30-04-20

KTH Research Assessment Exercise (RAE) 2020 – Periodic review of research

Self-evaluation report for Panel 4 – Computer Science

A) INTRODUCTION

0 a. *Description of the research field of the departments included in the research panel*

The research panel, namely, "Computer Science," covers a significant part of the School of Electrical Engineering and Computer Science (EECS). The School itself is newly formed (2018), created from merging three Schools. Within this newly formed EECS school, there are four new Departments: Computer Science (CSD), Electrical Engineering (EED), Intelligent Systems (ISD), and Human Centered Technology (HCTD). This panel, the Computer Science Panel, will cover two of the departments: CSD and HCTD.

CSD comprises five divisions and HCTD is a single-division department (the only one of its kind in EECS). Together, these two departments are responsible for a large part of the EECS research (and education). The six divisions cover a broad gamut of research topics, with diverse activities (in alphabetical order):

- In CSD:
  - (i) Communication Systems (CoS)
  - (ii) Computational Science and Technology (CST)
  - (iii) Network Systems Engineering (NSE)
  - (iv) Software and Computer Systems (SCS)
  - (v) Theoretical Computer Science (TCS)
- In HCTD:
  - (i) Media Technology and Interaction Design (MID).

In brief, the panel covers research activities, undertaken in the 2012-2019 period, ranging from networks, wireless and mobile systems, software engineering and verification, distributed and parallel systems, computer engineering, algorithms, to data science, machine learning, security and privacy, to modelling physical and biological systems, to natural language tools, media technology, and interaction design. The vast majority of members of faculty and researchers active in these areas can be clearly seen under the definition of Computer Science – except for some of the researchers in MID. Thus, the choice of the Panel name.

0 b. *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 the 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., came from 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 appendices (Part C). The contributions were integrated by the coordinating team, and revisions continued; by requesting,

receiving, and addressing remarks from the Division; by aligning the report to the quantitative data report created the Rector's team; by further addressing their comments.

0 c. *Identified research panel synergies*

Common challenges, both in terms of concerns as well as joint efforts, are articulated in many parts of the report. Notably so, under B.1, the SWOT analysis is common for the entire panel. Overall, the report was compiled so that it presents and emphasizes common viewpoints, visions, past and ongoing efforts and future opportunities. At the same time, we made sure that sufficient detail on differing views or division- or other smaller-constellation-specific information was clearly captured in B.2-B.6.

Here, in brief, we highlight few key synergies:

- Faculty from both Departments have been and will continue collaborating in large-scale and large-scope initiatives and centres. This builds on the diverse expertise onboard. It facilitates collaborations among researchers as well as with strategic industrial partners and stakeholders, towards addressing societal challenges.
- Teaching practices have been harmonized and departments are now responsible.
- Common research interests and converging visions, which lead to identified key research areas for further deployment.
- Running and participation in numerous infrastructures, which have served as fertile ground for collaborations.

In terms of common Challenges, both departments will strive to further:

- Renew faculty members and improve on gender balance, notably for CSD, as well as attract new talent.
- Improve on research impact and quality, international visibility, connection of research and education, and outreach.
- Improve on the internal organization of their research activities, working also together with other Departments beyond those involved in this panel.

B) REPORT FOR THE TWO DEPARTMENTS

1. Overall analysis and conclusion; strengths and development areas

a. *Limited SWOT-analysis*

The limited SWOT analysis is presented below under four headings, Research-Strengths, Research-Weaknesses, Organization-Strengths, and Organization-Weaknesses. Within each heading, a categorization is made. For research, the assessment (strengths, weaknesses) is done along these four axes: (i) areas and contributions, (ii) international visibility and collaborations, (iii) funding, and (iv) leadership and researcher quality. For organization, the assessment (for strengths and weaknesses) is done along four axes: (i) infrastructure and facilities, (ii) staff quality and recruitment, (iii) internal structure, and (iv) connection to education and outreach.

We present here points in short, reflecting the content of Part B (and C); with pointers to relevant sections as needed. The presentation of strengths and weaknesses is done jointly for the Computer Science Department (CSD) and the Human-Centred Technologies Department (HCTD). We differentiate when appropriate.

We note that the School of EECS was created last year, as a merger of three Schools, CS, EE, and ICT. Within EECS, Departments were formed during the first year of the School and they were kick-started

at the beginning of 2020. The recency of this organization should be taken into account when considering all points below and the rest of the self-evaluation report.

Research - Strengths

Areas and contributions

- Diverse portfolio of research in areas of high importance, both nationally and internationally. Research achievements range: (a) in CSD, from computer vision and software engineering, to networked systems and cyber-security and privacy, and (b) in HCTD, from interactive design to media design. Overall, good coverage of Computer Science.
- Complementary and related areas, from theory and basic technologies, to systems and applications. Interdisciplinary research. The spectrum of areas is detailed in B.2.a and B.2.b., with a coverage from fundamentals to contemporary and emerging applications, as well as interdisciplinary activities (e.g., computational brain science, in CSD, or sound and music computing, in HCTD), and sustainability studies (HCTD). In HCTD work on designing for health, projects on children's play, playfulness, wellbeing and people with cognitive disabilities.
- World class research, as demonstrated by the recognition of faculty, impactful results, including notably strong citation records, awards, and grants, as detailed in B.2.d and B.6 and further, in brief, in this section.
- Diversity as an advantage, allowing to engage across domains and research fields, towards addressing societal concerns.

International visibility and collaborations

- Numerous important roles in research communities. This is reflected by 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.
- Increased reputation and sustained international and national collaborations. This includes visits and exchanges, with KTH faculty in prestigious Universities abroad, as well as regularly hosting renowned researchers in Stockholm. Numerous joint projects.
- International recruitment of faculty, postdocs, and doctoral students.
- Industrial collaborations, through numerous projects, industrial doctoral students, and Master's theses.
- For HCTD, longstanding collaboration with and funding by (i) the Swedish Defence Research Agency (FOI), on design for airplane pilot interactions and training; and (ii) the Swedish Energy Agency on sustainable practices.

Funding

- Very strong record in attracting national and international external funding. Diverse funding profile, including highly selective grants. Notably, European Research Council (ERC) grants, Knut and Alice Wallenberg Academy Fellowships, Marianne and Marcus Wallenberg Projects, 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 projects and faculty positions, and funding by VINNOVA.
- 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, leading two out of three projects awarded and currently running within the SSF Big Data and Cybersecurity Program.
- Participation or leadership in research centres and government commissions.

- For CSD: (i) Leading the CASTOR software research centre (www.castor.kth.se); (ii) leading industrial competence groups in the Innovative Centre for Embedded Systems (ICES) (www.ices.kth.se); (iii) Steering committee of the Security Link centre, notably together with the Swedish Defence Research Agency (FOI); (iv) led the Wireless@KTH centre (wireless.kth.se); (v) led thematic areas in the Autonomic Complex Communication nEtworks, Signals and Systems (ACCESS) Linnaeus Centre (https://www.access.kth.se/en).
- For HCTD: (vi) chairing the Swedish Digitalisation Commission, a Government body analysing and monitoring progress in terms of meeting the ICT-policy goal; (vii) participating in NAVET[1], a research centre for Art, Technology and Design; (vi) led the Mobile Life Centre; (vii) participated in the Centre for Sustainable Communications.

Leadership and researcher quality

- Institute of Electrical and Electronics Engineers (IEEE) Fellows: Prof. G. Maguire and Prof. P. Papadimitratos.
- Academia Europea member: Prof. G. Maguire and Prof. J. Håstad.
- Knuth Prize: Prof. J. Håstad.
- Association for Computing Machinery (ACM) Special Interest Group on Computer Human Interaction (SIGCHI) Academy award & ACM Distinguished Scientist: Prof. K. Höök.
- European Data Science Technology Innovation award: group of Prof. S. Haridi.
- Applied Networking Research Prizes: groups of Prof. R. Stadler and Prof. P. Papadimitratos.
- Royal Society of Medicine Fellow: Prof. M. Boman.
- Numerous best paper awards for journal and conference papers. Details in B.2.d.
- Researchers currently with CSD and HCTD, whose work is the most cited in their respective areas in Sweden; for example: (i) Prof. G. Maguire in computer communications, (ii) Prof. K. Höök in interaction design, (iii) Prof. P. Papadimitratos in security and privacy, (iv) Prof. B. Baudry in Software Engineering, (v) Prof. S. Haridi in Distributed Systems, (vi) Prof. T. Lindberg in Computer Vision, (vii) Prof. A. Gionis in Data Mining. Several other very highly cited faculty members, among the top at KTH.
- Faculty that were the first in EECS in achieving distinctions, e.g., second ERC grant by Prof. D. Kostic; first KAW Academy fellowship by Prof. P. Papadimitratos.
- International and national visibility, distinguished roles in respective communities, and highly competitive funding, as elaborated above, further attest to leadership and quality of CSD and HCTD faculty.
- Young Academy Members: Prof. R. Lagerström (Swedish Young Academy), Prof. P. Papadimitratos (Young Academy of Europe).

Research – Weaknesses

Areas and contributions

- Areas of research in some divisions, for example, numerics, machine learning, wireless communications, and to some extent security and privacy, are foci in other KTH Schools and EECS Departments. This can make it harder to develop the corresponding research identities.
- Some divisions are diverse; as a consequence, their overall strategy can be somewhat vague, not particularly focused to encompass all groups. Rather, individual research groups form their own strategy.

1 https://www.kth.se/navet/navet-1.876907

- Important research areas not covered in CSD, including database management systems, computer architecture and operating systems.
- HCTD went through a generation shift in 2012, with concerted efforts to rebuild several research teams since. Some CSD divisions may face similar situations in the coming years.
- In some areas, there can be some research topics not pursued to the extent social needs require; for example, as HCTD points out, user-oriented IT design or media technology/production.

International visibility and collaborations
- Faculty and researchers across the two departments may choose to publish in specialized, topical, and perhaps not very visible journals and conferences; rather than aiming for top-tier journals and conferences. The result can be that research outcomes may have reduced impact.

Funding
- There is perhaps too strong dependence on external funding, for all CSD and HCTD faculty. The new Digital Futures Centre could perhaps play an important role in improving this.
- External funding, as obtained competitively, is unevenly distributed across teams within Departments and Divisions. Even though there is potential for many teams to attract more funding, the current situation is reflected in the numbers of doctoral students per faculty member.

Leadership and researcher qualities
- The overall performance on this front can be bimodal; with a number of very highly published, internationally leading and visible faculty members. On the other hand, particularly in CSD, a number of faculty are largely devoted to teaching and administration.

Organisation – Strengths

Infrastructure and facilities
- Research groups running their own local research infrastructures and making use of cloud providers for both processors and their data centre networks.
- KTH networking infrastructure with excellent performance.
- HCTD facilities: R1 (the former reactor hall) exhibition space, the MIDDLA [2] marketspace, a haptics laboratory, a multisensory studio for sound, music-and movement-based design, and a soma design laboratory.

Staff quality and recruitment
- 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.
- Recruitment across both departments has emphasized equality.
- Instances of excellent IT support personnel.
- HCTD has excellent gender balance: 38% female faculty, as compared to 21% overall at KTH; 57% female **postdoctoral** researchers (here after simply postdocs) and 31% doctoral students.
- HCTD implements an organized mentorship approach, based on a flat hierarchy.
    - A CSD faculty member is the first Head of the EECS. HCTD faculty members are involved in the university leadership at different levels (vice-head of EECS, vice-rector).

Internal structure

2 https://www.kth.se/mid/research/research-environment/middla-1.854121

- Well-defined groups in terms of own research and education profile, nationally or internationally recognized.
- Typically, Divisions have all teams collocated. In some cases, groups of the same division are at different locations. This allows for close interactions with the relevant research environment.
- Lack of barriers to co-operations across research groups.

Connection to education and outreach
- Strong system-oriented research that has resulted in widely adopted software platforms, new start-ups, and excellent alumni. Detailed information in B.6.
- Strong connections with the 2nd cycle education. Details in B.5, concerning:
  - Several very popular Master's level courses (e.g., data science, distributed systems,hacking).
  - Advanced courses (e.g., network systems 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 result in publications and patents.
  - Many theses are carried out in close collaboration with industry.
- Presence in the national media, on numerous topics and occasions, and government advisory roles. Detailed information in B.6.b.
  - For CSD, for example, 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).
  - For HCTD, for example, Profs. Höök, Bälter and Gulliksen have been interviewed more than 100 times. Prof. Höök has been repeatedly listed among the 50 most influential women in IT.
  - Government advising roles, notably HCTD's Prof. Gulliksen headed Sweden's Digital Commission; later, appointed Digital Champion of Sweden in EU DG Connect.

