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Research review 2023

Natural and engineering sciences

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Foreword

Research in natural and engineering sciences has a strong emphasis on scientific questions that push the frontiers of human knowledge forward. Historically, breakthroughs in natural and engineering sciences have irreversibly shaped our society and our lives. The main processes through which natural and engineering sciences have managed to impact our society to such a great extent is scientist-initiated research (also called bottom-up research) and peer review. Therefore, the Scientific Council for Natural and Engineering Sciences cannot stress enough the importance of maintaining these principles for research funding. There are cases where more directed research efforts may be appropriate, but such efforts are almost always strongly rooted in previous achievements of scientist-initiated research. Since the timescale between initiating new research and application of this research to societal challenges may be substantial, the best approach for answering future societal questions is to be prepared through proper funding of scientist-initiated research. For the 2023 review, the Council's emphasis is on future trends in natural and engineering sciences. The rationale for this is the close connection to investments in research infrastructure, for which the funding horizon is often much longer than the research grants available from the Swedish Research Council (and other funding agencies). Questions regarding the connection between research funding and infrastructure funding have therefore been given more weight in the 2023 research review.

The Scientific Council for Natural and Engineering Sciences has compiled this review. The purpose of the review is threefold: to work as a guideline for the internal work of the Scientific Council, to serve as input to the recommendations that the Swedish Research Council will submit to the Government for the next research bill, and finally to serve as a source of information for anyone interested.

Mattias Marklund

Secretary General for Natural and Engineering Sciences

Executive summary

Natural sciences in conjunction with engineering sciences have laid the foundation for most of the material part of modern society. The scope of natural and engineering sciences is extremely broad and diverse in nature, and continues to evolve with new insights and cross-fertilisation. Breakthroughs in natural and engineering sciences have irreversibly shaped our society and our lives, and have addressed existential questions, such as our place in the universe and the origin of life, as well as generation and storage of renewable energy and efficient vaccines. Natural and engineering sciences will continue to play this role in the foreseeable future.

Our society faces a number of major challenges, including climate change, sustainable energy generation and storage, food supply, fresh water supply, environmental contamination and public health. All these issues are multi-faceted and subject to political measures and positions. Nevertheless, the responses to societal challenges require and rely on science and technology to provide an in-depth understanding of the problems and how to address the challenges with appropriate means. Indeed, it is clear that the knowledge foundation relies heavily on previous investments made into scientist-initiated research, often spanning many decades back in time. It is therefore essential that such bottom-up research is given appropriate resources also in the future.Therefore, to enable Sweden to respond to future societal challenges, we need to make sure that today's investments in peer reviewed bottom-up research are sufficient.

This research review of Swedish natural and engineering sciences is based on statistics on the Swedish research system from the Swedish Research Council, a questionnaire to project grant recipients, together with written input from scientists who have been engaged in the review panel work. Input from the scientific community was collected via a survey and a web forum. This information has been interpreted on the basis of the collective experience of the Scientific Council for Natural and Engineering Sciences together with adjunct members taking part in the writing groups for the different subsidiary areas. The analyses of impact and trends provide a clear picture of the essential prerequisites for scientific progress and breakthroughs in this very broad area of science. In order to ensure that Swedish basic research in natural and engineering sciences remains at the highest international level, a number of central research initiatives and structural reforms that are urgently needed have been identified.

Recommendations

Research initiatives

- Increased funding for scientist-initiated research: Research that has been formulated by scientists and approved and granted in a rigorous evaluation process focused on scientific quality is the best investment society can make to meet future needs for new knowledge, for understanding, predicting and mitigating tomorrow's crises, to promote innovation, and for our fundamental understanding of the universe. At present, the Scientific Council for Natural and Engineering Sciences unfortunately has to reject many proposals of very high quality and the amounts awarded to those that are granted are insufficient, in particular when considering the rapid increase in costs. The funding for undirected project grants and starting grants in natural and engineering sciences needs to be increased to ensure that projects of very high quality are funded at sufficient levels.

- Artificial intelligence and machine learning: The capacity to generate vast amounts of data through a wide range of observational, experimental and numerical techniques has created a huge potential and need for deploying AI and machine learning in almost all of the research areas covered by the Scientific Council for Natural and Engineering Sciences, each with its own needs, requirements, and limitations. There is thus an urgent need to formulate, coordinate and implement a strategy for how to integrate and validate artificial intelligence and machine learning in the different areas of natural and engineering sciences. To enable navigation in this extremely rapidly evolving field, it is important to involve expertise from the disciplines that contribute to mathematical, algorithm and hardware advances for AI and machine learning to a greater extent than is done today.

- Interdisciplinary initiatives in research of the highest quality and societal significance: The latest Government Research Bill (2020) had a significant focus on national research programmes aimed at societal challenges. Although many of the societal challenges are closely related to natural and engineering sciences, initiatives in this direction were surprisingly lacking in the research bill. Therefore, we urgently need to launch new interdisciplinary initiatives in basic research of strategic relevance, strengthening the opportunities to address important challenges both today, and also in a long-term perspective. Research funded by the Scientific Council for Natural and Engineering Sciences has for decades addressed many of the societal challenges, for example climate change, renewable energy, biodiversity and health. New interdisciplinary research initiatives of the highest quality and societal significance in natural and engineering sciences would therefore be a sound and cost-effective effort to better understand, predict and mitigate important challenges related to sustainability. The Scientific Council has initiated a process to explore and finalise suggestions of suitable areas.

Structural reforms

- New funding initiatives for integrating research infrastructures and research: Linking necessary research infrastructure to research of high quality is a challenge that needs to be addressed on all levels and requires a clarification and clear allocation of responsibilities between the government, funding agencies and institutions. It is vital that the priorities for the investment, development and service offered by infrastructures are closely linked to Swedish research quality and needs, as defined by the research community in both established and emerging fields. Because the time scales for large research infrastructures usually is much longer than the duration of a normal project grant, there is room for new funding initiatives for research closely related to large infrastructures. Such funding initiatives can promote and secure optimal usage of and output from our current and future research infrastructures, and drive forward the development of new methods and technologies. Moreover, such new funding intitiative will promote the interaction between users of advanced infrastructures and technical experts, and be beneficial for many areas within natural and engineering sciences.

- Women remain under-represented in many areas of natural and engineering sciences: An improved balance will require gender-neutral selection procedures throughout the academic career, avoiding all kinds of bias. In this respect, education, self-reflection and reliable statistics are important tools that constantly need to be developed. Statistics for natural and engineering sciences from the Swedish Research Council indicate that men on average get slightly higher grades for merits than women, which shows a need to evaluate the system for assessing merits. The statistics also show that a lower percentage of eligible female scientists than eligible male scientists apply for external funding from the Swedish Research Council. The reasons for these observations are unknown, but the consequences are serious. The Swedish Research Council is analysing the reasons for this imbalance, and, based on the results, will take measures to mitigate the situation. These measures will need to be taken in collaboration with universities.

- An important discussion concerns the use of grants by the recipients: Project grants are often awarded to permanent faculty members at Swedish universities. It is known that the recipients of such grants sometimes have to use the grants to cover parts of their own salaries. When this occurs, it impacts on the overall research output from the grant. It would therefore be beneficial to have an in-depth discussion with Swedish universities regarding the use of project grants within their organisations. Similarly, starting grants from the Swedish Research Council are directed towards individuals who, with the help of such grants, have the prospect of becoming exceptional senior researchers in the future. Given this prerequisite, a discussion between the Scientific Council and Swedish universities should be held to ensure starting grant recipients will have good employment conditions.

Sammanfattning

Naturvetenskap och teknikvetenskap har tillsammans lagt grunden för vårt moderna samhälles materiella välfärd. Omfattningen av natur- och teknikvetenskap är extremt bred och mångsidig till sin natur och fortsätter att utvecklas via nya insikter och korsbefruktningar. Genombrott inom natur- och teknikvetenskap har oåterkalleligt format vårt samhälle och våra liv, och har behandlat existentiella frågor, såsom vår plats i universum och livets ursprung, skapande och lagring av förnybar energi samt effektiva vacciner. Natur- och teknikvetenskaperna kommer att fortsätta spela denna roll under överskådlig framtid.

Vårt samhälle står inför ett antal stora utmaningar, inklusive klimatförändring, hållbar energiproduktion och energilagring, livsmedelsförsörjning, färskvattenförsörjning, miljöförorening och folkhälsa. Alla dessa frågor är mångfacetterade och mynnar ut i politiska åtgärder och ställningstaganden. Ändå är det så att samhälleliga utmaningar kräver och förlitar sig på svar från vetenskap och teknik för att ge en djupgående förståelse för problematiken och hur man kan hantera utmaningarna med lämpligaste medel. Det är uppenbart att kunskapsgrunden är starkt beroende av tidigare investeringar som gjorts i forskarinitierade projekt, som ofta sträcker sig många decennier tillbaka i tiden. Det är därför väsentligt att sådan ”bottom-up” forskning ges lämpliga resurser även i framtiden. För att Sverige ska kunna svara på framtida samhällsutmaningar måste vi säkerställa att dagens investeringar i sakkunniggranskad bottom-up forskning är tillräckliga.

Denna forskningsöversikt av svensk natur- och teknikvetenskap baseras på statistik om det svenska forskningssystemet från Vetenskapsrådet, en enkät till projektbidragstagare, samt skriftlig input från forskare som varit engagerade i beredningsgruppernas arbete. Synpunkter från forskarsamhället samlades in via en enkät och ett webbforum. Den insamlade informationen har tolkats och sammanställts av ämnesrådet för naturvetenskap och teknikvetenskap, samt adjungerade medlemmar som tillsammans deltog i skrivgrupper ansvariga för de olika vetenskapliga delområdena. Analyserna av påverkan och trender ger en tydlig bild av de väsentliga förutsättningarna för vetenskapliga framsteg och genombrott inom detta mycket breda vetenskapsområde. För att säkerställa att svensk grundforskning inom natur- och teknikvetenskap ligger kvar på den högsta internationella nivån har ett antal centrala och angelägna forskningssatsningar och strukturella reformer identifierats.

