advanced Course in Large Scale Machine Learning and Deep Learning” (FID3020), “Research Course in Distributed Systems” (FID3011), “Data Mining” (FID3016), “Stream Processing” (FID3017), “Advanced Course in Distributed Algorithms” (FID3021), and “Advanced Topics in Distributed Systems” (FID3008).

TCS: 1st cycle courses – BSc-level: The role of the Computer Science Education research group at TCS deserves a special mention here. Recent research in computer science education is influencing many of the TCS courses, especially first cycle courses. Educational research studies have been performed in several courses, for example DD2350 Algorithms, Data Structures and Complexity, DD1337 Programming and DD1390 Program Integrating Course in Computer Science Engineering.

2nd cycle courses – MSc-level: In all second cycle courses given by TCS teachers, results from own and others’ research are included. TCS is teaching the DA2210 Introduction to the Philosophy of Science and Research Methodology for Computer Scientists, mandatory for all students (200 per year) of the Computer Science Master’s degree program, where the students learn scientific theories and methods relevant for research in computer science. In the advanced individual project courses, taken by about 20 students each year, students are given the opportunity to work on research projects.

3rd cycle courses – Doctoral-level: The interaction between teaching and research is strongest at the third (research) cycle of education, as its name suggests. Our school (EECS) is encouraging the development of new research-level courses by means of special funding through the budget of the doctoral programs. Furthermore, the Doctoral Program in Computer Science has a process for maintaining a third-cycle course curriculum that takes into account the latest developments in the areas of research of the faculty. In the other direction, third-cycle education directly influences research through the research-oriented character of the examination, which is typically based on paper presentations or the solving of research tasks (projects) of a theoretical or more practical nature.

6. Impact and engagement in society

Relevance of research to society at large

Our strong system-oriented research has resulted in widely adopted software platforms, several start-ups, contributions to standardization, and excellent alumni. Moreover, there has been significant presence in the national media, on numerous topics and occasions. Last but not least, extensive collaboration with strategic KTH partners, public authorities and organizations, municipalities, and the industry.

COS: The main forms of interaction with society at large are via degree projects (at 1st and 2nd cycle) carried out outside of KTH, production of new graduates (at all levels), industrial doctoral students, patent applications, and working with industrial partners to transition research to production applications. In more concrete terms, the CoS division has been in tight collaboration with Ericsson over the years and has provided Ericsson Research with more than some 25 doctoral graduates, many now in leading positions – including the current head of Ericsson Research, Magnus Frodigh, who is now also an adjunct professor at CoS.

Wireless technology is becoming an integral part of society; when stakeholders emphasize the importance of digitalization, wireless connectivity is always viewed as an enabling factor. Since we are moving towards a society where all devices are electronic and connected (from conventional terminals such as laptops and mobile phones to vehicles, sensors, and household appliances), the ability to provide cost- and energy-efficient wireless technology that meets the quality expectations will be key. People will expect the wireless connectivity to be as reliable and available as the electricity grid but large challenges related to reliability and massive connectivity are ahead; the research community has been more successful in improving the best-case performance than the worst-case performance. Since wireless research becomes increasingly important for both the agencies and companies, the division will broaden its collaboration with major stakeholders in the society; for example, through the KTH Digital Futures center.

Another important impact on society from COS activities has been on Swedish Telecom policy. This is due to the tight collaboration with the Swedish Telecom Regulator (PTS). Teams at CoS have been supporting PTS with technical investigations, mainly in the field of spectrum regulation. PTS was participating together with KTH in the FP7-project QUASAR, evaluating different spectrum sharing strategies, which has provided valuable input to the current national spectrum policy. KTH/CoS was coordinating this effort. Bengt Mölleryd, senior researcher at PTS, has for many years been a guest researcher at COS, involved in techno-economic studies of spectrum allocation strategies. COS has also been involved in providing technical studies, leading to the government decision not to launch a DAB audio broadcasting system in Sweden in 2016. J. Zander has also been on the board of PTS since 2007. He was a Senior Research Advisor of the Swedish Defense Research Agency (FOI) from 1992 to 2020.

CST: *Analysis of data* is an increasingly important part of the research workflows in all academic disciplines. Data becomes available to science by means of experimentation, computation, sensor networks, crowdsourcing, and other means. It is ubiquitous today and scientific progress hinges on understanding this data. Scientists in all domains increasingly face challenges when trying to analyze their data such as its sheer size, its high dimensionality, its noise level, or the complexity of data. In a broad sense, these are challenges we address, with a plethora of methods and approaches. Due to its multidisciplinary nature, CST utilizes bi-lateral as well as cross-domain collaborations. We have widespread active collaborations, within both teaching and research, with several hundreds of companies and organizations from a number of different domains, e.g. museums, new and emerging tech companies, non-profit organizations, games companies, manufacturing, medtech and fintech, e.g., Spotify, Google, City of Stockholm, Scania, Sveriges Kommuner och Landsting (SKL), IBM, Stockholm

Environment Institute (SEI), AstraZeneca, EA/Dice (www.dice.se), Avalanche Studios, and the Swedish Tax Agency among many others.

A computational theory of brain diseases and brain stimulation to repair the brain activity dynamics: As human longevity is increasing the incidence of brain diseases is rapidly rising and causes huge social and financial costs to the society. Current clinical approach is not very successful in treating brain diseases; therefore, we need new approaches. Based on our models and theory of neuronal networks we are building computational models of different brain diseases e.g., Parkinson's diseases. These models not only have provided new insights into the physiology and network mechanisms underlying the brain diseases but they also have proposed novel ways to stimulate the brain to restore brain activity dynamics and alleviate disease symptoms. This research effort is now well poised to develop a computational account of brain diseases and brings brain theory to the diagnosis, prognosis and therapies. This effort has also accumulated momentum through the KTH digital futures. In the next few years, we aim to develop the field of computational neurology and help patients with brain diseases by complementing current clinical practices with computational approaches. Patient-specific simulations for diagnosis and treatment of heart disease. Cardiovascular disease is the leading cause of death globally. Medical imaging of different modalities is today an integral part of diagnosis and treatment of heart disease, and by computer simulations based on patient-specific data more detailed information can be extracted, and disease and treatment scenarios can be investigated. The Swedish Research Council funds CST research aimed at developing new methods for simulation and visualization of the blood flow in the human heart based on patient-specific data, in collaboration with other research groups at KTH and at Karolinska Institute, and with clinicians at Karolinska Hospital.

CST in 2018-2020 participated in two projects researching sensing, simulating and visualizing air quality in hospitals. The projects were collaborations with Danderyd Hospital, Ericsson, Telia, Locum, Vattenfall, and Avidicare. The first project, VAKEN, deployed narrow-band IoT sensors in the operating rooms and sterilization facilities of the hospital. The project collected and modelled indoor climate to visualize and predict temperature, humidity and pressure. The visualizations ran as a dashboard on the hospital walls and the staff's computers and mobile phones. Stakeholders, including nurses, physicians, and facility managers, had accessible tools to take action to control indoor climate within working ranges. Thus, stakeholders were able to avoid cancelling operations or re-sterilizing equipment while improving working conditions. The second project, VizBac, created a model of a select operation room and the people within. Using this model, VisBac ran CFD simulations of the air streams in the room, and by releasing particles in a stochastic model of the air streams it provided a measure of bacteria-transporting contaminants. The project visualized the simulated data in virtual reality for the assessment of operation procedures and the training of new personnel in the operating room. Both projects received external funding and are applying towards a second round of funding and are currently editing publications under review.

Cancer research: Within CST, machine learning methodology is developed and applied to medical image analysis and for analysis of omics data, i.e., genomics and transcriptomics. An earlier research line focused on how genes evolve relative to the evolution of the species they belong to has been replaced by one focused on somatic evolution in cancer. How genes evolve is crucial to transforming results from model organisms, such as mice and Drosophila, to knowledge about human biology. However, evolutionary events such as lateral gene transfers are also vital for the development of antibiotic resistance in bacteria. That cancer tumors evolve constitutes the fundamental principle explaining many of this disease's most challenging properties, including common disease relapse following initially promising therapy response.

NSE: Future *wireless networks* for the society at large will require extremely high data rates, low latency communications, and massive access with IoT-services. To address this, NSE research has contributed with pioneering, seminal research. For instance, we have devised fundamentally novel

methods for centralized and distributed coordination schemes that allow the optimal operation of the network, avoiding interference while still balancing the computational complexity of the communication protocols and procedures.

Cyber security is an increasing concern with the digitalization of society. ICT infrastructures are interconnected and underpin virtually all parts of society, from critical infrastructure, self-driving vehicles, advanced healthcare, business administration, to national security. We see a flow of reported cyber-attacks (power grids shut down, record bank heists, election interference, billions of personal records leaked). In order to break this trend, we develop secure ICT components and ensure security of system-of-systems.

The research in *opportunistic communication* at the division provides both a novel communication mode directly between devices, for which several use cases have been demonstrated, and it serves as one of the most resilient forms of communication without an infrastructure. It will be further studied in the cyber-defense area.

SCS: *Distributed systems:* The outcomes of the research at the distributed systems group have a high impact on advanced analytics of different data types at large scale. The demand for such large-scale analytics has been ever growing since a few years ago. Many small and medium sized enterprises (SME), as well as non-expert data users (who may be subject matter experts in their own domains, e.g., healthcare, finance, etc.), are often faced with complex big data analytics ecosystem (including techniques, tools, algorithms, etc.). The platforms and tools that we build facilitate the use of advanced big data analytics by hiding the technological complexity and lowering the bar for SMEs and end-users to access, exploit and innovate. They also enable larger companies to easily adapt to existing workforce skills and competences. Moreover, one of the challenges of many end-users and companies' rests in the deployment of new types of analytics combining with different data types (e.g., batch, streaming, graph), where data is large and unstructured. The gap between the time where analytical results are delivered and the time where it is needed is a source of deep frustration in the whole process, from marketing to product development and operations. The distributed systems group research provides a key contribution in this respect, by enabling advanced new functionalities for real time analytics of massive data in a distributed manner over different environments, including cloud, edge, and mobile infrastructures.

Data science: Professional associations such as the ACM, FAT/ML, and IEEE have proposed guidelines and frameworks for Fairness, Accountability and Transparency (FAT) and explainable AI (XAI), incorporating societal demands to be placed on AI solutions, as well as evaluation criteria for explainability and FAT. Humans that interact with, or are affected by, AI need to be able to make informed judgments about when to trust a system and when to examine a decision in detail. The research at SCS contributes to the area of accountability with methods for uncertainty quantification, which are currently being applied to support predictive maintenance of trucks (in collaboration with Scania) and decision making for ferries (in collaboration with Stena Line). Research at SCS related to transparency is currently being applied to the problem of predicting the gross domestic product (in collaboration with the Swedish National Financial Management Authority), where one is not only interested in accurate predictions, but also needs to know what factors are of importance for specific predictions.

The research conducted at SCS on decentralized machine learning (ML) and data analytics contributes to eliminating dependence on currently highly centralized services, e.g., as provided by Facebook, Amazon, Fitbit/Google, forcing users to give up their personal data. Our research on decentralized ML on wearables (IoT for Sports) as well as on decentralized natural language processing (NLP) is a step further into this direction. Furthermore, the research at SCS within ML and graph analytics are being successfully applied within the field of proteomics, in collaboration with Karolinska Institutet. This

research has the potential to enable personalized life-saving treatments which target individually selected proteins responsible for certain types of tumors, that are discovered by our methodologies

Research within data science at SCS also concerns pre-processing and smart processing of vast data sets, including genetic data and electronic health records. The research on learning machines is currently being employed for clinical application in psychiatric care at Huddinge Hospital, where a randomized controlled trial is ongoing.

*Software construction and analysis***:** Our research on methods and techniques for efficient and reliable software tools are directly relevant to both engineers in industry and scientists working in other scientific domains. In particular, our fundamental research efforts on algorithms and formal semantics give engineers new methods to develop complex systems (models are used as blueprints of the real system), and scientists new ways of constructing models and interpreting data (reconstructing models by observing existing systems, such as biological systems). We perform our fundamental research with close connection to several industry partners and scientists from other disciplines (e.g., evolutionary biology and cardiology).

Network security and privacy: The majority of the research on security and privacy of contemporary and emerging networked systems pertains to technologies that have already been deployed or have a clear path for deployment. Research contributing to security- and privacy-by-design for those systems eradicates vulnerabilities and reinforces the prospect of reaping the benefits of their use without risks for the user and the systems. The industrial competence group of the KTH ICES center, the annual hacking competition and the Cyber-Security and Privacy Summer (CySeP) School provide all excellent fora for bringing together academia, industry, local/regional community of enthusiasts, as well as funding agencies. Notable: in 2019, a panel on trustworthy IoT brought to CySeP and KTH a member of the Swedish parliament, representatives of the Swedish armed forces and the civilian protection agency, and a political scientist.

TCS research impacts a wide range of societal actors, including: end users, government, healthcare and defense, schools, a wide range of national industry, and standardization and international bodies.

Complexity Theory: Modern society runs on algorithms, and in the age of big data it is crucial for both businesses and society to have efficient algorithms, for all sorts of tasks from routing Internet traffic to the processing of huge data sets in data centers. Furthermore, complexity research often has an impact on society, both in the form of surprising discoveries of ground-breaking applications (e.g., modern cryptography) and our education of strong problem-solvers and thinkers who are highly useful in all of modern society. For example, Ekerå is an industrial doctoral student from NCSA at the Swedish Armed Forces, connecting theoretical research with the security challenges facing today's society.

Computer Security: The provisioning of trustworthy platforms for software execution in both embedded and IT system contexts is one of the major challenges facing society today, viz critical systems in e.g., transportation, power generation and transmission, communication (5G) and manufacturing industry (industry 4.0). This has a direct impact on public safety and security. With the ever-hardening international climate, these critical systems are likely to face far more hostile environments in the near future. Also worrisome is the increasing brittleness of users' trust in Internet-connected technologies, as shown by the 2017's Special Eurobarometer in Cyber Security. Our research serves to address key aspects of these challenges in the form of languages, tools, and platforms that have some basic guaranteed level of security against high capability nation state adversaries. For privacy, the threats pose an increasing problem, to the point where this impedes adoption of new technologies (e.g., data analysis, IoT) due to lack of trust or results in unsustainable economics relying on inefficient monetization of individuals' behavioral data. Developing privacy-preserving methods and mechanisms counters these threats.

Computer science education: We study and develop computer science education in order to improve the learning of computer science in both secondary and tertiary education, both nationally and internationally. Naturally, KTH is the organization where most of our research results are used first. The most recent example is an introductory course for computer science teaching assistants, that was developed at KTH, based on research done and published 2018-2020. We are studying, implementing and disseminating methods and criteria for assessment and methods for improving program coherence in higher education. Our research has also been applied to training refugees in the Stockholm area who fled conflict but could not translate or update their prior skills into what the local IT market demands.

*Data Science***:** Much of our research is motivated by problems that have direct relevance to society and our methods have strong potential for societal impact. Our research in machine learning for software engineering contributes to safety and public trust of autonomous systems such as self-driving cars, air taxis, trains etc. It also stimulates public debate about safe and reliable IT infrastructure and explainable AI. Our research on clinical NLP has direct applications in developing better models for healthcare provision, while our work on processing spoken and visual material is a crucial aspect to prepare for the next generation of educational systems. Our work on content dissemination in social media has strong relevance in the functioning of our society. Finally, as a concrete societal contribution, we have developed, and made available, tools for analyzing and checking Swedish text, useful in the Swedish school, public administration, and in various language technology systems.

Software construction and analysis: Research at TCS is relevant and useful to society since it helps companies who develop software (IT, finance, commerce, administration, transportation) to improve the reliability and availability of their applications and products. In programming language systems, TCS research contributes to the development of distributed software systems that are more reliable, thereby preventing potentially catastrophic outages. In embedded and software systems, autonomous systems are seen as robotic systems of different kinds. Autonomous transportation can significantly reduce CO2 emission and increase safety. Home-assistant robots can help elderly population to maintain autonomy. In formal verification, the provisioning of trustworthy platforms for software execution is one of the major challenges facing society today, viz. critical systems in e.g., transportation, power generation and transmission, and manufacturing industry.

TCS has a small participation in start-up companies and consultative work. Meinke has been a co-founder of Ainomaly Software AB, and Kann has been a consultant in Euroling. Karlgren founded Gavagai AB in 2008 and worked there full time between 2010 and 2019. He is currently a research advisor to Recorded Future (since 2010), and a member of the academic board for Storytel. He has been a research board member for Kungliga Biblioteket (2010-2018), and a research advisor to several start-ups and tech companies.

Research dissemination beyond academia

COS: There are several ways to disseminate research results beyond academia. The first way is are: via people: by having students conducting degree projects (at the 1st and 2nd cycles) done outside of KTH, supervision of industrial doctoral students, having faculty who spend some portion of their time working at external organizations (e.g., startups or larger companies), having adjunct professors from the industry, and joint projects with external partners outside academia. The division has a long track-record in all of these areas. The collaborations with the industry have resulted in a multitude of patent applications, which is another way of research dissemination beyond academia. Key research results can also be disseminated through press releases and to succeed in this effort, we can get support from the university or external writers to make the text more accessible to a wider audience. When the Swedish media is reporting about 5G and other wireless technology matters, it is common that they contact the faculty of the COS division, which demonstrates the reputation that division has built. The division is mainly publishing in IEEE conferences and journals, which allow for parallel publishing of

full text papers in DiVA and arXiv.org, thus open access to research results is natural in our field of research. A new way to disseminate research beyond academia is by making use of social media, such as blogs, LinkedIn, YouTube, and podcasts. The COS division has recently released a podcast called "Wireless Future" and is planning to increase their activities related to other media platforms.

Several COS members have been directly involved in startups. For example, Claes Beckman has had assignments to the board of directors of the companies: In Coax AB (Public), Smarteq AB (Public), Allgon AB (Public), Medfield (Public), and Evam (Private). In addition, he has had assignments to the advisory board of Icomera AB (Part of Engie SA, public), Forsway AB (private), and Skysense AB (Private).

COS staff members have been participating as experts and presented internal reports in public (government) investigations supporting policy making. Recent examples are the National Spectrum Strategy (PTS) and investigations concerning the possible deployment of the Digital Audio Broadcasting (DAB)-service and the future Wireless Public Protection and Disaster Relief (PPDR)-system,

CST has for a long time collaborated with museums in and around Stockholm as an arena for dissemination of results, student collaborations and active research. In particular, together with the Museum for Science and Technology in Stockholm we co-organize several events a year (both public exhibits and presentations as well as data collection), student's exhibit their projects and we have also jointly produced a number of permanent exhibits, for example in the award-winning exhibits MegaMind and Play Beyond Play. We are also the primary academic partner in Stockholm in the Wallenberg-funded Wisdome, a national initiative that connects the five major Science Centers in Sweden with local academic and commercial partners at each node for advanced visualization exhibits, research and teaching.