Organisation- Weaknesses

Infrastructure and facilities
- Demand on office space will continue to increase. This needs to be addressed centrally by KTH, including more flexible types of shared office space given the faculty and teams in this panel are in multiple campi.
- Different divisions have their own facilities and smaller testbeds, but they do not own or share large testbed facilities. This is partially catered by access to external testbeds (e.g., Integrated Transport Research Lab (ITRL), Wallenberg AI, Autonomous Systems and Software Program (WASP), or industrial partners).
- There are specific needs for equipment (e.g., GPUs) that should be addressed.
- Much of the physical infrastructure is still not properly accessible to the physically disabled.
- CSD is spread over three campi and there is no public transit directly between them.

Staff quality and recruitment
- Groups/teams in several divisions have highly varying sizes, from 1 or 2 faculty to up to 5 faculty. Smaller groups are vulnerable to changes (e.g., faculty leaving). Moreover, it may be potentially difficult to balance research and education agendas.
- In many divisions, most of the current faculty is senior. Faculty renewal is slow. This contributes to continued gender imbalance.
- Recruitment needs to be faster and better synchronized, e.g., with US academic hiring periods.
- Weakness in hiring of top-tier faculty. The time from announcing a position to offering the position to a promising candidate is too long, and top-tier candidates have often committed to other

opportunities. The start-up package for such candidates has not been competitive (unless the positions are created as part of special programs, such as WASP or KTH Digital Futures).
- No faculty doing actively research in computer architecture and operating systems.
- Weak administrative support for recruitment, employment, and project management.
- Lack of support for establishing alumni networks.

Internal structure
- For some Divisions or groups, the research and education portfolio have overlaps with the research and education profile of other departments, in particular the Intelligent Systems Department (ISD). This is also true for some CSD teams, which overlap with teams in HCTD. One risk: it might be difficult to promote strategic interests across divisions and departments.
- Departments and Divisions spread over different locations face additional overhead. This also reduces the coherence of the division; even though there can be benefits as mentioned earlier.
- Divisions, based on their history, including recent formation, or in any case given their current activities, have broad research activities. Some groups are not well integrated in their current division or department (e.g., biological physics group in CSD/CST). Thus, the challenge to create synergies and create convincing visions within and across Divisions and the consideration for changes.

Connection to Education and outreach
- Weak connection to st cycle education, the exception being Bachelor's thesis projects. There are efforts to create courses covering all themes in all cycles.

Development
- Internal organization and structure:
  - Formation of groups with multiple faculty/teams, with closely related activities, for a more stable research and education environment.
  - No compartmentalization within and across departments, facilitation of cross- and intra-division fluidity; creation of smaller and more numerous focused divisions.
- Recruitment and personnel:
  - Broader advertisements to exploit the scale of departments (notably, CSD), anticipating renewal and growth mid- and long-term.
  - Recruitment aligned to needs and vision for further development.
- Further development of key research areas:
  - Considering the current strengths and weaknesses, as well as common interests and visions across divisions, specific areas can receive further attention with activities expanded and integrated with ongoing activities.
    - For CSD: (i) Security, privacy, and cryptography, (ii) Applied Artificial Intelligence, (iii) Software construction, and (iv) Data Science.
    - For HCT: (i) Interaction Design, (ii) Sound and music computing research, (iii) Novel Interaction techniques, and (iv) Technology-enhanced learning.
- Improved societal impact:
  - Building on current achievements, both Departments are keen to achieve this, planning and aligning future activities towards this objective.

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

- Impact (detailed information in B.2, B.3, and B.6):

- Participation and leading roles in research centers with continuing activities, including newly formed ones. Centres are in close collaboration with industrial and government partners, pursuing research, education, innovation, towards addressing societal needs.
  - Active centers: (i) KTH Centre for Software Technology Research (CASTOR), (ii) the centre for Cyber Defence and Information Security (CDIS), (iii) KTH Innovative Centre for Embedded Systems (ICES), (iv) Security Link, and (v) KTH Digital Futures.
- Highly cited research, with numerous awards.
- Distinguished faculty in their respective fields.
- Collaborations with industry and influence of standards
- Start-ups and spin-offs, building on research results.

- Infrastructure (detailed information in B.3.e)
  - CSD: (i) Visualization Studio, (ii) Neurocomputing Laboratory, (iii) FEniCS Project (fenicsproject.org) platform for solving partial differential equations (PDEs), (iv) Hopsworks platform for end-to-end machine learning pipeline. Contributions to and collaborations with: (v) Science for Life Laboratory, (vi) PDC Centre for High Performance Computing, (vii) SNIC, (viii) ITRL.
  - HCTD: (i) R1 (previously a reactor hall) Experimental Performance Space: a mix between a museum, cultural house, studio, and lab, (ii) MIDDLA physical interaction design lab, (iii) Visualization Studio, (iv) Multisensory Studio, (v) HapticLab, (vi) Soma Design.

- Sustainable development (detailed information in B.6.b)
  - Most of the research conducted in both CSD and HCTD has an indirect impact on sustainability goals. Many research activities are directly related. Highlights:
    - Projects on energy efficiency, affordable and clean energy, responsible consumption, in both CSD and HCTD.
    - Project on climate, notably visualization of flight patterns and CO_2 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 CSD and HCTD.

2. Research profile

a. *General information of the departments*

The Department of Computer Science (CSD) consists of the following divisions (listed in alphabetical order):

CoS Division of Communication Systems consists of the following groups: Mobile Services, Network System, Networked Systems Security (added in 2019), Optical Networks (moved to Chalmers with the retirement from KTH of Prof. Wosinska) and Radio Systems. COS members work in the broad area of Communications Systems with the emphasis on scalability, performance, reliability, and security of vital societal systems. These systems are proving to be key in allowing the society to function in the COVID-19 pandemic. in more detail:

*Networked systems***:** Cicek Cavdar (distributed learning, IoT radio resource management), Markus Hidell (energy-efficient networking, virtualization, IOT sensor networking), Peter Sjödin (energy-efficient networking, virtualization, IOT sensor networking), Dejan Kostic (data centers, geo-distributed storage systems, software-defined networking, network functions virtualization), Gerald

Q. Maguire Jr., P. Papadimitratos (secure routing, secure communication, credential management, IoT security).

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

Security and Privacy: Panagiotis Papadimitratos (networked systems security, privacy enhancing technologies).

*Mobile computing and communication systems***:** Marina Petrova (radio access virtualization, joint communication and computation), Cicek Cavdar (edge computing, energy efficiency, autonomous management) , Gerald Q. Maguire Jr., P. Papadimitratos (security and privacy for large-scale mobile systems).

*Wireless networks***:** Marina Petrova (mmWave systems, radar and sensing, spectrum sharing and co-existence), Cicek Cavdar (Edge-cloud radio access networks, aerospace networks, satellite networks, UAV communications, autonomous network management), Ki Won Sung (energy-efficient wireless systems, efficient and affordable spectrum sharing, performance evaluation of ultra-dense networks (UDN)), Anders Västberg (energy efficiency, internet of things, scheduling), P. Papadimitratos (information-theoretic and physical layer security, secure localization).

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.

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 modelling and project technology management.

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

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

Project and technology management: Joakim Lilliesköld: project management, product development; Liv Gingnell: project management, quality management, product development.

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) as well as Software Engineering.

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

Software construction and analysis: Benoit Baudry: software engineering, software testing, software diversity, DevOps[3]; David Broman: programming and modelling languages, cyber-physical systems, model-based computing systems, compilers, machine learning; Mihhail Matskin: software engineering, software technology; Mira Kajko Mattson: software engineering).

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

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: Per Austrin: algorithms for NP-hard problems, analytic methods in algorithms & complexity, hardness of approximation; Johan Karlander: General Algorithm Theory, Algorithms for Matching Problems, Algorithms in Game Theory; Danupon Na Nongkai: graph algorithms, distributed algorithms, dynamic algorithms, optimization, fine-grained complexity

Computer security: Musard Balliu: Software Security, Web and IoT Application Security, Foundations of Computer Security; Sonja Buchegger: privacy-enhancing technologies, applied cryptography, decentralized systems security; Mika Cohen: Provably secure systems, Intelligence and security informatics; Mads Dam: high assurance, low level security, security models, security verification; Roberto Guanciale: Security of low-level software, Security of hardware Architecture, virtualization; Douglas Wikström: security, cryptography, quantum computation.

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

Data science: Cyrille Artho: repository mining, ML for software engineering, visual analytics; Sonja Buchegger: synthetic data generation, privacy-preserving data analysis, adversarial learning; Aristides Gionis combinatorial optimization, knowledge discovery, graph mining, social-network analysis; Viggo Kann: natural language quality analysis, language policy, terminology; Philipp Haller: Programming

3 A set of practices that combines software development (*Dev*) and information-technology operations (*Ops*).

models for data science, Large-scale distributed programming; Karl Meinke: automaton learning, ML for software engineering, ML for digital pathology; Danupon Na Nongkai: massive graph algorithms and mining, learning-based online and dynamic algorithms; Elena Troubitsyna: autonomous systems.

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

Department of Human Centered Technology (HCTD) is the smallest of four departments at the School of Electrical Engineering and Computer Science. It consists mainly of the division Media Technology and Interaction Design (MID), but also includes 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. As HCT is trans-/interdisciplinary with a strong focus on human interaction with digital media technologies, our work does not belong solely in the field of computer science, but perhaps mostly in the **Human-computer interaction** (**HCI**) field which in itself is highly interdisciplinary.

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)

MID4Sustainability: Daniel Pargman (Ecological Sustainability, Energy, Futures studies, Art), Rob Comber (Social and ecological sustainability), Elina Eriksson (Sustainable HCI, Transition Design, Sustainability Education), Björn Hedin (Digital behaviour change interventions, Sustainable HCI, Behaviour change), 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

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

Media Lab: Haibo Li: Face Recognition, Gesture, Deconvulsion; Anders Hedman Cognitive Endurance, Mindfulness, Places

b. *Central research questions and themes, knowledge gaps addressed, main research activities and composition of research team(s)*

An overview of research topics is presented in Figure 1. The research carried by the departments in multi-disciplinary in nature and addresses a wide range of topics of fundamental and applied computer science and software engineering. Our research has a strong interdisciplinary aspect with a wide variety of fields including biology, physics, electrical engineering, psychology etc. Interdisciplinary 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 problem. 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 this Panel.

Computational complexity

How to achieve time improvement in graph algorithms? 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?

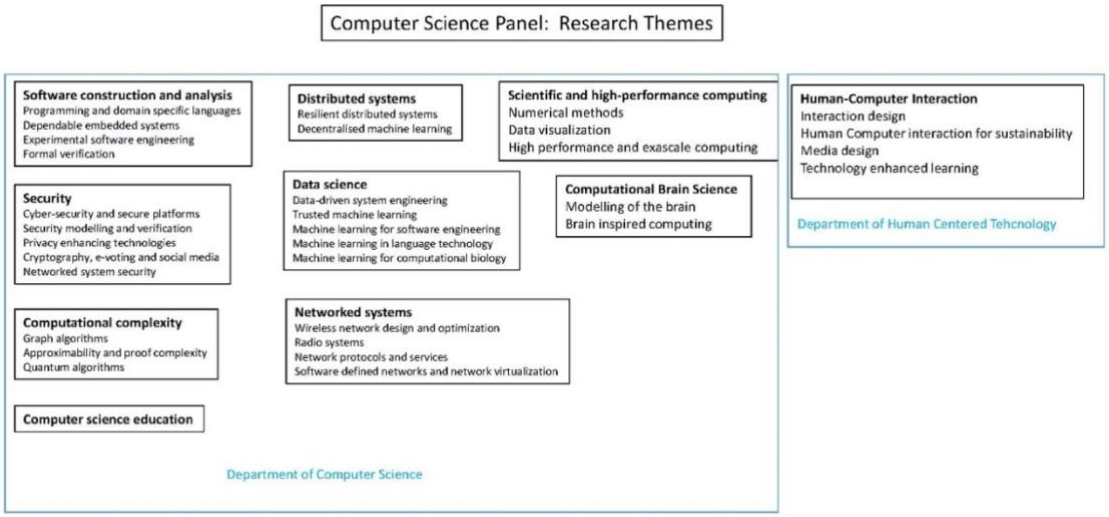


Figure 1: Research themes.

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.

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 to for software quality improvement?

We address the research challenge by developing techniques for automated program repair as well as use of machine learning techniques for enhancing code analysis and testing.

