Research overview 2023

Natural and engineering sciences
Trends, impact and challenges

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VRXX
Dnr xxxx
ISBN xxxx

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Foreword

The 2023 Research Overview in the Natural and Engineering Sciences represents a natural extension of the 2019 research overview. The 2019 overview aimed at highlighting changes and trends in the last 10 years, based on answers to a questionnaire directed to a large number of excellent scientists at Swedish institutions, a detailed review of the applications submitted to the Swedish Research Council, and an impact analysis with an international outlook. For the 2023 overview, the council has tried to put an emphasis on trends for the future within natural and engineering sciences. This has its natural connection to investments in research infrastructure, for which the funding horizon is often much longer than the research grants available from the 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 overview.

Research in the 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 science 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 funding research. There are also cases where more directed research efforts may be appropriate, but such efforts are strongly dependent on previous achievements in scientist-initiated research. The timescale between initiating new research and application to societal challenges may vary a great deal. The best approach for answering future societal questions is thus to be prepared through proper funding of scientist-initiated research.

The Scientific Council for Natural and Engineering Sciences has compiled this overview. The purpose of the overview 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 offer the Government for the next research bill, and finally to serve as a source of information for anyone interested.

Mattias Marklund

Secretary General, 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 scientific area is extremely broad in scope, covering everything from the composition of the smallest particles and largest structures in the universe, via the organisation of molecular constituents into the building blocks of materials, bedrock and biology, as well as technological advances. Breakthroughs in natural and engineering sciences have irreversibly shaped our society and our lives, and it has affected existential questions such as our place in the universe and the origin of life. Natural and engineering sciences will continue to have this role in the foreseeable future.

From a societal perspective, one can today identify a number of areas where there are major challenges, including climate change, sustainable energy generation and storage, information technology, food supply, fresh water supply, environmental contamination and the public health. All these issues are multifaceted and subject to political measures and positions. However, before the questions reach this level, they have been preceded by in-depth analyses based on scientific, technological and medical advances. The importance of so-called bottom-up, or scientist-initiated, research acting as a strong driving force for key developments in science and technology cannot be stressed enough. Our response to societal challenges, requiring research and development investments, relies heavily on previous investments made into scientist-initiated research, often spanning many decades back in time. Thus, in order for Sweden to be able to respond to future societal challenges, we need to make sure that today's investments into peer reviewed bottom-up research are sufficient.

This research overview 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 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 subareas. 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 maintain Swedish basic research in the natural and engineering sciences at the highest international level a number of central research initiatives and structural reforms have been identified.

Recommendations

Research initiatives

- Increased funding for scientist-initiated research: It cannot be over-emphasised that scientific break-throughs are virtually impossible to predict. Research that has been formulated by scientists and awarded 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 granted amounts are insufficient, in particular consider the rapid increase of 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. Here, it is important to involve expertise from the disciplines that contribute to mathematical, algorithm and hardware advances for AI and machine learning to be able to navigate in this extremely rapidly evolving field.

- 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, it is urgent to launch new interdisciplinary initiatives in basic research of strategic relevance, strengthening the opportunities to address important challenges both today, but also for the 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 initiatives research of the highest quality and societal significance in natural and engineering sciences would 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 finalize 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 could promote and secure optimal usage of and output from our current and future research infrastructures and drive the development of new methods and technologies. They would 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 needs to be developed. Statistics for natural and engineering sciences from the Swedish Research Council indicate that men in average get slightly higher grades on merits than women, calling for 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 the imbalance, and, based on the results, will take measures to mitigate the situation. These measures will need to be taken in collaboration with the universities.

- An important discussion concerns the use of the 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 gives very small effects on the overall research output from the grants. It would therefore be beneficial to have a deeper 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 that, 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 the Swedish universities should take place in order to give Starting Grant recipients good employment conditions.

1 Introduction

The Swedish Research Council supports research of the highest quality that pushes the frontier of knowledge forward. The Scientific Council for Natural and Engineering Sciences occupies a unique and critical position in the Swedish research funding ecosystem by supporting research of the highest quality, where our review panels evaluate scientist-initiated research projects that pursue everything 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 that 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 approach to the research funded is also a critical factor for success. It is the scientists that perform the highest quality research that are positioned at the summit of human knowledge in their respective fields and it is thus they that can see farthest ahead and plan for it.