Rekommendationer

Forskningssatsningar

- Ökad finansiering av forskarinitierad forskning: Forskning som har formulerats av forskare och godkänts och beviljats i en rigorös utvärderingsprocess fokuserad på vetenskaplig kvalitet är den bästa investering samhället kan göra för att möta framtida behov av ny kunskap, för att förstå, förutsäga och mildra framtida kriser, för att främja innovation och för vår grundläggande förståelse av universum. För närvarande måste ämnesrådet för naturvetenskap och teknikvetenskap tyvärr avslå många ansökningar av mycket hög kvalitet, och de bidragsbelopp som beviljas är otillräckliga, särskilt med tanke på den snabba kostnadsökningen. Bidragen till fria projektbidrag och etableringsbidrag inom natur- och teknikvetenskap behöver höjas för att säkerställa att projekt av mycket hög kvalitet får tillräcklig finansiering.

- Artificiell intelligens och maskininlärning: Förmågan att generera stora mängder data genom ett brett utbud av observationer, experimentella och numeriska metoder har skapat en enorm potential och ett stort behov av att implementera AI och maskininlärning inom nästan alla forskningsområden som omfattas av ämnesrådet för naturvetenskap och teknikvetenskap, var och en med sina egna behov, krav och begränsningar. Det finns ett akut behov av att formulera, samordna och implementera en strategi för hur man integrerar och validerar artificiell intelligens och maskininlärning inom natur- och teknikvetenskapernas olika områden. För att möjliggöra framsteg inom detta område som är under extremt snabb utveckling är det viktigt att involvera expertis från de discipliner som bidrar till matematiska, algoritmiska och hårdvaruframsteg för AI och maskininlärning i större utsträckning än vad som görs idag.

- Tvärvetenskapliga satsningar inom forskning av högsta kvalitet och samhällelig betydelse: Regeringens senaste forskningsproposition (2020) hade ett betydande fokus på nationella forskningsprogram riktade mot samhälleliga utmaningar. Även om många av samhällsutmaningarna är nära besläktade med natur- och teknikvetenskap, saknades initiativ i denna riktning överraskande nog i forskningspropositionen. Därför behöver vi snarast lansera nya tvärvetenskapliga satsningar inom grundforskning av strategisk relevans, vilket stärker möjligheterna att möta viktiga utmaningar både idag och i ett långsiktigt perspektiv. Forskning finansierad av ämnesrådet för naturvetenskap och teknikvetenskap har i decennier fokuserat kring många av dagens samhällsutmaningar, till exempel klimatförändringar, förnybar energi, biologisk mångfald och hälsa, långt innan dessa blev uppenbara utmaningar för samhället i stort. Nya tvärvetenskapliga forskningssatsningar av högsta kvalitet och samhällelig betydelse inom natur- och teknikvetenskap skulle därför vara en klok och kostnadseffektiv satsning för att bättre förstå, förutse och mildra viktiga utmaningar relaterade till hållbarhet. Ämnesrådet har inlett en process för att utforska och ta fram förslag på lämpliga områden.

Strukturella reformer

- Nya finansieringsinitiativ för att integrera forskningsinfrastruktur och forskning: Att koppla nödvändig forskningsinfrastruktur till forskning av hög kvalitet är en utmaning som behöver hanteras på alla nivåer, och som kräver en förtydligad ansvarsfördelning mellan regering, finansiärer och institutioner. Det är mycket viktigt att prioriteringarna för investeringar, utveckling och support som erbjuds av infrastrukturerna har en nära koppling till kvalitet och behov inom svensk forskning, som definieras av forskarsamhället inom såväl etablerade som framväxande områden. Eftersom tidsperspektivet för stora forskningsinfrastrukturer vanligtvis är mycket längre än varaktigheten för ett normalt projektbidrag finns det utrymme för nya finansieringsinsatser för forskning som är nära relaterad till stora infrastrukturer. Sådana finansieringsinitiativ skulle kunna främja och säkerställa optimal användning av och produktion från vår nuvarande och framtida forskningsinfrastruktur och driva på utvecklingen av nya metoder och teknologier. De skulle främja samspelet mellan användare av avancerad infrastruktur och tekniska experter och vara till nytta för många områden inom natur- och teknikvetenskap.

- Kvinnor är fortfarande underrepresenterade inom många områden inom natur- och teknikvetenskap: En förbättrad balans kommer att kräva könsneutrala urvalsförfaranden som undviker alla typer av partiskhet under hela den akademiska karriären. I detta avseende är utbildning, självreflektion och tillförlitlig statistik viktiga verktyg som ständigt behöver utvecklas. Statistik för natur- och teknikvetenskap från Vetenskapsrådet pekar på att män i genomsnitt får något högre meritbetyg än kvinnor, vilket visar på ett behov av att utvärdera systemet för meritbedömning. Statistiken visar också att en lägre andel av behöriga kvinnliga forskare än behöriga manliga forskare ansöker om externa medel från Vetenskapsrådet. Orsakerna till dessa observationer är okända, men konsekvenserna är allvarliga. Vetenskapsrådet analyserar orsakerna till obalansen och kommer utifrån resultaten att vidta åtgärder för att mildra situationen. Dessa åtgärder kommer att behöva vidtas i samarbete med universiteten.

- En viktig diskussion rör mottagarnas användning av bidrag: Projektbidrag delas ofta ut till tillsvidareanställda lärare vid svenska universitet. Det är känt att mottagarna av sådana bidrag ibland måste använda bidragen för att täcka delar av sin egen lön, vilket påverkar projektens utförande. Det skulle därför vara fördelaktigt att föra en fördjupad diskussion med svenska lärosäten om användningen av projektbidrag inom deras organisationer. Etableringsbidrag från Vetenskapsrådet riktas till personer som med hjälp av sådana bidrag bedöms kunna bli exceptionella seniora forskare i framtiden. En diskussion mellan Vetenskapsrådet och svenska lärosäten bör därför föras för att säkerställa att etableringsbidragsmottagarna har tillräckligt goda anställningsvillkor för att kunna förverkliga intentionerna med bidraget.

1 Introduction

The Swedish Research Council supports research of the highest quality, which moves the frontier of knowledge forward. Our review panels evaluate scientist-initiated research projects from fundamental natural sciences to applied engineering sciences. Fundamental and applied research should not be seen as a linear production process, much less as being in opposition, but rather as two mountaineers who take turns in leading the climb to the summit. Having a single entity with the competence to evaluate the broad scope of research and see the synergies greatly contributes to achieving research of the highest quality and long-term impact. The scientist-initiated nature of the funded research is also a pivotal factor for success. Scientists who perform the highest quality research are positioned at the summit of human knowledge in their respective fields and can see farthest ahead, and can therefore most efficiently pursue new research ideas and propose new research directions.

A trend towards funding narrowly-defined research and expecting quick solutions to current societal needs can be seen in Sweden. However, history shows that the solution to a sudden need is often found in scientist-initiated research that began 10-20 years earlier. A timely illustration of this is the success of rapidly developing an mRNA-based vaccine against SARS-CoV-2. This success was enabled by decades of scientist-initiated fundamental research from a diverse set of scientific communities. Building on the advances of our understanding of messenger RNA (mRNA) and its potential for use in medicines, together with improved knowledge in self-assembly of macromolecules, efficient and non-toxic lipid-based system for delivery of mRNA into the cells of healthy human beings could be formulated. Examples from technology include the 3G network, and also affordable OLED displays and photovoltaic solar cells, which were products of both decades of prior research and development of engineering solutions for large-scale manufacturing. The global climate policies that we nowadays talk about on a daily basis have their origins in climate science, the fruit of decades of scientist-initiated efforts to understand the coupling between Earth's different systems and their various feedbacks, as well as the causes and impacts of past, present and future climate change. So fundamental are these findings that some of its originators were awarded the Nobel Prize in physics in 2021. It thus cannot be stressed enough that our ability to address known and un-known challenges and problems require a strong knowledge-base that has been built up previously by scientist-initiated research. The research has often been performed over long periods of time, and sometimes even without the end goal of solving specific societal challenges, but rather to add new knowledge to expand the problem-solving toolbox. Thus, scientist-initiated and curiosity-driven research, performed by individuals and groups, are the foundations on which a response to societal challenges can be built. To discover what is on the other side of the hill, someone must climb it first.

In summary, we hope it is made clear that when society wakes up to new and unpredicted challenges, we may still be well prepared, thanks to knowledge built up from undirected scientist-initiated research. We therefore argue that, although new efforts should be aimed at investments in offering sustainable solutions to known and hitherto unknown societal challenges, this should be in the form of scientist-initiated questions, and should feature a balance between natural and engineering sciences.

The primary mandate of the Swedish Research Council is to fund research of the highest scientific quality based on a rigorous peer review process using expert panels. Natural and engineering sciences have effectively experienced a devaluation of its research funding, as the costs for research have increased over time. Consequently, if an adequate success rate for applications is to be maintained, this in turn leads to smaller amounts being awarded to individual research projects. As scientist-initiated research, subjected to a peer review process, is absolutely central for the future success of Swedish research at an international level, it is worrying if funding for this particular type of grants is not increased. If funding is not increased, Sweden stands less chance of being at the forefront of the research landscape, and will have less opportunities to prepare for future research needs relating to societal challenges.

There is an intimate relationship between major advances in new methods and new technologies, and breakthroughs across all areas of natural and engineering sciences. Access to advanced techniques and methods, from laboratory instrumentation to large national or multinational facilities, is also a requirement for performing research of the highest quality. Research teams in natural and engineering sciences rely to a large extent on infrastructures available at the host institutions, but increasingly also on large national and international infrastructures, delivering data not available from local infrastructures. The increasing demand for and cost of research infrastructure calls for improved coordination to ensure maximum benefits from infrastructure investments.

Between 2020 and 2021, the Scientific Council performed a survey of the research categories under which all the yearly review panel work is done. It had been noticed that the different panels had to handle an increasingly uneven distribution of applications, which was a reflection of the shift between different research fields. Such changes are the result of the emergence of new areas and the decrease of other areas, as well as of national and international funding streams. The uneven distribution of applications to the different review panels could in the end have affected the quality of the review process. Therefore, work was undertaken by the Scientific Council to alleviate this uneven distribution, making for a better distribution of applications to the different panels. The new (internal) subdivision of panels within natural and engineering sciences was first introduced in the 2021 review process, resulting in a more even distribution of the number of proposals between the 19 panels. It is also essential that the review panel structure is adapted to handle research that falls between different traditional fields. In the revised panel structure, some areas that fall on the boundaries between panels are listed explicitly as keywords for more than one panel. Examples of such areas are bioinformatics, biophysics, biomechanics, machine learning, and data science. In these and other cases, applicants are advised to apply to the panel that best reflects the application's main scientific contribution.