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 a 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 and tailoring general-purpose verification techniques to address security challenge. The challenges addressed along this direction is 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 enable 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 centred around the idea of building an e-voting system that follow cryptographic theory and at the same, adopt the best practices from contemporary software engineering. The work on secure social media focus on studying anonymity-preserving techniques.

How to design trustworthy networked systems, addressing both the security of networked systems and the 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: (i) Secure communication: secure neighbour discovery, secure route discovery and data communication, (ii) Security for vehicular communication/intelligent transportation systems (ITS): protocols and security architectures, (iii) Security for wireless sensor networks: confidentiality, aggregation, key management, (iv) Secure ranging and localization: security for ultra-wideband (UWB) and Global Navigation Satellite System (GNSS), distance bounding, position verification, (v) Privacy enhancing technologies for: ITS, location based services, online social networks, smart spaces, (vi) Physical layer and information-theoretic security: secure and reliable communication in a multitude of settings, scaling laws for secure communication, (viii) Security and privacy for participatory sensing systems.

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 behaviour 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 research 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 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 co-existence 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 exploiting 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 properly 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 datacenters.

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 question was tackled by the research on (1) reliability in Software-Defined Networking and (2) resource allocation in the virtualized cloud environments, (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 by 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 use methodologies from Machine learning and discrete algorithm design to solve problems of computational biology in particular regarding the evolution?

Several research topics have been explored to answer this research question. In particular, 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 create models and tools enabling a deeper understanding brain functions?

The research challenge has been addressed by the development of 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 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 the stability of Navier-Stokes, 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 been addressing 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 phenomenon.

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 behaviour and generation of artificial social and mobile behaviour.

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 application 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.

Human Computer Interaction

The technologies and interactions we develop shape our interactions with information, society, organisations, policies, and with other humans—socially, intellectually, collaboratively. As a collective we are interdisciplinary. We position ourselves at the intersection between computer science, psychology, media and communication studies, design and sound and music computing.

Interaction design

How to utilize first-person perspective and develop somaesthetic appreciation for design of interactive artefacts?

Within Interaction Design there is a clear focus on reinventing the very nature of how we interact with the digital, prioritising the design of interactions which have concern for the whole body (its soma), which invite pleasure, and which heighten, change awareness of the body, and which ultimately may transform the way that we live. We have developed a strong concept of somaesthetic appreciation and complemented this with a soma design methodology, which invites and instructs designers and developers to utilise first-person perspectives, to develop somaesthetic appreciation, and to train their 'soma design' judgement. This combination of theoretical and methodological contributions has been successful in building an international research network of researchers who focus on soma design (and design for the body). In addition, we have provided clear, refined research artefacts that illustrate the specifics of how design differs when you attend to the body. 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

What is the role of ICT in the transition towards a more sustainable society?

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.

Media technology

How to design technologies and tools facilitating new interactive possibilities in music and create sounds to improve humane machine interaction and communication?

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; sound-based methods for rehabilitation/training; music information retrieval; and computational ethnomusicology.

Technology enhanced learning

How to design tools and processes that make learning more effective and efficient?

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. Self-regulated learning skills can predict academic performance and are critical in emerging online learning contexts. Learning analytics, which has emerged based on access to learner 'big' data, is an important tool for supporting learners and teachers in fostering effective self-regulated learning skills and strategies and improving: learning outcomes, learner support and teaching. Question-based learning relies on constructive feedback on questions interspersed in the learning material. It has been proven to reduce learning times with 50% while still maintaining quality. It is time-consuming to construct such learning material and our current research targets efficiency in creation through student-generated material. 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 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

How do we design for accessibility and digital transformation 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 digitalised society as well as business transformation through digitalization in work environments.

Interaction Techniques

In an era of internet of things, what are the novel interaction techniques we may design?

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.

c. *Contributions to the advancement of the state of the art within the research fields of the department*

In this section, we present and integrated overview 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 individual researchers. The composition of the groups is defined in Section 2a.

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 to appear 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 publications in the top software technology journals Journal of Systems and Software (JSS) and EMSE; in the successful defence of two doctoral theses; in the development of two mature tools that were experimented on various industrial settings; and in the successful completion of the EU Framework Programme for Research and Innovation Horizon 2020 (H2020) STAMP project (www.stamp-project.eu).

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 (https://github.com/timed-c/ktc) – a language and tool for real-time programming (used in the MIST satellite project[4]), and UNISON (https://unison-code.github.io/) – a code generation system based on constraint models (developed together with Ericsson).

4 https://www.kth.se/en/sci/centra/rymdcenter/studentsatellit/studentsatelliten-mist-1.481707

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 to avoid 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

Cyber security: A core topic of NSE cyber security research is to develop methods for modelling and assessment of the security of large, heterogenous 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 it relies on the development of domain specific modelling languages for various ICT infrastructures (such as industrial control systems, vehicles, cloud infrastructures). To support this probabilistic approach, we are performing data-driven and empirical research on the complexity of attack vectors. To assess the effectiveness of various security controls we are developing tools and frameworks for ethical hacking, for automated observation of third parties in cyber ranges, and we work with expert elicitation techniques. In addition, we are advancing the state of the art in 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.

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). 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 is in area has also allowed the group to give the first comprehensive account of security monitoring for multithreaded Java programs (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 (https://haspoc.sics.se/) 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) formalisation of the ARMv8-A architecture.

The work on proof-based security verification has also led to a development of a new platform HolBA for binary verification (https://github.com/kth-step/HolBA). The platform is tightly integrated with the HOL4 theorem prover (https://hol-theorem-prover.org/), and applicable to MIPS and ARM[5] 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 (PIM). We also evaluated uses and limitations of synthetic data for privacy-preserving data analysis ensuring that even if leaked, fully synthetic data cannot be linked to individuals. This removes the risk of re-identification of merely anonymized data. 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 (ifttt.com), Zapier (www.zapier.com), and Microsoft Flow (CCS).

[5] **Arm Holdings (**https://www.arm.com/company**)**

The CoS security and privacy team (NSS) 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 approach for cooperative LBS privacy protection, along with security. A novel 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.

Cryptograthy, 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 the 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 research community mixnet implementation considered fit for use by national election authorities, and was deployed, for instance, in the Norwegian parliamentary election in 2013. Other crypto-related research is the work on post-quantum cryptography, reported as part of the complexity theory group.

In cooperation with Swedish Defence 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 defence 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 ($1^{st}/2^{nd}$ 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 ($1^{st}/2^{nd}$ 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 in secure ranging, distance bounding, and secure positioning. Recent results: VR young researcher award on this topic (2012); US patent (2012); bilateral project with European Space Agency (ESA) (2019).

Networked systems

Wireless network design and optimization: The wireless network design group at NSE has progressed 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 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.

Radio systems, Network protocols and services, Software defined networks and network virtualization

Deep understanding of service chains (in the context of network function virtualization) synthesis of equivalent service chains that can be partitions across network switches and processor to provide very high performance and near zero latency variance (open source Metron and SCC)

Deep understanding of delay and delay variance of interdatacenter links methods for exploiting geo-distributed datacenters to reduce violation of service level objectives – outputs include GeoPerf and very extensive datasets of interdatacenter communication delay measurements

Deep understanding of interaction between network interfaces and processors & caches CacheDirector and recent understanding of when to use and not use Intel® **Data Direct I/O** Technology (DDIO) – 4 patent application filings with industrial partner

Deep understanding of how to implement high performance user space packet processing contributed to each of the above and enables the implementation and measurement of network services at 100 Gbps.

Deep understanding regarding a wide range of fundamental problems in system design for wireless communication from propagation, antennas and spectrum management to business modelling.

Deep understanding on modular and flexible design of wireless medium access protocols and their implementation in different software defined radio platforms. Key knowledge about performance-computing resources trade-offs. DMDL design framework, open source code available. Also used in education (project courses).

Expert knowledge in aerial (airborne) communication, the key problems enabling direct air to ground communications (DA2GC). Solutions to the ground station deployment problem to provide Gbps backhaul link for an aircraft. Understanding of the feasible operation points for the key network parameters: the number of ground stations, antenna array size, transmission power and bandwidth. Strategic partnership with Airbus (https://www.airbus.com/).

Competence in virtualized Cloud-Radio Access Network (CRAN) Architecture where virtualization takes place in all network segments starting from radio to optical and central cloud. Expertise in design of energy-efficient architectures.

Expertise and deep understanding of the technological, economical and regulatory aspects of spectrum sharing and technology co-existence in licensed bands and spectrum commons.

Deep understanding and knowledge of the obstacles (and sometimes) show-stoppers for market entry of new technical concepts. Systems meeting the technical requirements and challenges e.g. high capacity, low energy consumption also need to work in a business context, e.g. to be scalable in the business domain.

Deep understanding of resilient mechanisms in packed-switched Internet networks. Solid theoretical and practical contributions to the problem of enhancing resilience in a network.

Deep understanding of load balancer services in Cloud provider environments. Solutions to pressing load balancer issues such as scalability, performance, robustness, and flexibility.

Deep understanding of emerging programmable network packet processing pipelines (e.g., Protocol Independent Switch Architecture (PISA)). Solid theoretical and practical contributions to the problem of enhancing performance and reactiveness in a network.

Deep understanding of traffic-engineering problems in a variety of different networks (e.g., Wide area networks, datacenters). Solid theoretical and practical solutions to the problem of optimizing the flow of traffic in a network in a scalable and robust manner.

A central research challenge is how to understand the deployment and scaling of mobile services. Up to now, this has been quantified using quality of service (QoS) metrics from a network perspective. However, what matters more is the perceived quality, and hence new measurements are needed. Bio-sensing and other approaches to put the human in the loop is a wanted. Our work shows that bandwidth saving of more the 90% is possible without affecting the perceived quality when considering these factors.

Expert knowledge in efficient, systematic testing of unmodified OpenFlow controller programs and deep understanding of bugs in this new environment. The main work called NICE was highly cited, with the source code downloaded more than 250 times, and used by other research groups.

Deep understanding of OpenFlow switch interoperability as well as differences and performance characteristics (multiple publications, widely cited).

Expert knowledge in dynamic, fine-grain monitoring of open flow switch data planes (Monocle)

Expert knowledge in accelerating resource allocation and dealing with interference in virtualized cloud environments (DejaVu and DeepDive systems, widely cited; US patent filed)

Deep understanding and pioneering work in the areas of light-weight network virtualization as an enabler for cloud networking, and open platforms for software-defined networking.

Expert knowledge in the field of energy-efficient communication through the combination of energy-aware routing and uncoordinated link power savings.

Expertise and deep understanding of integrated solutions for environmental sensing systems and application platforms enabling innovations based on open data.

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. 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 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.

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-base 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 other.

In the second half of 2019, WASP Professor Gionis joined the TCS division. Thus timewise, his research on foundations of data science and applications in social network analysis is largely outside the scope of this RAE, however, more activities in these topics are expected in the future, also supported by anticipated recruitment in the area.

Machine learning in computational biology and bio-image processing: Within CST, the line of research 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 transfer of results from model organisms, such as mice and Drosophila, to knowledge about human biology. That cancer tumors evolve is the fundamental principle explaining many of this disease's most challenging properties, including common disease relapse following initially promising therapy response.

The evolution of genes as well as species are, typically, modelled by trees, i.e., phylogenetic trees. CST group had previously developed a model for how gene trees evolve relative to a species tree that is based on a generalization of a birth-death process. The generalized process takes place in a tree rather than in an interval. The generalized birth-death process integrated with a model of nucleotide substitution provides a principled mathematical and biologically realistic model for reconstructing phylogenetic trees, understanding how genes have evolved with respect to gene duplication and loss. We have during the period reported here extended this model and showed how to build tools based on it. For example, we have extended the model by also including lateral gene transfer. Lateral gene transfer is a transfer of a gene from one organism to another, of the same or different species, and is a key event in bacterial evolution, e.g., providing a means to spread antibiotic resistance. A second example is the orthology analysis tools built based on the model, which can be used to translate functional classifications of genes between species.

The research on somatic evolution in cancer is supported by cutting-edge biotechnology today. It allows CST group to investigate single-cells as well as where in a tumor cross-section which genes are active. We are developing models and inference algorithms that can reveal, for instance, (1) how individual tumors have evolved, (2) the typical pattern of evolution across a set of tumors, of the same type, say, breast cancer, (3) how the different subpopulations of cancer cells are distributed in a tumor, and (4) how cancer and immune cells are interacting.

Computational Brain Science

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 behaviour and reward learning. The models are built at different levels of biological detail, from subcellular signalling 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 make possible 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-inspired 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 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 is 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 software, industrial use, and successful creation of spinoff companies.

In the area of statistical physics and open quantum physics, the CST group has done the significant contribution 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 tool to predict epistatic components of fitness from population-wide genomic data.