NSE collaborates with the industrial research divisions of Ericsson, ABB, and Siemens. This collaboration has contributed to the definition of 5G communication standards and new industrial standards for wireless communication. Some 16 patents have been approved as part of these collaborations. Specifically, we have built up a long-standing collaboration with Ericsson with focus on applying AI and ML to network engineering. This has involved a core set of researchers on both sides in many forms and has resulted in more than ten joint publications. Other examples are the Threat MOVE project conducted with Volvo Cars and Scania, Energy Shield with PSI and Iren, and SOCCRATES with ATOS and Vattenfall. Papers have been published together with people from, e.g., Svensk Kärnbränslehantering Aktiebolag (SKB), Siemens, Ericsson, and Foreseeti.

NSE is very active in the public debate; Prof. G. Karlsson and Prof. P. Johnson have been very active in public debates and popular science news (with outlets to newspapers and public TV and radio). Outlets include daily news (Dagens Nyheter, Metro), Swedish Radio, TV (Swedish Television, TV4), popular science news (Computer Sweden, NyTeknik), popular science books (Ett kalejdoskop av kunskap (David Håkansson et al., *Ett kalejdoskop av kunskap. Sveriges unga akademi om vetenskap och samhälle*. Stockholm: Santérus Förlag, 2019, ISBN: 978-91-7359-140-9.)), talks (KTH executive school, Swedish book fair, CS3 ICS/SCADA security, ISACA), youth outreach (science talks at film festivals), blogs, and more.

SCS: *Industry forums:* the software industry is a key societal actor who can benefit from our scientific contributions. As such, we have a systematic activity of dissemination through technical talks on companies' premises, in industry fairs and conferences. We made and continue to provide presentations and invited talks for industrial audiences at project meetings, workshops, seminars, conferences and summits. The examples include academic, research and industry forums at CASTOR Software Days, RISE SICS Software Week, SPARK+AI Summit Europe (the largest data and machine

learning conference in Europe), Flink Forward (the conference for Apache Flink and the stream processing communities), Arctic Circle Assembly (the largest annual international gathering on the Arctic, attended by more than 2000 participants from 60 countries).

CASTOR *Software Days*. We have provided a number of presentations at the CASTOR Software Days, organized by the CASTOR software research center led by Professor Benoit Baudry. At those days software researchers, engineers and students from both academia and industry meet to present and discuss cutting-edge technology, state of the art and current challenges in three areas DevOps, Safety and Security, and Large-Scale Distributed Systems. The days mix keynotes, academic and industry talks, demos, lightning talks and student events. At the CASTOR Software Days, held on October 14-16, 2019, KTH, Stockholm, we have given a number of talks for scientific and industrial audiences.

RISE SICS Software Week is an annual multi conference organized by the RISE research institute in Stockholm, Sweden. The week includes two-three software conferences, such as Data Science & AI Day and Multicore Day (2019).

Security and Privacy: Participation in discussions and contributions to documents and activities pertaining to policy matters (*Young Academy of Europe*). Contributions for *European Union Agency for Cybersecurity* (ENISA), e.g., on the security of 5G. Panellist/speaker for events with attention to multidisciplinary issues and policy (e.g., Computers, Privacy and Data Protection conference), as well as industry-run events (e.g., *Huawei Security Summit*, or *Auto Apps and Connected Driving Technologies Conference)*. Swedish Viktoria ICT project on airfield automation. Participation in the Car-to-Car Communication Consortium (C2C-CC) and the Trust in Digital Life activities. Outreach to high-school students (Swedish and international) on cybersecurity and privacy. Survey on training for cybersecurity, with SecurityLink and Linköping Science Park.

TCS: *Complexity Theory***:** Ekerå's collaboration with Google Quantum AI received significant attention in the technology media, and Ekerå has appeared in several forums (e.g., the F-Secure podcast "Säkerhetssnack" and in a Global Risk Institute survey on the "Quantum Threat") to raise awareness about these issues.

Computer security: An important piece of technology dissemination has been the influential Verificatum mixnet-based e-voting system. Verificatum has spawned a number of international collaborations, in Israel (the Wombat e-voting system), Norway through deployment in the 2013 parliamentary elections, and with groups in Spain and Estonia. Other outreach activities include involvement in research centers such as the KTH Center for Software Technology Research (CASTOR), the center for Cyber Defense and Information Security (CDIS), and KTH Innovative Center for Embedded Systems (ICES). Dam was co-founder of the CDIS center, a new research center funded by the Swedish Armed Forces for the purpose of knowledge transfer and defense technology development. Additionally, Balliu and Sabelfeld's popular science article "Securing IoT Apps" published at IEEE Security & Privacy Magazine raises awareness on security and privacy issues within the emerging domain of IoT apps. Through discussions with Ericsson Research, we are pushing strong security and privacy techniques to drive the new standardization activities within Internet Research Task Force (IRTF) in the IoT app domain. Finally, there have been several discussions with external parties on various training courses with a security focus, with Sweden's Television (Sveriges Television (SVT)) and with the National Defense Radio Establishment.

Computer science education: We have reached out to Swedish secondary schools through education of teachers, by participation in two Vinnova projects (*Trippel Helix - Nationell samling för skolans digitalisering* (English: Triple Helix - National collection for school digitization) 2016-2017 and *Digitalisering av svenska för invandrare* (English: Digitization of Swedish for immigrants) 2016-

2019), and conferences for teachers. We have made our open-source tool set for managing courses with version control for everyone.

Data science: Meinke has participated in research dissemination through startup incubators, e.g., KTH Innovation, MobilityXLabs. Kann is a member of Svenska datatermgruppen. He has contributed to the article "*Nej, så dåligt skriver inte studenter*," (English: No, not bad writing students) published in the Swedish national magazine for language (Språktidningen) on 7/2017. Gionis delivered a keynote speech in the conference "Artificial Intelligence: The European approach for citizens' wellbeing" in the European Parliament, in Brussels, on 19th November 2019. Karlgren has occasionally published opinion pieces in popular national newspapers, such as Dagens Nyheter and Svenska Dagbladet. Velupillai has co-organized a dissemination workshop (London, November 2019) targeted at healthcare service users and carers, healthcare governance representatives, and industry representatives.

Software construction and analysis: Monperrus had appearances on Sweden's Television (SVT) and Swedish Radio Ltd. (Sveriges Radio (SR)) as well as press articles in English and Chinese. Dam was co-founder, with Baudry and Schulte of the SCS division, of the CASTOR software center in 2018. Initial industry partners of CASTOR are Ericsson and Saab. The purpose of CASTOR is to serve as a bridge between KTH, its chief partners in the software research and development domain, and the broader public. CASTOR organizes an annual conference open to the general public, joint events, and collaborative projects. Dam and Meinke were also board members of the research center ICES, a research network hosted at the KTH School of Industrial Engineering and Management (ITM) with a large industrial membership network focused on the embedded systems industry.

Sustainability and the United Nations' Sustainable Development Goals (SDG)

Most basic computer science research will have an indirect impact on the Sustainable Development goals. In that sense, we feel that the entirety, 100%, of the CSD work can contribute to sustainability. because digital solutions enter into all societal and industrial processes, making them more efficient, as well as everyday life and health. Work by CSD divisions directly towards specific sustainability goals reinforces this; specific concrete example include:

- *Goal 12 Responsible Consumption and Production:* CoS has a project on Energy-Efficient Ethernet and several projects related to the design of energy-efficient infrastructure for wireless networks, as well as energy-efficient operation of existing infrastructure.
- *Goal 7 Affordable and clean energy:* NSE is involved in a large project with MIT and Harvard.
- *Goal 3 Good health and wellbeing*: A recent study in Nature (Vinuesa, R., Azizpour, H., Leite, I., Balaam, M., Dignum, V., Domisch, S., ... & Nerini, F. F. (2020). The role of artificial intelligence in achieving the Sustainable Development Goals. Nature Communications, 11(1), 1-10.)
  - Communications (with authors from several divisions, including HCT/MID) found that Artificial Intelligence can enable the accomplishment of 134 of the 169 defined sustainability targets across all goals, but may inhibit 59 targets.
  - CST has a broad portfolio of research in cancer, biomedical image analysis, and understanding of brain dysfunction.
  - CST also has a project VisBac (funded by Formas) is exploring the modelling, simulation and visualization in virtual and augmented reality of airflow and airborne bacteria in operating rooms at hospitals. This project is in collaboration with area hospitals Danderyd's sjukhus and Sophiahemmet Sjukhus.
  - CST has a project funded by the Swedish Research Council to develop patient-specific simulations of the human heart, in collaboration with other researchers at KTH, Karolinska Institute (KI) and clinicians at Karolinska Hospital.
  - SCS works together with Karolinska on the so-called AI@KI project, which is meant to feed into the Stockholm Trio (KTH, KI, SU) cooperation introduced to facilitate international research cooperation with the University of Tokyo, already broadened to many international partners.

KTH has secured funding from the Welcome Trust, to continue to play a bridge role between the computational and medical sciences.

- *Goal 4 Quality Education:* TCS Computer Science Education group. Five TCS staff have supported the SDA teaching program for newly arrived immigrants to Sweden in 7 rounds from 2017 to 2020, teaching approximately 210 students in total. The teaching outcomes of this work have been used to support new research publications in CS pedagogy. This work has been partly funded by the European Social Fund.
- *Goal 11 Sustainable Cities and Communities*: CST is numerical methods and high-performance computing. Here, modelling and simulations used for virtual prototyping of renewable energy technology and forecasting air pollution for sustainable urban planning have direct impacts towards Goal 7 (Affordable and Clean Energy) and Goal 11 (Sustainable Cities and Communities).
- *Goal 3 Ensure healthy lives and promote well-being for all at all ages*: At CST several research activities involving the study of cancer, in particular solid tumors, and also Streptococcus genomics. Streptococcus infections are common in people living with HIV and other diseases that impair immune defense. Moreover, experimental studies suggest Mycobacterium tuberculosis infection predisposes to Streptococcus pneumoniae infection. This research consists of method development as well as collaborative projects together with high profile groups at Karolinska Hospital.
- *Goal 9 Industry, Innovation and Infrastructure*: SCS has department-wide engagement with questions pertaining to computer- and program efficiency, relevant to saving energy, such as optimization, i.e., to build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation. For research into data science and machine learning this includes responsible training regimes for deep learning and other compute-intensive methods.
- *Goal 11 Sustainable cities and communities*: Since January 1st 2018, SCS has been involved in the national Strategic Innovation Program *Viable Cities* (1000 MSEK, 2017-2030, coordinated by KTH School of Architecture and the Built Environment (ABE)).

Structure for increased impact

Increasing impact is a process of finding the right venues, the right contacts, spreading our research results in the various forms that make most sense depending on the content. It may be through spin-off companies, policies, standards, direct contact with an industrial or societal partner, or through the general media. The two departments are involved in all of these forms of dissemination. This said, the demands on impact are increasing and each of the divisions are working on how to best ensure good practices in this area.

Several of the divisions note that one of the most important structures for increased impact will come through the different centers the divisions are involved in. Most recently, the KTH DF center was established – official inauguration in 2020. It has received substantial, targeted funding from the government. The aim is to make sure Sweden does research in basic computer science topics as well as their implications for transformations of industrial and societal processes. The research will in turn guarantee that the faculty is up to date, delivering well-educated engineers to handle the digital transformation of society.

Many of the most prominent researchers in the two departments have taken on various leadership roles with the Digital Futures (DF) center, for example, Karl H. Johansson of the IS department is the director and Marina Petrova, at COS at CSD is the deputy director. Several other CSD faculty are involved in and contribute to workgroups, committees, lead or participate in projects funded by DF.

For certain topics, the influence is sometimes indirect: by doing basic research on computer science topics, they may change the fundamentals of how digitalization can and should work. Their results may need to be filtered through education, reaching our young engineers who in turn bring these results with them out into society and industry. Measuring impact is therefore difficult – as is understanding

whether we are achieving increased impact. This said, all divisions see the need and highly encourage their faculty to work towards impact beyond academia.

Apart from KTH Digital Futures, there are other centers with the Computer Science Department that will serve a similar role to increase impact, such as the KTH Center for Software Technology Research (CASTOR), the center for Cyber Defense and Information Security (CDIS), the KTH Innovative Center for Embedded Systems (ICES), and the SecurityLink center. All centers are developed in close collaboration with industrial partners and they all have strategies for communicating their results.

Another path to increased impact is commissioned education programs together with KTH Executive school and external partners. These are very useful dissemination and knowledge-sharing arenas, but also extend the network of stakeholders and collaborative partners for upcoming joint research activities.

Department of Human-Centered Technology (HCTD)

Self-evaluation

Head of Department: Prof. Henrik Artman

Included divisions:

Division of Media Technology and Interaction Design (MID)

Department of HCT

1. Overall analysis and conclusion; strengths and development areas

Limited SWOT Analysis

	Strengths	Weaknesses
Research	Bulleted list, in order of magnitude 1. Strong research and practice-based skills relating to interaction design, media technology and HCI - in high demand by industry and society 2. A highly interdisciplinary profile, involving: computer science; hardware engineering; software engineering; industrial design; sociology; psychology; learning sciences; music; arts; fashion design; and HCI. Together addressing topics such as sound and music computing; designing for sustainability awareness; health and wellbeing applications; female health; children's play; special needs; automation.	Bulleted list, in order of magnitude 1. There are research topics not strongly pursued but where there is a clear societal need; such as user-oriented IT-design for work settings; accessibility issues for media technology/production; service design; and so on. HCTD could grow considerably - but needs a sustainable strategy to ensure the basic funding needed for employing faculty 2. HCTD faculty has a strong network of international contacts, but more could be done to attract, for example, EU-funding. 3. The overall performance can be seen as bimodal; there are several highly published, internationally leading and visible faculty members; and on the other hand, a number of faculty largely devoted solely to teaching and administration.
Organization	Bulleted list, in order of magnitude 1. HCTD drives several key facilities for building interactive applications: MIDDLA makerspace, a haptics laboratory, a multisensory studio for sound, music and movement-based design, and a soma design laboratory. 2. HCTD has excellent gender balance compared to the rest of KTH: 32% female faculty compared to 21% overall at KTH); 50% female postdoctoral researchers and 33% female doctoral students.	Bulleted list, in order of magnitude 1. Demand on office space continues to increase. There is an increasing need for design spaces where we can build systems - as faculty but also PhD-students and undergraduates. 2. There is an opportunity to reconsider the internal organization of HCTD - as well as how some of the research in HCTD overlaps with work in other schools within KTH. It might make sense to have more than one division within the department - if such a reorganization across KTH is made.

Summary statement on contributions of department on impact, infrastructure and sustainable development

Development areas

HCTD could grow substantially and thereby address important needs in society and industry. HCTD faculty also have a heavy teaching load. But given the current requirements on basic faculty funding as a prerequisite for recruiting permanent faculty, there is not enough basic faculty funding. We are stuck in a situation where some of the faculty do not have time to apply for external funding, which in turn means that the school will not increase our share of basic funding. The recent developments with the establishment of the DF center have to some extent helped change this situation. HCTD has successfully attracted grants from the DF center, but as these are short-term grants, we cannot create faculty positions based on that funding.

A second problem concerns the uneven, bimodal, performance of our faculty. Some successfully pull in funding, allowing them to employ PhD-students and post-doc, generate good research and publications. Others are mainly engaged in teaching, management or administrative tasks. We have successfully turned this negative spiral in some cases through changing the distribution of faculty funding; engaging in writing camps; having a dedicated resource for helping faculty when writing funding proposals; etc. But more could and should be done to let everyone have a better balance between research work and other tasks.

HCTD is a small department which means that the administrative overhead is too high. As the EECS school was recently joined, there are not yet been time to reconsider how the different departments should be organized. There could be overlaps not only within the school but also with other schools that could create for a different internal organization.

Impact: Participation and leading roles in research centers with continuing activities, including newly formed ones. Centers are in close collaboration with industrial and government partners, pursuing research, education, innovation, towards addressing societal needs. Active centers: Digital Futures and NAVET. Highly cited research, including numerous awards.

Infrastructure: (i) MIDDLA physical interaction design lab, (ii) Visualization Studio, (iii) Multisensory Studio, (iv) HapticLab, (v) Soma Design.

Sustainable development: Most of the research conducted in HCTD has a direct or indirect impact on sustainability goals. More importantly, we have one whole research team specifically devoted to sustainability topics. Highlights:

- Projects on energy efficiency, affordable and clean energy, responsible consumption.
- Project on climate, notably visualization of flight patterns and CO2 emissions by HCTD, towards achieving the KTH target to reduce its own air travel by 60% by 2030.
- Program for newly arriving immigrants' education.
- Good health and well-being; promoted by multiple projects across HCTD.

2. Research profile

General information of the department

HCTD is the smallest of four departments at EECS. It consists mainly of the MID-division, alongside some faculty from the Computer Science and Intelligent Systems division. During the recent reorganization, the faculty chose to be a department of its own rather than to be part of CSD. HCT is trans-/interdisciplinary with a strong focus on human interaction with digital media technologies. Our

work does not belong solely to the computer science field, but instead the Human-computer interaction (HCI) field and media technology. The department is organized in four teams:

Interaction Design: Kristina Höök (Soma Design), Madeline Balaam (Soma Design and Female Health), Ylva Fernaeus (tangible and embedded computing, design), Cristian Bogdan (Interaction Programming and design with energy), Marianela Ciolfi (Female Health) and associated professor Barry Brown, Stockholm University.

MID4Sustainability: Daniel Pargman (Ecological Sustainability, Energy, Futures studies, Art), Rob Comber (Social and ecological sustainability), Elina Eriksson (Sustainable HCI, Transition Design, Sustainability Education), Leif Dahlberg (Climate communication, Disinformation, Climate activism, Media activism), Eva Lotta Sallnäs-Pysander (Haptics, Outdoor play design).

Sound and Music Computing: Roberto Bresin (sonification, emotion perception in sound and music, expressive music performance, sonic interaction design), Sandra Pauletto (sonification, sonic interaction design, sound design, media production), Andre Holzapfel (ethics of AI in sound and music, Music Information Retrieval, Ethnomusicology), Kjetil Falkenberg Hansen (sound interaction in rehabilitation, new musical instruments, active listening, sonification).

Technology Enhanced Learning: Olle Bälter (Learning and teaching efficiency, Learning Analytics); Olga Viberg (Learning Analytics, Self-Regulated Learning, Mobile Learning, Responsible Use of Learner Data); Henrik Artman (Simulator training, Visualization, Transparency, Cyber and Aircraft Situation Awareness).

There are also smaller teams in formation:

Accessibility and Digital Transformation: Jan Gulliksen (User-Centered Design, Accessibility, Policy Making, Digitalization)

Novel Interaction Techniques: Haibo Li (Visual technology, Humanistic AI, Phenomenology of Interaction); Anders Hedman (Cognitive Endurance, Mindfulness, Places)

Central research questions and themes, knowledge gaps addressed, main research activities

Human Computer Interaction: The overarching research question for HCTD concerns developing, designing and studying (digital) technologies and interactive technologies. We explore how those interactions help shape our relationships with information, society, organizations, policies, and with others —socially, intellectually, collaboratively. As a collective we are, by necessity, interdisciplinary. We position ourselves at the intersection between computer science, psychology, media and communication studies, industrial design, arts and sound and music computing.