The statistical analysis by the Swedish Research Council shows some variation in the total number of submitted proposals over the last ten-year period. However, the number of applications during the last five years has been relatively stable (where fluctuations could be attributed to factors such as other funding schemes and/or university policies). The balance between the number of grants to younger researchers (starting grants) and senior researchers (project grants) has been discussed extensively. Here, the Scientific Council for Natural and Engineering Sciences has, over a period of years, worked with a budget division of approximately 20% for starting grants and 80% for project grants. This division is based on the opportunities for the universities to employ younger researchers, and the opportunities for these younger researchers to later be able to compete for project grants as senior researchers.

Biology research has progressed tremendously in recent years by following technological advances, especially, in the areas of ‘omics’, genome editing with CRISPR-Cas, large-scale DNA sequencing, cryo-electron microscopy (cryo-EM) and other sensor and visualisation technologies. Modern biology research has become increasingly data-driven and dependent on computational tools, where AI and systems biology approaches are used more frequently in combination with advanced analytical tools. Predictively, biology research will be more collaborative and integrated with other disciplines in natural science and technology, medicine and social science for solving large and complex problems aligned with societal needs.

Chemistry is at the heart of challenges related to the sustainability development goals. The rapid introduction of machine learning and AI and the need to develop solutions to rapidly reduce emissions of green-house gases and to reduce or eliminate the use and release of toxic chemicals and compounds is having a profound influence on research in chemistry. Researcher-initiated projects and challenge-driven research in larger constellations are expected to continue to support and benefit each other to promote the development of areas such as analytical techniques and new characterisation methods, new materials, catalysis, light-matter interactions, photochemical processes and formulation of molecules to achieve or improve functional performance.

Geoscience provides fundamental understanding of the processes within and between Earth’s different spheres: the lithosphere, atmosphere, hydrosphere, cryosphere and biosphere, and is strongly linked to many of the sustainability development goals. Research will continue to focus on climate and environmental change processes on short and long time scales, including the Arctic and circum-polar region, but also on a better understanding of molecular-scale mechanisms and processes, natural resources and space exploration to supply the necessary knowledge for decision making.

Electrical engineering and computer sciences are developing rapidly to meet the societal challenges of digitalisation and electrification. Machine learning has its roots in this area, where new research contributes to dedicated hardware, methodologies, 'big data' and cloud implementations, and not least their application in all kind of domains.

The scientific revolution caused by digitalisation has a major effect on mathematical sciences, as it builds on and accelerates the development of a wide range of mathematical areas, from probability, statistics and data science via optimisation and numerical analysis to differential geometry and algebraic topology for topological data analysis. Continued increase in both interdisciplinary and intradisciplinary activities is expected, driven and inspired both by the rising prominence of mathematical modelling in application-oriented research and by internal developments.

In applied mechanics, further development of high-resolution computational tools and multi-scale modelling, including computational homogenisation and other scale-bridging strategies, will continue as necessitated by the complexity of the problems addressed. In chemical, environmental and bioprocess engineering, the strong focus on sustainability continues, and the research is increasingly multi-disciplinary as needed to tackle these challenges. Biomedical engineering research is aided by the continued development of the large number of methods now available for observing biomedical processes in both space and time, across multiple modalities, and with increasing resolution and multiplexity.

In physics, the improved abilities to study physical processes on both the smallest and largest length and time scales, that is, in atoms and in space, that come with access to novel research infrastructures advance our understanding of our universe in unprecedented detail. The continued realisation of quantum materials and technology accelerates the striving to realise quantum computing as well as novel "quantum" applications, including meta-materials. The development and implementation of novel “green” key technologies continues to pick up the pace, and nowadays encompass both realisation of more efficient energy storage and conversion devices, as well as implementation of green materials and sustainable fabrication and recycling processes. Continued development in all these fields is expected to take place within the near future, to the benefit of society.

2 Research Impact

Information on infrastructures and acronyms, see Appendix 1.

2.1 Biology

2.1.1 Introduction

Biology is the branch of science that aims to understand the fundamental processes that constitute 'life'. It spans a number of sub-disciplines, including molecular biology, biochemistry, structural biology, genetics, cell and organism biology, developmental biology, evolutionary biology, and ecology. Modern biological research has benefited tremendously from methodological advances in recent years, and has become truly interdisciplinary, integrating several sub-disciplines of biology and also other branches of natural, medical and social sciences. Technological advances, mainly in the areas of 'omics', CRISPR-Cas based gene editing, cryo-Electron Microscopy (cryo-EM), other sensor and visualisation technologies, have transformed global life science research.

Biological research in Sweden has been of high quality for decades. Early adoption of recent technological developments has revolutionised the entire biology research landscape in Sweden and opened up new avenues. Rooted in scientist-initiated basic research, biologists now address a range of societal sustainability challenges, including human health and wellbeing, drug design, use and preservation of natural resources, climate change and biodiversity loss. Biology research in Sweden has also become increasingly data-driven and collaborative, involving scientists with complementary skills and expertise.

2.1.2 Research infrastructure often utilised by actors active in the field

Swedish research in biology is strongly and increasingly dependent on adequate mid to large-scale infrastructure. This includes both heavy instrumentation and e-infrastructure, such as cutting-edge DNA sequencing, cryo-EM, other structure determination and imaging platforms, mass-spectrometry, and bioinformatics infrastructures. Biologists routinely collect massive datasets, which also require adequate support for their storage and analysis.

Biologists in Sweden have benefitted from the recent push towards more centralised and professionally managed national research infrastructures, providing both instrumentation and other resources. Infrastructures of particular relevance for biological research include EMBRC, MAX IV, NBIS, NGI, NMI, SBDI, SciLifeLab, SITES and SNIC.

In order to conduct internationally competitive impactful research, it is important that biology researchers in Sweden have access to infrastructure that follows global trends. One current requirement is further advancement in national and local imaging infrastructure and creating necessary platforms to facilitate tomography and time-resolved microscopy techniques that are operable in the physiologically-relevant millisecond range. Developing local infrastructures for large scale protein expression, purification and mass-spectrometry is also essential. Furthermore, advancing national resources for data storage, and developing national and local platforms for exploring biological problems with modern and advanced statistical modelling, AI and ML should also be prioritised.

2.1.3 Publications, citations and funding

Biology is a research area in which Sweden has a stable and internationally significant impact with highly cited publications. The fields of evolutionary biology, ecology and genetics, as well as the areas of cell and molecular biology, biochemistry and structural biology have a long tradition of high-quality output. However, a large proportion of the research in these categories overlap with the areas covered by medicine and health, making the publication analysis challenging. Similarly, research into method development, which often results in high-impact publication with large numbers of citations, is considered to be cross-disciplinary, since it also involves important advances in fields such as physics, chemistry and computer science.

It has become apparent from recent publication figures that Sweden is losing its internationally leading position in biology research areas. This can be attributed, at least partially, to a mismatch between the increased demand for experiments for for inclusion in high-impact publications in biology and the limited Swedish grant amounts and insufficient infrastructure, compared to competing countries.

The funding from the Swedish Research Council is of great significance for Swedish biology researchers. Although limited and highly competitive, it is considered as the gold-standard for funding in Swedish biology research, with varying impact in different disciplines. The broader fields of molecular life sciences, evolutionary biology and ecology have also been highly successful in acquiring funding from other national and international sources, such as the Knut & Alice Wallenberg Foundation and the European Research Council, enabling internationally competitive biology research and significant faculty renewal in Swedish universities and research institutes. However, this highly directed funding also comes with risks of steering the field in particular directions. It is therefore imperative that the Swedish Research Council funding for individual project grants increases to a level where the researchers can actually run a project on such a grant, rather than being dependent on additional funding. Furthermore, Swedish biology research will benefit greatly if funding can be provided to initiate collaborative interdisciplinary research and if short-term seed money can be allocated for initiating high-risk, high-gain innovative projects.

2.1.4 Research trends and conclusions

Genomics and other 'omics' techniques, including the possibilities of sequencing single cells and precisely editing the genomes of organisms, are continuing to drive research across many biological research disciplines in Sweden. Recent developments allowing application of these techniques to non-standard model organisms are likely to have a tremendous impact over the coming years. Genetic methods (metabarcoding and metagenomics) have opened the door to new possibilities in charting biological diversity and studying the structure and function of whole ecosystems. This will lead to revolutionary changes in a number of biological disciplines, including taxonomy, symbiosis research and systems ecology, to name a few.

Cryo-EM is increasingly expanding from single-particle structure determination into tomography and diffraction, and progressing towards time-resolved techniques to reveal mechanistic details of different processes. The field is developing towards solving structures at cellular level, often in combination with super-resolution fluorescence microscopy, high-throughput sequencing and computational methods. This would pave the way towards whole-cell models, to understand how healthy and diseased cells function and respond to changes in their environment, which will eventually address problems that range from biochemistry and structural biology to cellular biology and medicine.

Across biology, we see international teams collecting larger, integrative datasets and using them to address complex systems-level questions, regardless of whether these systems are cells with all their chemical components and their interactions, or entire ecosystems with all constituent species and their interactions with each other and the environment. Increasing amounts of data, integration of results from several techniques, and also the growing interest in interaction models has led to great interest in the use of AI, computation, systems biology and other advanced analytical methods to solve large and complex biological problems, and in addressing societal challenges where improved biological understanding is essential.

In conclusion, biology research in Sweden is of high international standard, but only adequate funding and infrastructure for individual and collaborative projects can maintain this position. Biology researchers in Sweden are eager to conduct cutting-edge research, taking advantage of the technological developments in the field. Supporting such initiatives will allow biology research to flourish beyond its current state and to set the mark for the international standard.

2.2 Chemistry

2.2.1 Introduction

According to the Encyclopedia Britannica, chemistry is the science that deals with the properties, composition, and structure of substances, the transformations they undergo, and the energy that is released or absorbed during these processes. Chemistry is divided into different sub-disciplines – analytical, inorganic, organic, physical and theoretical chemistry, as well as materials chemistry and biochemistry. Chemistry is also central in fields such as molecular biology, environmental sciences and geosciences, and materials physics, with the growing focus on molecular processes and species within these disciplines.