A trend towards funding narrowly-defined research expecting quick solutions to current social 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, which was enabled by decades of scientist-initiated fundamental research featuring large scientific communities dealing with the advancement of our understanding of messenger RNA (mRNA) and its potential for use in medicines, as well as theoretical and experimental studies of intermolecular interactions and self-assembly of charged polymers and lipids, and, lately, RNA and charge-switchable synthetic amphiphiles that was formulated into an efficient and non-toxic system for delivery of mRNA into the cells of healthy human beings. Examples from technology include the 3G network and OLED displays that were not commanded into existence to meet the sudden need created by smartphones and tablets, but instead were the product of decades of prior research spanning both natural and engineering sciences. The global climate policies that we talk about on a daily basis have their origins in climate science, the fruit of decades of scientist-initiated efforts to understand the impact of climate change, the connection between oceanic systems and the atmosphere, the interplay between local weather systems and long term climate effects etc. 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 directed efforts towards a time-critical solution of a problem require that a strong knowledge-base has been built up previously by scientist-initiated research, research often performed over longer periods of time and sometimes even without the end goal of solving a 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 first climb it.

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 hence argue that though 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 feature a balance between natural and engineering sciences.

The Swedish Research Council has as its main criteria 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 in research funding as the costs for research have increased over time. If an adequate success rate for applications is to be maintained, this in turn leads to smaller amounts being awarded to individual researchers. 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 diminished. This implies that Sweden stands less chances at being part of the frontiers of the research landscape, as well as giving Sweden less opportunities to be prepared for future research needs into societal challenges.

There is an intimate relationship between major advances of 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 to perform research of the highest quality. Research groups 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 and cost of research infrastructures calls for an improved coordination to ensure maximum benefits from infrastructure investments

During the 2020-2021, the Scientific Council performed an overview of the research categories under which all the yearly review panel work is done. It had been noticed that, over the years, there was an increasingly uneven distribution of applications to be handled by the different panels, a reflection of the shift in different research fields. Such shifts in research fields are the result of new fields emerging and other ones diminishing, as well as of national and international funding streams. The uneven distribution of applications to the different review panels could in the end affect 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 within natural and engineering sciences was first introduced in the 2021 review process, resulting in a significantly more even distribution of number of proposals between the 19 panels. It is also essential that the review panel structure is adapted to handle research that falls in 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 from the Swedish Research Council shows some variation in the total number of submitted proposals over the 10-year period investigated, but there has been a relatively steady number of applications of the last five years (where fluctuations could be attributed to, e.g., other funding schemes and/or university policies). There is also the question of balance between the number of grants to younger researchers (Starting Grants) and senior researchers (Project Grants). Here, the Scientific Council for Natural and Engineering Sciences has, over a period of years, worked with a budget division into approximately 20% starting grants and 80% project grants. The numbers in this division are based on the possibilities of the universities to employ younger researchers, and the possibilities of these younger researchers later being 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 DNA sequencing, cryo-electron microscopy (cryo-EM) and other sensor and visualization 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 of natural science and technology, medicine and social science for solving large and complex problems aligned with societal needs.

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 has 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 e.g. analytical techniques and new characterisation methods, new materials, catalysis, formulation and new methods, light-matter interactions, and photochemical processes.

Geoscience provides a fundamental understanding of the processes within and between Planet Earth’s different spheres: the lithosphere, atmosphere, hydrosphere, cryosphere and biosphere. 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.

Electrical Engineering and Computer Sciences are in rapid development to meet the societal challenges in 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 the least applications in all kind of domains.

The scientific revolution caused by digitalization has a large effect on the mathematical sciences, as it builds on and accelerates the development of a wide range of mathematical areas, from probability, statistics and data science via optimization and numerical analysis to differential geometry and algebraic topology for topological data analysis. A continued increase in both interdisciplinary and intradisciplinary activity is expected, as driven and inspired both by the rising prominence of mathematical modelling in problem driven research as well as by internal developments.