Interaction design: New materials are coming closer to our bodies, some with the ability to self-modify their physical properties, their shape, color, stiffness, temperature or texture – allowing for shaping novel types of interaction relying on dynamic actuation that can act in response to our bodily rhythms, movements, biochemical changes on or inside bodies or in the surrounding environment. Exploring the design space these novel materials enable requires a deep, well-grounded understanding of human morphology and meaning-making processes. Methodologically, theoretically and practically, we have a long-standing commitment to soma design Soma Design, a design stance distinguished by four key characteristics. First, Soma Design is grounded in a first-person approach foregrounds the lived body of the designer, involving extensive bodily experience through personal practice. A second characteristic of Soma Design is that it adopts a holistic stance towards the mindbody rather than building on the dualist schools of thought that separate the cognitive from the physical and that have underpinned much previous work in HCI. Third, it emphasizes the aesthetic appreciation of bodily

experience, striving for an altered sensibility with respect to one's own somasensory experiences. And fourth, following on from this, it is an active stance, inviting us to seek out new bodily practices and, in its application within HCI, new digital technologies to support these. Soma Design therefore encourages us to design for deepening aesthetic appreciation and meaning-making from a position as sentient, subjective selves. Through engaging somatically with the digital materials we design with, their somaesthetic potential is revealed and can be shaped into felt experiences relevant to the design aims. The Interaction Design research group includes one strong growing theme focusing on female health, building on the soma design philosophy, but engaging in particular on the female body and bodily transitions throughout our life.

Human Computer interaction for sustainability: The central question for the Sustainability research is: "what is the role of ICT in the transition towards a more sustainable society?". We contribute to sustainability through ICT and have research projects in each of four application areas: food, energy, transport and cities. Part of our research makes use of and explores the use of futuring techniques (backcastring, counterfactual scenarios, design fiction, critical and speculative design) in Human-Computer Interaction. Key persons in the research team worked with an ambitious literature review in 2017 and the numerous knowledge gaps identified helped us articulate three research projects that have obtained funding in the area of sustainability, food and digital technology for behavior change interventions.

Sound and Music Computing: The long-term vision of the Sound and Music Computing research group is to understand human communication and interaction by sound and music so as to make them a natural part of everyday technology. As the group creates technologies and tools to facilitate new interactive possibilities in music as well as studies and creates sounds to improve human-machine interaction and communication it strongly addresses the media technology side of MID. The research addresses knowledge gaps between music studies in engineering, humanities, and philosophy (ethics), as well as between media production, sound and music computing, sonic interaction design, interaction design, and HCI. Sub-disciplines include modelling music expression; sensor-based movement analysis; sonification and data representation; sonic interaction design; non-verbal communication in human robot interaction; methods for media production; sonic interaction design for energy efficiency; sound-based methods for rehabilitation/training; music information retrieval; and computational ethnomusicology.

Technology enhanced learning: The Technology Enhanced Learning research focuses on devising tools and processes that makes learning more effective and efficient. Our research efforts are based on the lenses of self-regulated learning, question-based learning, collaborative learning, artificial intelligence, learning analytic and simulator-training. Together with the KTH Visualisation studio, we have involved master students in developing visualization tools (i) to foster students' self-reflection skills in engineering education and (ii) to improve students' SRL (goal setting- and time management skills) with the help of interactive visualization. Our recent interest regards responsible use of learner data in education, linked to the increasing integration of digital technologies in education.

Design for all: We advance research accessibility and digital transformation that aims to make use of collaborative design to support people with the widest range of capabilities to become included in a digitalized society as well as business transformation through digitalization in work environments.

Interaction Techniques: Our research on Novel Interaction Techniques based on AI and Big Data has been interdisciplinary where advanced engineering with philosophy, art, aesthetics and other disciplines from the humanities are combined. Our aim is to create disruptive media and interaction technologies, which will radically change not only the way people entertain themselves but how they live, work and think. Our research has been focused on visual communication and computing from a perspective of phenomenology. In visual communication we study how to effectively utilize visual

entities (e.g., images, videos and 3D representations) to offer new interactions techniques for direct manipulation without artifacts, for other forms of advanced interaction, and also for entertainment, informational and educational purposes. Our primary aim of visual computing is to understand and read people accurately and to use visual entities for the manipulation of the world around us, tangible or intangible.

Contributions to the advancement of the state of the art within the research fields of the department

Within the field of **interaction design**, our main contribution during the last few years has been the establishment of soma design – a theoretical, analytical and pragmatic approach to designing with novel hybrid digital/physical materials. Our impact in soma design is showcased by our academic publications impact, but also for example, the number of keynotes and media appearances our work on this topic has attracted.

Second, the interaction design research group was heavily involved with the Mobile Life center (which ended in 2017) where we – together with strong industrial partners – became a strong voice advocating a human centered focus on digitalization – focusing on what makes a good life for all. The center provided design-led exploration of novel technology, based on social science, art, design thinking, aesthetics and value-based concerns, is a unique approach that has rendered results that will continue to inspire. Our design work included, for example, early work on wearable biosensors for wellbeing and health and tools for amateur video production. The center initiated and developed unusual and evocative research topics such as: integrating digitalization with the fashion industry; connecting back to nature and engaging animals in interaction; designing with felt life and bodily engagement; pervasive games; or studying the lifestyle changes that follow from the sharing economy. Furthermore, the center did not shun from the political and ethical implications of our work, dealing with topics such as the importance of empowerment of all to be makers and participants in a highly technologically-infused society. These research topics have changed the academic frontiers of the interaction design research field.

In the field of **ICT for sustainability** there was no research team specifically devoted to this topic at the time of the previous RAE. The establishment of the MID4S team is a spin-off of the work done at the Center for Sustainable Communications (CESC) until 2017 when the center closed. Results from CESC projects include recommendations for the governance of future smart sustainable cities (SSC), evaluating the environmental consequences of a variety of scenarios for future Swedish ICT societies, and, the creation of methods and tools for visualizing and bridging the gap between sustainability data and (the creation of) sustainable practices. Interesting examples of tangible outcomes is the work on a car-free year and of designing for better waste management in grocery stores. The team recently systematically investigated behavior change for food practices as reported in the literature, showing that there is a lack of evidence that such designs have had any effects at all – partly as these designs are not based on proper theories of how behavior change comes about.

In the field of **sound and music computing** one of our major contributions has been to establish the group within the field of sonification, sonic interaction design, and both cross-cultural and interdisciplinary aspects of sound and music computing. In 2013 we published a systematic review of mapping strategies for the sonification of physical quantities which included the analysis of 179 studies in the field. This was the first review covering a large corpus of research; it is a highly cited paper that has been of help for the entire research community as well as our research team for further developing the field of sonification and for placing our team internationally. This study has been used as the base for funded research proposals in the field of interactive sonification, in which we also made new experimental findings on the use of sound in health communication and other areas of societal impact, including humanoid robots. We have developed a new methodology for the use of voice sketching in sound design based on a new system for music notation. We have also constructed the first cross-

cultural datasets of interactions between dancers and musicians; developed novel theoretical frameworks for ethical guidelines for the applications of artificial intelligence in the context of arts; developed new methods for the transfer of knowledge from media production (in theatre, film) to sound and music computing, sonic interaction design, interaction design.

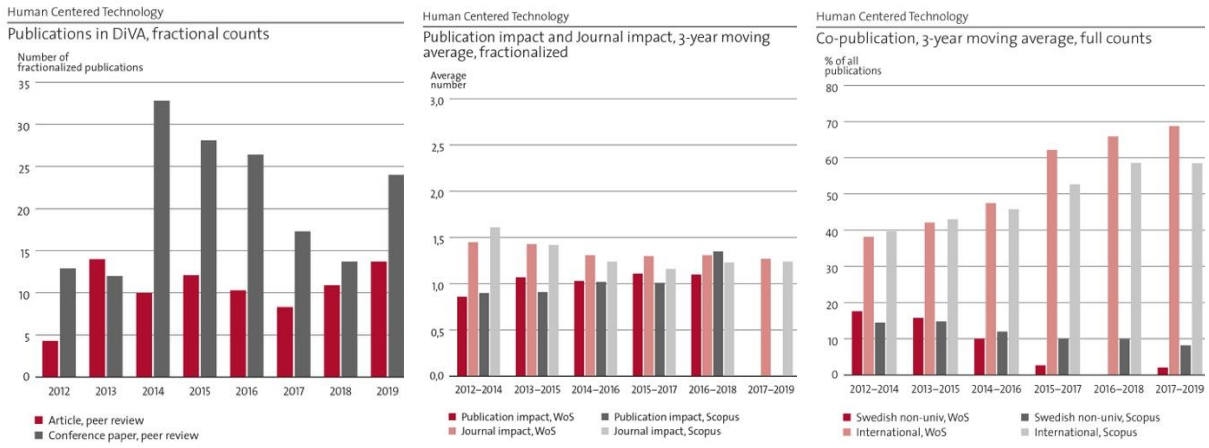
In the field of **technology-enhanced learning** our main contributions relate to the three key areas. First, the establishment of the field of learning analytics in the Swedish context, with a specific focus on the measurement and support of student self-regulated learning strategies (conceptual, methodological and practical contributions). Second, effective integration of digital technologies in Swedish K-12 education (linked to the recently undertaken National Digital Strategy (Sveriges Kommuner och Regioner (SKR), (English: Swedish municipalities and counties) 2017) and the National Plan for the Digitalization of the Swedish School Sector (SKR, 2019). Third, establishment of infrastructure at KTH that enables learning analytics on learning material that is shared with other universities, the first such establishment outside the US.

The **accessibility and digital transformation** research grew out of prior work on socio-technical practices but later several of the senior researchers took on leadership roles within KTH as well as towards society, slowing down the development in this area. However, the earlier research work continued to make an impact in several 'action research' projects, such as establishing how the digitalization impacts the digital work environment for workers in practical settings, commissioned by the Swedish Work environment authority. This work is now turning into international ISO standards and has led to the award-winning Swedish book on "Digitalization and the work environment". We also had several projects aiming to deepen our understanding of how to include people with disabilities in society. In one strand, we designed for homeless people, where many have several cognitive disabilities. Based on our findings, the Statistics Sweden (SCB) will change its procedures of conducting national surveys to better include people with disabilities. We also took part in the formation of Begripsam AB, a company and non-profit organization aiming for increased inclusion of people with disabilities in society. The team was also heavily involved with impacting the digital transformation of society through active participation in politics and policy making. Based on this work several hundred public speeches, keynote addresses at scientific conferences and public debates have been undertaken.

The advancement of **Novel Interaction Techniques** based on AI and Big Data depends on a broad view of those fields that not only operates within the paradigms but also transcends them through interdisciplinary and transdisciplinary work. The key disciplines that we seek to cross pollinate in such a holistic approach are: engineering, cognitive science, human-computer interaction, philosophy and psychology. We study and redesign the ways people interact with AI systems from a humanistic AI approach and make sure we develop technologies that are ethical, sustainable, and compatible with our free liberal democratic society's core values. The work has resulted in a large number of high-impact publications as well as start-up companies such as Mano Motion. Our impact crucially depends on utilizing potentially fruitful but nevertheless relatively unexplored ideas from cognitive science, philosophy and psychology in an effort to go beyond the state of the art.

Quality and quantity of contributions to the body of scientific knowledge

MID members have published at many top (A*) conferences (e.g. ACM CHI Conference on Human Factors in Computing Systems (CHI), International Society for Music Information Retrieval (ISMIR), ACM conference on Designing Interactive Systems (DIS), Learning Analytics and Knowledge Conference (LAK), European Conference on Technology Enhanced Learning (ECTEL), European conference on Computer Vision, IEEE Virtual Reality, and many top journals e.g. ACM Transactions on Computer-Human Interaction (TOCHI); International Journal of Human-Computer Studies; International journal of technology and design education, Cognition, Technology and Work; Leonardo; Computers & Education, Computers in Human Behavior, British Journal of Educational Technology), IEEE Transaction on Affective Computing, IEEE Transaction on Image Processing, IEEE Transaction



(a) (b) (c)

Figure 6. Bibliometric indices for HCTD.

on Multimedia in their respective field of specialization. The quality and quantity of contributions by the division are high. Between 2012-2020, more than 22 publications from the division received best paper/journal paper awards.

Total number of MID publications during the period (conference, journal, book chapters) = 1 321

Total number of MID citations during the period (source Google Scholar) = 48 037

Citation indices for the 23 MID faculty:

H-index: 1-10: 4 people; 11-20: 14 people; 21-30: 5 people; 31 - 40: 2 people; 41-50: 1 people
i10-index: 1-10: 4 people; 11-20: 7 people; 21-40: 7 people; 41-50: 0 people; 51-123: 7 people

Interaction design

1. **Fernaeus, Y**. and Sundström, P., 2012. The material move: how materials matter in interaction design research. In proceedings of the designing interactive systems conference (pp. 486-495). (Citations: 77 In this paper, some first outlines of what has been framed as the material turn in HCI were given.)
2. **Höök, K.** Designing with the Body: Somaesthetic Interaction Design. MIT Press, 2018. (Citations: 105. This MIT Press book defines our take on Soma Design - an aesthetically and somatically grounded approach to designing with our whole selves: body, emotion, thinking and sociality as one.)
3. **Campo Woytuk, N., Juul Søndergaard, M.L., Ciolfi, M. Felice, and Balaam, M**. 2020. Touching and Being in Touch with the Menstruating Body. In Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems (CHI '20). Association for Computing Machinery, New York, NY, USA, 1–14. (Citations: 13. This paper won a best paper award at the ACM SIGCHI flagship conference CHI in 2020. A set of body-close, shape-changing and probing materials were provided to those menstruating as a path to increase bodily awareness.)
4. **Höök, K.** and Löwgren, J. 2012. Strong concepts: Intermediate-level knowledge in interaction design research. ACM Trans. Comput.-Hum. Interact. 19, 3, Article 23 (October 2012), 18 pages. (Citations: 374. The epistemology of interaction design is still in formation. In this paper, we outline ideas for what knowledge criteria to put on design concepts that can go across domains and settings. We name them strong concepts to indicate that they are generative to design beyond a couple of

applications. Example strong concepts are social navigation, seamfulness, trajectories and other such generic design concepts.)

Accessibility

5. **Persson, H., Åhman, H**., Yngling, A. A., & **Gulliksen, J.** (2015). Universal design, inclusive design, accessible design, design for all: different concepts—one goal? On the concept of accessibility—historical, methodological and philosophical aspects. Universal Access in the Information Society, 14(4), 505-526. (Citations: 199. This paper provides a theoretical analysis of the concept of accessibility and related concepts from historical, methodological, philosophical and proposes a concluding proposal of a definition of the concept based on the analysis. The first author Hans Persson was an industrial PhD student at KTH but passed away during the publication of the paper and this important work was published posthumously in honor of Hans.)

Learning technologies

6. **Viberg**, O., Hatakka, M., **Bälter**, O., & **Mavroudi**, A. (2018). The current landscape of learning analytics in higher education. Computers in Human Behavior, 89, 98-110. (Citations: 200. A literature survey on learning analytics)

Novel interaction techniques

7. Lv, Z., Halawani, A., Feng, S., Ur Réhman, S., & **Li, H.** (2015). Touch-less interactive augmented reality game on a vision-based wearable device. Personal and Ubiquitous Computing, 19(3-4), 551-567. (Citations: 298. A novel interaction technique enabling users to interact with the augmented reality games with hands/feet gestures. It was the first time to demonstrate that one could perform 'in air' interaction gestures with both hands and feet on a smartphone. The developed touchless motion interaction technique offers us a new way to interact with virtual objects in the scene.)

Sustainability

8. **Hasselqvist, H., Hesselgren, M., & Bogdan, C**. (2016, May). Challenging the car norm: Opportunities for ICT to support sustainable transportation practices. In Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems (pp. 1300-1311). (Citations: 36. Best paper award at the CHI conference.)
9. **Pargman, D.,** & Raghavan, B. (2014, October). Rethinking sustainability in computing: From buzzword to non-negotiable limits. In Proceedings of the 8th Nordic Conference on Human-Computer Interaction: Fun, Fast, Foundational (pp. 638-647). (Citations: 64. Much work has been criticized for focusing on technological solutions or on altering individual behavior (e.g., "nudging" and "persuasive" systems). This paper shifts the focus from changing individual behavior to supporting sustainable transitions at a societal level.)

Sound and Music Computing

10. Dubus, G. & **Bresin, R.** (2013, December). A Systematic Review of Mapping Strategies for the Sonification of Physical Quantities. PLoS ONE, 8(12), e82491. (Citations: 198. This is the first paper in the field of sonification which systematically investigates a large corpus of publications (179) and provides both quantitative and qualitative conclusions and guideline that can be used by researchers and designers when implementing new sonifications.)
11. Eerola, T., **Friberg, A., & Bresin, R**. (2013, July). Emotional expression in music: contribution, linearity, and additivity of primary musical cues. Frontiers in psychology, 4, 487. (Citations: 99. This

is the first paper that analyses in a systematic way the effects that primary music cues have in characterizing the communication of emotional expression in music. Results provided the ranked importance of the cues and their linear contributions to emotions. The study is based on quantitative results previously published in Cortex by Bresin & Friberg (2011).)

Engagement in national and international research collaboration within academia and its outcomes

The **interaction design** team has strong ties to other design teams across the globe, especially concerning soma design, female health, and hybrid crafting. For example, a range of workshops on Soma Design have been organized at the ACM SIGCHI flagship CHI conference, and we recently organized a special issue of the TOCHI journal on female health (Spring 2020). We are a partner in an EU Initial Training Networks (ITN) project on mental health with groups such as Corina Sas at Lancaster University. Höök is also editor in chief of the TOCHI-journal - an important journal in the HCI-field. We are furthermore actively engaged in particular with the ACM conferences CHI, DIS, NordiCHI and International Conference on Tangible, Embedded and Embodied Interaction (TEI). In fact, in 2017, TEI was held in Stockholm.

The **MID4S** research team is a central actor in establishing computing and sustainability as a research area in HCI- and ICT research worldwide. The research group regularly submits to and participates in conferences on ICT and Sustainability, including organizing workshops at the ICT4S conference, at CHI and NordiCHI, in organizing the annual two-day Computing within Limits workshop (mini-conference). The team has also organized a one-week workshop and a one-week summer school at the Lorentz Center at the University of Leiden (Netherlands).

The **sound and music computing** team has actively helped establish an international network of researchers through their work on the Sound and Music Computing (SMC) network, organizing an annual conference. The team also helped establish the NAVET center mentioned above. We have established collaborations with the UK through the Arts and Humanities Research Council funded project Listening Across Disciplines, and the EPSRC funded Intelligent Games & Game Intelligence (IGGI) center. Sandra Pauletto is also a Member of the Peer Review College for UK Research Council.