Research in analytical chemistry focuses on new or improved methods to detect, identify, and quantify chemical species in increasingly complex mixtures, down to extremely small quantities and even single molecules. This involves separation technologies and spectrometric and spectroscopic techniques, as well as electrochemistry, sensor technology, non-targeted and targeted analysis and automation. Methods for the generation and handling of large datasets are rapidly growing in importance. Inorganic chemistry involves studies of the synthesis, structure and properties of inorganic, coordination, organometallic and bio-inorganic compounds. Research in organic chemistry is directed towards the synthesis and studies of carbon-based compounds. Such studies include the structure and chemical properties of these compounds, and their reactions and interactions with other chemical species, for example in the fields of catalysis and medicinal chemistry. In physical chemistry, the focus of research is towards studies of molecular properties and chemical processes and the energy transfer during molecular processes. Important research areas include spectroscopy, thermodynamics, reaction kinetics, intermolecular forces, electrochemistry, surface and colloid chemistry and biophysical chemistry. Theoretical chemistry research aims to study molecular structure, dynamics, binding properties, stability and reactivity using quantum mechanical and molecular modelling methodologies. Materials chemistry covers experimental and theoretical studies of chemical synthesis, processing, structure, and properties and performance of organic, inorganic and hybrid materials, including also biomaterials. Materials chemistry research is cross-disciplinary with strong connections to inorganic chemistry, organic chemistry and physical chemistry, together with materials science and engineering and solid-state physics. Biochemistry, which in this review is described under the heading "Biology", covers studies of chemical processes in biological systems. In recent years, research at the interfaces of these traditional disciplines has become increasingly common, and has thereby made it possible to address new types of research questions.

2.2.2 Research infrastructure often utilised by actors active in the field

Within the different fields of chemistry, research groups rely on infrastructures available at the host institutions, but increasingly also on large national and international infrastructures, delivering data not available from local infrastructures. Important large infrastructures include synchrotron X-ray and neutron-scattering facilities. After several years' delay, MAX IV is now finally able to serve the Swedish research community more broadly, by providing data on structure and dynamics for a wide range of systems and research questions. Despite this, international facilities such as Petra III and ESRF continue to be essential. Within the neutron-scattering field, Swedish researchers currently rely on international facilities (such as ILL, ISIS and PSI) and will continue do so for several more years, due to delays in the construction of ESS. Well up-and-running, SciLifeLab is extensively used for research in biochemistry, medicinal chemistry, biophysical chemistry and environmental science. Nuclear magnetic resonance (NMR), both locally and at SwedNMR, is an essential technique in organic, inorganic, materials and physical chemistry. With higher demands on data quality and quantity, access to such national and international infrastructures is expected to become increasingly important for a wide range of fields within chemistry and its application. Electron microscopy (EM) is an essential tool in materials chemistry, biochemistry and physical chemistry, with the vast majority of EM studies being performed on local infrastructures. Mass spectrometry (MS) is an essential technique in analytical chemistry, biochemistry and organic chemistry where the research teams usually have access to local MS facilities. Analogously to experimental facilities, access to national high-performance computing resources, such as SNIC (now NAIS), is very important for many groups, in particular in theoretical chemistry. Adding to this, there is a strong tradition in Sweden involving software development, such as MOLCAS and GROMACS. With the importance of such infrastructures, it is important to balance the needs for funding of infrastructure with those of personnel, as the latter is crucial in many labour-intensive branches of chemistry.

2.2.3 Publications, citations and funding

The number of grant applications to the two chemistry panels has remained relatively constant over the last four-year period. The grades awarded in the Swedish Research Council's review process indicate that the quality of the applications is very high. The number of Swedish publications in chemistry has remained relatively constant during the period 2012-2019. Sweden's share of world production (or articles) in chemistry, as in most other areas, has decreased, likely due to stronger growth elsewhere. The share of highly-cited Swedish articles in chemistry is close to the world average. The proportion of articles in chemistry published with open access is increasing, and is now nearly 50%. Multi-disciplinary chemistry and physical chemistry are the largest sub-areas with respect to the number of publications by Swedish researchers, and have grown over the last 10 years. The number of publications in analytical and organic chemistry is about half as many as in physical chemistry, and has decreased during the same period, whereas publications in inorganic chemistry have stayed fairly constant. The decreasing number of publications mirrors the decrease in the number of researchers in analytical and organic chemistry in Sweden, but could also reflect the fact that chemists publish a larger percentage of their work in multi-disciplinary journals.

2.2.4 Research trends and conclusions

Chemistry is at the heart of challenges related to several of the United Nations (UN) Sustainable Development Goals (SDGs), and in particular to solutions to rapidly reduce emissions of green-house gases (GHGs) and to reduce or eliminate the use and release of toxic chemicals and compounds. The research that addresses these questions is performed in both smaller projects funded by the Swedish Research Council and in larger multi-disciplinary research centres or projects (funded by bodies such as KAW, MISTRA, and the EU). It is clear that researcher-initiated projects and challenge-driven research in larger constellations support and benefit each other. For instance, attempts to reduce effects of anthropogenic release of GHGs motivate research on solar cells, carbon capture and utilisation of carbon dioxide, light-emitting diodes, and batteries, which drives and requires the development and studies of synthetic methods, catalysis, light-matter interactions, ultra-fast spectroscopy, and molecular dynamics simulations incorporating excited states, electronic transitions, and photochemical processes. In another area of key importance for the green transition, the increasing cost and restrictions on the use and release of toxic chemicals provides a major incentive for new and improved analytical techniques, capable of detailed characterisation of complex soil, water, air, and food samples and improved routes to producing and formulating chemicals. Green and sustainable chemistry is also being integrated with the traditional fields of chemistry in both research and education.

Within the areas of health and an ageing population, the need to understand and eventually cure diseases is increasing. Alzheimer's and Parkinson's diseases will, for example, continue to fuel research into intermolecular interactions between biomacromolecules, as well as in medicinal chemistry, drug formulation and drug delivery. Related questions are central also in the search for new approaches to combat cancer, as well as infectious disease. These, and many other research areas in chemistry, are already influenced by the increasingly wide-spread use of machine learning and AI, not only for finding correlations in the vast amounts of data produced by modern analytical techniques applied to environmental and biological samples, time-resolved spectroscopic studies of chemical reactions, or in computational investigations of molecular systems, but also to control automated experimental processes or simulations and to optimise reaction conditions in a rational manner. Harnessing the power of artificial intelligence requires both access to computing facilities and education of the research community in how, when, and when not to apply the new techniques. In order to harness the full potential of this development, there is also a need for developing ways to integrate data handling methods throughout the research process, ranging from study and system design, to experiment/data execution, data analysis, and integration between different types of data generated in this way. As such, this development will likely have a wide-ranging influence on the way research is being done, but particularly so in areas such as chemistry, where molecular information needs to be refined, supplemented, and integrated with other data for this research to fully contribute to the transition we are inevitably facing.

2.3 Geosciences

2.3.1 Introduction

The overarching theme for geosciences is to advance our understanding of the processes on planetary bodies and, in particular, within and between Earth’s different spheres: inner-Earth, lithosphere, atmosphere, hydrosphere, cryosphere and biosphere. The detailed study of Earth’s geological evolution allows geoscientists to provide long-term perspectives on climate and environmental changes (past, present and future); on the occurrence and recurrence of extreme events, natural hazards and associated risks (such as earthquakes, flooding, volcanic eruptions, landslides, drought, solar storms, and meteorite impacts); and in respect to the potentials and limitations of natural resources (such as minerals, metals, water) and energy sources (such as oil, coal, gas, nuclear power). Geoscience research forms the basis for understanding the development of life and allows assessing human impact on Earth. It provides key expertise for a sustainable development of society, for new technologies and for mitigation strategies, and contributes to all 17 of the UN Sustainable Development Goals.

Geosciences is an interdisciplinary field covering traditional subjects such as geology, mineralogy, palaeontology, geochemistry, geophysics, geography, hydrology, oceanography, and atmospheric sciences, but is also increasingly bridging scientific disciplines by utilising knowledge and methods from physics, chemistry, biology and engineering. The increased focus on societal needs and sustainable development has, moreover, enhanced interaction with other scientific domains in recent years, in particularly social sciences.

Research during the last 20 years in Sweden has focused on: (1) Climate change, in the past, present and future, including the evolution of life, extinction and extreme climatic events. Climate models and climate proxy data are increasingly compared with each other to test model performance and to assess natural versus human-induced climate change. Climate prediction benefits from an improved understanding of the physics and chemistry governing the climate system, such as aerosol-cloud or ocean-ice interactions. Similarly, the integration of satellite and instrumental data to better understand climate processes from micro to global scales, the role of freshwater systems, including the cryosphere, the global carbon cycle, and ocean circulation modelling in space and time are important research topics. (2) The sub-surface environment, to address fundamental questions regarding subduction zone processes, plate tectonics, Earth's magnetic field, mountain building, erosion and weathering processes, and volcanic eruptions. This offers crucial information about natural resources and future technological challenges, such as carbon dioxide and nuclear waste storage, earthquake risk assessment, and urban developments below surface. (3) Recent advances in analytical and technical methods include the simultaneous analysis of a wide spectrum of chemicals, paleo-genetics, x-ray and neutron analysis, Lidar topographic and multibeam bathymetric maps, unmanned vehicles, Eddy-covariance measurements, and satellite-based observations. Increased computer capabilities now allow the use of highly detailed numerical models and methods using big data sources, in particular the development of machine learning tools.

2.3.2 Research infrastructure often utilised by actors active in the field

Local, national and international research infrastructures are the basis for geoscience research. Significant advances in the understanding of Earth's different systems have been possible, due to new technological developments, cutting-edge analytical possibilities and enhanced computing resources.

Local infrastructures at universities, funded through external and internal grants, include, for example, marine field stations and research vessels, geophysical field equipment, electron microscopes, and (accelerator) mass spectrometers. National infrastructures, which are operated by one or several universities and jointly financed by the Swedish Research Council and the universities, comprise spatially-distributed field and long-term monitoring stations within the Swedish Infrastructure for Ecosystem Science (SITES) (such as Abisko, Tarfala); laboratories with high-precision instrumentation (such as stable isotopes and core scanning; NordSIMS/Vegacenter; Paleogenetics); large national resources and laboratories (MAX IV, SciLifeLab, Onsala Space Laboratory); marine research vessels (such as the ice-breaker Oden); high-performance computers (SNIC); digital infrastructure and data repositories (such as geo-data and maps; SBDI, Swedish biodiversity data infrastructure, drill-core repository); and research stations in the Antarctic.