Data visualization: The research performed by CST 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. The CST results extend persistent homology to the separatrices of the Morse-Smale complex, 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. The CST group has also provided the only topological denoising method with guarantees on the topology and the level of smoothness in the resulting data.

In flow visualization, the CST 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, we 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 open tools.

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 10^{19} 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 to efficiently use heterogeneous hardware (particularly CPUs and GPUs) and help managing 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 programme integrating course for students of computer science and engineering, including reflection, self-regulated learning, study skills, quality enhancement, programme 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.

Human Computer Interaction

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 centre* (which ended in 2017) where we – together with strong industrial partners – became a strong voice advocating a human centred focus on digitalisation – focusing on what makes a good life for all. The centre 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 centre initiated and developed unusual and evocative research topics such as: integrating digitalisation 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 centre 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 Centre for Sustainable Communications (CESC) until 2017 when the centre 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 behaviour 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 behaviour 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 a 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 Landsting (SKL), (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[6], 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 startup 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.

d. *Quality and quantity of contributions to the body of scientific knowledge*

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: 9 people; 11-20: 6 people; 21-40: 5 people; 41-80: 2 people

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

We would like to highlight P. Papadimitratos, as he has had in the 2012-2019 period on the average 1000 citations per year (Google Scholar). At the beginning of 2020, based on citation

6 AB is an abbreviation for the Swedish "Aktiebolag" and limited company or corporation.

count (approx. 13000) he ranks 24nd for all KTH and 8th among EECS faculty. Indicatively: in his broad areas, according to Google Scholar, *globally*, he is 88nd among those with "security" as one of their research areas; and 46rd globally among those with "privacy".

Selected papers from COS (see also Appendix 2):

Most cited publications in reverse order of citations per year:

- 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)
- Ahlgren, M. Hidell, and E. C.-H. Ngai, "Internet of Things for Smart Cities: Interoperability and Open Data", IEEE Internet Computing, Vol 20, No 06, Nov-Dec 2016. (35 citations per year, 139 total)
- Lema, M. A., Laya, A., Mahmoodi, T., Cuevas, M., Sachs, J., Markendahl, J., & Dohler, M. (2017). Business case and technology analysis for 5G low latency applications. IEEE Access, 5, 5917-5935. (27 citations per year, 81 total)

Other representative publications:

- 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)
- Munari, P. Mähönen, M. Petrova, "A stochastic geometry approach to asynchronous aloha full-duplex networks," IEEE/ACM Transactions on Networking 25 (6), 3695-3708, 2017 (top networking Journal)
- 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)

CST

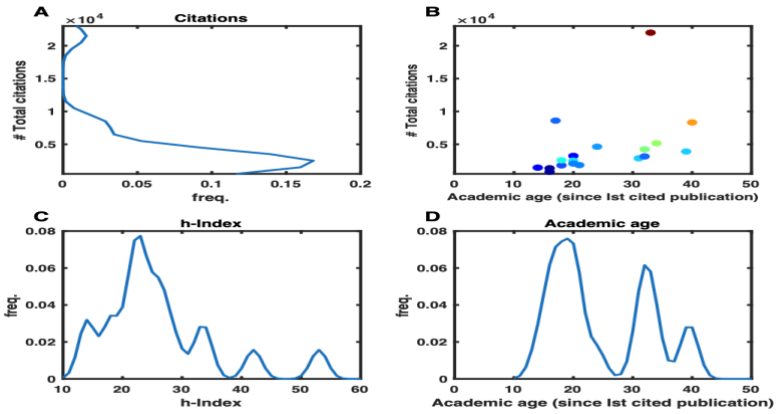


Figure 2. Bibliometric profile of CST faculty.

(A) Distribution of citation of all the faculty members.

(B) Scatter diagram with academic age and number of citations. Each dot shows the number of citations and academic age of a faculty member. The colour of dot shows h-index of that faculty member (warmer colours indicate higher h-index).

(C) Distribution of h-Index of all the faculty members.

(D) Distribution of academic age (since first cited publication) of all the faculty members.

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 85, and the field normalized citation index is 22.

h-index: 1-10: 0 people; 11-20: 2 people; 21-40: 7 people;

i10-index: 1-10: 0 people; 11-20: 1 person; 21-40: 1 person; 41-80: 6 people; 81-100: 1 person

The following are examples of publications from the division (see also Appendix 2):

- 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 (**TCOM**) in 2018, namely the “O. Rice” Award)
- 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
- 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
- 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 (2018 IEEE Sweden Joint VT-COM-IT Chapter Best Student Conference Paper award for the conference version of the paper, which appeared in IEEE Infocom 2017)

Cybersecurity

- P. Johnson, Robert Lagerström, Mathias 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.
- 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.
- W. Xiong and R. Lagerström, “Threat Modeling: A Systematic Literature Review,” in Computers & Security, vol. 84, July 2019, pp. 53-69.

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) = 17533

Citation indices for 13 research active SCS staff:

h-index: 1-10: 0 people; 11-20: 5 people; 21-40: 7 people; 41-80: 1 person

i10-index: 1-10: 0 people; 11-20: 1 person; 21-40: 6 people; 41-80: 4 people; 81-160: 2 people

Selected papers from SCS:

Distributed systems

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.*

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

OL 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.*

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

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*

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*

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 specialisation. A selection of 10 significant TCS publications is included as an ***Appendix*** below.

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 26 research active TCS faculty members (not including doctoral students):
Total number of TCS publications in period (conference, journal, book chapters) = 417
Total number of TCS citations in period (source Google Scholar) = 17524
Citation indices for 26 research active TCS staff:
h-index: 1-10: 7 people; 11-20: 8 people; 21-40: 9 people; 41-80: 2 people
i10-index: 1-10: 7 people; 11-20: 4 people; 21-40: 6 people; 41-80: 6 people; 81-160: 3 people

Most impactful papers per research theme
Security
Ulrik Franke and Joel Brynielsson. Cyber situational awareness – A systematic review of the literature. Computers & Security, 46:18–31, October 2014. doi:10.1016/j.cose.2014.06.008. (Citations 194).

Dam, M., Guanciale, R., Khakpour, N., Nemati, H., & Schwarz, O. (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 68)

Software construction and analysis
Martin Monperrus, Automatic Software Repair: A Bibliography, ACM Computing Surveys (CSUR), January 2018, Article No.: 17 (Citations 135)

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. (6700 downloads).

Computational complexity
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 137).

P Austrin, V Guruswami, J Håstad, (2+eps)-Sat Is NP-hard, SIAM Journal on Computing 46 (5), 1554-1573, 2017. (Citations 30)

HCT

MID members have published at many top (A*) conferences (e.g. ACM CHI Conference on Human Factors in Computing Systems (CHI), NordiCHI (www.nordichi.eu), **International Society for Music Information Retrieval** (ISMIR), ACM **conference** on Designing Interactive Systems (**DIS**)) 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) in their respective field of specialisation. The quality and quantity of contributions by the division are high. Between 2012-2019, more than **20** 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) = **33.043**

Citation indices for 24 (the research active) MID faculty:

H-index: 1-10: 6 people; 11-20: 12 people; 21-30: 4 people; 31 - 40: 1 person; 41-50: 1 person

i10-index: 1-10: 5 people; 11-20: 5 people; 21-40: 6 people; 41-50: 3 people; 51-111: 4 people

When analysing our publication patterns, we note that in particular, our younger faculty have a better publication trajectory than most of our 'old' professors. Since 2018, we have therefore step by step given more space and resources to our assistant and associate professors, building new research teams and contributing to the research development of our field.

Interaction design

1. Balaam, M., Comber, R., Clarke, R. E., Windlin, C., Ståhl, A., Höök, K., and Fitzpatrick, G. (2019). Emotion Work in Experience-Centered Design. In *Proceedings of the 2019 CHI Conference on Human Factors in Computing Systems (CHI '19)*. ACM, New York, NY, USA, **Honorable mention. Citations: 1**
2. 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: 63**
3. Höök, K. *Designing with the Body: Somaesthetic Interaction Design*. MIT Press, 2018. **Citations: 31**
4. Höök, K., & Löwgren, J. (2012). Strong concepts: Intermediate-level knowledge in interaction design research. *ACM Transactions on Computer-Human Interaction (TOCHI)*, 19(3), 1-18. **Best of ACM 2012. Citations: 291**

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: 119**

Learning technologies

6. Viberg, O., Hatakka, M., Bälter, O., & Mavroudi, A. (2018). The current landscape of learning analytics in higher education. Computers in Human Behaviour, 89, 98-110. **Citations: 66**

Novel interaction techniques

7. Lv, Z., Halawani, A., Feng, S., Ur Réhman, S., & Li, H. (2015). Touch-less interactive augmented reality game on vision-based wearable device. Personal and Ubiquitous Computing, 19(3-4), 551-567. **Citations: 244**

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: 28**
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: 58**

Sound and Music Computing

10. Dubus, G. & Bresin, R. (2013). A Systematic Review of Mapping Strategies for the Sonification of Physical Quantities. *PLoS ONE*, 8(12), e82491. **Citations: 156**

e. *Engagement in national and international research collaboration within academia and its outcomes*

CSD

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), IIT Madras, Shanghai Jiao Tong University, Tsinghua University, TNO, 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 journal and conferences of the division's research areas, but also extended period of visiting to and from these universities. For example, Robert Lagerström and Carlo Fischione spent sabbatical years at Harvard University and MIT. 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 students exchange. Moreover, several joint conference and workshops 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 Smart Grids Comm.

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

Karolinska Institutet. Researchers at SCS have a long-standing collaboration with Karolinska Institutet (KI), one of 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, 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. This is Sweden's largest individual research program ever. It spans the scientific domains of data science, machine learning, dependable software, software technology, which are some of the core research areas of the department. B. Baudry has a WASP Professor chair, the division also has two WASP Expedition projects, 3 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 (devoxx.com), FOSDEM (fosdem.org)).

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.

TCS: All groups have participated in multiple nationally funded projects from, e.g., KAW, MSB, VR, Vinnova, SSF, WASP, Wallenbergs Stiftelse.

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 **É**cole Normale Supérieure, Paris and is a member of the Interest Group on Algorithmic Foundations of Information Technology (IGAFIT).

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

Computer science education: The group collaborates with the *UpCERG* research group at Uppsala University (https://www.it.uu.se/research/group/upcerg). 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) (https://www.stint.se/) stipends for 5-month sabbaticals to the USA and Singapore. Ric Glassey will go to National University of Singapore (NUS) , in Fall 2020. He has also been on two 1-month exchange trips to Northeastern University (https://english.neu.edu.cn/), Liaoning Province, China (2015, 2016). STINT sabbaticals have led to course improvements and new research studies at KTH.

Data Science: Karlgren is a member of European Commission Sixth Framework Programme (**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. Gionnis is an ISI Foundation Fellow in Torino. Meinke organised 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 (www.mbat-artemis.eu), SafeCOP (www.safecop.eu), and Testomat (www.testomatproject.eu). 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 Signalling, Automation and Communication Systems”. Dam, Gurov and Meinke participated in EU-FP7, Highly Adaptable and Trustworthy Systems (HATS), 2009-2013.

HCTD

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 organised at the ACM SIGCHI flagship CHI conference, and we recently

7 https://ec.europa.eu/programmes/horizon2020/en/news/emergency-alert-system-europe

organised a special issue of the TOCHI journal on female health (coming out Spring 2020). We also collaborate with 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 MID for *sustainability* (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 organising workshops at the ICT4S conference (ict4s.org), at CHI and NordiCHI, in organising the annual two-day Computing within Limits workshop (mini-conference). The team has also organised 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, organising 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*) centre. Sandra Pauletto is also a Member of the Peer Review College for UK Research Council.

The *technology-enhanced learning* team collaborates nationally with 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 2020. Internationally we collaborate with the universities of Bergen, Oulu and the Open University (UK) in relation to self-regulated learning, mobile assisted language learning and learning analytics. The team also has a collaboration with Kanda University (Japan). Moreover, the team collaborates with Stanford and Carnegie Mellon University regarding Question-based learning (Open Learning Initiative, OLI, 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.

f. *Follow up from previous evaluations*

CSD

The last research assessment exercise was carried out in 2012. Following the recommendation of tighter integration between the research group, the department of computer science was established. The department integrated five divisions (former departments). The integration resulted in more streamlined educational programs at all levels and encouraged tighter cross-division collaborations. The examples of them include joint research centers, research projects as well as joint doctoral students' supervision.