The **technology-enhanced learning** team collaborates nationally with Mälardalen's University (MdH), Örebro University (ÖU), University of Gothenburg, Stockholm's University (SU), and Malmö University. Together with SU and Malmö University, the team is organizing the Nordic Learning Analytics Summer Institute 2021. Internationally we collaborate with universities such as Bergen (Norway), Oulu (Finland), the Open University (UK), Erasmus Rotterdam University (Netherlands), University of Technology Sydney (Australia). The team also has a project-funded collaboration with Kanda University (Japan). Moreover, the team collaborates with Stanford and Carnegie Mellon University regarding Question-based learning (which is being implemented at KTH) and also Athabasca University in Canada.

The **accessibility and digital transformation** team has extensive national and international collaboration. In particular, we are doing research on the accessibility of digital technologies to support the inclusion in working life for people with disabilities with the Nordic countries for the Nordic council of ministers.

With respect to the advancement of **novel interaction techniques** based on AI and Big Data, we have, for example, teamed up with Swedish National Forensic Centrum (NFC) to work on developing multimodal biometric techniques for forensics tools. The objective is to provide effective and efficient means to handle the increased complexity and amount of forensic data to overcome the shortcomings of manual comparison and uni-modal biometry.

Follow up from previous evaluations

RAE 2012 found that the department had: "research output quality that is recognized internationally for the majority of the UoA; outstanding impact and engagement with society for the majority of the UoA; and a research environment that is conducive to producing research quality somewhat above 'internationally recognized' (but not 'world leading') for the majority of the UoA."

The evaluators saw he following weaknesses:

- A potential to improve rigor/depth in the methodologies used, shifting from one-off projects to more structured research inquiries
- Low number of publications
- Lacking a good pace of research projects and outcomes (likely to accelerate as the new faculty get situated and collaborations begin to grow)

As a consequence of RAE 2012 the division immediately established functions, routines and resources for staffing faculty members, resulting in more **evenly distributed faculty funding** for the permanently employed faculty. In 2012, most permanent faculty had no faculty funding attached to their position, which instead went to doctoral students. Currently 20-25% of a full-time equivalent is assigned to each research-active faculty at the division. Through this change, more faculty could spend time on writing funding proposals, engage in research projects, and ultimately, increase research output and impact. An internal role dedicated to supporting faculty when writing funding proposals has also been established.

The division also established a plan for **increasing publication impact** through targeting high impact journals, international collaboration and high impact conference venues.

To further foster the academic culture, we have since 2015 introduced so called **writing camps**. They are 2–3-day internal conferences held twice a year dedicated to writing articles and grant proposals. This has had a significant payoff in terms of accepted publications and funding proposals.

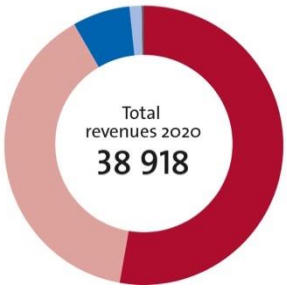
Newly employed assistant or associate professors have been provided with funding for a postdoc each.

3. Viability

Funding; internal and external

Department of Human Centered Technology

Sources of research income (2012, 2016, 2020)



Research income, kSEK	2012	2016	2020
Government grants for research and doctoral studies	21 528	18 925	20 571
Collaborative research funding	17 320	11 956	15 175
Contract research funding	0	0	2 567
Other revenues	3 954	2 058	604
Financial income	2	2	1
Total revenues	42 804	32 941	38 918

Figure 7. HCTD research income.

Internal research funding: The internal research funding has increased to by approx. 894 KSEK (88.4 KEUR) per year. During 2014 and 2016 funding increased as we had recruited more faculty resulting in more funding from KTH.

External funding: The seven largest external funding agencies between 2012-2020 are (in order of

funding): (i) VINNOVA (Sweden's Innovation Agency). (ii) Stiftelsen för Strategisk Forskning (Swedish Foundation for Strategic Research). (iii) EU. (iv) Vetenskapsrådet (Swedish Research Council). (v) Energimyndigheten (Swedish Energy Agency. (vi) Wallenberg Foundations. (vii) Forskningsrådet för arbetsliv och Socialvetenskap (Swedish Research Council for Health, Working Life and Welfare). A detailed analysis of the sources of funding for HCT/MID indicates that the four largest funding agencies are relatively stable. The Swedish Energy Agency has provided an increasing funding scheme since 2014 following the increasing focus on sustainability practices. Figure 7 summarizes the HCTD research income evolution.

Overall, HCTD has landed fewer small grants during the last four years and instead more large-scale projects. This in turn means we are able to fund more doctoral candidates – increasing by 6 doctoral students in 2020. Overall, our funding has grown a lot (on average 0.750 MSEK annually) since 2012. For example, we secured 80% more external funding in 2019 compared to 2012. As the division went through a generation shift in 2012, the new faculty that came in have been eager to grow new groups and directions of research, showing proficiency in applying for grants. Indeed, for 2020 we have even more grants awarded: 16 new grants with a total external funding of 30 MSEK spread over the coming years.

The division is co-funding external resources, when necessary, for example European Institute of Technology (EIT) funding, where KTH is a member, as well as the Wallenberg grants where only a limited overhead is allowed.

Academic culture

The research in this Division has grown out of the participatory design traditions rooted in seminal projects such as UTOPIA[1] and it has maintained and renewed the focus on creating useful digital tools and exceptional user experiences in close collaboration with users and other stakeholders. There also entailed a strong political and ethical agenda. Although the department has undergone a major generation shift since the last evaluation the core values are still present and has further deepened which can be seen based on the vast number of projects and PhD doctoral thesis relating to user-centered development, interaction design for meaningful user experiences, sustainability, transformation of media, and designing with ethical concerns.

The research is highly transdisciplinary, involving disciplines such as engineering and computer science, behavioral and social sciences, design and the arts/crafts, medicine and health. The research is also impact driven in that it wants to deal with the important and emerging problems in the society that we face today, such as sustainability, equity, inclusion and engagement. A lot of the research done and the researchers involved are engaged in collaboration with industry and the society at large, creating startups (e.g., Forsslund Systems, Manomotion) and fostering innovation, focusing on sustainability, influencing international standardization and shaping the digitalization of the society through politics and policy making.

Our research environment is inclusive, covering many different disciplines, not hesitating to explore novel unorthodox disciplinary collaborations and topics such as: engaging with designing singing drones for the opera stage; designing for bodily awareness of menopausal women; sharing what it feels to sing through a shape-changing corset; or designing systems for debriefing jet fighter pilots. It is also inclusive in the sense of research touching people with diverse abilities or from underprivileged

[1] UTOPIA was a unique project in the 1980ies in parts responsible for innovating the whole participatory design movement – today often referred to as user-centerd design. Sundblad, Yngve, 2010, UTOPIA - Participatory Design from Scandinavia to the World, In: History of Nordic Computing 3 / [eds] John Impagliazzo, Per Lundin, Benkt Wangler, Berlin, London: Springer Publishing Company, 2010, p. 176-186.

backgrounds, e.g., research on mobile phone use in poor countries. It is a truly international research environment, strongly engaged in the international community with active participation in community building in ACM SIGCHI, NordiCHI, IFIP Conference on Human-Computer Interaction (INTERACT), TEI, LAK, Sound and Music Computing Conference, NordicSMC, ISon.

The close collaboration with the education is key to success where all faculty are involved in both research and teaching and students are frequently engaged and invited to be parts of our research projects.

Finally, there is an increasing focus on research quality both in publication strategy and research funding based on peer mentoring and support for growing the quality and self confidence in focusing on the right publication venues for the particular research.

As mentioned elsewhere we foster the academic culture by organizing writing camps twice a year, all doctoral students are disseminating their research accomplishments, as part of the education, annually, and we work in teams who have specific vision statements and research agenda. Besides these activities we also have monthly workplace and faculty meetings.

Current faculty situation

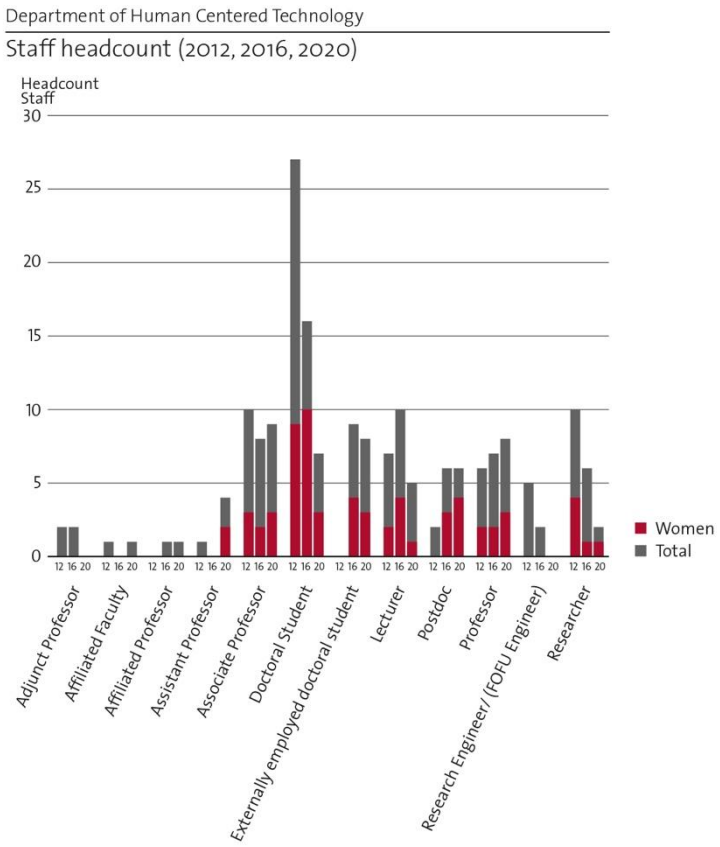


Figure 8. Faculty and research personnel at HCTD.

Figure 8 summarizes the faculty and research personnel situation at MID. The MID-division has eight full professors, all 50+. Three are women. Three of the full professors currently have management appointments with limited to no research time, thus the full-time equivalent should be approximately five full-time professors.

Out of the 13 associate professors, five are female. The associate professors age range is about 35-58 years. All but two are docents. Two to three have the qualifications to become full professors within five years.

We have one newly (2020) recruited female assistant professor.

The recruitment of doctoral candidates, post-docs and researchers typically follows on landing external grants and are therefore based on the needs of the project.

For the upcoming 5-10 years it will be important for the division to recruit more assistant professors in the range around 30+ years in

order to follow a sound progress of promotion. We believe that research topics such as Media Technology and HCI are important for both Swedish competitiveness and technology development in general. We expect another strong boost for these two research topics.

Recruitment strategies

Since 2016 we have recruited:

- Three associate professors: Interaction Design, Communication, Media Production;
- Five assistant professors: two in Sound and Music Computing, one in Sustainability, one Technology Enhanced Learning, one in Interaction Design. We are currently shaping a position for one more assistant professor.
- Nine post-docs.

All recruitments have been made in open competition resulting in hiring international and external candidates.

From a staffing perspective we are in need of more faculty positions, especially to cover “Technology Enhanced Learning”, “Human-Computer Interaction” and “Digital transformation”.

Equal opportunity: we have policies for how much time permanent faculty positions are funded as well as how much teaching their position includes. All faculty who are employed at and funded via MID on a full-time basis are guaranteed 20% faculty time. Docents get 25% of their time funded by the faculty. Professors are required to teach at least 20% of their time. Associate professors teach minimally 40% of their time.

Infrastructure and facilities

The Department has several unique facilities that support our research practice as well as our undergraduate teaching:

MIDDLA is our physical interaction design lab, including a range of tools and equipment of relevance to making interactive physical artefacts. This includes 3D-printers, a laser cutter, materials for working with electronics as well as basic mechanics, smart fabrics, conductive materials, a knitting machine, and materials for making in general. The availability of this space and equipment is of fundamental value for research projects as well as in teaching, which is increasingly based on physical as well as electronic and computational design work. The lab space has been expanded and improved significantly since RAE2012. The current setup, with a dedicated room next to our offices, opened in February 2019. We frame MIDDLA as a feminist maker space, engaging with inclusivity and design for all.

The **Visualization Studio, VIC,** at KTH hosts state-of-the-art technology supporting high-end graphics and visualization of complex data over many platforms, from hand-held mobile devices to wall-sized 4K displays to immersive augmented and virtual reality environments. It supports cutting-edge interaction including gesture- and speech-based control, haptic feedback, eye tracking, and multitouch. VIC benefits from its tight coupling with the supercomputing center (PDC) at KTH, which, for example, houses Beskow, one of the fastest supercomputers in Scandinavia. The studio is a research environment with modern technology for visualization and interaction where students, researchers and industry meet. The studio opened at the end of 2011, and since then has continued to host various activities, such as workshops, lectures, events and talks. The visualization studio is used as an education and lab environment for researchers and students who want to explore the technology and its uses, and thus many courses take place partially or completely in the studio.

The **Multisensory studio** is a space for various perceptual experimentation. It has surround-sound capabilities (8 channels) and infrared cameras (16) in order to investigate and capture the relation between sound and movements (OptiTrack motion capture system by Naturalpoint). The room also has a one-way mirror which makes it ideal for doing a variety of experimental research including usability studies. The Multisensory studio is used for both research and educational activities including lab sessions and projects in courses, Bachelor's and Master's thesis projects.

The **HapticLab** has haptic interfaces ranging from tactile vibration in mobile phones to robotic systems that allow users to feel and manipulate 3D graphical objects as if they were real physical objects with material properties such as weight, texture, softness, or magnetic forces. In the Haptic Lab more than 15 haptic devices such as the high-resolution devices Touch X and Geomagic Touch are used. The haptic Falcon devices are used in the courses by students in the computer rooms at KTH. A haptic device called WoodenHaptics has been developed in the Haptic Lab now available from the HCT/MID spinoff Forsslund systems AB.

4. Strategies and organization

Goals for development 5–10 years ahead

HCTDs objective is to create new technological opportunities that improve and develop our practices and quality of life. Our starting point is that technology and human experience are mutually influencing one-another and the knowledge on how to shape those interactions are of key importance – to society, to industry and to users. We expect to grow in size in order to cover the many different research areas that KTH is expected to contribute to and be able to teach. Let us outline a few areas where we see that HCTD should and can contribute:

In **interaction design,** we will continue to focus on soma design and in particular mutual touch. Touch has a deep emotional psychological signification; it is one of the underpinning experiences to all areas of human development. In a survey on the expectations on the 'Internet of the Senses' done by Ericsson, six out of ten believe that by 2030 we will be able to mediate the feeling of almost anything, from something as simple as a ball to the skin of another person, including experiencing the texture, heat, weight or motion. Beyond mediating digital objects, our vision is interactive applications that designers can shape to self-modify their physical properties – their shape, color, stiffness, temperature, texture or permittivity – in response to our bodily rhythms, movements or biochemical changes on or inside bodies, thereby creating touch-based interactions that unfold and proactively adapt over time. To turn those predictions into reality, a deep, well-grounded understanding of human morphology and meaning-making processes is needed. More importantly, the whole design process needs to shift from the contemporary predominantly symbolic, language-oriented stance in interaction design, to an experiential, felt, aesthetic stance permeating the whole design and use cycle. Here, we aim to explore how different modalities, including haptics, change-changing materials and sound, may help to make the future internet experience richer – not the least to enable distance working, health or simply pleasures and enjoyments as part of our everyday life. A particular application domain of interest to us is women's health. Through our explicit feminist soma design stance, we aim to continue to address the undervalued, taboo topics around female bodies. We are also developing novel wearable materials in collaboration with researchers in material science and sensor networks – often using machine learning to connect input and output modalities.

In fact, one of the contemporary changes in society follows in the wake of the introduction of artificial intelligence and machine learning. These technologies increasingly influence people's work and everyday life practices. There is growing concern around ethics, automation of work, surveillance, or privacy issues. We recently got funding from the WASP-HS to explore how ethics unfold between autonomous systems and people. Our starting point is exploring how autonomous technologies and

interactions encourage certain movements, certain aesthetic experiences, certain practices and responses, while discouraging others. The argument driving this work is that it is precisely in that interplay – in those movements and adaptations of behaviors – that ethics is enacted and enforced. As such, ethics is not a bunch of abstract principles residing in committees and institutions, nor is it something that can be described in terms of individual, rational, decision making. Instead, ethics is situated in and enacted with our somas – our concrete, practical, everyday lives – and thus requires considering ethical disruptions in specific corporeal ways. Two doctoral students have been recruited and their projects focus on exploring ethics and drone design. In another project, funded by Länsförsäkringar, a doctoral student is focusing on transparency in algorithms in the insurance domain.

The change towards a **sustainable society** is possibly the greatest global challenge of the 21st century. As climate and other challenges mount, more political effort as well as money for research has become available. We assume that these trends will continue and that the sustainability research group will be able to contribute to generate new knowledge and develop socio-technical solutions pertaining to the transition to a more sustainable society. In a recently started research project that visualizes energy footprints of modern lifestyles, group members cooperate with artists from the Royal Academy of Arts and the People's Movements for Art Promotion. This project has been invited to exhibit Augmented Reality installations in the permanent exhibition of the Swedish pavilion at the upcoming 2020-2021 World Expo in Dubai. One goal for the coming years is to continue to explore questions relating to sustainability at the intersection of interaction design and art. Three doctoral students have been recruited to the group (to work in projects pertaining to transport, energy and food) during 2020 and the goal for the next five years is to add on faculty position with a specialization in sustainability and to draw in project funds that would finance at least one doctoral student or postdoc per year.

In **sound and music computing** research we aim to further our understanding of human communication and interaction through sound and music in order to embed them as a natural part of everyday technology. To this end we are developing an approach that we have termed Historically Informed Design (HID): understanding existing music instrument and sound design traditions and practices by learning from the past to inform and develop new digital instrument and sound design tools for the digital society. We are also using sound design, sonification (the representation of data through sound), interaction design and media production to develop ways to imagine, experience and evaluate the soundscapes of the future taking into account transformations related to sustainability, energy efficiency, digitalization, automation, and AI. Finally, we are investigating the ethical implications of AI applied to the arts by extending previous research on ethics of AI in the context of music. VR, WASP, Swedish Energy Agency, Hakon Swenson Stiftelsen, and Swedish Post and Telecom Authority (PTS) are all recent sources of funding. In early 2021 we are further extending our group by three doctoral students, reaching a size of 18 members.

In **technology-enhanced learning** research, our current focus is on the rapid digital transformation of education, where the use of student data is crucial for providing improved conditions for (personalized) learning and continuous improvement of learner support and teaching. One goal for the upcoming years is to continue to explore questions relating to learning- and teaching analytics at the intersection of learning sciences, computer sciences and HCI. This also includes the largely unexplored area of learning analytics with respect to privacy of student data. One of our goals is to perform research on how to enact a responsible use of student data in education. A second goal targets the increased need and interest in developing and sustaining effective architectures for student learning in increasingly emerging online distance educational settings (not the least due to the recent pandemic, but also for sustainability reasons).