In applied mechanics, the further development of high-resolution computational tools and multiscale modelling, including computational homogenization 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 both in 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, i.e. in atoms and in space, that come with access to novel research infrastructures advance our understanding of our universe in unprecedented detail. The continued realization of quantum materials and technology accelerates the strive for realization of quantum computing as well as novel "quantum" applications, including metamaterials. The development and implementation of novel “green” key technologies continues to pick up pace and encompasses nowadays both the realization of more efficient energy storage and conversion devices as well as the implementation of green materials and sustainable fabrication and recycling processes. A continued development in all these fields is expected to take place within the near future, to the benefit of mankind.

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 at understanding the fundamental processes that constitute 'life'. It spans a vast 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. The technological advances, mainly in the areas of 'omics', CRISPR-Cas, cryo-electron microscopy (cryo-EM), and other sensor and visualization technologies have transformed global life science research.

Biological research in Sweden has been of high quality for decades and has been an early adopter of these technological advances. Rooted in curiosity-driven basic research, biologists now address a range of societal sustainability challenges involving 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 utilized 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 and other structure determination and imaging platforms, mass-spectrometry, and bioinformatics infrastructures. Biologists routinely collect massive datasets, which also calls for adequate support for their storage and analysis.

Biologists in Sweden have benefitted from the recent push towards more centralized and professionally managed national research infrastructures providing both the instrumentation and services, which include, SciLifeLab, MAX IV, NGI (National Genomics Infrastructure), NBIS (National Bioinformatics Infrastructure Sweden) and the computing resources provided by SNIC (Swedish National Infrastructure for Computing)/NAIS (National Academic Infrastructure for Supercomputing), NMI (National Microscopy Infrastructure), SBDI (Swedish Biodiversity Data Infrastructure), SITES (Swedish Infrastructure for Ecosystem Science - SITES) and EMBRC (European Marine Biological Resource Centre) among others.

One obvious current requirement of Biology research in Sweden is further advancement in national and local imaging infrastructure and to create necessary developments to facilitate tomography and time-resolved microscopy techniques operable in the physiologically-relevant millisecond range. Other requirements include developing local infrastructures for large scale protein expression, purification and mass-spectrometry. The growing demand for national resources for data storage, and for support in exploring biological problems with modern and advanced statistical modelling, artificial intelligence and machine learning should also be accounted for within the growing landscape of Swedish research.

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 and Genetics are at the international forefront in terms of scientific impact, and the areas of Cell and Molecular Biology, Biochemistry and Structural Biology also have a long tradition of high-quality output. However, a large proportion of research within these categories overlap with the areas covered by Medicine and Health, which can make the publication analysis challenging. Similarly, research for method development, which often results in high impact publication with very large numbers of citations, can be considered cross-disciplinary and also involve e.g. physics, chemistry and computer science, rather than just “biology”.

The worldwide competition is however increasing, and Sweden no longer has the unique position it once had in certain biology research areas. This can be attributed, at least partially, to a mismatch between the increased experimental demands for modern high impact publications in biology vs. very limited Swedish grant amounts and insufficient infrastructure compared to competing countries. This puts a question mark to the sustainability of cutting-edge biological research in Sweden with risk for significant decrease in the output of PhD students in biology. The direct impact of funding structure in different sub-disciplines is hard to analyse due to lack of appropriate statistics on publication data.

The funding from the Swedish Research Council has great significance for the Swedish biology researchers in general with varying impact in different disciplines. The broader field of molecular life science has also been highly successful in acquiring funding from other sources, such as the Knut & Alice Wallenberg foundation and the European Research Council and funders of more applied research, enabling significant faculty renewal. However, this type of highly directed funding also comes with risks of steering the field in particular directions, and thus it is imperative that the funding for individual project grants from the Swedish Research Council increases to the level where the strongest researchers can actually run a project on such a grant, rather than being dependent on additional funding. Further, Swedish biology research will largely benefit if funding can be provided to initiate collaborative interdisciplinary research and also to provide short-term seed money for initiating high-risk 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 tremendous impact over the coming years. Genetic methods (metabarcoding and metagenomics) have opened 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 ranges 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. Both increasing amounts of data, integration of results from several techniques and the growing interest in interactions models has led to large 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 has a high International standard, but only adequate funding and infrastructure for individual and collaborative projects can maintain it. 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 the biology research to flourish beyond the current state and to set marks in the International standard. Across biology, we often 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 of their chemical components and their interactions, or entire ecosystems with all of the constituent species and their interactions with each other and the environment. This is coupled with an increased interest in the use of AI and other advanced analytical methods to solve large and complex biological problems.