Since the last evaluations all divisions worked on increasing the publication impact through targeting venues with a high impact factor, arranging tutorials as well as invited keynote lectures. The international collaboration has intensified and widen geographically. The research cooperation via research visits and joint projects made a positive impact on research. The interdisciplinary collaboration intensified as well.

Strengthening research impact was also achieved via hiring the top young talents and prominent established professors, e.g., though WASP program.

Significant efforts have been also made in achieving better gender balance via hiring female researchers in traditionally male-dominated disciplines as e.g., theoretical computer science.

HCT

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.

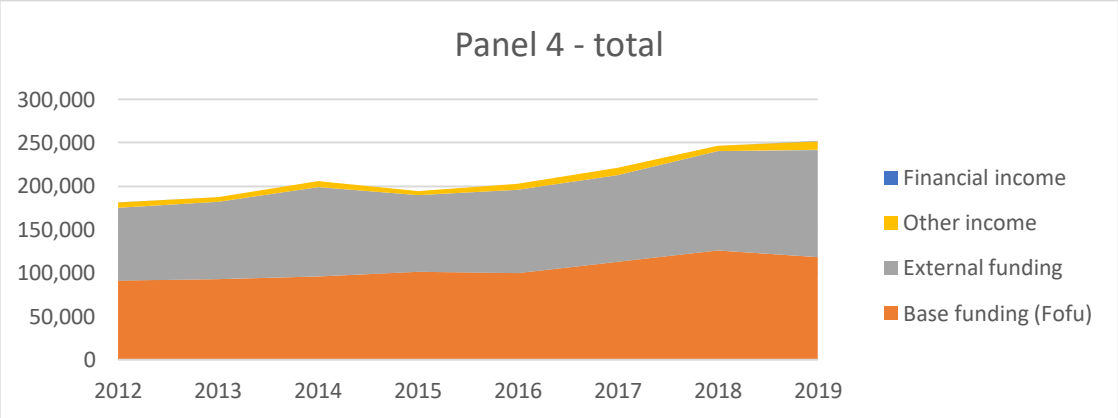
The division has also established a plan for increasing publication impact through targeting high impact journals, international collaboration and high impact conference venues.

To further foster the academic culture we have since 2015 introduced so called *writing camps*, 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

a. *Funding; internal and external*

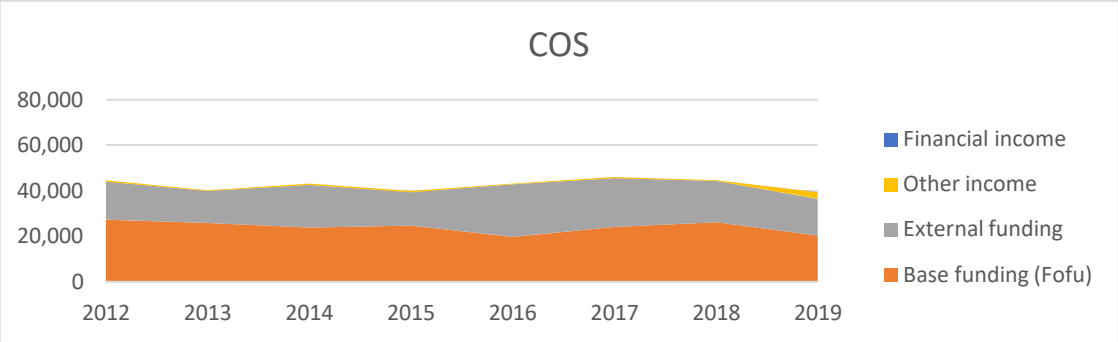


The overall funding for the Computer Science funding has been constantly increasing for the assessment period. The main sources of funding include:

- FP7 and H2020: European Union research framework programs, past and current.
- VR: The Swedish Research Council, which focuses on fundamental research.
- SSF: The Foundation for Strategic Research in Sweden, which focus on applied research of strategic relevance for Sweden.
- VINNOVA: The Swedish agency sponsoring technological innovation.

- Knut and Alice Wallenberg Foundation: it funds Academy Fellows, in conjunction with the Swedish Academies, as well as a gamut of (collaborative) projects.
- 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.
- Digital Future: 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.
- EIT Digital: The European Institute of Technology and innovation (https://www.eitdigital.eu/), which sponsors pre-commercial research.
- The Swedish Energy Agency.
- MSB: The Swedish Civil Contingencies Agency.

CoS



The amount of funding has been largely steady, with a mild decrease very recently due to ONLAB departure. Some of the funding highlights are shown below.

RSlab: ~100MSEK external funding between 2012-2019. Funding agencies EU: FP7 and Horizon 2020, CELTIC PLUS (www.celticnext.eu), EIT ICT, EIT Digital, Vinnova, SSF, Internet foundation, IoT Sweden, Viable cities.

NSlab (Chiesa): Vinnova Datalab (SE-CAID)[8]

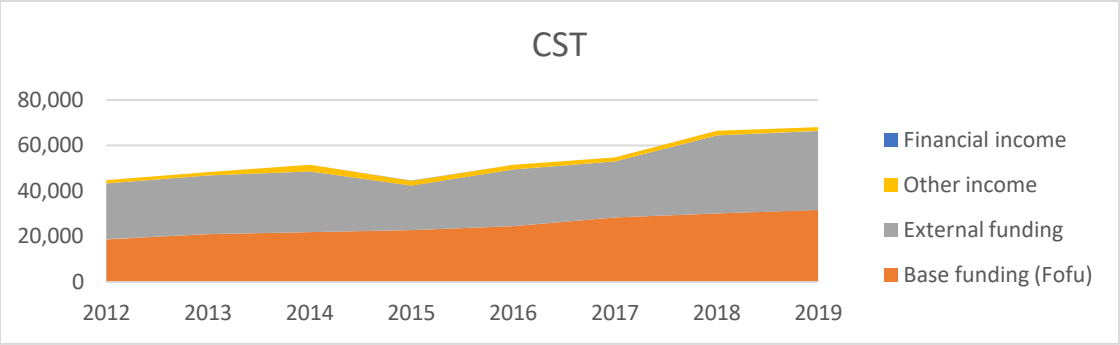
NSlab (Hidell & Sjödin): ~13MSEK external funding between 2012-2019. Funding agencies Vinnova, Swedish International Development Cooperation Agency (Sida), Trafikverket.

NSS: Three projects funded by the European Commission (EU FP7), four by the EIT ICT Labs, a Young Researcher Project award and a framework grant funded by the Swedish Science Foundation (VR), and a Knut and Alice Wallenberg Academy Fellowship. Additional external funding: KAW WASP, SRA ICT TNG, VINNOVA, EIT Digital, Viktoria Swedish ICT, Security Link. Most recent, a framework grant by SSF, which involves 5 Swedish Universities and 4 industrial partners. Approximately, in the covered period, 52MSEK (including own shares for collaborative projects).

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

8 https://www.vinnova.se/en/p/se-caid-swedish-communications-and-ai-research-data-lab/

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.

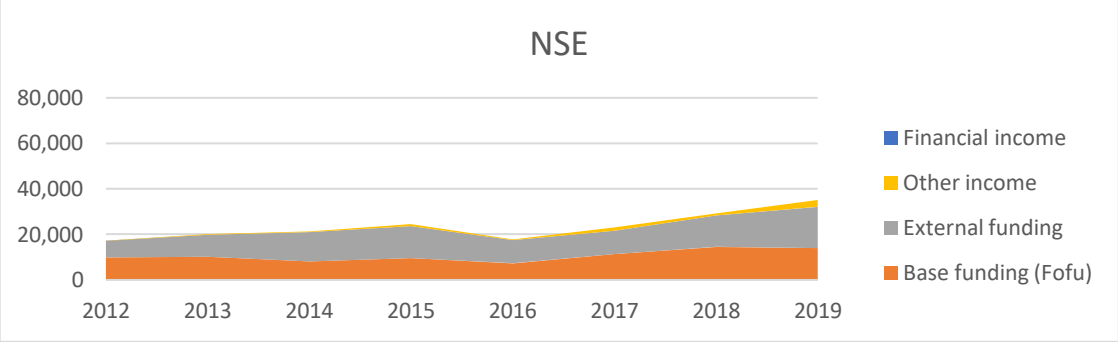
As of January 2020, external funding is distributed as follows:

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



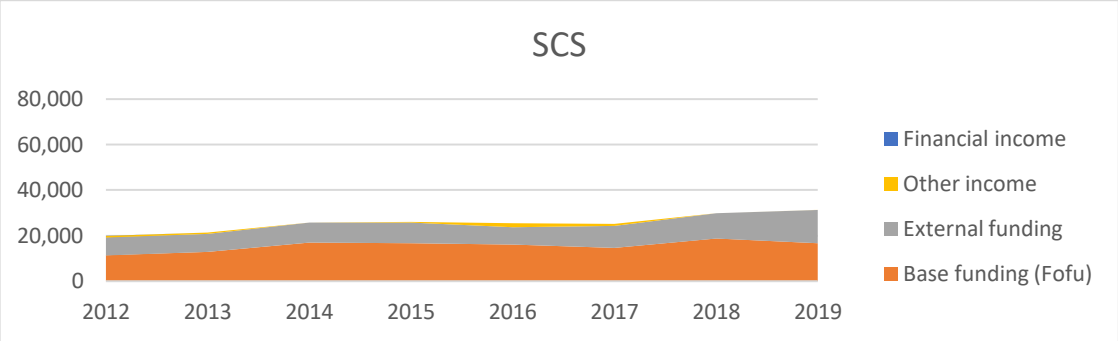
The NSE division is at the moment very well-funded. NSE is funded roughly 20% from teaching and 80% from research. Research funding is about one third from internal sources (KTH FOFU, TNG, etc.) and two thirds from external sources. External funding comes from Swedish organization (VR, SSF, Vinnova (Sweden's Innovation Agency - https://www.Vinnova.se/), FM, etc.) as well as from European funding sources and programs (H2020, EIT, ITEA (https://itea3.org/), etc.). There is a small amount of 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 have a budget larger than 10MSEK. 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. The external funding mainly come from the following sources:

- the Swedish research council (VR), currently supporting two basic research projects at SCS, including one jointly with Karolinska Institutet (KI)
- the Swedish foundation for strategic research (SSF), supporting a large individual grant for future leaders and two large framework grants, jointly with Swedish Research Institutes (RISE) and Uppsala University, respectively
- Sweden's innovation agency (Vinnova), supporting projects in collaboration with industry and society, e.g., one project lead by Scania and another lead by the Swedish National Financial Management Authority
- the research framework of the European Union (H2020, previously also FP7), including the ExtremeEarth project and funding of doctoral students through the Marie Curie (both FP7 and H2020)
- the Wallenberg Artificial Intelligence, Autonomous Systems and Software Program (WASP), supporting one WASP chair, two postdocs and several doctoral positions
- European Institute of Innovation and Technology (EIT)
- Erling-Persson family foundation
- Marianne and Marcus Wallenberg Foundation (MMW)

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.

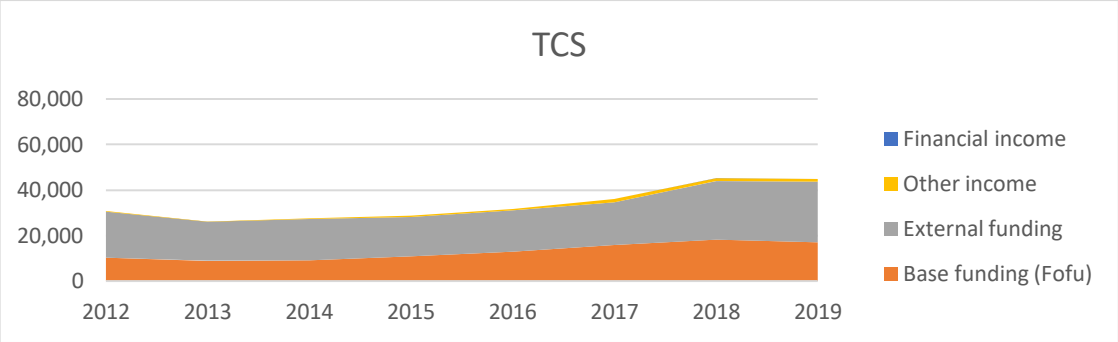
The research at SCS is funded by e.g., SSF Trustfull; SSF Continuous Deep Analytics (CDA); CELTIC Internet of Devops; H2020 STAMP; WASP chair; WASP Expedition; WASP Industrial doctoral students; Vinnova CODA[9]; and Vinnova Resultaten i Staten[10].

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)

TCS



The graph above shows that combined internal and external research funding for TCS has increased from 30MSEK (2012) to 44MSEK (2019). There is a period of falling or flat research funding from 2012 to 2016, but the situation has improved since 2016.