International infrastructures allow the participation of Swedish researchers in larger consortiums and programmes, and provide access to advanced state-of-the-art facilities, remote sensing infrastructures and long-term monitoring field stations, as well as networks and data services. International and interdisciplinary infrastructures and networks offer exceptional opportunities to study processes in the atmosphere, ocean, ice, soil and below ground (ACTRIS-ERIC, ICOS, EISCAT-3D, EPOS-ERIC), and provide long-term climatic and environmental data series, especially in polar regions. These infrastructures are of great importance for surveying the ocean floor and for obtaining unprecedentedly long sediment and bedrock records on land and in the ocean (ICDP, IODP/ECORD, the ice-breaker Oden, and Riksriggen - the Swedish national drilling infrastructure), which in turn offer the possibility to study Earth’s evolution, and groundwater and mineral resources.

2.3.3 Publications, citations and funding

The publication trend for Swedish geosciences shows a steady increase from around 500 to more than 800 articles per year between 2007 and 2019. However, seen in a global perspective and over the same time period, the total share of Swedish publications in the field decreased slightly, similar to other scientific disciplines in natural and engineering sciences. The impact within the global geoscience field, measured as the proportion of highly cited publications, was 2-3% above the world average, showing that Swedish geoscience research continues to produce high-impact research results. The average number of authors on articles with at least one author affiliated to Sweden has increased distinctly, and reached an average of eight authors per paper in 2017. This follows an international trend where scientific collaboration and publication have become significantly more international during the last 15 years. Open access publication has increased considerably between 2007 and 2019, and continues to increase.

The majority of articles in geosciences relate to environmental sciences, followed by multidisciplinary geosciences, meteorology and atmospheric sciences, and geochemistry and geophysics. The high number of publications within environmental sciences (almost 1 200 in 2019) could relate to the establishment of larger research environments at Stockholm University (Bolin Centre for Climate Research) and Lund University (Lund Centre for the Study of the Carbon Cycle and Climate, LUCCI), which were funded by the Swedish Research Council through a Linnaeus research environment grant.

Support from the Swedish Research Council is acknowledged in around 20% of the published work between 2007-2019, which suggests that research projects are funded through other sources, such as for example Formas, the Wallenberg Foundations, the Swedish Energy Agency, Vinnova, the Geological Survey of Sweden, the Swedish Nuclear Fuel and Waste Management Company, the European Research Council, and the European Union. However, the Swedish Research Council remains one of the most important funding sources for basic geoscience research.

2.3.4 Research trends and conclusions

The growing reliance on advanced modelling and data analysis techniques is a clear trend that will continue into the future and will depend on up-to-date computing infrastructures. Common to many research areas is the development of new measurement and analytical techniques that allow insight into processes from micro to global scales. This ranges, for example, from new sensitive isotope techniques, chemical and structural analyses at micro- and nano-scales (including 2D and 3D imaging), and genomics, to the development of small sensors and up-to-date measuring platforms and satellite-based observations of Earth, the solar system and the universe. Big data analytical techniques such as machine learning will become more and more important for geosciences.

New space missions place Earth's history, the origin of life and the solar system in a cosmic context. Geosciences will provide part of the foundation for future space missions, again relying on and integrating many research fields in natural sciences.

Linking processes from micro to global scales both in time and space advances our in-depth understanding of Earth’s different systems and of the interactions within and between these. This holistic perspective allows deciphering human impact on the natural environment and offers solutions for how to switch paths to a sustainable future. A sustainable supply of natural resources, including sources of energy, is one of the great challenges of our times. Fundamental understanding of how natural resources are concentrated in Earth’s crust and the assessment of the potentials, problems and limitations associated with geo-energy sources relies on sound knowledge of the complexity of Earth's systems.

Natural disasters will occur more frequently with global warming, and will lead to more damaging impacts with increasing population density and infrastructure often built with little regard for natural hazard risks. Mitigation strategies will depend on solid geoscience knowledge.

The relevance of geoscience is increasing, and the field will play a major role for the well-being of society and for a sustainable future.

2.4 Electrical engineering and computer sciences

2.4.1 Introduction

Electrical engineering and computer sciences research the scientific foundation of the information age. It includes modelling, analysis, design and implementation of systems, from electronic and computing devices via software and algorithms, to their integration into large-scale cyber-physical systems.

Electrical engineering is concerned with the study, design, and application of devices and systems based on electricity, electronics, and electromagnetism. It incorporates many aspects, from hardware components and electrical circuits to algorithms and software, including principles for systems engineering, learning, optimisation and control.

Computer science is the study of computation, automation, and information. It includes areas such as algorithms, artificial intelligence (AI), computer systems, human-machine interaction, information systems, parallel and distributed computing, programming languages and systems, security, software engineering and the theory of computation.

This research area is seeing dramatic development. It covers the basic science behind the enormous success of AI and machine learning, and the broader digital transformation and electrification of society, including, for example, the development of cyber-physical systems, cloud computing and communication technology. Challenges associated with societal sustainability and resilience have put an increased focus on re-thinking the fundamental principles in this area, and have broadened the research to involve ethical, legal and societal aspects of the use of these systems.

2.4.2 Research infrastructure often utilised by actors active in the field

National research infrastructures are of great importance to researchers in electrical engineering and computer sciences. For instance, the cleanroom facilities at Chalmers University of Technology, KTH Royal Institute of Technology, Lund University and Uppsala University that form Myfab are a critical resource for researchers in semiconductor electronics. There is a growing need for testing and evaluating research methodologies and results under realistic conditions, and independent of commercial interests, where experimental infrastructure for intelligent transportation systems, cyber security and the various Wallenberg AI, Autonomous Systems and Software Programs (WASP) research arenas, are becoming more important.

Researchers in this area also develop research infrastructure that are essential for users not only in the area but in many other fields of science as well. A prime example is NAIS, the successor of SNIC. It serves a large and growing community with computing resources, cloud infrastructure and data storage. Another example is the newly launched National Research Infrastructure for

Data Visualisation (InfraVis), which supports researchers with cutting-edge visualisation solutions.

2.4.3 Publications, citations and funding

Swedish research in the area has a solid international standing. The publication tradition varies strongly across subdisciplines, involving different emphases on conference contributions and journal articles, which makes it challenging to apply standard bibliometric tools when comparing subdisciplines with each other, or with other fields of science. As a general trend in both engineering and computer sciences, the amount of publications is steadily increasing with almost a doubling over the decade 2009-2019.

Funding for both pure and applied research in this area has increased substantially in recent years, thanks to strategic initiatives from public and private funding agencies. For instance, WASP (Wallenberg AI, Autonomous Systems and Software Program) is funding more than 80 faculty positions, targeting internationally competitive researchers with attractive starting packages in an effort to strengthen scientific excellence in the area. Interestingly, the number of project applications to the Swedish Research Council in this area has not yet been affected by this, but in the long term we expect to see a significant increase. The percentage of published articles that mention the Swedish Research Council in their acknowledgements is low, at around 10%, indicating that there is a variety of other funding sources.

Finally, we note that to stay competitive in the long term, Swedish academia, industry, and society are in great need, not only of excellent basic research in this field of science, but also a steady production of graduates with doctoral degrees who can take advantage of the dramatic developments in meeting corporate and societal challenges.

2.4.4 Research trends and conclusions

As was alluded to above, the research area of electrical engineering and computer sciences has gone through transformational developments. There are several large drivers for future research needs. Digitisation involves new sensing technologies and integration of them in larger information systems to create situational awareness. Communication systems are constantly evolving to meet future needs. The energy grid is moving towards integrating distributed and renewable energy sources and also flexible loads including new ones coming from electrification. The whole transportation sector is moving towards more autonomy. Finally, cyber security is of utmost importance in all these areas.

Notable trends include the machine learning revolution, the development of quantum computing, advances in satifiability modulo theory solving, the increased importance of GPU-driven computing, and the growing emphasis on scalable software development. Many goals, such as scalability and high performance, are important to balance against environmental and societal sustainability concerns, such as energy efficiency. Security and privacy are at the core of long-term scientific questions in a variety of areas. Much progress has occurred in the area of AI. Yet, explainable, robust, dependable, and secure AI methods are still to be developed.

National infrastructures, such as SNIC (now NAIS) and other high-performance infrastructures, are of high importance for research excellence, and that also applies for creative environments, such as centres, networks and graduate schools. Supporting open-access artifacts and open-source software is crucial for researchers to enable them to collaborate beyond the limits of infrastructures and research centres.

While other funding agencies successfully attract excellent researchers with ample funding opportunities, this often comes at the price of tailoring research agendas to address specific needs. The Swedish Research Council plays a vital role in enabling basic, bottom-up research, such as the research that resulted in the machine learning revolution. The Swedish Research Council has a critical role to play in the area with dramatic yet fragmented developments driven by the interests of a variety of actors, none of whom has basic research as their primary mandate.

2.5 Mathematical sciences

2.5.1 Introduction

Throughout its very long history, mathematics has developed through the interplay between theoretical aspects and practical use, and the stability and universality of its results gives it a unique character among the sciences. Mathematical sciences constitute a large body of theoretical research, ranging from the main areas of pure mathematics (algebra, geometry, analysis, number theory and probability), to modelling, statistics, and computational mathematics. No Swedish university alone covers all subjects of mathematical research, but together, Swedish universities provide a good coverage. Swedish research teams at several universities are at the centre of rapidly evolving focus areas in the main fields of mathematics.

Sweden has a strong tradition in mathematical research, including the oldest mathematical research institute in the world, Institut Mittag-Leffler (IML) and one of the most prestigious international mathematical journals, Acta Mathematica. Today, the importance of mathematics, both in science and society, is steadily growing. Digitalisation is revolutionising our world, and advances in mathematical sciences ranging from the very abstract to applied areas are central to this revolution. Wide mathematical competence at national level is essential: as illustrated by the many recent new usages of mathematics, it is impossible to predict which mathematical area will contribute to the next breakthrough application.

2.5.2 Research infrastructure often utilised by actors active in the field

IML is one of the top mathematical research institutes worldwide. Each year it hosts two semester-long programs and 8-10 summer conferences. In total, around 500 researchers from leading universities all over the world visit IML every year. IML is vital for Swedish mathematics, for recruitment to Swedish universities, and for making Sweden a hub for mathematical research internationally and particularly in the Nordic countries. IML currently receives funding from the Swedish Research Council directed to research institutes, and it is of critical importance that this continues.

Access to computing resources and storage capacities is critical for several areas of Swedish mathematical research. Adequate local resources are needed for easy access and testing, combined with national infrastructures, as currently coordinated by SNIC (now NAIS), for resources on a larger scale. The need for such resources will continue to increase, partly because of research in machine learning and big data.