For the **accessibility and digital transformation** topic, our current focus is on the digital transformation of society. Many organizations are undergoing tremendous change due to opportunities

offered by digitalization. The field of Human Computer Interaction, with its focus on user-centered iterative and agile development, and Media Technology, with its focus on communication, reception, retrieval and media distribution, has much to offer to make this transition smoother. By adopting human-centered methodologies when introducing digitalization practices, a more sustainable, inclusive, engaging and secure society can be achieved. But these require knowledge on how to design for good user experiences, as well as deep material knowledge on limitations and possibilities of technologies and media expressions -- especially as many of these are in constant flux. We need to derive new knowledge and educate our students to actively take part in this transformation, hence we need to have strong competence in digitalization and digital transformation as part of our research.

The advancement of **Novel Interaction Techniques** aims to meet some of the complex challenges introduced by AI and big data – ranging from those pertaining to mathematics and engineering to challenges of philosophical and psychological natures. In our estimate the research field will increasingly move towards approaches that are holistic and consonant with ours. Our aim is to be a significant player in the evolution of those approaches, to pioneer them and to apply our insights in, not only research and industry, but also in education.

Congruence with university-level goals for “A leading KTH” as set out in KTH´s “Development Plan 2018-23” (page 5)

The research at HCT aligns with the core areas in KTH development plan:

A leading KTH

- We have a truly international research group, both when it comes to faculty and students
- Several of our faculty have been invited to sabbaticals at different international colleges and universities (Stanford, Williams College (www.williams.edu), Florida Atlantic University, University of California, Santa Cruz (UCSC))
- Internationally our most respected researcher Kristina Höök was awarded the ACM SIGCHI CHI Academy award in 2020

A KTH for a more sustainable world

- An increasingly important domain within Media Technology and Human-Computer Interaction generally, and more specifically in our research we focus on social but in particular ecological sustainability

An equal opportunity KTH

- We are an almost 50-50% gender balanced division
- The gender perspective is vivid in our research and teaching, for example, we explicitly refer to our makerspace MIDDLA as an open, non-hierarchical research and education facility where researchers and students can explore and develop innovative technology together and where we facilitate designing with intimate technologies and aims engaging with feminist theory on making

A KTH for a more digitalized world

- Is a key topic in our research – for the transformation of society, for accessibility, for the transformation of industry
- The NAVET center is expanding our perspectives through bringing in the art perspectives on research and societal aims.
- We engage in the KTH Center for Cyber Defense and Information Security, Digital Demo, KTH Digital Futures and digitalization politics

Finally, HCTD/MID is following the general KTH recommendation to publish under Open Access.

Leadership structure and collegial structure

The division is led by a division head and a vice head. The MID leadership group comprises the head and deputy head of Division, faculty members with responsibility for educational programs, and other representatives of the faculty, including a doctoral student representative.

HCTD has a director of studies and a director of graduate studies. The division has monthly staff meetings and regular faculty meetings. The doctoral students meet regularly. The division has several regular seminar series where research topics are discussed.

Strategies for high quality

Doctoral students

- Progress is monitored through the Individual Study Plan (eISP).
- All students are required to hold a seminar at 30, 50 and 80% level.
- There is a yearly mentor meeting where all students get to see a supervisor other than their own
- All students have at least two, often three supervisors.
- Courses given to doctoral students are evaluated in course evaluations upon which a course analysis is written.
- The division has a dedicated head of doctoral studies.
- Before sending the thesis for printing, a senior researcher at the division will make an “internal” review of the text.
- At the defense, external experts, often recruited internationally serve on the thesis committee alongside an opponent that leads the defense, asks questions and put a perspective to the research done (but the opponent does not get to vote).
- The quality of the research by the doctoral student is in the normal case also assured by having substantial parts of the work published in peer-reviewed publications prior to the doctoral defense, although this is not a formal requirement.

Research quality

- The division aims for high quality international conferences and journals, with peer review – often in conference proceedings.
- The division pays for open access.
- Internal peer review of papers before they are sent is common practice, or engaging in writing camps or writing workshops where researchers reads and comments on one-another’s drafts.
- The division several internal seminar series with internal as well as invited speakers.
- Quality is privileged compared to quantity: the publication of few articles of high quality per year is strongly encouraged, whereby the content of the articles is elaborated over longer periods and cultivated to avoid marginal or incremental contributions.
- Collaboration with national and international highly competent researchers is encouraged for what concerns the most forefront topics or high-risk research.
- At HCTD, a senior researcher is supporting the division’s PIs in writing grant proposals and in general organizing writing retreats, bringing in best practices for the improving quality of writing, which venues to publish in and similar. In terms of outcome the service seems to be effective as HCT has been endorsed with more external grants during the last couple of years.

Faculty development

- Promotion to associate professor is seen as the target for all assistant professors and they are coached in this process.

- Promotion to “docent” is encouraged for all full-time faculty
- Promotions function as reviews and quality assurances of individual researchers, a process which involves both a faculty committee and external experts
- The promotion to full professor is endorsed by the EECS school only for candidates that effectively drive their own independent research agenda, in a new sufficiently distinct area from the “parent group”. The candidates should also have taken an active part in management, development and/or operation of education in the first cycle, second cycle and third cycle. Here, we believe more could be done to make promotions better suited to our needs, to the needs of faculty to see a path towards independence.

Industrial & societal impact

- As industrial impact is a significant strength of many of our research groups, we should also establish a better way to assess research and innovation impact for future research assessments.

5. Interaction between research and teaching

1st cycle courses – BSc-level: On 1st cycle studies we introduce research results in lectures and assignments. Most Bachelor’s thesis projects are connected to our research themes.

2nd cycle courses – MSc-Level: During the 2nd cycle studies we often teach students latest insights from our own research, and we also integrate students in our research endeavors. For example, one of our design courses is based on the Soma Design research, involving students in projects where movement is the basis for design. This course and how we do our teaching is described in a paper, Teaching Soma Design, at the DIS 2019-conference (winning an honorable mention award). Based on this description, a similar course will be given at Bauhaus universität in Germany, at Uppsala University and at Chalmers in Gothenburg. As a parallel example, strategies on how to involve students in research in Sound and Music Computing were presented in a paper at the Nordic SMC conference in 2019.

Another example of a course tightly linked to our research endeavors is a much-appreciated project course focusing on research challenges, where all project proposals are formulated by the faculty. This course often sets the background for MSc-thesis work. Our aim is that many MSc-theses should be done in close collaboration with research projects. We are proud that several MSc-theses have later led to publications in the highest renowned venues of our field -- even winning best paper awards, see example list below.

As one of our research teams focused on technology-enhanced learning, we also have a strong interaction between 1st and 2nd cycle teaching and research on a very practical level. One unique example, arising from our research in learning, is our “walking seminars”: by transforming an on-campus course into a blended course, we were able to conduct seminars outdoors in nearby nature while walking. These walking seminars were evaluated and the results indicate that discussions, sense of well-being and the general quality of the seminar improved, regardless of how physically active participants were the rest of the time. These walking seminars lead to interviews in KTH-local magazine and a KTH press release. Thereafter followed interviews in several magazines and newspapers including radio. KTH made a promotional video with 100.000 views on Facebook. A short segment of the video was included in KTH’s promotion of Master’s degree programs (study at KTH and you may walk with me). This led to more interviews and invitations to other universities (Linköping, Umeå, Luleå) and Akademiska Hus.

A number of Masters students’ dissertation projects result in publications at top-tier venues, e.g.:

- **Aronsson**, S., Artman, H., Lindquist, S., Mitchell, M., Persson, T., Ramberg, R., Romero, M., ter Vehn, P. (2019) Supporting after action review in simulator mission training: Co-creating

visualization concepts for training of fast-jet fighter pilots, The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, vol. 16, no. 3, pp. 219-231, 2019. Citations: 1

- **Bergsmark** M, Fernaeus Y. From Patchwork to Appliqué: Reflections from an Interaction Design Remake. In Proceedings of the TEI'16: Tenth International Conference on Tangible, Embedded, and Embodied Interaction, 14 February 2016 (pp. 236-244). Citations: 4.
- **Campo Woytuk**, N., Juul Sondergaard, M.L., Ciolfi Felice, M. and Balaam, M., 2020. Touching and Being in Touch with the Menstruating Body. In CHI 2020. *Best paper award***.** Citations: 13.
- **Eriksson,** S., Unander-Scharin, Å., Trichon, V., Unander-Scharin, C., Kjellström, H. and Höök, K., 2019, May. Dancing with drones: Crafting novel artistic expressions through intercorporeality. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (pp. 1-12). *Honorable mention award*. Citations: 15
- **Eriksson**, S., Höök, K., Shusterman, R., Svanaes, D., Unander-Scharin, Å., Unander-Scharin, C. 2020. Ethics in Movement: Shaping and Being Shaped in Human-Drone Interaction, In CHI 2020. *Honorable mention award*. Citations: 11.
- **Gaissmaier**, M., Karlsson, A., Aschan Eriksson, S., Kosmack Vaara, E., Komazec, K. and Fernaeus, Y., 2020. Designing for Workplace Safety: Exploring Interactive Textiles as Personal Alert Systems. In Proceedings of the Fourteenth International Conference on Tangible, Embedded, and Embodied Interaction (pp. 53-65). Citations: 1.
- **Parviainen**, E. and Juul Sondergaard, M L, 2020. Experiential Qualities of Whispering with Voice Assistants, In CHI 2020. *Honorable mention award*. Citations: 4.
- **Windlin**, C. and Laaksolahti, J., 2017. Unpacking visible light communication as a material for design. In Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems (pp. 2019-2023). Citations: 3.

3rd cycle courses – Doctoral-level: For the 3rd-level courses, a program committee suggests, reviews and funds three to four doctoral level courses every year. These doctoral level courses may either be suggested by doctoral-students or by faculty. The content and the number of doctoral courses are negotiated between doctoral-students and supervisors. --

The first general study plan for the doctoral program was established in 2010. An updated general study plan was established in 2017. All doctoral students receive information about the general study plan when they are admitted to the doctoral program and continuously at tutorials, for example in connection with preparation and updates of their individual study plan.

The doctoral students update their individual study plans every year, which are reviewed by the supervisors and those responsible for the doctoral program. The doctoral students hold 30%, 50% and 80% seminars that constitute important phases in the doctoral steps. At 50% and 80%, an opponent must review the doctoral student's research work and discuss this with the doctoral student at the seminar.

The program council for the Mediated communication program ensures the quality of the doctoral program and constitutes a platform where teachers and doctoral students can influence and develop the program in a continuous ongoing dialogue. The program council plans which courses are to be given and when it is appropriate to give certain courses depending on the phase of the doctoral student work in which the various doctoral students attending the program are. The program council reviews and provides feedback on all course descriptions for new courses before they are approved. The budget for the coming year is reviewed and anchored in the program council. The annual group supervision activity "Supervisory panel" is planned in the program council. All supervisors, including assistant supervisors within the doctoral program, participate in the group supervision meeting. This is an important competence development activity in the department.

Learning objectives: For the two subjects *Human-Computer Interaction* and *Media Technology* included in the doctoral program *Mediated Communication*, concretizations of the respective learning objectives that are advocated in the Higher Education Ordinance are outlined in the study plans. These study plans also describe how these learning objectives are to be achieved.

To achieve the learning objectives, the doctoral program offers a compulsory course, FDM3514 *Research methods in media technology and human-computer interaction* and a large number of elective courses. The course FDM3506 *ICT and sustainability* is strongly recommended to the doctoral students in the program. Doctoral students are also encouraged to take broad courses in academic writing held at KTH. A course FDH3378 *Dis-Course* has been specifically designed to give doctoral students the opportunity to practice planning and writing and defending their doctoral dissertation. In this course, the doctoral students read dissertations that will be presented in the near future by other doctoral students in the department or at other universities. The doctoral students under the supervision of a senior researcher examine and discuss strengths and weaknesses in the dissertation and then attend each dissertation. This trains the doctoral students in how to present research results and how these are then communicated to other researchers and to the public. An additional instrument that ensures that doctoral students practice planning, conducting and presenting their research is the mandatory presentations that doctoral students give when they have completed 30%, 50% and 80% of their dissertation work, respectively. At 50% and 80%, an opponent must also review the doctoral student work and discuss this at the seminar with the doctoral student. The learning objective of judgment and attitude is achieved partly through the compulsory course FDM3514

Ethics: The course *Research methods in media technology and human-computer interaction* explicitly addresses criteria for how ethically correct research is conducted are included as a course element. Ethical principles and attitudes are also addressed in the elective courses. The subjects *Media Technology* and *Human-Computer Interaction* have historically had a strong ethical focus as research on how technology affects people and society in general has always been considered important.

Sustainability: Media technology and in particular human-computer interaction are areas that for several years have focused on social sustainability by focusing on user inclusion in the design of new artifacts. An analysis is also made of the consequences of systems for people in society and how technology can support different groups of people in their daily lives in different contexts. Today, there is an assistant lecturer with a focus on Human-computer interaction and environmental sustainability. In the third cycle course DM3506 ICT and Sustainability given to doctoral students' sustainability aspects are discussed and doctoral students reflect on sustainability related to their research projects.

Diversity: Of the active doctoral students who were registered in 2021, 35% are women. For these doctoral students, 31% of the main supervisors are women.

Supportive activities: In the doctoral program, a so-called *Supervisory panel* is held annually, where each doctoral student is given the opportunity to discuss their supervisor situation and the development of the dissertation with two senior researchers who are not part of the regular supervisor group. Other activities where doctoral students can discuss their research are during the *Writing camps* organized twice a year. Both faculty and doctoral students bring drafts of articles or funding proposals that they want feedback on. The idea is that you have an intensive writing activity in combination with the opportunity to get feedback on your work and read other's work. The department has got several funding proposals accepted and has increased publishing during this period, which may be an effect of this activity. At these camps, workshops are also held with specific focus areas such as sustainability.

A forum for doctoral students and supervisors has been created in the tool Canvas where the annual planning for the doctoral program is clearly visible and where agendas for meetings and other relevant

material can be posted continuously. This forum functions as a common digital workplace where drafts of ideas for future courses can be posted before they are completely formalized. Doctoral students can also plan social activities through this forum.

In the program council, recurring activities are planned that are arranged by doctoral students for the doctoral student group, which are financed by the doctoral program. Students are supported in arranging activities that they find relevant to their dissertation and that also build a social cohesion. Such an activity is called an *Exit seminar* where a recently defended doctoral student talks about his or her experience of doing a doctorate in the department for those doctoral students who still have more or less long time left of their doctoral studies.

6. Impact and engagement in society

Relevance of research to society at large

Our research has had a strong impact on society in many different ways: through direct collaboration with industrial and societal actors; through spin-off companies; through policy making; etc.

In the **interaction design** research projects we have, for example, worked directly with industry partners such as:

- Electrolux in 2018: together we explored how Soma Design could be used to design everyday products, such as blenders, vacuum cleaners, and so on.
- Google in 2017: through a grant from Google, we were collaborating with Alex Olwal on designing novel sensor-network based interactions on or around the body
- Samsung in 2019: we have developed new concepts for Samsung 'ONE UI' for Samsung Galaxy phones. Drawing on findings from that project about how AI and user interfaces can be combined, this collaboration has started to outline 'post-app' user interface (UI) design methods

Earlier, as the interaction design research team was heavily involved with Mobile Life, we worked tightly with both industrial partners and municipalities. While Mobile Life discussed the consequences of both the proliferation of mobile services and the internet of things, Professor Kristina Höök provided advice for the infrastructure minister, input to various official inquiries into new laws such as the new law related to privacy or the one on digitalization. See http://mobilelifecentre.org.

The **sustainability** research has been, for example been working with:

- Several small start-up companies on the development and evaluation of sustainable services and apps for climate action such as Budkeep, Habits, Consupedia, and Deedster.
- Starting 2020 collaboration with the non-government organization Omställningsnätverket (the Transition Network Sweden), and municipalities and regions, in particular Länsstyrelsen i Västernorrland (English: County Administrative Board in Västernorrland) and Ragunda Kommun (English: Ragunda Municipality). Huddinge, Örebro and Linköping municipalities have been partners in projects addressing sustainable urban play environments. Collaboration with The Swedish Association of the Visually Impaired (SRF) and The National Agency for Special Needs Education and Schools (SPSM) in research addressing inclusion in school contexts.
- Through the research at CESC, the group did research with companies such as Ericsson, TeliaSonera, Coop, and the Interactive Institute. In this research also Täby municipality, City of Stockholm, and Stockholm County Council were involved.
- The group has also collaborated with several design companies such as NoPicnic Design (www.nopicnic.com) in a project regarding photovoltaics, Futerra regarding the workshop material Målgruppsarenan, and Propeller in relation to the project A Car-Free Year. Collaboration with Axess

Lab and Forsslund Systems in inclusion research. In projects addressing sustainable urban play environments, URBIO, Nordic Parks, HAGS, Prisma Tibro, NCC, HiQ and ST Solutions.

The **sound of music computing** research team has, for example, been working with:

- Swedish Museum of Performing Arts: Sound forest and other installation.
- Volvo Cars, in collaboration with Windows and Bower & Wilkins: We participated in the three main auto exhibitions (New York, Shanghai, Geneva) with a public of more than 2 million. We created a sound design tool that was used by the visitors for around two months.
- Sony: since 2018 we are working with Sony and the UK IGGI (Intelligent Games and Game Intelligence) Center in a project on procedural audio for games.
- Special schools: research on active listening.
- Collaboration with Culture Associations in Crete (Greece) for UNESCO Intangible Heritage application of local traditional dance (Example: https://youtu.be/4XtoAa2pTzY).
- Swedish Music Industry: we organize an annual meeting, called X-day, together with Royal College of Music (KMH) to which main partners from the Swedish Music Industry participate (i.e., Dolby, concert halls, Electrolux sound design, Genelec). The main is to connect research from KTH and KMH to companies.
- Creative Industries: we have a large network of collaborations with media professionals and SMEs (e.g., Foleyworks, The Foley Barn, The Audio Suite, etc.), designers and artists (digital artists Mark Fell, Laurence Payot, Ambrose Field, film directors Erik Gandini, David Hickman)
- The connection with academic art institutions and creative industries facilitates the collaboration with large networks of artists and designers.

The **technology-based learning** research team has for example, been working with:

- Swedish Association of Local Authorities and Regions: We contributed to the evaluation work (digital voting process) related to the development of a national digitalization strategy for the educational system in Sweden during 2019. We have also investigated possible digital solutions and digital learning platforms that can be used for teaching Swedish for Immigrants on a national level.
- Natur & Kultur (Member of the Research Board)
- Edtech companies: we collaborate with (1) Advania designing and validating an instrument to measure K-12 teachers' preparedness to use digital technologies in schools, (2) Mathleaks AB examining how we can effectively integrate mobile technology in teaching mathematics in Swedish high schools, and (3) Collaboration with Swedish for Professionals and Språkkraft.