2.2 Chemistry

2.2.1 Introduction

Chemistry is, according to Encyclopedia Britannica, 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 e.g. molecular biology, environmental and geo sciences, 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 generation and handling of large datasets is 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, e.g. 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 connection to inorganic chemistry, organic chemistry and physical chemistry together with materials science and engineering and solid state physics. Biochemistry covers studies of chemical processes in biological systems. In this overview, biochemistry is described under the heading "Biology". 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 utilized 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, but international facilities such as Petra III and ESRF continue to be essential. Within the neutron scattering field, Swedish researchers currently rely on international facilities (e.g. ILL, PSI) and will continue do so for several more years due to delays with 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 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 groups usually have access to local MS facilities. Analogously to experimental facilities, access to national high-performance computing resources, e.g. 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 needs for funding of infrastructure with those of personnel, as the latter is crucial in many labour-intense branches of chemistry.

2.2.3 Publications, citations and funding

The number of grant applications in the two chemistry panels (NT-5/NT-G, and NT-6/NT-H including material chemistry) 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 is relatively flat 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 fraction of articles in chemistry published open access is increasing, and now reaches nearly 50%. Multi-disciplinary chemistry and physical chemistry are the largest sub-areas with respect to the number of publications by Swedish researchers, and has grown over the last 10 years. The number of publications in analytical and organic chemistry is about half as many compared to physical chemistry, and has decreased during the same period, whereas publications in inorganic chemistry has stayed fairly constant. The decreasing number of publications mirrors the decrease in the number of researchers within analytical and organic chemistry in Sweden, and could also reflect that chemists publish a larger fraction 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 sustainability 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 are performed in both smaller (VR-funded) projects and in larger multi-disciplinary research centers or projects (funded by e.g. KAW, MISTRA, and 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 utilization of carbon dioxide, light-emitting diodes, and batteries, which drives and requires development and studies of synthetic methods, catalysis, light-matter interactions, ultrafast 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 to use and release toxic chemicals provides a major incentive for new and improved analytical techniques capable of detailed characterization 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 such as Alzheimer's and Parkinson's will continue to fuel research of intermolecular interactions between biomacromolecules and other types of drugs, as well as in medicinal chemistry and drug formulation and delivery. Related questions are central also in the search of 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 artificial intelligence, not only for finding correlations in the vast amount 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 optimize reaction conditions in a rational manner. Harnessing the power of artificial intelligence requires both access to computing facilities and education of the 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 thus generated. As such, this development will likely have a wide-ranging influence on the way that 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 Planet Earth's different spheres: inner-Earth, lithosphere, atmosphere, hydrosphere, cryosphere and biosphere. The detailed study of Planet 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 (e.g., earthquakes, flooding, volcanic eruptions, landslides, drought, solar storms, and meteorite impacts); and in respect to the potentials and limitations of natural resources (e.g., minerals, metals, water) and energy sources (e.g., oil, coal, gas, nuclear power). Geoscience research forms the basis for understanding the development of life and allows assessing human impact on Planet Earth. It provides key expertise for a sustainable development of society, for new technologies and for mitigation strategies and contributes to all seventeen Sustainable Development Goals.

Geosciences is an interdisciplinary field covering traditional subjects such as for example geology, mineralogy, palaeontology, geochemistry, geophysics, geography, hydrology, oceanography, and atmospheric sciences and is increasingly utilizing physics, chemistry, biology and engineering knowledge and methods, thus bridging across science disciplines. The increased focus on societal needs and sustainable development has moreover enhanced interaction with other scientific domains during 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 in respect to natural resources and regarding 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 particularly the development of Machine Learning tools.