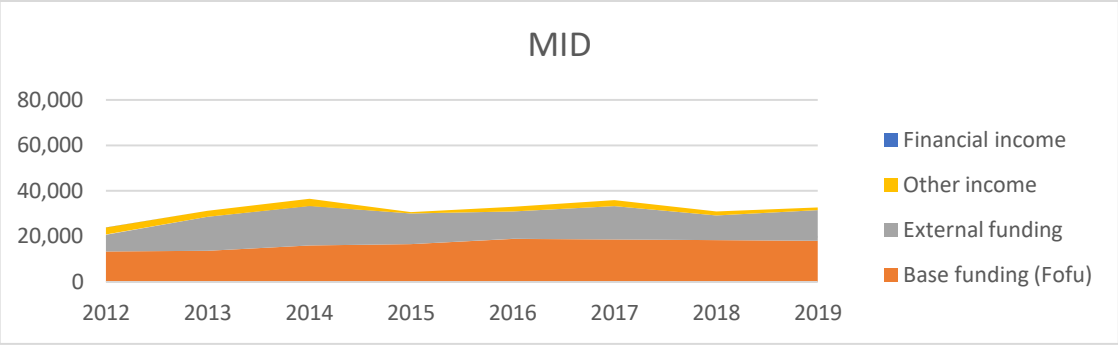
A detailed analysis of the sources of funding for TCS indicates substantial changes. For example, funding for pure science research from VR has fallen significantly from 10MSEK (2012) to 3MSEK (2019). Funding from the EU (including ERC grants) has fallen (almost steadily) from 7MSEK (2012) to 3MSEK (2019). Funding for applied science research from Vinnova has increased from 0MSEK (2012) to 4MSEK (2019). Funding for large scale science projects has increased, e.g. from the Wallenberg Foundation from 0MSEK (2012) to 10MSEK (2019) and from SSF 2MSEK (2012) to 5MSEK (2019).

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).

9 https://www.vinnova.se/p/coda---prognostiserande-modeller-med-tolkningsbarhet-och-analys-av-datadrift/

10 https://www.vinnova.se/p/datalabb-resultaten-i-staten/

HCTD (MID)



Internal research funding: The internal research funding has increased with approx. 0.6 MSEK (0.054MEUR) per year since 2012. 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 2012-2019 are (in order of funding)

- VINNOVA (Sweden Innovation Agency)
- Stiftelsen för Strategisk Forskning (Swedish Foundation for Strategic Research)
- EU
- Vetenskapsrådet (Swedish Research Council)
- Energimyndigheten (Swedish Energy Agency)
- Wallenberg Foundations
- 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.

Overall, HCT 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 more doctoral students in 2020. Overall, our funding has grown a lot (on average 0.750MSEK 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: so far 9 grants with a total external funding of 20MSEK 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.

b. *Academic culture*

The nature of research varies significantly across divisions, which is reflected by different academic cultures. In common, all divisions run regular seminars at which doctoral students present their results, faculties discuss their on-going research work as well as invite external research visitors to talk about their research. At CoS, there is a tradition of regular seminar of research groups. At SCS, the most important meeting places to discuss research are at seminar series, e.g., in model-based computing and distributed systems and data science. At TCS, academic culture is for the most part based on personal collaboration, often without the need for specific equipment or infrastructure.

Shared externally funded projects are increasingly common, and staff sometimes mentor each other in funding calls. There is a strong "whiteboard culture" in open spaces such as corridors and coffee rooms. Larger research groups increasingly occupy larger dedicated lab spaces. 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. Across all the divisions, we make an active use of teleconferencing facilities such as Zoom or Skype Business. KTH also provides a support to exchange and share research documents within KTH.

At CST, the research culture is diverse reflecting the breadth of scientific disciplines represented by the faculty. For example, there are different patterns of disseminating scientific results (peer reviewed journals vs. conferences), different types of venues for scientific interactions (ranging from large conferences to focused workshops and symposia) and varying forms/schemes of research quality assessment (scientific credit assignment). To jointly discuss matters of importance, the board of CST division currently comprises the majority of the professors and one junior faculty representative.

Despite the diversity, CST has developed multiple strategies to build common academic culture that paves the way for new collaborative research opportunities with the ambition to further enhance our scientific portfolio. These strategies include a joint seminar series combined with doctoral student progress seminars where faculty representatives of different research environments interview a given doctoral student (seminars advertised at the division and school level, and communicated via email to collaborators at Karolinska Institutet and Stockholm University). Strategies also include 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 level (EU Horizon 2020, projects Epigram-HS and Sage2), and publications by members of different research environments at CST. Furthermore, despite the aforementioned research diversity many faculty members are part of strategic research platforms at KTH, which provide additional fora and venues for discussing research matters. Suitable examples are Swedish e-Science Research Centre (SeRC) and the emerging KTH Digital Futures initiative, where CST faculty are part of two TechLab pilot projects. In both cases there is a special office space designated for organizing regular meetings, discussions and seminars.

Due to the global nature of research collaborations that CST staff are engaged in as well as geographical distribution of CST research groups in Stockholm, a great deal of research discussions and meetings are handled with the use of the available teleconference infrastructure. For this purpose, there is an easily accessible designated room with dedicated teleconference equipment and there is also an opportunity to exploit a large screen to facilitate communication in larger groups in the Visualization Studio (VIC)[11] .

Similar to CST, the academic culture at NSE is diverse, which is explained by a recent formation of the division. It is a mix of the cultural traditions of basic research, which rewards the development of basic principles, as well as 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. Moreover, such a culture allows the senior faculty to engage in fruitful cross-disciplinary collaborations, which have already resulted in large research projects. The result is that, in general, the academic culture promotes high-quality research, as shown by the high academic impact of the division.

11 https://www.kth.se/cst/research/vicstudio/the-visualization-studio-1.859336

NSE has the following meeting arrangements: Weekly individual meetings between the doctoral supervisors and their doctoral students and post-docs.

- At least bi-weekly research group meetings of the faculty with their respective research groups;
- Regular bi-weekly faculty meetings of the division, where strategic research matters as well as the division culture are discussed and decided upon;
- Weekly division meetings including faculty and young researchers (doctoral students and post-docs), where doctoral students present their ongoing research and receive detailed feedback;
- Annual division meetings, where faculty perform a thorough review and planning of the division's activities and external speakers give inspiring seminars on selected topics (e.g., career development paths, popular science public speaking, research impact in the society, or innovation).

HCT: The research in this Division has grown out of the *participatory design* traditions rooted in seminal projects such as UTOPIA[12] 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-centred 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, behavioural 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; 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 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, and Sound and Music Computing.

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.

[12] UTOPIA was a unique project in the 1980ies in parts responsible for innovating the whole participatory design movement – today often referred to as user-centred 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

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.

c. *Current faculty situation*

The following table summarizes the faculty situation for all divisions in the Computer Science panel.

	Professors		Associate professors		Assistant professors		Adjunct professors		Lecturers		Doctoral students		Research engineers		Postdocs		Emeritus	
	F	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**	**F**	**M**
CoS		5	1	9	1	1		1		1	2	14		3		4		
CST	1	6		8		1		3	1	1	7	13	3	6	2	1		
NSE	1	6	0	2					1	0	5	15	0	2	1	5	0	1
SCS	0	9	2	7	0	1			0	4	12	27	1	3	0	3	0	1
TCS	1	5	1	8	0	1	0	1	1	3	3	20	0	7	0	4	0	1
MID	3	5	3	6	2	2		3	1	4	5	17			4	2	1	1

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. See also the figure in the publication section for the age distribution. Note, all who originally were employed as assistant professor are now associate professor. 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.

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 an adjunct). 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: The number of female faculty is low. One of the two female lecturers is furthermore on leave of absence to uphold a professorship in Norway. 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 applied AI. 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.

Currently **TCS** faculty (non-doctoral and non-teaching assistant positions) consists of 35 men and 4 women (10%). Among doctoral students, we have 20 men and 3 women (13%). Among teaching assistants we have 16 men and 1 woman (6%). During the assessment period TCS has improved the gender imbalance by hiring 3 women. In further addressing the gender imbalance we will follow the guidelines and principles provided by KTH and the EECS school.

TCS has the following age distribution of faculty: 20-30 years (2), 31-40 years (14), 41-50 years (13), 51-60 years (8), 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.

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 at least two assistant professor positions. We are also open to trying to hire at higher levels (professor or associate professor). The only category in which we have gender balance is assistant professors. Getting to the balance point for associate professors will take time. We hope to overcome the deficiency of female full professors in a future promotion.

HCTD

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 nine associate professors, three 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.

The assistant professors are gender balanced, and ~35-43 years old. All four assistant professors are expected to be promoted to associate professors during the year 2020. We expect them to be promoted to 'docent'[13] around the same time.

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.

d. *Recruitment strategies*

CoS: Priority should be given to recruiting postdocs over doctoral students – due to both their ability to contribute to research and the limited funding (period) that is necessary for them

13 A docent is able to be the main advisor for a student.

The focus on tenure track recruiting is to recruit the most competent people possible as faculty members – there should be near zero hiring of research staff (other than for specific projects and for only limited periods of time).

CST: As can be deduced from the current faculty situation in the division, we recognise 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 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 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 visualisation, 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 recognise 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's 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 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 synchronisation 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.

The recruited faculty at **TCS** during 2012-2019 is very international. 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 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.

HCTD

Since 2016 we have recruited:

- three associate professors: Interaction Design, Communication, Media Production;
- four assistant professors: two in Sound and Music Computing, one in Sustainability and Technology Enhanced Learning, respectively
- four post-docs

All of these recruitments are new positions. We are currently in the process of hiring an assistant professor in Interaction design with focus on AI-based systems. 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 "Physical Interaction Design", "Human-Computer Interaction" and "Digital transformation".

During 2019 we also have recruited one affiliated professor and one affiliated faculty. During 2012-2018 we have had 1 adjunct professor, 2 affiliated professors and 1 affiliated faculty.

Doctoral candidates' positions at MID are dependent on external funding.

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 50% of their time.

Newly appointed associate professors are given resources for at least one postdoc each.

e. *Infrastructure and facilities*

CSD

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 Center for High Performance Computing (PDC) (www.pdc.kth.se).

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 Centre of Excellence (https://www.excellerat.eu/wp/).

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 Centre for High Performance Computing (HPC)[14], the leading HPC center in Sweden.

NSE: The division has modest infrastructure and research facilities, which can limit systems research. However, the division has access to larger infrastructure and research facilities present at KTH and offered by collaborating institutions (e.g., RISE and FOI) or industries (e.g., Ericsson or ABB). To build and operate large research facilities and infrastructures, significant investments will be needed, which are difficult to obtain, since the Swedish academic system favors relatively short-term projects (2-5) years which need to show abundant research productivity, whereas experimental research often has associated heavy coordination and maintenance efforts that reduce the requested research output. To make an infrastructure internationally competitive, a strategy could be to join efforts with other divisions of the School. 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 centre facility ICE (https://ice.sics.se/) 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.

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.

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 centralised 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

14 https://www.pdc.kth.se/about/what-is-pdc-1.736889

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.

HCTD

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

R1: The MID division hosts the KTH *R1 Experimental Performance Space*: a mix between a museum, cultural house, studio, and lab. It is located in the underground space which originally hosted Sweden's first nuclear reactor R1. This research cultural heritage site is being used for several research and research dissemination activities, both from the MID department and from KTH in general. Since 2012 there have been a number of TEDxKTH events with participation from KTH researchers, and there has been a number of successful Hackatons and research seminars taking place in this inspiring environment. There have also been a couple of exhibitions, with corresponding doctoral defenses, in the increasing area of research within science and arts, and there have been several presentations and discussions with politicians and business leaders, where the reactor hall as a creative meeting space have played an important part.

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.

HapticLab: Haptic interfaces range 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

a. *Goals for development 5–10 years ahead*

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 neighbouring 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,

defence, 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 initiative 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 down the line help 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 develop further 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 a 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.

CoS: 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 divison. 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.

A second major goal is to develop building blocks for a trustworthy, secure and privacy preserving, Internet of Things. One KAW Academy Fellowship and its continuation, one SSF Framework grant, 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.

Moreover, the new center called KTH Digital Futures provides a number of instruments for fostering tenure track and postdoctoral position, in a similar fashion to that used successfully in Information and Communication Technology – The Next Generation (SRA ICT TNG) effort that occurred during the period of this RAE.

NSE: We plan to make significant contributions and to become a leading group in *data-driven analysis, design, and operation of networked systems* with application to radio access networks and other critical infrastructures like energy distribution systems, water distribution systems, etc. The focus will be on enabling automation, reducing energy consumption, and achieving high reliability 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. 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) - https://www.kth.se/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 department will expand its contract teaching offering, in particular in the field of cyber defense.