2.5.3 Publications, citations and funding

The funding of project grants in mathematics by the Swedish Research Council has been approximately constant during the last decade if adjusted for inflation. The total external funding for mathematics in Sweden has, however, increased. Following the Swedish Research Council report in 2010[1], where the insufficient funding of Swedish mathematics was clearly exposed, the Knut and Alice Wallenberg (KAW) Foundation initiated the KAW Mathematics programme in 2013. Later, the Wallenberg AI, Autonomous Systems and Software Program (WASP), in 2017 launched a subsidiary focused on the mathematical foundations of AI (WASP-AI/Math).

Despite these additional funding opportunities, Swedish Research Council projects are of utmost importance. The WASP funding is directed towards math for AI, while the KAW mathematics funding is free in terms of topic, but available only to support postdoctoral and guest researchers. Apart from a few large excellence grants, the Swedish Research Council is the only unrestricted external source for research and doctoral student support in all fields of the mathematical sciences. This importance is clearly demonstrated by the growth in the number of applications in mathematics to the Swedish Research Council. In 2021, NT-1 was split into NT-S (Mathematics) and NT-R (Computational Mathematics, Statistics and Data Science), where the latter includes some elements also from former review panels other than NT-1. Mathematical analysis, computational mathematics, and probability and statistics remain the three largest areas according to the SCB/Statistics Sweden code classification. An increasing share of the grant proposals has applications in data science (not well captured by the SCB/Statistics Sweden codes), and the new panel NT-R is expected to grow.

The bar to obtaining a Swedish Research Council project grant in mathematics is very high, and commonly perceived as being too high. The average success rate

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[1] Evaluation of Swedish Research in Mathematics. Vetenskapsrådets rapportserie 16:2010.

in the NT-1 panel during the period 2014-2020 was below 20%, which is critically low in mathematics, as other funding options in this field are limited.

The number of publications in mathematics has increased somewhat during the last decade, while the share of the world production has decreased slightly. About 25% of publications in Mathematics have an acknowledgement to the Swedish Research Council. International collaborations are essential. Compared to other fields in natural and engineering sciences, the average number of authors for each publication is small, but the proportion of international authors is large. There is an open-access culture in the field, and preprints are typically made available on ArXiv.org at the time of submission, which has extra value since the lead time for publication can be long in mathematics. The percentage of journal articles that are published with open access is increasing, but is currently still only around 30%, which is surprisingly low. The three-year citation window that is used when compiling bibliography data is too short for mathematics, and the expected positive trend cannot be seen in the resulting fluctuating numbers. One can, however, note that during the last three years, several Swedish researchers have published their work in the five most prestigious journals in the world, and Sweden has been well represented at the International Congress of Mathematics (ICM). The number of papers in these journals and speakers at the ICM is considerably greater than corresponding numbers for other Nordic countries.

2.5.4 Research trends and conclusions

The research frontier in mathematics is advancing through scientist-initiated research inspired by internal developments, and through challenges posed by applications. The scientific revolution caused by digitalisation and data science builds on and accelerates the development of mathematical theory in a wide variety of its subsidiary fields, ranging from probability and statistics via optimisation and numerical analysis to areas such as algebraic topology for topological data analysis and differential geometry. As always in mathematics, the most important future advances will quite likely come from unexpected directions.

The importance of mathematics as a language for the natural and engineering sciences is increasing. The classical and modern ties between physics, geometry, mathematical analysis, probability, and combinatorics include many recent fruitful developments and challenges; mathematical advances are made in new areas of biology and life sciences; there is a rising prominence of both deterministic and stochastic mathematical modelling and numerical algorithms for computer simulation in a wide field of applications, and the entire range of engineering sciences use more and more advanced mathematics. This trend will lead to fundamental mathematical contributions towards meeting our major societal challenges, including sustainability and climate change.

The number of mathematics research teams at Swedish universities at the centre of international developments, and hence with a strong international impact, is increasing. Many exceptionally good researchers are currently starting their careers in Sweden, and Swedish mathematics holds significant promise for the future. There is now an opportunity to retain internationally high-level mathematical research in Sweden, and to build on these environments in a gender-aware and diversity-aware manner, to further strengthen the competitiveness of Swedish mathematics. This will require both long-term adequate funding channelled through the universities, and increased investment in undirected project grants via the Swedish Research Council.

2.6 Mechanical, chemical and biomedical engineering

2.6.1 Introduction

The field of mechanical, chemical, environmental, bioprocess, and biomedical engineering covers broad technological and engineering research. Mechanical engineering contains the classical fundamental disciplines of fluid and solid mechanics that constitute the scientific basis for a vast majority of industrial processes and product development. Chemical engineering provides the fundamentals for the design of chemical processes, including catalysis, reaction engineering and separation operations, whereas environmental engineering aims to create solutions for protecting the environment and living organisms. Bioprocess engineering integrates the use of cells, organisms, and parts thereof for the production of goods and services. Biomedical engineering covers a broad spectrum of research, with much focus on methods for measurement, modelling, and modification of biomedical processes.

In Sweden, mechanical engineering largely consists of applied mechanics research related to fields such as fluid mechanics, tribology, material science, climate and geophysics, aerospace, biomechanics and paper production. In environmental engineering, research into energy efficient carbon capture and storage, and carbon capture and utilisation, to mitigate greenhouse gas emissions and climate change is noteworthy. Chemical and bioprocess engineering of biomass such as cellulose, hemicellulose, lignin and algae to produce new materials, chemical building blocks and fuels are important activities. Biomedical engineering includes research in medical imaging, biomedical sensors and signal processing as well as modelling and simulation, but also molecular, pharmaceutical and biotechnology-related sciences.

2.6.2 Research infrastructure often utilised by actors active in the field

A great focus has been placed on the establishment of large national and international infrastructures, including distributed facilities, such as synchrotron X-ray sources and neutron scattering sources (MAX IV and ESS, the European Spallation Source), SciLifeLab (Science for Life Laboratory) for large-scale multiomics (such as genomics, transcriptomics, proteomics and metabolomics), and SwedNMR (Swedish Nuclear Magnetic Resonance). The use of these large infrastructures is seen as a current and future need. However, within the field of mechanical, chemical, environmental, bioprocess, and biomedical engineering, research teams often rely heavily on the use of small and middle-sized infrastructure available at their host institutions. Access to national high-performance computing resources, such as SNIC, is very important for many groups, but here too, the importance of access to small- and middle-sized (local and distributed) computational infrastructure at each host institution is stressed. Strong national and local infrastructure will also be essential for the success of the Knut and Alice Wallenberg Foundation's recent investment in Data Driven Life Science (DDLS), which relies on the availability of high-quality data from the multi-disciplinary domain of mechanical, chemical, and biomedical engineering.

2.6.3 Publications, citations, and funding

Mechanical, chemical, environmental, bioprocess, and biomedical engineering covers a very broad range of research fields that are in most cases multidisciplinary. This makes bibliometric analysis complicated. We do see a general trend where the number of publications is stable or increasing (especially for research connected to green and sustainable science and technology), but the percentage of Swedish publications and the share of highly-cited publications is decreasing, reflecting the emergence of strong international research efforts in countries such as China.

Swedish Research Council grants are essential for supporting basic, high-risk, high-quality research in these areas. The role of the Swedish Research Council is even more important now, as there is an obvious shift towards more applied research. The excellent basic research funded by the Swedish Research Council is of the highest importance and can form the basis for more applied research projects funded by other agencies (such as Formas, the Swedish Foundation for Strategic Research (SSF), Vinnova, the Swedish Energy Agency, the EU) that might require industrial co-financing.

2.6.4 Research trends and conclusions

In applied mechanics, several recent trends can be seen. Research in fluid mechanics has focused on the computational resolution of turbulence and complex phenomena in suspensions and multiphase flows, including heat transfer and chemical reactions. Other examples are the rheology of dense suspensions (such as gels), microfluids in capillary systems, the freezing and thawing of liquid drops, and “green” materials and fluids for lubrication. Computational fluid dynamics has become an accepted and versatile tool in addressing life science problems. Fluid-Structure-Interaction (FSI) with large deformations and complex tissue properties constitutes a bio-medical problem that can be solved for a patient-specific application, such as “virtual surgery”. FSI is also a key feature of the micro-scale modelling of various porous media that are (partly) saturated with fluids. Multiscale modelling, including computational homogenisation and other scale-bridging strategies, has developed significantly in recent years. This scientific tool is essential for new materials design on different geometric scales, including materials with optimised design for selected properties and applications. Phase-field modelling has also emerged as an important research field, used to model and simulate complex fracture patterns, and to simulate the evolution of microstructural phases due to changing temperature and environment, for example. Additive manufacturing (3D-printing) continues to attract technological interest with extension to areas such as biomaterials and other composites, offering great potential for collaboration and use across multiple scientific fields.

In the recent years, the main trend of research in chemical, environmental and bioprocess engineering has been in the sustainability of processes, powered by the changes in resource availability and the challenges from waste management and climate change. The design and implementation of bio-refineries using chemical, thermal and biological processes for the transformation of renewable resources (biomass) into bio-based materials, chemicals and fuels, has been a large research challenge in the past decade that will continue to develop. Selectivity, robustness, efficiency, and scalability of the processes will be key, together with a focus on circularity (use of residues, recyclability). The development of energy efficient processes for green hydrogen production and storage, and for carbon capture and storage (CCS) and carbon capture and utilisation (CCU) will be fundamental for the transition of the chemical industry. The integration of environmental engineering in the quantification of environmental impacts and life cycle assessment will also be necessary. Recent advances in synthetic and chemical biology such as CRISPR), faster multiomic approaches, directed evolution, and new tools to predict protein structures will be key advances for improved bioprocess technology. An important emerging societal challenge to be addressed is food security, supporting a sustainable and competitive Swedish food system.

For biomedical engineering, a clear trend is the use of a large number of methods for observing biomedical processes, both in space and time, across multiple modalities, and with increasing resolution and multiplexity. This includes not only spatial 'omics', but also medical imaging techniques, such as advanced X-ray and MRI (magnetic resonance imaging). Moving forward, it will become important to integrate these techniques (both physically and computationally) and scaling up their use in exploration of biomedically relevant questions.

A common major trend for all the research fields is the increased multidisciplinarity of the projects that is needed to tackle the challenges, which reflects on the close connections to other scientific fields, such as material sciences, chemistry, biology, and applied physics. Also, AI (artificial intelligence, or, more specifically, different approaches to machine learning), including data processing and analysis, has become a very important tool for most of the research areas, enabling modelling and pattern recognition that has previously been very difficult to automate.