The **novel interaction techniques** research has for example, been working with:

- National Forensic Center (NFC) on developing multimodal biometric techniques for forensics tools. The objective is to provide effective and efficient means to handle the increased complexity and amount of forensic data to overcome the shortcomings of manual comparison and unimodal biometry. The goal is to make the developed tools usable in forensic applications.
- We are working with Skogstekniska klustret, Vattenfall, Mellanskog, Boxholms Skogar, Räddningstjänsten Östra Götaland to develop intelligent digital twins for i) forestry and long-term environmental monitoring and ii) time-critical wildfire detection and firefighting in rural areas.

Research dissemination beyond academia

HCTD reaches outside academia in many different forms: startups; patents; standards; industrial practices; and through media appearances. Let us provide a few examples in each category.

Startups

- Manomotion AB: a computer vision company which offers precise hand tracking and gesture recognition technology in 3D-space simply using a 2-D camera - available on any smart device.
- Begripsam AB: Focusing on accessibility for people with cognitive disabilities and particularly for homeless people. Showing how people with cognitive disabilities use digital tools and how digitalization may improve their quality of life, currently with 7 full-time equivalent (FTE) employees. The Begripsam Association was formed with people representing the target population, to focus on Accessibility for people with cognitive disabilities, with close to 90 people on the payroll. Additionally, the research made the government increase its focus on Digital Inclusion and changed the way that Statistics Sweden (SCB) conducts its annual services to get a more representative sample of the population with all its capabilities. The work has also resulted in an ISO standard on IT for Cognitive Disabilities.
- Yohoo AB: founded by doctoral student Bin Zhu, creating tools for mindfulness practices.
- BioSync Technology AB: a stress management system developed by Kristina Höök was turned into a startup in 2015
- Forsslund Systems AB: Jonas Forsslund was a doctoral student at HCT/MID, with Professor Sallnäs as head supervisor. One of his main contributions is the WoodenHaptics system, which is now being commercialized by the Forsslund Systems spinoff. WoodenHaptics provides an open-source, open-hardware module-based kit that allows an interaction designer with little electro-mechanical experience to manufacture and assemble a fully working spatial haptic interface. The Haptic Lab software has been developed continuously in several application areas such as support systems for multi-disciplinary clinical team meetings for liver surgery planning, oral surgery training using haptic simulation systems, haptic systems supporting co-manipulation tasks and assistive technology supporting visually impaired pupils in school.

  Forsslund, J., Yip, M., and Sallnäs, E-L. (2015). WoodenHaptics: A Starting Kit for Crafting Force-Reflecting Spatial Haptic Devices. Proceedings of the Ninth International Conference on Tangible, Embedded, and Embodied Interaction (TEI'15). ACM, New York, NY, USA, 133-140. Citations: 23

  Patents: Shahrouz Yousefi, Haibo Li, Real-time 3d gesture recognition and tracking system for mobile devices, WO2015102527A1, World Intellectual Property Organization (WIPO) Patent Cooperation Treaty (PCT).

Standards: Jan Gulliksen, Åke Walldius (now retired) and Stefan Johansson have contributed to international standardization within ISO Ergonomics standardization.

Industrial Practices and Understanding: Jan Gulliksen headed Sweden's Digital Commission between 2012-2016 writing 6 Statens Offentliga Utredningar (SOU) (English: The government's official investigations) advising the last 5 ministers of digitalization for the ministry of the enterprise for the Swedish Government. Now a member of the Digitalization Council.

Jan Gulliksen was appointed Digital Champion of Sweden serving the European Commission under Directorates-General Connect on the Digital Single Market Strategy between 2012-2019.

Jan Gulliksen was one of the 12 members of the EU high level group on maximizing the impact of Horizon 2020 and formulating the input to Horizon Europe, the so called "Lamy group" producing the highly cited report FAB–LAB–APP.

Kristina Höök served as an advisor to the Swedish government on topics relating to the future Swedish ICT and telecom in the IT delegation under the leadership of IT-minister Anna-Karin Hatt. The delegation consists of 26 experts from industry, academia and governance.

Sustainability and the United Nations' Sustainable Development Goals (SDG)

100% of the work at HCTD can be related to the United Nations sustainability goals in one form or other. To provide a few examples:

- Goal 13 Climate action: for example, in a project on visualizing flight patterns and CO2 emissions from business travel to support the KTH climate targets of reducing CO2 emissions from air travel 60% reduction between 2020 and 2030.
- Goal 12 Responsible Consumption and Production: actively designing for reduced energy consumption through novel design processes, applied to e.g., electric vehicle interaction design, and, to decrease food waste at retail and consumer levels through novel low-tech technologies at the supermarket and in the home.
- Goal 7 Affordable and clean energy: for example, through ethnographic studies to explore consumers' understanding and use of smart grid technologies in order to change behaviors, decrease energy use and enable the transition to a renewable energy system.
- Goal 10 Reduced Inequalities: for example, in a project on changing practices in society to address accessibility and participation in design processes for vulnerable user groups such the homeless.
- Goal 3 Good health and wellbeing: for example, through designing for a rich and healthy life through soma design and engaging with female health topics, increasing accessibility for homeless people or enabling accessibility through sound and music.
- Goal 4 Quality Education: for example, in a project to ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
- Goal 5 Equality: for example, through policy work on creating equitable digital solutions for all people regardless of gender, function or national background.
- Goal 8 Decent work conditions and economic growth: for example, through our research on digital work environments and accessibility works to endure an efficient and effective work situation for everyone.

We would also like to point to the MID4S team at MID devoting their whole research agenda to projects that aim to reduce carbon emission and the transition to a more sustainable society.

Structure for increased impact

HCTD already has a very strong impact on both society and industry, but our strategies for the future include:

In *sustainability*: our strong agenda in the sustainability field aims to have an impact both on societal organization, such as the internal organization of universities where we target a sustainable academic life reducing travel, or the healthcare system, where we target female health. We also work with persuasive design solutions that may impact food waste.

In *interaction design*: our strong focus on soma design, aiming for a 'good life', promoting socially, somatically, and compassionate sustainable life styles, engage with consumer product industry, such as IKEA, Volvo or Ericsson; designing tools for work in companies such as Sandvik; or engaging with healthcare and art.

In *sound and music computing*: will bring forth tools and practices to help produce humane soundscapes for our homes; work places; cars; and so on, will have an impact on the Internet of Things-sector. These tools will also be used by the creative sector (where the music sector is very strong in Sweden).

In *technology enhanced learning*: we aim to not only influence our own teaching at KTH, but also ways of speeding up teaching of, e.g., programming for newly arrived immigrants to Sweden, Swedish as a second language, and so on.

In *accessibility*: here our impact will continue to be mainly through policy work. We note that one of the most important structures for increased impact will come through centers with specific research agendas. Most recently, the KTH Digital Futures center (www.digitalfutures.kth.se) was established – official inauguration in 2020. It has received substantial, targeted funding from the government. The aim is to make sure Sweden does research in basic computer science topics as well as their implications for transformations of industrial and societal processes. The research will in turn guarantee that the faculty is up to date, delivering well-educated engineers to handle the digital transformation of society. Many of the most prominent researchers in the two departments have taken on various leadership roles with the Digital Futures center: Madeline Balaam serves in the *board of the center*; Kristina Höök, leads the domain theme *Rich and Healthy Life*; Olga Viberg is a member of the domain theme *Engineering Education*; and Elina Eriksson is a member of *Smart Society* theme.

Impact cases

We selected the eleven impact cases presented below for two main reasons. First, to show the diversity of impact coming out of the research at KTH, including, e.g., spin-offs, software used by big companies, healthcare, notably, through groundbreaking models of the brain and speeding up the training of deep learning networks. Second, to illustrate our objectives for the future.

Impact cases - CSD

Impact Case I: Repairnator: the first ever artificial software development robot

Background: There is a fundamental shortage of software developers that is going to last for the foreseeable future, this is a hard limit on the engineering creativity of humanity. To overcome this problem, we aim at creating the first artificial software developer. This artificial software developer would smoothly cooperate with human developers to create ever more grand software.

Scope: The project started in 2016, has been running since then, and is still very active.

Key researchers: KTH: Martin Monperrus (Prof), Benoit Baudry (Prof), Thomas Durieux (Postdoctoral researcher), Fernanda Madeiral (Postdoctoral researcher) plus doctoral-students' International collaborators: Simon Urli (XWiki), Matias Martinez (University of Valenciennes)

Artifact description: Monperrus and his group at TCS have developed the core algorithms and technology of an artificial software developer. This was founded on preliminary research on Repairnator. Repairnator, also called Luc, is a nice, junior software development bot. It is already known worldwide, there have been press articles about Repairnator in 12+ more different languages. Tomorrow, this artificial software development bot will have worldwide fame, one million followers on Twitter and be interviewed in the media.

Societal and research needs addressed: The area is software development: software developers create and maintain the software infrastructure that is the backbone of our society: financial software systems, communication software systems, entertainment software systems, defense software systems. There are 12 million developers today and this is not enough. As a result, it is hard to recruit qualified personnel, and this hinders sustainable growth of the Swedish software industry.

To fix this problem, we have augmented human developers with robot developers. This poses two key challenges: (1) there is a strong need for technical research in the area of automated program repair and code synthesis, with fundamentally new algorithms, (2) human developers are not used to working with robot developers, education and good communication channels must be found to achieve smooth and constructive cooperation between both. The TCS group is uniquely positioned in the world to address those challenges.

Selected Press and Research Articles in English

- MIT Technology Review: A bot disguised as a human software developer fixes bugs
- ACM TechNews: Bot Disguised as a Human Software Developer Fixes Bugs
- M. Monperrus, S. Urli, T. Durieux, M. Martinez, B. Baudry, L. Seinturier, Repairnator patches programs automatically, CoRR abs/1910.06247, 2019.

- S. Urli, Z. Yu, L. Seinturier, M. Monperrus, How to design a program repair bot?: insights from the repairnator project, Proc. 40th Int. Conference on Software Engineering: Software Engineering in Practice (SEIP), pp. 95-104, ACM, 2018.

Selected Press articles in Swedish:

- TechWorld: KTH-forskare har byggt en bot som patchar kod lika bra som en människa (English: KTH researchers have built a cure that patches code as well as a human being)
  SVT: AI och samhällsutvecklingen (AI and social development)

Impact on future research at TCS: Repairnator functions as a highly visible research demonstrator around which a variety of research contributions can take place. It will inspire new research at the intersection of AI and SE for many years to come.

Impact Case II: Spin-off Foreseeti AB

In 2014 Foreseeti (www.foreseeti.com) was founded as a spin-off by three NSE professors. The company develops a software product, securiCAD, which can be used for quantitative cyber security risk analysis using threat models on which attack simulations can be run. The simulations help decision-makers to better understand their IT architecture and its weaknesses.

Foreseeti has been listed on NyTeknik's 33-list (2016 & 2017), Royal Swedish Academy of Engineering Sciences (IVA) top 100-list (2019), mentioned by Dagens Industri as one of the ten hottest IT security companies in Sweden (2020), and the securiCAD tool was top-rated solution among Automated Breachand Attack Simulation Solutions globally along with the company being rated as the Emerging Leader in the field by Markets & Markets (2020). Initial funding came from EIT InnoEnergy, after that additional funding has come from angel investors and venture capital. The latest investment round, during 2020, secured 30 MSEK.

Business Operations: Foreseeti has 20 employees. Customers include companies worldwide, such as Klarna, Swedavia, RWE, and Scania, but also many confidential organizations in several different domains such as banking/fintech, critical infrastructure, medical technology, food & drugs, armed forces, and also academia. The company also has several certified partners reselling the securiCAD tool as well as applying it in project assignment. Partners are located in Europe (Sweden, Germany and UK), North America, Middle-east, and south-east Asia (India and Singapore), working with a large variety of organizations and sectors. *Technology:* securiCAD enables IT architects to design virtual models of current and future IT environments. By running attack simulations on a virtual model, securiCAD will provide detailed insights about your security posture. This allows for prioritizing security mitigations as well as comparing different design alternatives. securiCAD will look at your IT assets from an intruder's perspective and will reveal the most likely attack paths in your IT environment. Attack simulations are based on domain-specific languages (DSLs) encoding probabilistic attack graphs. The language for developing these DSLs were developed by researchers at KTH along with early versions of used DSLs. Current products include DSLs for on-premise enterprise IT environments, Amazon Web Services, and Microsoft Azure in a beta phase, where the usage of the latter two are fully automated so that analysis results can be achieved with a single click after login.

Key researchers and timeline

- Professor Pontus Johnson (www.kth.se/profile/pontusj), NSE, EECS, KTH
- Professor Mathias Ekstedt (www.kth.se/profile/mekstedt), NSE, EECS, KTH
- Associate professor Robert Lagerström (www.kth.se/profile/robertl), NSE, EECS, KTH

Research related to this impact case started already in 2005 and has been ongoing since. Currently, NSE and Foreseeti are collaborating on six joint projects, two funded by the Swedish Innovation Agency (Vinnova), one by the Swedish Energy Agency (Energimyndigheten), one by EU ERA-Net (/Swedish Energy Agency), and two within EU Horizon2020.

Research papers associated with the impact case (five examples out of many):

- P. Johnson, D. Gorton, R. Lagerström, and M. Ekstedt, "Time Between Vulnerability Disclosures: A Measure of Software Product Vulnerability," in *Computers & Security*, vol. 62, pp. 278-295, 2016.
- P. Johnson, R. Lagerström, M. Ekstedt, and U. Franke, Can the Common Vulnerability Scoring System be Trusted? A Bayesian Analysis," in *Transactions on Dependable and Secure Computing*, vol. 15, no. 6, pp. 1002-1015, 2018.

- A. Vernotte, M. Välja, M. Korman, G. Björkman, Mathias Ekstedt, and Robert Lagerström, "Load Balancing of Renewable Energy: A Cyber Security Analysis," in *Energy Informatics*, vol. 1, no. 1, Springer Open, 2018.
- P. Johnson, A. Vernotte, M. Ekstedt, and R. Lagerström, "pwnPr3d: An Attack Graph Driven Probabilistic Threat Modeling Approach," in Proc. of the *International Conference on Availability, Reliability and Security* (ARES), Sept. 2016.
- P. Johnson, R. Lagerström, and M. Ekstedt, "A Meta Language for Threat Modeling and Attack Simulations," in Proc. of the International Conference on Availability, Reliability and Security (ARES 2018) and the joint *International Workshop on Cyber Threat Intelligence* (WCTI 2018), 2018.
- Katsikeas S. et al., "An Attack Simulation Language for the IT Domain." In: Eades III H., Gadyatskaya O. (eds) Graphical Models for Security. GraMSec 2020. Lecture Notes in Computer Science, vol 12419. Springer, Cham. 2020.

Popular media examples related to this impact case (three out of many):

- https://www.nyteknik.se/startup/33-listan/har-hittar-du-alla-foretag-pa-33-listan-6539822
- https://mail.aktuellsakerhet.se/foreseeti-vann-almi-invests-pris-arets-titthalsinvestering/
- https://digital.di.se/artikel/de-forebygger-hackerattacker-mot-foretag-sebs-riskkapitalbolag-investerar

Impact Case III: Constraint-based systems and applications

The Gecode toolkit developed by Prof. Christian Schulte and his team is an open source-based software for developing constraint-based systems and applications. It is now used as a core part of the German company SAP's product S/4HANA, which is used by nearly 400,000 customers and it is also included in distributions such as Debian, Ubuntu, OpenSUSE, Gentoo, and FreeBSD.

Research papers associated with the impact case: The following publications describe several technical aspects of Gecode in more detail.

- L. Ingmar, C. Schulte, Making Compact-Table Compact, Twenty-Fourth International Conference on Principles and Practice of Constraint Programming, 2018.

Relation: How compact-table is implemented in Gecode

- C. Schulte, G. Tack, View-based Propagator Derivation. Constraints, 2013.

Relation: Design and evaluation of generic propagators as used in Gecode

- C. Schulte, G. Tack. Implementing Efficient Propagation Control. TRICS 2010, Third workshop on techniques for implementing constraint programming systems, 2010.

Relation: Explains propagator scheduling in the Gecode kernel

- R. M. Reischuk, C. Schulte, P. J. Stuckey, G. Tack. Maintaining State in Propagation Solvers, Fifteenth International Conference on Principles and Practice of Constraint Programming, 2009.

Relation: Includes an evaluation of how well hybrid re-computation in Gecode works compared to trailing

- C. Schulte, G. Tack. Weakly Monotonic Propagators, Fifteenth International Conference on Principles and Practice of Constraint Programming, 2009.

Relation: Model and example for weakly monotonic propagators as used in Gecode

- M.Z. Lagerkvist, Techniques for Efficient Constraint Propagation. Licentiate dissertation, Royal Institute of Technology, 2008

Relation: Development of advisors, placement problems using regular.

- G. Tack, Constraint Propagation – Models, Techniques, Implementation. Doctoral dissertation, Saarland University, Germany, 2009.

Relation: Models and techniques used in the Gecode kernel, views, and propagators for set constraints

- C. Schulte, P. J. Stuckey. Efficient Constraint Propagation Engines. Transactions on Programming Languages and Systems, 2008.

Relation: Design and optimizations of Gecode's propagation engine

- M. Z. Lagerkvist, C. Schulte. Advisors for Incremental Propagation. Thirteenth International Conference on Principles and Practice of Constraint Programming, 2007.

Relation: Design, implementation, and evaluation of advisors for incremental propagation

- C. Schulte, G. Tack. Views and Iterators for Generic Constraint Implementations, Recent Advances in Constraints (2005), 2006.

Relation: Design and evaluation of generic propagators

- C. Schulte Programming Constraint Services, Lecture Notes in Artificial Intelligence, Springer-Verlag, 2002.

Relation: Search architecture also used in Gecode

Technology: Schulte led the development of Unison: a simple, flexible, and potentially optimal tool that performs integrated register allocation and instruction scheduling using constraint programming as a modern method for combinatorial optimization. Unison is a collaboration between KTH, RISE, and Ericsson. Its design and development have been partially funded by KTH, Ericsson AB, and the Swedish Research Council.

Code generation in a compiler creates the assembly code to be executed on a specific processor. It is crucial for efficiency and state-of-the-art compilers such as GCC and low-level virtual machine (LLVM)(llvm.org) to devote many person-years of development and maintenance to it. These compilers decompose code generation into multiple tasks (instruction selection, instruction scheduling, and register allocation) and solve each task in isolation with heuristic algorithms. While this approach is modular and speeds up compilation, code quality is sacrificed by it as the essential combinatorial inter dependencies between tasks are ignored.

Unison pursues a radically different route: it embraces and exploits the combinatorial, interdependent nature of code generation to drastically improve code quality. In Unison, the inter dependent code generation tasks are translated into a single combinatorial model that accurately reflects all inter dependencies. Solving the model with constraint programming, a modern combinatorial optimization technology, results in the desired high-quality assembly code.

Prof. Schulte tragically passed away in the Spring of 2020.