On the KTH and national level, NSE faculty will contribute to research centres 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, 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, and KDDI.

CST: 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.

Goals: We research fundamental and relevant questions in our specific fields.

1. We publish in journals and conferences of the highest standard in our fields.
2. 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.
3. Our impact on industry and society is strong (see section 6) 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.
4. 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.

Means identified to reach the goals:

1. 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.
2. Identify top visiting senior researchers.
3. Identify top-talent to recruit to our faculty.
4. Develop strategies for alumni relations as well as life-long learning.

5. Improve the visibility of our research output -not only in the form of publications, but also for research impact and innovations.

SCS: Goals related to main research areas at the 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.

HCTD

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, colour, 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. 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 are being recruited and their projects will focus on exploring ethics and drones 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 are currently being recruited to the group (to work in projects pertaining to transport, energy and food) 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, digitalisation, automation, and AI. Finally, we plan to investigate the ethical implications of AI applied to the arts by extending previous research on ethics of AI in the context of music. VR, Hakon Swenson Stiftelsen, and Swedish Post and Telecom Authority (PTS) are all recent sources of funding. In early 2020 we are further extending our group by a new Postdoc and a doctoral student, reaching a size of 15 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 wrt 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 transformatio*n 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-centred 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-centred 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.

b. *Congruence with university-level goals for research as set out in "A leading KTH - Development Plan 2018-23" and with the school(s) development plan(s) respectively.*

CSD

The research at the Computer Science Department 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 or Assist. Prof Conradt in Neurocomputing. 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.
- 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.
- CST: our researchers are part of the Human Brain Project and many other international collaboration projects.
- 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.

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.

An open KTH

- 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

- TCS: progress has been made through the creation of the CASTOR (www.castor.kth.se) and CDIS (www.kth.se/cdis) centers.
- 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.
- SCS: the main research areas at SCS, distributed systems, data science, and software construction and analysis, all are 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.

A KTH for a more sustainable world

- TCS: considerable progress through the development of new research areas: secure execution platforms, data science and AI, autonomous systems
- NSE: our focus is on critical societal infrastructure
- 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.
- 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.

An equal opportunity KTH

- TCS: The gender balance remains unsatisfactory
- SCS: is of high relevance for the division, as large 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

Finally, CSD follows the general KTH recommendation to publish under Open Access.

HCTD

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 recently awarded the ACM SIGCHI CHI Academy award

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 newly founded 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.

c. *Leadership structure and collegial structure*

Each division is led by a division head and a vice head. All divisions have a typical KTH leadership 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.

The two departments (CSD and HCTD) have 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.

d. *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 pay for open access
- 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. 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. 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

a. *Interaction between research and teaching at all three levels (1st, 2nd, and 3rd cycles)[15] 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 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.

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 Programme 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 programme, 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 programmes. Furthermore, the Doctoral Programme 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.

CoS

1st cycle courses – BSc-level

There is limited coupling between research and 1st cycle education. One area where there is coupling is in courses 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).

15 The levels are undergraduate, graduate, and postgraduate - the problem is that 2nd cycle studies in Sweden are considered an undergraduate degree (Swedish: grundutbildning).

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 care out a small research assignment in a step-wise fashion during the course. Many courses include a research component or explicitly include studying recent research papers. Many courses are in areas where the involved faculty are doing research. 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 are done together with industry and research institutes.

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 own infrastructure. *EP2510 Advanced Networked Systems Security (ANSS),* a 'paper-chasing' and research-oriented course, coaches undergraduate students to perform targeted research. Numerous students move on with MSc thesis. Most important, ANSS project work has repeatedly led to full-length conference papers, short conference papers and demos (notably, ACM WiSec'18 best demo award), and, in one occasion, to a journal publication.

3rd cycle courses – Doctoral-level

A very large portion of the doctoral education is coupled to research, both directly and indirectly (for example by using research results in courses).

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.

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 area. The project *IoT for fresh water quality* monitoring relates directly to the Vinnova *iWater* research project. 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.

There are several examples: 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 11 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* includes small projects that are inspired by our research in wireless networking as well as cloud and edge computing.

The *Summer School on Internet of Things* invites speakers from the company participants of our research projects, such as Ericsson, ABB, Imagimob, to talk about their research activities, connected to the VINNOVA iWater and SpiceDrives projects.

3rd cycle courses – Doctoral-level

Research is directly coupled to teaching in all of our courses for doctoral candidates. For example, the course *FEP3340 Stochastic Models and the Theory of Queues* includes small projects with the aim that students apply the theories and methods learned in the course to solve problems related to their own research topic. 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 the creation of two life-long learning or contract education graduate programs: one in the area of *Data Science* and one in the area of *Cyber Defence*. The programs are directly connected to the most recent research in their respective areas. The programs are expected to start during 2020 or 2021 and have received already considerable industrial and institutional interest.

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 (http://www.csc.kth.se/~chpeters/ESAL/), 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's theses (computer science and engineering physics programmes) and Master's theses (computer science, human-computer interaction, interactive media technology programmes), 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 (grant no. 765955, 3.89MEUR, 2018-2021, http://www.animatas.eu) 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 (grant no. 860768, 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 endeavours. 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.

Introducing current research topics to existing courses engaging in original research at all three levels (BSc, MSc, Doctoral)

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 analyse 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.

Creating courses to cover research interest themes at all three levels (BSc, MSc, Doctoral)

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 0,118MSEK 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 visualisation 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 the 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: DD3434 Advanced Course in Machine Learning, DD3336 Interactive Entertainment Technologies, DD3401 Neuroscience, DD3437 Artificial Neural Networks and deep Architectures, DD3451 Individual Course in Computational Biology, and DD3435 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 Visualization3. Master's theses have also explored the role of interactive and immersive graphics4and gamification in the advancement of active learning. Completing the loop between research and teaching, the ProsocialLearn (grant no. 644204, 4.2MEUR, 2015-2018) and ANIMATAS projects are directly concerned with the research and development of pedagogical ICT platforms to support teaching.

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 include 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 obtained a doctoral degree.

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 do 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).

HCTD (MID)

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 endeavours. 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 honourable 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 endeavours 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 programmes (study at KTH and you may walk with me). This led to more interviews and invitations to other universities (Linköping, Umeå, Luleå) and and Akademiska Hus[16].

A number of Masters students' dissertation projects result in top-tier venues, for example:

- 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 Defence Modeling and Simulation : Applications, Methodology, Technology, vol. 16, no. 3, pp. 219-231, 2019.
- 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).
- 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.**
- 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.**

- 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.**
- Gaissmaier, M., Karlsson, A., Aschan Eriksson, S., Kosmack Vaara, E., Komazec, K. and Ferneaus, 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).
- Parviainen, E. and Juul Sondergaard, M L, 2020. Experiential Qualities of Whispering with Voice Assistants, In CHI 2020. **Honourable mention award.**
- 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)

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.

6. Impact and engagement in society

a. *Relevance of research to society at large*

TCS

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

16 The owners and managers of the academic buildings in Sweden - https://www.akademiskahus.se/

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' behavioural 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 CO_2 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.

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.

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 centre, the annual hacking competition and the Cyber-Security and Privacy Summer (CySeP) School (https://cysep.conf.kth.se) 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 parliament, representatives of armed forces and civilian protection agency, and political scientist.

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 on the 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 a most the resilient form of communication without an infrastructure. It will be further studied in the cyber-defence area.

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 multi-disciplinary 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.

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 (www.fatml.org), 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 need 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 a 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).

HCTD

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.

The *interaction design* research has, 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 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.

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 (budkeep.com), Habits, Consupedia (consupedia.se), and Deedster (www.deedster.com),
- 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),
- Through the research at CESC, the group did research with companies such as Ericsson, TeliaSonera, Coop (coop.se), 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.

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) Centre 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/4Xt0Aa2pTzY).
- 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 facilitate 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.
- Edtech companies: we collaborate with (1) Advania (https://www.advania.se/en/) designing and validating an instrument to measure K-12 teachers' preparedness to use digital technologies in schools, (2) Mathleaks AB (https://mathleaks.com) examining how we can effectively integrate mobile technology in teaching mathematics in Swedish high schools, and (3) Collaboration with Swedish for Professionals (swedishforprofessionals.com) and Språkkraft (www.sprakkraft.org).

b. *Research dissemination beyond academia*

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 Centre for Software Technology Research (CASTOR), the center for Cyber Defence and Information Security (CDIS), and KTH Innovative Centre 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 security focus, with Sweden's Television (Sveriges Television (SVT)) and with the National Defence 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 (https://repobee.org/) public 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 Bruxelles, on 19th November 2019. Karlgren has occasionally published opinion pieces in popular national newspapers, such as Dagens Nyheter and Svenska Dagbladet. Velupillai has co-organised 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) (www.svt.se/nyheter/inrikes/de-lyfter-sveriges-ai-satsning) and Swedish Radio Ltd. (Sveriges Radio (SR)) (sverigesradio.se/sida/artikel.aspx?programid=1637&artikel=7138149) 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 centre 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.

CoS

The main forms of dissemination beyond academia are:

- Via people: degree projects (at the 1st and 2nd cycles) done outside of KTH, industrial doctoral students, faculty who spend some portion of their time working at external organizations, and joint projects with external partners
- Open access publications and press releases
- Patent applications

An important strategy was to hire external writers as necessary to help write press releases that would be accessible to a wider audience.

With a Young Academy of Europe member, P. Papadimitratos, participation in discussions and contributions to documents and activities pertaining to policy matters. Contributions as expert advisor for European Union Agency for Cybersecurity (ENISA), e.g., on the security of 5G (report released recently). Participation as panellist or speaker for events with attention to multidisciplinary issues and policy (e.g., Computers, Privacy and Data Protection conference), as well as industry-run or focused events (e.g., Huawei Security Summit, or *Auto Apps and Connected Driving Technologies Conference).* Swedish Viktoria ICT project on airfield automation. Steering committee of SecurityLink, which addresses a broad scope of safety issues.

Participation and contributions to the Car-to-Car Communication Consortium (C2C-CC) that brings together original equipment manufacturers (OEMs) and first-tier providers and drives harmonization and progress on all relevant connected-vehicle and intelligent transportation technologies. Starting prior to 2012-2019 but continuing throughout: work on security and privacy, starting from the first field demonstration, influenced industry and standardization (IEEE and European Telecommunications Standards Institute (ETSI)) on security and privacy for intelligent transportation systems. Followed by work in the context of EIT ICT Labs (now EIT Digital) and a project on electrified roads. Importance of the work practicality recognized by a recent IETF ANRP Contributions. Participation and contributions to the Trust in Digital Life activities, blending research and development. Addressing high-school students (Swedish and international) on cybersecurity and privacy.

NSE

NSE is 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 the Threat MOVE project conducted with Volvo Cars and Scania, Energy Shield with PSI and Iren, EU SOCCRATES project (www.soccrates.eu) with ATOS (atos.net), and Vattenfall. Papers have been published together with people from, e.g. Stockholms Kooperativa Bostadsförening (SKB), Siemens, and Foreseeti.

NSE is very active in the public debate with outlets daily news (Dagens Nyheter, Metro), Swedish Radio, TV (Swedish Television, TV4), popular science news (Computer Sweden, NyTeknik), popular science books (Ett kalejdoskop av kunskap[17]), talks (KTH executive school, Swedish book fair, CS3 ICS/SCADA security (https://cs3sthlm.se/), ISACA (https://www.isaca.org/)), youth outreach (science talks at film festivals), blogs2, and more.

CST

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

[17] David Håkansson, *Ett kalejdoskop av kunskap. Sveriges unga akademi om vetenskap och samhälle.* Stockholm: Santérus Förlag, 2019, ISBN: 978-91-7359-140-9.

Sweden with local academic and commercial partners at each node for advanced visualization exhibits, research and teaching.

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 have 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, https://databricks.com/sparkaisummit/europe), Flink Forward (the conference for Apache Flink and the stream processing communities, https://www.flink-forward.org/), Arctic Circle Assembly (the largest annual international gathering on the Arctic, attended by more than 2000 participants from 60 countries, http://www.arcticcircle.org/assemblies/2019).

CASTOR *Software Days.* We have provided a number of presentations at the CASTOR Software Days, organized by the CASTOR software research centre 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 (find the program at https://castor-software-days-2019.github.io/#program).

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).

HCTD

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 member of the EU high level group on maximising 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[18].

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.