2.7 Physical sciences

2.7.1 Introduction

Physics is a fundamental scientific discipline that covers research on size scales from the smallest elementary particle all the way to the size of the universe, and on time scales from attoseconds to the lifetime of the universe. The field is developing through interplay between the formulation of theoretical models, observations, and experimental efforts. Mainly comprising fields such as subatomic physics, astronomy, physics of light and matter, and materials science and engineering, it is also integrated with applied and engineering physics, generating new characterisation techniques, materials, as well as science. It also often couples to several other fields of science, not least mathematics, chemistry and geosciences, as well as mechanical, biomedical and electrical engineering.

The field of subatomic physics encompasses experimental and theoretical aspects of fundamental physics, particle physics, nuclear physics, accelerator physics, and fusion. Since these fields are inherently international, Swedish researchers in this field are to a large extent organised into large international collaborations. This community thereby has one of the largest incidences of international collaborations in the field of natural sciences.

The field of astronomy also comprises astrophysics, cosmology, and space physics. This field too is organised into large international collaborations. In astrophysics, Sweden has strong research in planetary, stellar, and galactic astrophysics, with scientists being involved in observational studies of exoplanets, modelling of planet formation, studies of the black hole in our galactic centre, neutrino physics, and detailed solar observations. Within the field of space physics, Sweden is contributing to satellite missions, for use in atmospheric, ionospheric, and solar physics and in geosciences.

The field of physics of light and matter encompasses primarily the fields of atomic, molecular, and optical (AMO) physics and condensed matter physics, in which fundamental structures and processes are under scrutiny. Sweden has strong research activities in both these fields. The first one, involving experimental studies based on advanced light sources, such as those producing synchrotron or X-ray radiation, attosecond pulses and frequency combs, includes studies of atomic and molecular structures, ion collisions, and reaction dynamics, often based on non-linear phenomena. The second field, which to a large degree utilises the same experimental instrumentation as the AMO field, comprises development and characterisation of materials, primarily in the solid phase, with novel types of macroscopic and microscopic physical properties. There is a strong synergy between the experimental research and condensed matter theory and modelling.

The field of materials science and engineering comprises primarily the study of structure-processing-property relationships of substances, with strong connections to applied physics, materials and polymer chemistry, mathematics, and computational science. Much recent research effort in Sweden has been towards addressing challenges in health and sustainability with various advanced functional materials, though traditional disciplines in classical metallurgy and synthetic chemistry remains strong, with application areas within the automotive, chemical and forest industries, for example.

The field of applied and engineering physics is a notably broad research area, with strong connections to activities in fields such as medicine, biology and chemistry. Subsidiary fields that currently are seeing rapid development include the development and utilisation of emerging quantum and meta-materials, the design and fabrication of advanced electronic and photonic devices and systems, and the realisation and improvement of energy conversion and storage technologies.

2.7.2 Research infrastructure often utilised in the field

Swedish scientists are strongly dependent on access to both national and international infrastructures. Synchrotron radiation facilities (such as MAX IV, ESRF, and Petra III) and neutron scattering facilities are of central importance for materials science, applied and engineering physics and the search of fundamentally new physics, in particular within the field of development of novel quantum materials. Scientists within the fields of AMO sciences additionally make use of large-scale light sources, such as the European XFEL and LaserLab Europe, as well as ion storage rings (such as DESIREE), where the latter ones allow for detailed studies of ion-ion interactions in well-defined quantum states.

Within the fields of subatomic physics, astrophysics, astronomy (including atmospheric and space physics), and particle and high-energy physics, Swedish scientists frequently utilise large-scale international infrastructures, such as CERN (including the LHC), EISCAT_3D, ESO ground-based telescopes such as VLT, and space observatories, such as the HUBBLE and the TESS telescopes.

Swedish researchers are also frequently using a number of important distributed and local infrastructures, in particular computational infrastructures (such as SNIC), nanofabrication facilities (such as Myfab), state-of-the-art laser instrumentation (Laserlab Sweden), as well as facilities comprising advanced light microscopes, electron microscopes, and NMR instrumentation.

Since all these infrastructures play a fundamental role for the quality of the research, the progress and impact of Swedish physical sciences are strongly dependent on access to research infrastructures at all levels.

2.7.3 Publications, citations and funding

The level of research in the field of physics is in general very good to excellent, slightly above the international average when it comes to the publication of highly-cited papers; a situation that has prevailed over the last few years. The total number of publications is fairly constant, although there may be a beginning trend of a decrease in output (which is not yet reflected in the number of highly-cited papers, however). The proportion of the Swedish contribution to the world output in physical sciences has decreased over the last years, in common with most research fields. This can probably largely be attributed to the rise in scientific impact of China and other emerging nations, which have lately made significant investments in science and technology. In view of this, Sweden is doing well to keep up the proportion of highly-cited work.

The Swedish Research Council constitutes the main source of financing for both established and young researchers in smaller research constellations in the field, allowing them to perform research in a variety of research fields by a true bottom-up process. This support is not only crucial when it comes to supporting fundamental science, it is also of crucial importance for the prosperous and multi-faceted applied research that is being carried out in Sweden.

Other national sources of funding for the field of physical sciences in Sweden are the Knut and Alice Wallenberg (KAW) Foundation and the Swedish Foundation for Strategic Research (SSF). While the former plays an important role in financing research using medium-size project grants awarded to consortia promoting innovative research outside the beaten tracks, and larger, longer-term grants (above 1 billion SEK) allocated to specific research fields, for example by the WISE and the WACQT programmes, the latter supports research in natural sciences, engineering and medicine, with the aim of strengthening Sweden's competitiveness. International sources of funding comprise mainly the European Research Council (ERC) and the Marie Skłodowska-Curie Actions (MSCA).

2.7.4 Research trends and conclusions

It is anticipated that in several areas of physics, more research will be done in the future in large international collaborations, using national or international research facilities. For example, in the fields of high-energy subatomic physics, particle physics, plasma physics, and fusion, Swedish researchers will use upgraded versions of LHC, JET, ITER, and the upcoming FAIR facility. The latter will be accessible to Swedish scientists also in fields of atomic and anti-matter physics, as well as in high-density plasma physics, condensed matter physics, biology, and biomedical sciences. Within the fields of materials science and engineering, our scientists will use new beam-lines at MAX IV and the upcoming ESS. These are expected to provide unprecedented research opportunities for Swedish scientists.

The field of astronomy is undergoing fundamental changes, replacing individuals studying a few cosmic objects over an extensive period of time with large-scale comprehensive surveys providing homogenous, statistically-significant and diverse data collections that are analysed using various method by many scientists working in the field. Such examples can be found in studies of stars in our galaxy, using the ESA's Gaia and 4MOST telescopes, in the search of transiting exoplanets, using NASA's Kepler and TESS telescopes and ESA's Plato programme, and in studies of very distant galaxies using radio facilities, such as the SKA telescope. The latter will provide high resolution images of our universe through the use of a multitude of small antennas spread over several thousand kilometres, to simulate a single giant radio telescope capable of extremely high sensitivity and angular resolution. Interesting targets discovered in such surveys require in-depth studies, which are done using the largest telescopes and the most advanced instruments, not least the ones developed and constructed by Swedish researchers or with strong Swedish participation, such as the ESO's VLT instruments and ALMA, the future ELT instruments, and NASA's and ESA's space observatories, such as HUBBLE and JWST.

The field of AMO sciences, in which the most recent scientific advances have been (and still are) technology-driven, is expected to continue to flourish and grow with the increased access to research infrastructures such as MAX IV, XFEL, DESIREE, and Laserlab Sweden. A field of particular importance is the development of ultra-fast light sources (from attosecond lasers to XFELS) that are allowing dynamic behaviour at atomic level to be probed in unprecedented detail. Within this field, there is also a pronounced “opposite” trend, namely towards small-scale, high-precision experiments, such as for investigations of fundamental physics, or to advance the field of meteorology, in particular using emerging quantum technologies.

The field of condensed matter physics partially overlaps and has many connections to material science, applied physics, and engineering sciences. In Sweden, experimental condensed matter research is strong in areas such as nano materials and devices, surface physics and energy-related materials, while condensed matter theory remains strong across all fields. Both experimental and theoretical condensed matter physics are well positioned to benefit greatly from the opportunities presented by MAX IV, XFEL, and ESS.

In materials science and engineering, the major trend is materials for sustainability. This is followed by research based on fundamental phenomena at nanoscale, including synthesis, characterisation and computer modelling of nano-materials and nano-devices, design of novel materials and structures, from the atomic to the structural scale, and transformation of bio-based raw materials into high-value products, such as new materials with unprecedented characteristics derived from wood and other biomass. Future progress in these fields is also expected to involve the design of "soft and strong" hybrid materials, high-concentration alloys, as well as bio-inspired materials, in which organic and biological materials, even enzymes and organisms, are included.

Within the field of applied and engineering physics, current 'hot topics' include quantum materials, quantum technology, and meta-materials, with the promise of quantum computing, and the realisation of various improved and novel "quantum" applications, based on novel effects, such as shrinking the active part of electronic devices to atomic and even subatomic level for the emergence of novel quantum phenomena. Research into energy conversion and energy storage, utilising new advanced material systems, is also growing.

Theoretical physics and modelling have strengthened their role in physical sciences in recent years, mainly as a tool for predicting and interpreting experimental observations, and in areas where experiments or observations are lacking or difficult to perform. It is expected that this will continue into the near future. In addition, the field of artificial intelligence is expected to continue its development into various subsidiary fields of physical sciences, not least applied and engineering physics. For data interpretation, cross fertilisation with the fields of computer science and machine learning will continue to be important.

A joint important topic spanning many of the subsidiary fields in physical sciences is the development and implementation of “green”/sustainable key technologies, which both encompass the realisation of more efficient energy storage and conversion devices, but also the development and implementation of green materials, sustainable fabrication, and recycling processes.

In conclusion, significant numbers of Swedish scientists in the field of physical sciences are using, and are heavily dependent on, various research facilities. Since some targeted national or international research facilities are still under construction, whenever they are finalised, the numbers of Swedish researchers that utilise large-scale facilities are expected to increase even more.

3 Future challenges

3.1 Scientist-initiated research and societal challenges

It cannot be over-emphasised that scientific breakthroughs are virtually impossible to predict. For this reason, undirected, scientist-initiated project grants remain the best investment society can make to meet future needs for new knowledge, to form the basis for new industry, for handling tomorrow's unforeseen crisis, and for our fundamental understanding of the world. It follows that it is vital to ensure sufficient success rates for such project grant applications, with budgets that allow research of the highest quality. At present, both the grant amounts and the number of research project that can be granted are insufficient to promote the foundation for Swedish research.