Impact Case IV: Brain science in silico

Background:

The brain science field is vast and diverse with the multitude of experimental data describing the brain dynamics and its function at multiple spatial and temporal scales. To account for these multiple levels of brain organization and develop theories on how the brain processes information, learns and interacts with the environment, it is essential to complement a hypothesis driven computational modelling approach with data driven efforts. At CST computational brain science group as contributed immensely to both data-driven modelling and hypothesis-driven theoretical work to develop (1) theories of memory function (2) theory of brain diseases. In addition, CST has been a key contributor to the development of simulation infrastructure for brain modelling. As a consequence of CST's forefront work in computational brain sciences, also CST is coordinating both a SeRC project (Brain-IT) as well as a Digital Futures project (dBrain).

Case 1.1: Infrastructure for the neuroscience community
The Human Brain Project is one of the FET Flagship projects, the largest scientific projects ever funded by the European Union. Several researchers within CST are a part of the Flagship project, the Human Brain Project (HBP), since its start at the end of 2013. In particular, Prof Jeanette Hellgren Kotaleski has co-directed the Brain Simulation Division of the HBP over many years. An important long-term HBP goal is to develop and promote the EBRAINS (ebrains.eu), a distributed brain research infrastructure planned for entering the Esfri roadmap.

In this regard CST is also heavily involved in the International Neuroinformatics Coordinating Facility (INCF) in promoting standards and best practices for brain research. CST members Assoc Prof Arvind Kumar, Prof Erwin Laure, and Prof Jeanette Hellgren Kotaleski have represented, or are currently representing, both the science and infrastructure aspects for Sweden within the INCF Council for Training, Science and Infrastructure.

Case 1.2: Theory of memory function:
Research conducted at CST has been influential in the understanding of the cortical neural network mechanisms underlying memory function – ranging from short-term to long-term memory effects. In particular, our computational theory of working memory is one of the dominant hypotheses in the field and has received a lot of attention in the realm of both in theoretical and experimental neuroscience. In addition, the pioneering theoretical work at CST on a Bayesian probabilistic description/interpretation of synaptic learning machinery in the brain has paved the way not only for a unifying theory of human memory operating at multiple time scales but also for development of cognitive architectures for brain-like machine intelligence as well as algorithms for brain-like machine learning, with a great potential for implementations on neuromorphic hardware.

Case 1.3: Theory of brain diseases
Researchers at KTH have extended the understanding of the dynamics of neuronal networks and their interaction to build a framework to understand set of brain diseases as a 'diseases of brain dynamics'. The research has primarily focused on Parkinson's diseases, the second most common neurodegenerative disease. The understanding of brain dynamics has allowed us to use theory and models to find causal links between the disease symptoms and underlying changes in the neural hardware. These efforts have now culminated in the formation of the dBRAIN – an inter-school consortium to develop mathematical and machine learning tools to quantify disease related changes in

the brain and link them to the disease symptoms. The long-term goal of this line of research is to develop the field of computational neurology.

Key CST researchers:

HBP CST researchers over the years: Prof. Jeanette Hellgren Kotaleski, Prof. Anders Lansner, Prof Erwin Laure, Prof. Dirk Pleiter, Assoc. Prof. Mikael Djurfeldt, Assoc. Prof. Jörg Conradt;

SeRC Brain-IT PIs: Assoc. Prof. Pawel Herman, Prof. Jeanette Hellgren Kotaleski

Digital Futures PI: Assoc. Prof. Arvind Kumar, Assoc. Prof. Pawel Herman, Prof. Jeanette Hellgren Kotaleski, Prof. Erik Fransén

INCF engagement: Assoc. Prof. Arvind Kumar, Prof. Jeanette Hellgren Kotaleski

Selected research articles and presence in media:

Hjorth et al. (2020) The microcircuits of striatum in silico. PNAS, 117(17):9554-9565. doi: 10.1073/pnas.2000671117

Fiebig, F., **Herman, P.**, & Lansner, A. (2020). An Indexing Theory for Working Memory based on Fast Hebbian Plasticity. eNeuro, 7(2). https://doi.org/10.1523/ENEURO.0374-19.2020

Hahn G, Ponce-Alvarez A, Deco G, Aertsen A, **Kumar A**. Portraits of communication in neuronal networks. Nature Reviews Neuroscience. 2019 Feb;20(2):117-27.

Bahuguna J, Aertsen A, **Kumar A**. Existence and control of Go/No-Go decision transition threshold in the striatum. PLoS Comput Biol. 2015 Apr 24;11(4):e1004233.

Lindahl M, **Kotaleski JH**. Untangling basal ganglia network dynamics and function: Role of dopamine depletion and inhibition investigated in a spiking network model. ENeuro. 2016 Nov;3(6).

Cizeron M, Qiu Z, Koniaris B, Gokhale R, Komiyama NH, **Fransén E**, Grant SG. A brainwide atlas of synapses across the mouse life span. Science. 2020 Jul 17;369(6501):270-5.

Webinar: https://www.humanbrainproject.eu/en/follow-hbp/events/brain-matters-4/
How the brain keeps useful information while ignoring unuseful noise
Hjärnan kan bli grundsten i artificiell intelligens
Ny forskning kan ge ökad förståelse för schizofreni
Why the brain can only learn so much
The space-time fabric of brain networks
Nervenleitungen im Gehirn: zehn Prozent reichen

Societal and research needs addressed:

There is a large need in better understanding the brain to be able to prevent or treat brain diseases. Here modeling and in silico experimentation play crucial roles when creating new hypotheses regarding casual mechanisms. Furthermore, the brain system offers an attractive framework to operationalize the notion of intelligence and can thus serve as an inspiration for artificial intelligence. Finally, brain diseases pose a major challenge in the modern society and our computational/theoretical approach to brain science is crucial to advance the diagnosis, prognosis and treatment of brain diseases.

Impact Case V: An AI model to identify high-risk and difficult-to-diagnose breast cancer screens

Background: Every woman in Stockholm between the ages 40 to 74 is invited for breast cancer screening every two years, at minimum. Each screening exam is examined by two radiologists. But this may not be the case in the near future. Today, many companies and researchers are racing to develop a deep learning computer-aided detection (CAD) system with super-human performance. Recent works from NYU and Google have come close to achieving this, and our own study has shown commercial algorithms already perform on par with radiologists. While this is a laudable goal, we are not convinced this CAD is a sufficient solution. Radiologists are already quite good at detecting cancer -improving this isn't the most interesting research question -the real key to better health is detecting cancer earlier. Our goal is to develop AI-models that can identify cases that are high-risk or difficult for radiologists to interpret, and offer these women more frequent and sensitive screening.

Scope: The project started in 2016, has been running since then, and is still very active.

Key researchers: KTH: Kevin Smith (Associate Prof), Hossein Azizpour (Assistant Prof), Yue Liu (PhD student), Moein Sorkhei (PhD student). KI/KS: Fredrik Strand (PhD/MD), Karin Dembrower (MD), Mattie Salim (MD), Johan Hartman (Associate Prof./MD), Mattias Rantalainen (PhD)

Artifact description: Smith and his group at CST through the MammoAI, BCAIND, and ScreenTrust projects have collected and curated data and trained three AI models to assess breast cancer mammography screens. The first is a long-term risk model published in Radiology and MICCAI that is able to predict which women are more likely to develop cancer in the future. Another model mimics the ability of a radiologist to gauge how difficult it is to correctly diagnose a mammogram. A third model looks for cancer signs in a manner similar to CAD detection systems. The models are trained on millions of images, including screening images from all women in Stockholm County between 2005 and 2019. In March 2021, we begin a clinical study in which women selected by our AI algorithms are invited for additional screening using more sensitive MRI scanners. We project that this study will find approximately 50 cancers missed in regular screening over the next year.

Societal and research needs addressed: This project has the potential to affect the lives of every woman in Stockholm between the ages of 40 and 74 and their families, as it promises to catch more breast cancers earlier. Women with fast-growing tumors or difficult-to-detect tumors identified by our models will be screened using magnetic resonance imaging (MRI), which is more sensitive than mammograms. The cost of MRI screening means it cannot be offered to the general population, but AI models can potentially identify and prioritize women with higher risk by recognizing subtle patterns in regular screening mammograms. If the clinical trial is successful and it is shown that enough cancers are identified by the AI+MRI screening for it to be economically viable, it may be adopted as standard procedure at Karolinska and hospitals in Stockholm County.

From a research perspective, the questions of AI-based risk modeling and AI-based detectability modeling are not well studied. Our group, along with a team from MIT who we collaborate with, were the first to show promising results using AI to model risk of breast cancer in mammograms, both articles appearing in *Radiology*.

Selected Press and Research Articles in English

- Karolinska Institutet News: AI as good as the average radiologist in identifying breast cancer
- Science Daily News: AI improves breast cancer risk prediction

- K. Dembrower, E. Wåhlin, Y. Liu, M. Salim, P. Lindholm, K. Smith, M. Eklund, F. Strand. AI-based triaging of breast cancer screening mammograms to reduce radiologist workload and promote earlier cancer detection: a retrospective simulation study. *The Lancet Digital Health*, 2.9 (2020): e468-e474. https://doi.org/10.1016/S2589-7500(20)30185-0

- K. Dembrower, Y. Liu, H. Azizpour, M. Eklund, K. Smith, P. Lindholm, & F. Strand. (2019). Comparison of a deep learning risk score and standard mammographic density score for breast cancer risk prediction. *Radiology*, 190872. https://pubs.rsna.org/doi/abs/10.1148/radiol.2019190872

- Y. Liu, H. Azizpour, F. Strand, K. Smith. Decoupling Inherent Risk and Early Cancer Signs in Image-based Breast Cancer Risk Models. *Medical Image Computing and Computer-Assisted Intervention (MICCAI)*. Springer Berlin Heidelberg. Lima, Peru, 2020 https://link.springer.com/chapter/10.1007/978-3-030-59725-2_23f

Selected Press articles in Swedish:

- Ny Teknik: Ai ska upptäcka cancer lättare i bröst med tät vävnad

- Onkologi i sverige: AI lika bra på att identifiera bröstcancer som en genomsnittlig röntgenläkare

Impact on future research at CST: The MammoAI/ScreenTrust/BCAIND project is a highly visible research demonstrator with tangible human impact involving cross-disciplinary collaborations. While we have made great strides, there is much work to be done and we believe this collaboration will strengthen for many years to come.

Impact case VI: Distributed Computing

Background: In distributed computing, the major research activities have been mainly financed by SSF in two research projects: End-to-End Clouds (E2E-Clouds), a project that addressed the complete software stack of data-intensive clouds, from 2012 to 2017; and Continuous Deep Analytics (CDA), from 2018 to 2023, which focused on real-time scalable decision-making and analytics for uniform batch and streaming data and machine learning. A complete description of the e2e-clouds project results is found in the final SSF report at e2e-clouds. The CDA project is still running and can be accessed through the project webpage. A major result is Hopsworks, a Big Data analytics and AI platform with unique support for project-based multi-tenancy.

We commercialized Hopsworks through a company called Logical Clocks at 2018 that raised initial venture capital investment of 1.25 M€ from outside Sweden. Currently Logical Clocks has grown to over 30 staff members with many customers, and do not depend on venture capital. Another industrial contribution is **Apache Flink**, where four research members of the project are committers to the Flink open-source Apache project. Flink has many contributors and is part of the Big Data ecosystem. **We are the core founders of Flink together with a research group at TU-Berlin.**

Scope: Hopsworks has been running as a managed service on RISE ICE since 2016 and currently has over 1000 users. RISE ICE is a national large-scale datacenter for research and innovations. Other Hopsworks installations are deployed and running at organizations such as Karolinska Institute (KI), Scania, Ericsson, and Swedbank. We significantly contributed to the design and implementation of Apache Flink. Flink is currently the major system for scalable stream analytics in the world. It is run in production by major companies including NETFLIX, Alibaba group, Uber, Microsoft and King. A major reason for Alibaba choosing Apache Flink as their platform for all data analytics is our work on continuous fault tolerance as mentioned in their blogpost.

The research competence gained during the project has led to novel and attractive master courses at KTH on the systems of data science: Data-Intensive Computing (ID2221), Data Mining and Graph Analytics (ID2222), and Scalable Machine Learning (ID2223) (currently 140 students annually) where the students use the Hops platform for experimental work in Big Data science. The group also developed two Massive Open Online Courses (MOOCs) on reliable distributed algorithms, provided by KTH as part of the edX consortium led by MIT and Harvard, (in total around 8500 learners worldwide).

Standardization: Beyond Flink, many communities have embraced our methods and algorithms for reliable continuous processing. Since our initial contribution there have been several adaptations of our original work. Examples are Apache Storm's snapshotting by Hortonworks as well as the Continuous Processing Mode of Apache Spark. Another aspect that shows the impact of our work is the modeling effort of stream snapshots, that was initiated by Google, from the team that worked on Google Dataflow. The creation of a standard for stream snapshots can further serve as a strong interoperability link, enabling the redeployment and consistent migration of applications across systems upon demand.

More on Hopsworks platform: The Hops platform supports the complete software process for developing, training on massive data, testing and deploying data-intensive and AI applications. Hops leverages existing open-source software in addition to our own contributions to create a complete and useful state-of-the-art platform for developing data-intensive applications. Hops platform consists of a stack of various software components. Starting bottom-up. HopsFS and YARN . HopFS is the storage layer and YARN manages the allocation of computing resources to various applications. Spark, FLINK, TensorFlow are open-source data processing engines for advanced analytics, Spark for batch processing, FLINK for continuous analytics, and TensorFlow for machine learning. Jupyter and Zeppelin are open-source services that allows developers to create and share documents that contain

live code, equations, visualizations and narrative text used extensively for developing applications. These in addition to various tools for visualization, monitoring and deployment.

Researchers of the Distributed Computing group added support to Hopsworks for the Adam framework, developed at Berkeley, for processing large genomic data using Spark. This work was demonstrated at the Big Data for Life Sciences Training School, during a half-day workshop in Sep 2017.

The second study involved acquiring beta users for the Hops platform, with emphasis on genomics and education. This platform was used by students in the ID2223 course at KTH to perform projects on deep learning and big data. To the best of our knowledge at 2016-2017, this was the first university course in the world where students were able to work with large volumes of data (10s - 1000s of GB) to train deep neural networks using GPU hardware. In addition to this, we are managing a Hops cluster at Karolinska, run by Prof Joakim Dillner, that is used to store and process sequenced genomic data, generated by Next Generation Sequencing machines. Another effort involved integration of apache Flink in Hops. This was financed by the European H2020 project StreamLine (2016-2018).

Apache Flink and contributions to open source at Apache Foundation: We have mentioned above the industrial impact of the Apache Flink open-source project. Our research group have been active in the development of Apache Flink. Among research and other code contributions our work were integrated to the core of Flink and included in major releases of the system: (1) DataStream API, 0.6.0 release onward, (2) User-Defined Windows, (3) Gelly, The Graph Processing Library, (4) Pipelined Snapshots and Exactly-Once Processing, (5) FlinkML, Distributed Machine Learning on Flink, and (6) Redesign of Stream Iterations.

A distinct showcase of knowledge transfer and industrial impact of our work at King is Rbea, a stream-centric solution to data analytics which was architected and implemented by a member of our SSF project research team Gyula Fóra. King is the largest mobile gaming company at the time of writing and has, since Rbea, based their data analytics infrastructure on top of Flink's flexible state management. Rbea makes sophisticated use of all features we have developed on Flink to allow data analysts to submit and monitor the progress of simple queries on top of streaming data. The Rbea pipeline can grow and scale out together with the data as well as deal with failures without losing any progress or data involved. King's approach to streaming-first data analytics has given them a competitive advantage to how data analysts can interact with live data and spot trends and A/B testing results on-the-fly.

Key researchers: Jim Dowling, Seif Haridi, and Paris Carbone.

Artifact description: Hopsworks main innovation is its storage layer HopsFS, which is the world's most scalable distributed hierarchical file system**. HopsFS won the IEEE 2017 SCALE prize for its scalability**. Our main innovation in Flink was the design of novel algorithms for continuous fault tolerant processing, dynamic configuration and state management. These algorithms are now in Apache Flink and have also been adopted by other stream processing systems, including Google Dataflow (Apache Beam), Apache Storm and Spark.

Selected Press and Research Articles (in English /Swedish)

- Paris Carbone, Seif Haridi, et al. "State management in Apache Flink®: Consistent Stateful Distributed Stream Processing." Proceedings of the VLDB Endowment, 2017.
- Paris Carbone, Seif Haridi, et al: "Apache Flink: Stream and Batch Processing in a Single Engine." Bulletin of the IEEE Computer Society Technical Committee on Data Engineering 36, 2015. *(The main paper on Flink with more than 1100 google scholar citations.)*

Impact cases – HCTD

The impact cases from HCTD were chosen as they illustrate the many different forms of impact we have had. Through the research center Mobile Life, we worked closely with both big and small companies and societal organizations for 10 years, fostering a joint research agenda. With the digitalization policy for Sweden, we had a huge impact on the political aims for digitalization in Sweden. In our collaborations with FOI, we brought forth simulator-based training for jet flight pilots. We engage with the arts, as in the permanent Soundforest installation at the Swedish Museum for Performing Arts, putting high demands on durable and engaging technology design. Finally, we also have spin-off companies, engaging with deep tech. The diversity directly reflects the research aims of HCTD.

For the upcoming period (as discussed above) we expect to have impact: politically – in particular to towards sustainability issues; societally, particularly towards healthcare and education; as well as industrial impact on consumer-product companies as well as the ICT-industry.

Impact Case I: Mobile Life 2012-2017

Description: Mobile Life was a highly successful research center set up in collaboration and co-funded by companies such as Microsoft Research, Ericsson, Nokia, IKEA, ABB, alongside Stockholm City Municipality. In the final report[2], when the center closed in March 2017, we noted how the Center's contribution goes beyond any number of "things" that are packaged and delivered to the world. By consciously taking a radical stance on research – taking the "unserious" seriously, focusing on enjoyment – Mobile Life has opened a path to understanding some of the main drivers of the technological and societal change that we now see emerging.

One important function of the center was to act as a neutral pre-competitive arena where our partners could discuss the future. There are simply no other comparable forums where companies that are either competitors or come from different industries can meet on equal ground and discuss future visions and challenges. Mikael Anneroth at Ericsson emphasized this: "Ericsson can use the center as a non-competitive arena for us, not only to meet with the researchers, but also with the partners – Nokia, Microsoft, TeliaSonera – people or companies that are sometimes seen as competitors or customers. In the context of Mobile Life, we can discuss issues in a non-competitive environment, and of interest to all of us to move forward." For instance, IKEA organized a workshop with Microsoft Research about research on the home environment, and in a workshop with all partners Movinto Fun received advice on their market strategy.

The main tangible outputs from the center are prototypes, concepts, studies and methods. Most visibly, working prototypes of enjoyment services were often implemented to demonstrate future ideas and act as probes to explore potential use cases. But it is sometimes enough to present potential services as concepts that pinpoint possibilities. Concepts are often impossible to build with current technology but invite innovation and promote explorations of ideas. To ground its work, the Center often performed empirical studies of real users in the wild. These studies could then form the basis for design ideas or be aimed at evaluating prototypes. The most important output of studies is often discovering unexpected uses of technology in everyday life, or identifying whole domains that are ripe of technological innovation. At a higher level of abstraction, the Center produced design methods, which have broader applications than any single service or study. These may take the form of practical guidelines for how to do successful design processes, or documented design knowledge that can help guide future product development.