Media appearances: Kristina Höök, Olle Bälter and Jan Gulliksen have been interviewed over 100 times each in television, radio, journals, and newspapers. Höök was on the list of the 50 most influential women in IT for many years in a row.

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

CSD

Most basic computer science research will have an indirect impact on the Sustainable Development goals. But several divisions also work directly towards specific goals. Let us provide a few examples:

[18] http://ec.europa.eu/research/evaluations/pdf/archive/other_reports_studies_and_documents/hlg_2017_report.pdf

- *Goal 12 Responsible Consumption and Production:* CoS has a project on Energy-Efficient Ethernet.
- *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 from Vineusa et al[19] in Nature 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.

  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 Wellcome 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* (1000MSEK, 2017-2030, coordinated by KTH School of Architecture and the Built Environment (ABE).

[19] 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

HCTD

Most 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 CO_2 emissions from business travel to support the KTH climate targets of reducing CO_2 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 everybody.

We would 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.

d. *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 (Univiversity 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 a 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, defence 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,in: 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[20]
- SVT: AI och samhällsutvecklingen[21]

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 was founded as a spin-off by three NSE professors. The company develops a software, 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 20 employees. Its tool suite is being used by organization worldwide, e.g. Klarna, Swedavia, RWE, and Scania. Foreseeti has been listed on NyTeknik's 33-list (2016 & 2017), Royal Swedish Academy of Engineering Sciences (IVA) top 100-list (2019), and was recently (Feb 2020) mentioned by Dagens Industri as one of the ten hottest IT security companies in Sweden.

Partners: Foreseeti has certified partners on three continents. In *Europe*, Applied Security GmbH (short: *Apsec*) one of Germany's Top10 companies in the field of information security, *securiThon* was founded in 2018 with the only goal to provide German, Austrian and Swiss companies with securiCAD

20 English: KTH researchers have built a cure that patches code as well as a human being

21 English: AI and social development

(www.foreseeti.com) and associated services, and *QinetiQ* a British security & defense contractor with over 6,000 dedicated people providing technological and scientific expertise to help their customers protect, improve and advance vital interests. In *North America*, *Red Clay* an Atlanta-based leading consultancy for the utility industry, delivering technical and business solutions for over eighteen years along with the industry-leading SecureGrid security solution. And in *Asia, Quadrant360* an independent privately-owned company, with headquarters in Singapore focusing solely on cyber security, risk and compliance audit as well as managed services.

Technology: The securiCAD tool suite currently contains three products; securiCAD Professional, securiCAD Enterprise, and securiCAD Vanguard. Further information about the technology and background can be found here https://community.securicad.com.

securiCAD *Professional* 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.

Some key features are; Security by design, Modeling tool, Attack simulations, Spot weaknesses, Structural vulnerabilities, Sharable components, Critical paths, and Non-intrusive.

securiCAD *Enterprise* features cyber risk simulation, collaboration, and reporting features. securiCAD Enterprise can be deployed on-premise, air-gapped, or in cloud environment with access- and permission controls for sensitive information.

Use securiCAD Enterprise for continuous risk assessment of your IT-architecture while planning, sharing and assessing models of future architectural designs. Assess security mitigations automatically suggested by securiCAD and generate reports of results. securiCAD Enterprise also features the possibility of parsing data from e.g. common inventory and scanning tools for automatic modeling.

Some key features are; Risk assessment, Model generation, Chokepoints, On-premises or Air-gapped, Report generation, Suggested mitigations, and API & software-development-kit.

securiCAD *Vanguard* allows developers and cloud security architects to get an overview of the cyber security characteristics of their Amazon Web Services (AWS) environment.

Attack simulations and automated threat modelling will enable you to automatically simulate attacks on a virtual model of your AWS environment. By providing securiCAD Vanguard with read access to standard AWS APIs, a model of your environment is automatically built and visualized. By simulating attacks on the model, securiCAD Vanguard will assess your AWS configuration, existing vulnerabilities and misconfigurations.

AWS concepts, services and their configurations are represented in the virtual model. Find the most critical paths from the attacker's entry point to your high value assets and the chokepoints (key assets) in your architecture that the attacker is expected to exploit to reach the high value assets.

- Prevent breaches by analyzing your AWS configuration, allowing you to detect misconfigurations, potential lateral movements and to prioritize vulnerabilities
- Generate and visualize a digital twin of your AWS environment and run automated attack simulations, to get reports with the most likely attack paths, weak spots and risk exposure

- Secure, on-demand analysis of AWS configurations including Identity and Access Management (**IAM**), Virtual Private Cloud (**Amazon VPC**), Elastic Compute Cloud (EC2), Simple Storage Service (**S3**), Inspector, and more. No installation or privileged access needed.

Vanguard is available on AWS Marketplace.

"*It is a cost-effective way to assess vulnerabilities, the effort to get insights is minimal, but above all, gives us consistent and unbiased results*"

Mark Strande, CSO, Klarna

"*A great security technology for DevOps that enables Shift-Left and Continuous Delivery for AWS Cloud*"

– Kevin Valdek, CTO, HIGH MOBILITY (www.high-mobility.com)

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

- Pontus Johnson, Dan Gorton, Robert Lagerström, and Mathias Ekstedt, "Time Between Vulnerability Disclosures: A Measure of Software Product Vulnerability," in *Computers & Security*, vol. 62, pp. 278-295, 2016.
- Pontus Johnson, Robert Lagerström, Mathias Ekstedt, and Ulrik 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.
- Alexandre Vernotte, Margus Välja, Matus Korman, Gunnar 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.
- Pontus Johnson, Alexandre Vernotte, Mathias Ekstedt, and Robert Lagerström, "pwnPr3d: an Attack Graph Driven Probabilistic Threat Modeling Approach," in Proc. of the *International Conference on Availability, Reliability and Security* (ARES), Sept. 2016.
- Pontus Johnson, Robert Lagerström, and Mathias 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.
- Sotirios Katsikeas, Pontus Johnson, Simon Hacks, and Robert Lagerström, "Probabilistic Modeling and Simulation of Vehicular Cyber Attacks: An Application of the Meta Attack Language," in the Proc. of the *International Conference on Information Systems Security and Privacy* (ICISSP), February 2019.

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 joint projects funded by the Swedish Innovation Agency (Vinnova), the Swedish Energy Agency (Energimyndigheten), and Horizon2020. See for more information:

- https://www.Vinnova.se/en/p/proactive-risk-and-threat-simulations-in-the-cloud/
- https://www.Vinnova.se/en/p/threat-move-threat-modeling-and-simulation-of-vehicle-it/
- https://www.viablecities.se/hotmodellering-och-attacksimulering

- https://energy-shield.eu

Popular media examples related to this impact case

- https://www.nyteknik.se/startup/33-listan/har-hittar-du-alla-foretag-pa-33-listan-6539822
- https://www.nyteknik.se/startup/33-listan/foreseeti-systemet-avslojar-svaga-punkterna-i-natverken-6838501
- https://www.iva.se/projekt/research2business/100listan/
- https://digital.di.se/artikel/har-ar-tio-av-sveriges-hetaste-it-sakerhetsbolag
- https://computersweden.idg.se/2.2683/1.723214/sakerhet-trend-hotmodellering
- https://www.nyteknik.se/digitalisering/foreseetis-kod-ska-skydda-uppkopplade-bilar-fran-hackare-6892180
- https://www.nyteknik.se/sakerhet/foreeseti-laddar-om-med-20-miljoner-och-en-ny-vd-6971548
- https://www.kth.se/eecs/nyheter/ett-av-landets-mest-lovande-teknikbolag-1.720193
- https://www.kth.se/eecs/nyheter/fem-projekt-som-kommer-forandra-framtidens-industri-1.889692
- https://www.energivarlden.se/artikel/foretaget-som-hittar-energisystemens-sakerhetshal/
- https://etn.se/index.php/reportage/63411-foreseeti-rangordnar-dina-saekerhetshal
- https://www.affarsvarlden.se/33listan/deras-kod-ska-skydda-uppkopplade-bilar-fran-hackare-6893973
- https://it-finans.se/ska-skydda-bade-banker-och-karnkraftverk/
- https://mail.aktuellsakerhet.se/foreseeti-vann-almi-invests-pris-arets-titthalsinvestering/

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.

- Making Compact-Table Compact, Linnea Ingmar, Christian Schulte, Twenty-Fourth International Conference on Principles and Practice of Constraint Programming, 2018.
  Relation: How compact-table is implemented in Gecode
- View-based Propagator Derivation, Christian Schulte, Guido Tack. Constraints, 2013.
  Relation: Design and evaluation of generic propagators as used in Gecode
- Implementing Efficient Propagation Control, Christian Schulte, Guido Tack. TRICS 2010, Third workshop on techniques for implementing constraint programming systems, 2010.
  Relation: Explains propagator scheduling in the Gecode kernel
- Maintaining State in Propagation Solvers, Raphael M. Reischuk, Christian Schulte, Peter J. Stuckey, Guido Tack. Fifteenth International Conference on Principles and Practice of Constraint Programming, 2009.
  Relation: Includes an evaluation of how well hybrid recomputation in Gecode works compared to trailin
- Weakly Monotonic Propagators, Christian Schulte, Guido Tack. Fifteenth International Conference on Principles and Practice of Constraint Programming, 2009.
  Relation: Model and example for weakly monotonic propagators as used in Gecode

- Techniques for Efficient Constraint Propagation, Mikael Z. Lagerkvist. Licentiate dissertation, Royal Institute of Technology, 2008
  Relation: Development of advisors, placement problems using regular.
- Constraint Propagation – Models, Techniques, Implementation, Guido Tack. Doctoral dissertation, Saarland University, Germany, 2009.
  Relation: Models and techniques used in the Gecode kernel, views, and propagators for set constraints
- Efficient Constraint Propagation Engines, Christian Schulte, Peter J. Stuckey. Transactions on Programming Languages and Systems, 2008.
  Relation: Design and optimizations of Gecode's propagation engine
- Advisors for Incremental Propagation, Mikael Z. Lagerkvist, Christian Schulte. Thirteenth International Conference on Principles and Practice of Constraint Programming, 2007.
  Relation: Design, implementation, and evaluation of advisors for incremental propagation
- Views and Iterators for Generic Constraint Implementations, Christian Schulte, Guido Tack. Recent Advances in Constraints (2005), 2006.
  Relation: Design and evaluation of generic propagators
- Programming Constraint Services, Christian Schulte. 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.

HCTD

Impact Case I: Mobile Life 2012-2017

Description: Mobile Life was a highly successful research center, 2007-2017. The center was 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, when the center closed in March 2017, we noted how the Centre'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 emphasised this: "*Ericsson can use the centre 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 organised 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 Centre 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 Centre 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.

Taken together, the value of these tangible outputs was much higher than the sum of the parts. For the Centre'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 centre 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 centre lives on in HCT. In particular, the Soma Design work came out of the Mobile Life centre 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 Centre has published 6 books and later, Höök's book on soma design came as a direct result of the work in the centre (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 appearance 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[22] 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 analyse 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

[22] https://www.diva-portal.org/smash/get/diva2:1152798/FULLTEXT01.pdf

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 maximising 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 Defence Agency (FOI), and especially The Swedish Air Force Combat Simulation Centre (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 Defence 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 Defence 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), lead 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 SAabb 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) (http://www.kks.se/) 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

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

e. *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 makes 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 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 centre: (i) Marina Petrova, CoS, is the deputy director; (ii) Kristina Höök, HCT/MID, leads the domain theme Rich and Healthy Life

The two departments are slightly different in terms of how to achieve impact. For HCT, the involved with society, industry and end-users is a natural and required part of their research methods. For the CS department, for certain topics, the influence is sometimes indirect: by doing basic research on computer science topics they may change the fundaments 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.

CSD

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 Centre for Software Technology Research (CASTOR), the center for Cyber Defense and Information Security (CDIS), and KTH Innovative Centre for Embedded Systems (ICES). 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 extends the network of stakeholders and collaborative partners for upcoming joint research activities.

HCTD

Based on the impact cases, it should be clear that HCT engages with society and industrial partners in many different ways: as part of research centers (such as KTH Digital Futures), in policy making, in direct involvement with end-user groups, through spin-offs, and through media appearances reaching the general audience. We expect to continue working with partners in this manner in the years to come. In particular, in the area of sustainable societal and personal practices, we hope to have an increasing impact through the research projects we have recently obtained funding for.

7. Other
a. *Specifics that the department wishes to mention and describe*

C) POSSIBLE ATTACHMENTS

Relevant material/URL-links formulated succinctly that support the self-evaluation. No limitation in length, but do not expect panel members to read extensive added material.

Appendix 1: Bibliometrics

Appendix 2: Representative papers