The latest Government Research Bill (2020) was characterised by an increasing imbalance between funding for undirected and directed research that is risking not only to jeopardize Sweden's position as a leading research nation, but also diminish the return on the directed research efforts. This can have a severe impact on scientific excellence, technical advancements and innovation, and can limit our preparedness for future societal crises.

The interdisciplinary component of excellent research in the areas of natural and engineering sciences is becoming increasingly prevalent. Theories, methodologies, factual knowledge and/or data from differing disciplines are combined in ways that open up new interdisciplinary research fields and research approaches. To encourage and support interdisciplinary research is challenging and requires a spectrum of funding systems that both stimulate deepening of traditional subject-related competence and create opportunities for individual researchers and larger research constellations to address research questions of an interdisciplinary nature. Moreover, there are recognised challenges in the evaluation of interdisciplinary research, and a need for improvements of the structures for peer review to better handle both such research and research falling at the intersection between the traditional disciplines.

3.2 Research infrastructures and research

Linking necessary research infrastructure to research of high quality is a challenge that needs to be addressed on all levels, and requires a clarification and clear allocation of responsibilities between national government, funding agencies and institutions. It is vital that the priorities for the investment, development and services offered by infrastructures are closely linked to Swedish research quality and research needs, as defined by the research community in both established and emerging fields. Because the time scales for large research infrastructures usually are much longer than the duration of a normal project grant, there is a need for new funding initiatives for research that is closely related to large infrastructures. Such funding initiatives could promote and secure optimal usage of and output from current and future research infrastructures, and drive the development of new methods and technologies. Such initiatives would promote the interaction between users of advanced infrastructures and technical experts, and be beneficial for many areas within natural and engineering sciences.

The three large international infrastructures situated in Sweden, SciLifeLab, MAX IV and ESS, are responsible for a large part of the investment in research infrastructure in Sweden. SciLifeLab is extensively used and of pivotal importance for research in areas such as molecular biology, biochemistry, and environmental science. Research proposals that intend to use SciLifeLab are frequently considered to be of very high quality in the evaluations of project proposals performed by the Scientific Council. After several years delay, MAX IV is now – more than 6 years after the inauguration – finally able to serve the Swedish research community more broadly. Within the neutron scattering field, Swedish researchers currently rely on international facilities (such as ILL, ISIS and SINQ) and, due to delays in the construction of ESS, will continue do so for several more years.

3.3 Artificial intelligence and machine learning

Vast investments have been made in AI and machine learning, both at national and international level, covering fundamental research as well as implementation, for application in almost all research fields. Through the increasing impact of data/driven research, the importance of AI and machine learning has become very clear. There is huge potential for deploying these methods in almost all the research areas covered by the Scientific Council for Natural Science and Engineering. Each (subsidiary) field comes with its own needs, requirements, and limitations, so how to adapt and integrate the tools provided by AI and machine learning for maximum effect is a challenge, as is validating the techniques. This highlights the need for experts in AI and machine learning to work together with the application communities, to ensure that state-of-the-art methods are used as the research front rapidly advances, and to educate a new generation of scientists combining expertise in machine learning with deep insights into the relevant research questions in the application domain. Continued fundamental research into issues such as explainability of AI and model quality assurance for machine learning is essential for the optimal future use of this methodology in the applied fields.

There now exists a capacity to generate vast amounts of data through a wide range of observational, experimental and numerical techniques, and there is a need to re-examine the collection and handling of data throughout the research process, from study design to data storage and sharing. Together with increased awareness of strengths and limitations of the methods used for data-driven research, improved peer review of published research should be on the agenda. Addressing these challenges will likely have wide-ranging effects on both research practices and research output throughout the natural and engineering sciences.

3.4 Terms and use of research funding

In order for Swedish research to continue to stay at the international forefront in natural and engineering sciences, long-term conditions for research have to be addressed. Long-term efforts are important for researchers to be able to tackle high risk-high gain problems. Such research topics often lead to significant leaps in our understanding of the world, or major technological breakthroughs, and without long term stability of funding, we risk being left behind the absolute forefront of international research. Much of what we today perceive as the absolute state-of-the-art in different research fields often started many decades ago, on a small scale. How do we, as a nation, strike a balance between collectively striving towards producing the highest quality research, often funded in very stiff competition, at the same time as we make proper arrangements for long-term investments? As mentioned, this also affects the way we prioritise and utilise national and international infrastructures.

The success of Swedish research also depends on Swedish universities being able to foster and attract world-leading scientists from Sweden and abroad. In order for this to be possible, proper conditions for such scientists have to be met, such as the previously mentioned long term stability in funding of free research. A great strength of the Swedish research system is the well-defined roles of its actors where e.g. the Swedish Research Council supports research of the highest quality and the universities support researchers of highest quality. This division of labor has been undermined, however, to the point where university lecturers and professors now often are dependent on using project grants from the Swedish Research Council to (in part) finance their own salary rather than to finance their research. Additional challenges in the university system that reduce the attractiveness of doing academic research in Sweden includes the connection between high university overhead costs, an expanded central administration, and an increasing administrative load for the scientists. The universities are thus faced with the important task of finding the right balance between funding faculty and funding administrative staff, as well as between the size of the faculty and the size of individual support. The Scientific Council for Natural and Engineering Sciences can here assist the universities by e.g. exploring new guidelines for use of project grants so that they primarily fund salaries of PhD students and post-doctoral researchers.

In general, the Scientific Council for Natural and Engineering Sciences believes that the broad Swedish funding landscape, with well-defined roles for different funding agencies and foundations, is a strong asset. If Sweden should end up in a situation where all funding organizations tend toward the same funding goals, it is believed that this would weaken Swedish research. Therefore, clearly defined roles for various funding agencies are of great importance for the quality of Swedish research. However, as has been argued in this text, funding of scientist-initiated research with high scientific quality is an extremely important investment in the future. It must therefore be ensured that a sufficiently large share of the total research funds is directed this way.

3.5 Gender equality

Many areas of natural and engineering sciences suffer from gender imbalance. A gender gap reduces the pool of excellence and hampers the quality of research and innovation. To close the gender gap and make these fields more accessible would also ensure a wider variety of viewpoints when addressing tomorrow's scientific challenges.

The gender imbalance holds true already at the first steps of university education; an issue that concerns the whole of society. To retain as many talented women as possible in research requires gender-neutral selection procedures throughout the academic career. In this respect, education, self-reflection and reliable statistics are important tools, and universities and funding agencies need to continuously address these issues. Statistics for natural and engineering sciences do, however, show that a lower percentage of eligible female scientists than eligible male scientists apply for external funding from the Swedish Research Council. The reasons for this are currently unknown, and to enable this situation to be mitigated, the Swedish Research Council is analysing the reasons for this imbalance.

Once applications reach the Swedish Research Council, they must be assessed objectively and thus in a gender-neutral way. Gender equality is integrated at all levels of the Swedish Research Council. The review panels that assess applications for research funding have even gender balance, with at least 40 per cent of each gender, and during the last decade there has been an overall equal success rate for project and starting grant applications. Still, there is a risk of unconscious bias in all evaluation processes, and therefore a need to constantly raise awareness. The Swedish Research Council is currently performing a broad analysis of the assessment of researchers' merits, including an analysis of the contemporary international environment, and of the effects of different CV formats. Although the analysis has a broader scope, it might also have an impact on aspects of gender equality.

3.6 Graduate studies

Students graduating from a research education programme in natural and engineering sciences are perhaps the most important research-related output from Swedish academia to society, not least to the private sector. Here, the universities have an important mission to provide good research education, where a good research environment is a critical component. The Swedish Research Council serves an important role in this by funding research of the highest quality that typically enables a doctoral student or a post-doctoral researcher to work at the absolute forefront of their field, while being tutored by top researchers, often in an international environment. However, according to statistics from the Swedish Higher Education Authority, the number of Swedish citizens that start research studies has clearly decreased over the last ten years, which is alarming. The number of foreign doctoral students has increased over the same period, but after graduation too many of them leave Sweden to compensate for the decrease in national students. There is thus an apparent imbalance between the outflux of persons with doctoral degrees awarded in Sweden and the influx of persons with doctoral degrees awarded in other countries, which in the long term will have negative consequences for the supply of skills for Swedish industry, academia, large-scale infrastructures, and public agencies.

4 Abbreviations

ACTRIS	Aerosols, Clouds and Trace Gases Research Infrastructure
ALMA	Atacama Large Millimeter Array
Cryo-EM	Cryo-electron microscopy
CERN	European Organisation for Nuclear Research
DESIREE	Double ElectroStatic Ion Ring Experiment, Stockholm University
EMBRC	European Marine Biological Resource Centre
EPOS	European Plate Observing System
ESRF	European Synchrotron Radiation Facility
ESS	European Spallation Source
EISCAT	European Incoherent Scatter Scientific Association
FAIR	Facility for Antiproton and Ion Research
FORMAS	Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
GPU	Graphics processing unit
GROMACS	Groningen Machine for Chemical Simulations
HPC	High performance computing
ICDP	International Continental Scientific Drilling Program
ICOS	Integrated Carbon Observation System
ILL	Institut Laue-Langevin
IML	Institut Mittag-Leffler
KAW	Knut and Alice Wallenberg Foundation
LHC	Large Hadron Collider, CERN
MAX IV	MAX IV synchrotron, Lund University
MSCA	Marie Skłodowska-Curie Actions
MOLCAS	An ab initio quantum chemistry software package
MS	Mass spectrometry
Myfab	The Swedish Research Infrastructure for Micro and Nano Fabrication
NAIS	National Academic Infrastructure for Supercomputing
NBIS	National Bioinformatics Infrastructure
NGI	National Genomics Infrastructure
NMI	National Microscopy Infrastructure
NMR	Nuclear Magnetic Resonance
NT-X	The review panels within natural and engineering sciences are normally denoted NT-A, NT-B etc., and the scientific areas the cover are explained in the appendix
SBDI	Swedish biodiversity data infrastructure
SciLifeLab	Science for Life Laboratory
SDGs	UN's Sustainable Development Goals
SITES	Swedish Infrastructure for Ecosystem Science
SKA	Square Kilometre Array
SNIC	Swedish National Infrastructure for Computing
VR	Swedish Research Council
XFEL	European X-Ray Free-Electron Laser Facility

Swedish
Research Council