[2] http://soda.swedishict.se/6165/1/10_years_of_Mobile_Life_FINAL_incl_Appendices_.pdf

Taken together, the value of these tangible outputs was much higher than the sum of the parts. For the Center's partners, they formed the basis of strategic innovation – identifying new usage domains, user groups, and technological opportunities. Time and again we saw how these high-level results directly influenced our partners future strategy and product offerings. To quote Jyri Huopaniemi at Nokia: "Our target was to really understand the user better, not that we would get a certain set of technologies or algorithms we could integrate into a product, but more of an understanding of the future – what would be the user need in 5 years' time? Particularly with regard to mobility, wearable devices for healthcare or wellness, and other seemingly futuristic ideas."

In the final report, we summaries our main impacts as:

- Result 1: Putting enjoyment on the map for IT and telecom partners
- Result 2: Putting IoT on the map for consumer-oriented partners
- Result 3: Designing with IoT materials: tinkering, actuation-driven data analytics and sensuous design methods

Turn to the full report for deeper descriptions of each of these results and some case studies that explain in detail what kind of work this entailed, such as:

- Case 1: Putting the IoT vision at the center of a partner's strategy: IKEA and hybrid media in the home
- Case 2: Bringing enjoyment to the control room: Changing how ABB think about the work environment
- Case 3: Staging a public performance game: Engaging Stockholm City youth
- Case 4: Bringing enjoyment and wellbeing through somaesthetics: Changing how IKEA thinks about Internet of Things and wellbeing

The work in the Mobile Life center lives on in HCT. In particular, the Soma Design work came out of the Mobile Life center and is now thriving in the interaction design team-work.

Research papers associated with the impact case: The impact of Mobile Life was based on 52 journal papers, including four in ACM Transactions on Computer-Human Interaction and seven in Personal and Ubiquitous Computing. There were 184 full peer-reviewed conference papers in total, with more than half in top-tier conferences in our field, including CHI and ACM Conference on Supported Cooperative Work and Social Computing. There were an additional 113 short papers, posters, workshop papers and other conference contributions. The Center has published 6 books and later, Höök's book on soma design came as a direct result of the work in the center (with MIT Press in 2018). 5 contributions were selected as Best Papers at the CHI conference. Of particular note is that Höök and Löwgren's ToCHI paper was included in ACM Computing Review's selection of Notable Computing Books and Articles of 2012, taken from across all ACM computer science publications in that year.

Popular media examples related to this impact case: The Mobile Life center had about 196 media appearances over the 10 years – in national as well as international media. More than 80 delegations visited the center. Researchers in the center did 182 talks and demos. Turn to the final report for a full account.

Impact Case II: Digitalization policy for Sweden

Description: In 2012 Jan Gulliksen was appointed chair of Sweden's Digital Commission for the Ministry of the Enterprise with the Swedish Government. The task was to analyze and propose policy decisions within the broad area of digitalization, covering a diverse set of areas such as digitalization of the public sector, eHealth, digital inclusion, digital trust, security and safety, digital skills, development of the education system and lifelong learning, AI and machine learning, digital innovation and transformation, digitalization and gender equity, etc. the work was published in 6 SOU (Statens Offentliga Utredningar) covering wide areas such as the potential in using data, digital transformation of higher education, digitalization for a sustainable climate, digitalization and democracy. The work meant advising the last 5 Ministers of Digitalization for the Swedish Government. Within this we also drafted the current strategy for Digitalization that was adopted by the Swedish Government in 2016. As an effect of this the Minister of Digitalization formed a new advisory group in 2016, the Digitalization Council, and Jan Gulliksen was appointed expert in this group as well and has served since then. It has meant over 8 years of extensive impact on Swedish Digitalization policy.

Based on this work Jan Gulliksen was also appointed for the role of Digital Champion of Sweden serving the European Commission under DG Connect on the Digital Single Market Strategy between 2012-2019. The role was defined by madame commissioner and vice president Neelie Kroes, who was leading the work for the first years. After that the group had several leaders; Andrus Ansip, Günther Oettinger and Maria Gabriel. The job description was to, based on the European union platform, serve the purpose of helping everyone in Sweden to get online and improve their digital skills. Between the digital champions of the European countries, we exchanged ideas of policy that could be implemented across the European member states. One such mutual construct was the Digital Skills and Jobs Coalition, working to increase the number of digital leading professionals to increase European impact and growth in the digital area

One important outcome of this was that Jan Gulliksen was chosen to be one of the 12 members of the EU high level group on maximizing the impact of Horizon 2020 and formulating the input to Horizon Europe, the so called "Lamy group" producing the highly cited report FAB–LAB–APP under DG Research Commissioner Carlos Moedas. This work was the major input to the formulation of the upcoming European framework program Horizon Europe.

Finally, Jan Gulliksen was appointed vice president for digitalization at KTH, with the task to develop the university's strategy when it comes to digitalization for education, research, administration and collaboration.

Research papers associated with the impact case:

- Gulliksen, J. (2019). Incorporating Europe's values in future research. Communications of the ACM, 62(4), 40-41.
- Gulliksen, J. (2017). Institutionalizing human-computer interaction for global health. Global health action, 10(sup3), 1344003.
- Lazar, J., Abascal, J., Barbosa, S., Barksdale, J., Friedman, B., Grossklags, J., Gulliksen, J., Johnson, J., McEwan, T., Martínez-Normand, L., Michalk, W., Tsai, J., van der Veer, G., von Axelson, H., Walldius, Å., Whitney, G., Winckler, M., Wulf, V., Churchill, E.F., Cranor, L., Davis, J., Hedge, A., Hochheiser, H., Hourcade, J.P., Lewis, C., Nathan, L., Paterno, F., Reid, B., Quesenbery, W., Selker, T. and Wentz, B. (2016), "Human–Computer Interaction and International Public Policymaking: A Framework for Understanding and Taking Future Actions", Foundations and Trends® in Human–Computer Interaction, 9(2), 69-149.

Impact Case III: Simulator-Based Training and Business Intelligence

Description: The Swedish Defense Agency (FOI), and especially The Swedish Air Force Combat Simulation Center (FLSC) has a longstanding (2009--) research collaboration with KTH through Prof Henrik Artman (and Joel Brynielsson, Computer Science). The research focuses on simulator-based training, with particular focus on fast-jet fighter pilots, but has also included business-intelligence and situation awareness.

Research papers associated with the impact case: The collaboration has resulted in two high impact journal publications, a CHI-conference publication, an Information Systems for Crisis Response and Management (ISCRAM) conference publication and several technical reports (in Swedish):

- Aronsson, S., Artman, H., Lindquist, S., Mitchell, M., Persson, T., Ramberg, R., Romero, M., ter Vehn, P. (2019) Supporting after action review in simulator mission training: Co-creating visualization concepts for training of fast-jet fighter pilots, The Journal of Defense Modeling and Simulation: Applications, Methodology, Technology, vol. 16, no. 3, pp. 219-231, 2019. Citations: 1.
- Aronsson, S., Artman, H., Brynielsson, J., Lindquist, S., Ramberg, R. (2019). Design of Simulator Training: A comparative study of Swedish dynamic decision-making training facilities. International Journal of Cognition, Technology and Work (CTW)
- Eriksson, E., Artman, H., Swartling, A. (2013) The secret life of a persona: when the personal becomes private. CHI '13: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, April 2013 Citations: 27
- H. Artman, Brynielsson, J., Trnka, J., Johansson., B. (2011) in Proceedings of the 8th International ISCRAM Conference, 2011. Citations: 29

In 2016, at the I/ITSEC, the world's largest modeling, simulation and training conference, the Swedish Defense Agency (FOI) and Henrik Artman, KTH was involved in a large-scale Live, Virtual, and Constructive (LVC) demonstration together with US Air-Force Research Laboratory (AFRL). The demonstration involved real/live aircraft, several manned virtual simulators and different AI-agents/Constructives. Swedish airboss Captain Mikael Mitchell (co-author), led the demonstration from the conference in Orlando, US, and FLSC contributed with two manned virtual aircraft in the same scenario from Stockholm, Sweden. The demonstration showcased that it is possible to connect a wide variety of different actors/simulators, distributed over the Atlantic, to one specific scenario without latency. Furthermore, we did research on how the different actors experienced the demonstration, the scenario and the LVC-concept. The demonstration was followed by a short debriefing. A video of the demo can be found at: https://www.foi.se/download-streamed/18.7fd35d7f166c56ebe0bdc51/IITSEC-2016-Demo-SD-PA.mp4

Impact: The demonstration as such, accompanied with research efforts on simulator training facilities and design-based research on distributed after-action reviews, has led to that LVC-might become a reality within the next ten years. The concept "LVC-in everyday training", which means that a fast-jet fighter pilot doing regular live aircraft training can connect to simulator facilities, and act in collaboration with manned virtual simulators, has received attention within both Swedish Armed Forces and SAAB Group who manufactures the next generation of the Swedish Aircraft - Gripen. During 2017-2020 the research has continued focusing on how to design scenarios that give the best training benefits for all LVC-participants by formulating a new role "LVC-Allocator". This design-based research has involved over 20 active fast-jet fighter pilots. The scenarios have also been tested and evaluated at the FOI FLSC flight-simulator facility, involving approximately 60 pilots. At least three collaborative scientific articles are expected during 2020-2021.

Policy papers (in Swedish):

- Aronsson, S., Artman, H., Larsson, M., Lindquist, S., Mitchell, M., Ramberg, R., Ungerth, S. (2017). LVC i vardagen – framtidens flygträning, [LVC in everyday training - the future of aircraft training] FOI Memo 6094.
- Aronsson, S., Artman, H., Lindquist, S., & Ramberg, R., (2017). Effektiv simulatorträning: Slutrapport projekt Effektiv flygträning och utbildning [Efficient simulator training] 2015–2017. FOI-R–4520–SE. ISSN: 1650-1942

Impact Case IV: Sound forest – a permanent installation at the Swedish Museum of Performing Arts

Description: Sound Forest (Ljudskogen in Swedish) is a permanent large scale (5x10 meters) multisensory interactive sonic installation located at the Swedish Museum of Performing Arts in Stockholm. Sound Forest includes interactive sound and lighting, and a vibrating floor. It makes use of real-time sound, vibration and light feedback as a response to users' physical interaction with the installation, which is captured by means of sensors. The installation has been designed by the Sound and Music Computing team at KTH and it reflects several of the research areas of the team, including sound design, sonic interaction design, multisensory perception, inclusiveness, adaptive music production, musical expression. One of the main aims of the Sound Forest project was to create a Digital Musical Instrument (DMI) that facilitates intuitive musical interaction, allowing visitors to quickly start creating music either alone or collaboratively. Sound Forest was designed to enable users without any prior knowledge of musical instruments to express themselves through bodily interaction and engage in musical activities in a rewarding way. One important goal was that the DMI should be able to serve as a pedagogical tool allowing users to learn about concepts related to music making, but also for the instrument to facilitate long-term engagement. Participants should be encouraged to return to the museum for continued music exploration. Another important aspect in the design of Sound Forest was accessibility, i.e., that the instrument should be able to provide rich musical experiences for all museum visitors, regardless of age or abilities. Sound Forest provides all inputs and outputs in a transparent and accessible way so that composers can create their musical interactions by using their preferred tools without bothering on the technology behind the installation.

Impact: Since the opening of the installation in April 2017, about 75 000 people have visited it, including 37 000 of them being between 0-20 year of age, and more than 100 school and pre-school groups, 225 adult groups, 60 groups from special needs education schools, and about 20 "Swedish for immigrants" groups. Research published as three full papers in two international conferences so far (SMC 2016 and ACM CHI 2019). Every year, several students from the KMH Royal College of Music in Stockholm compose new sonic interactions which are testing with museum's visitors, and KTH students develop new ways of interacting with the installation. A new project using the installation and focusing on inclusion has received one of the most prestigious awards in music research in Sweden in 2020 (The Royal Swedish Academy of Music, Bernadotte-programmet). New project proposals, both national and international, have been submitted and other are in preparation.

Relates SDG 3 Good health, and article 27 of the UN declaration of Human Rights (everyone has the right to freely participate in the cultural life of the community).

Research papers associated with the impact case

- E. Frid, H. Lindetorp, K. Falkenberg Hansen, L. Elblaus, and R. Bresin. 2019. Sound Forest: Evaluation of an Accessible Multisensory Music Installation. In Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19).
- Bresin, R., Elblaus, L., Frid, E., Favero, F., Annersten, L., Berner, D., & Morreale, F. (2016). Sound Forest/Ljudskogen: A Large-scale String-based Interactive Musical Instrument. In Proceedings of SMC Sound and Music Computing Conference 2016 (pp. 79–84).
- Paloranta, J., Lundström, A., Elblaus, L., Bresin, R., & Frid, E. (2016). Interaction with a large sized augmented string instrument intended for a public setting. In Sound and Music Computing 2016 (pp. 388–395). Hamburg: Zentrum für Mikrotonale Musik und Multimediale Komposition (ZM4).

Impact Case V: Mano Motion AB – a spinoff deeptech company

Description: ManoMotion was founded in 2015 by Shahrouz Yousefi (a former doctoral student in Media Technology, MID) and Haibo Li, Professor in Media Technology, MID. ManoMotion's deep tech solution is based on more than 7 years of research done by Dr. Yousefi and Prof. Li on Human Motion Analysis and Gestural Interaction at KTH. The concept of shifting the interaction space from 2D touch screen to 3D space was proposed by Dr. Yousefi and Prof. Li in 2008. This concept has been developed during the doctoral research of Dr. Yousefi at KTH and is highly inspired by the advancements in big data, visualization technologies and advanced displays / smart glasses for AR / VR applications. The developed technology has won several innovation competitions in Europe and received significant recognition from the academy of science and engineering in Sweden as one of the promising technologies for the future. Our research in hand-gesture recognition and tracking has generated one doctoral thesis and 25 scientific publications. Patents have been granted include:

- "Real-time 3D gesture recognition and tracking system for mobile devices", US20160334877A1, US, EP3090382A1, EP, JP2017505965A, Japan, CN106030610A, China, and KR20160129000A, Korea.

Our research on understanding of human behaviors has been funded by VR, Vinnova, Knowledge Foundation (KK) and EU. In 2015 Dr. Yousefi received the Chester Carlson Research Prize (Forskningspris) award for his scientific contributions within the field of natural human computer interaction.

In 2017 ManoMotion was listed as one of the 10 companies that use AI to transform industries by Crunchbase. ManoMotion has also been selected to "33-Listan" in 2017, a list showing the most promising Swedish technology startups compiled each year by "Ny Teknik". In 2019, Dr. Yousefi was nominated as one of six finalists of the Chief Technology Officer (CTO) of the Year Europe Award based on that he has shown to be outstanding role models who will inspire growth and strengthen European innovation and technology leadership.

Impact: ManoMotion provides the most advanced software-based hand tracking technology for mobile platforms without any requirement for heavy processing units or extra sensors. Solutions with similar features are heavily relying on advanced sensors, stationary computers for heavy computations and extra controllers or gadgets for tracking human hands in 3D. The ManoMotion deep tech solution, has proven in third-party applications to deliver high quality AR / VR capabilities to users.

ManoMotion has been recognized as a market leader in providing software-based hand gesture technology. Recently, ManoMotion has been granted funding of 2.2MEUR under the EU program Horizon 2020 to promote its leadership in the market10. ManoMotion today provides both software-development-kit (SDK) and OEM solutions to the market. The SDK was awarded "Best Software Interaction Tool" Annual Auggie Award at Augmented Reality World Expo in San Francisco 2018 which brought together many competing technologies in the AR / VR space from the world. The SDK has been downloaded by 6000+ developers, most of them are from companies specifically building mobile games. Some of the international game companies have released applications made available to the public in the app-store with over 300M+ downloads. ManoMotion has signed MNDA's with over 35 OEMs, including Samsung, Apple, LG, Motorola, Snapchat, Alibaba, and others, all of which are in different stages in the process towards a licensing deal.

Mano Motion Technology has at least shown three potential benefits to our society:

- Europe has the opportunity to be the global leader in VR, AR & Mixed reality (MR): The total production value of the European VR & AR industry is expected to increase to between EUR 15

billion and EUR 34 billion by 2020 and account directly or indirectly for 225,000 to 480,000 jobs. Such a significant economic uplift would make Europe's VR and AR market first-in-class. ManoMotion foresees to contribute to the creation of new jobs directly via hiring but, more importantly, allowing the engaging of approximately 10% developers and OEMs to develop new apps.

- Education and professional training: According to Deloitte, over the next 10 years, more than 2.7 M baby boomers are retiring from manufacturing, taking their embedded knowledge with them. Effective offboarding is critical to developing the next generation of controls engineers. However, developing traditional training materials is time-intensive and materials quickly become out-of-date. With AR, capturing expert knowledge becomes significantly more efficient. Advancements in AR/VR for creating and documenting work procedures for training have shown a 37% reduction in time spent training and a 75% reduction in time required to document work instructions. ManoMotion's solution can be used for remote guidance which will speed up the process.
- Health: For Europe, Goldman Sachs has estimated healthcare's potential to reach 5.1 B$ by 2025, which makes it the number one enterprise application before engineering and education. A most promising field where AR can help is AR-assisted surgery. Some surgeries last so long (12-18 hours) that battery life of technology can become an issue. The Microsoft HoLolens, for instance, has a battery life of about 5.5 hours, and the Google Glass's battery lasted about 30 minutes while recording video, one of its main uses. ManoMotion software, with its reduced CPU and battery consumption (thanks to its patented "lighter" framework) can become an important building block of newer AR applications to be used in the operation room.

Popular media examples related to this impact case

- https://www.crunchbase.com/hub/virtual-reality-startups#section-overview
- https://www.manomotion.com/manomotion-nominated-33-listan-nyteknik-affarsvarlden/
- https://scholar.google.com/citations?user=MGZuzNEAAAAJ&hl=en
- https://www.xerox.com/about-xerox/chester-carlson-science-award/svse.html
- https://patentscope.wipo.int/search/en/detail.jsf?docId=WO2015102527
- https://patents.google.com/patent/US20160334877
- https://www.inc.com/peter-cohan/kth-mit-of-stockholm-produced-these-three-mind-blowing-startups.html
- https://www.ctoeurope.net/news/2019/10/23/odymker3ls200uauuxqkd59l7txcci
- https://www.awexr.com/blog/45-meet-the-9th-annual-auggie-awards-winners
- https://www.mynewsdesk.com/manomotion-ab/pressreleases/manomotion-ab-has-been-granted-over-euros-2-m-from-eu-and-appoints-new-ceo-2861183
- https://www.kth.se/en/innovation/nyheter/vinnare-i-idetavlingen-ict-korad-1.395118