2.3.2 Research infrastructure often utilized by actors active in the field

Local, national and international research infrastructures are the basis for Geoscience research. Significant advancements 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) (e.g., Abisko, Tarfala); laboratories with high-precision instrumentation (e.g., stable isotopes and core scanning; NordSIMS/Vegacenter; Paleogenetics); large national resources and laboratories (MAX IV, SciLifeLab, Onsala Space Laboratory); marine research vessels (e.g., Icebreaker Oden); high-performance computers (SNIC); digital infrastructure and data repositories (e.g., geo data and maps; SBDI, Swedish biodiversity data infrastructure, drill-core repository); and research stations in Antarctica.

International infrastructures allow the participation of Swedish researchers in larger consortia and programs, 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 region. These infrastructures are of great importance for surveying the ocean floor and for obtaining unprecedented long sediment and bedrock records on land and in the ocean (ICDP, IODP/ECORD, Icebreaker Oden, Riksriggen - the Swedish National Drilling Infrastructure), which in turn offer the possibility to study Earth's evolution, 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 slightly more than 800 articles per year between 2007 and 2019. However, seen in a global perspective and over the same time period, the total amount of Swedish publications in the field decreased slightly, similar to other science disciplines within Science and Engineering. The impact within the global Geoscience field, measured as the proportion of highly cited publications, was 2-3% above 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 affiliation from 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 1200 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 granted research environment.

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, SGU, SKB, ERC, and EU. The Swedish Research Council remains however one of the most important funding sources for fundamental 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 planet 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 change path to a sustainable future. A sustainable supply of natural resources, including sources of energy, is one of the great challenges of our times. The 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 rely on a sound knowledge of the complexity of the Earth System.

Natural disasters will occur more frequently with global warming and will lead to more damaging impacts with increasing population density and infrastructure often build 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 the modelling, analysis, design and implementation of systems, from electronic and computing devices over 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, 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 under 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, e.g., the development of cyber-physical systems, cloud computing and communication technology. Challenges associated with societal sustainability and resilience have put an increased focus on rethinking 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 utilized 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, KTH, Lund and Uppsala that form myfab, is 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 WASP research arenas, are becoming more important.

Researchers in this area also develop research infrastructure that is essential for users not only in the area but in many other fields of science as well. A prime example is NAIS (National Academic Infrastructure for Supercomputing), the successor of SNIC (Swedish National Infrastructure Computing). It serves a large and growing community with computing resources, cloud infrastructure and data storage. Another example is the newly launched InfraVis (National Research Infrastructure for Data Visualization), which supports researchers with cutting-edge visualisation solutions.

2.4.3 Publications, citations and funding

The 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 in 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 quickly 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 start packages in an effort to strengthen scientific excellence in the area. Interestingly, the number of VR project applications in the area has not yet been affected by this, but long term we expect to see a significant increase. The fraction of papers that mention VR in their acknowledgement is low, around 10%, in this area, 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 of not only excellent basic research in this field of science, but also a steady production of graduated PhD students that allow them to take advantage of the dramatic developments in meeting corporate and societal challenges

2.4.4 Research trends and conclusions

As foreshadowed earlier, the research area of Electrical Engineering and Computer Sciences has gone through transformational developments. There are several large drivers for future research needs. Digitalization 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 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 SMT solving, the increased importance of GPU-driven computing, and the growing emphasis on scalable software development. Many goals like 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 been in the area of AI. Yet explainable, robust, dependable, and secure AI methods are still to be developed.

National infrastructures like NAIS and other high-performance infrastructures are of high importance for research excellence, and that holds also for creative environments such as centers, networks and PhD schools. Supporting open-access artifacts and open-source software is crucial for researchers to collaborate beyond the limits of infrastructures and research centers.

While other funding agencies successfully attract excellent researchers with ample funding opportunities, this comes often at the price of tailoring research agendas to address specific needs. VR plays a vital role in enabling fundamental, curiosity-driven research, such as the research that resulted in the machine learning revolution. VR 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 the main mission.

2.5 Mathematical sciences

2.5.1 Introduction

Throughout its very long history mathematics has developed through interplay between theoretical aspects and practical use, and the stability and universality of its results is 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 taken together, Swedish universities give a good coverage. Swedish research groups at several universities are at the center 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. Digitalization is revolutionizing our world and advances in mathematical sciences ranging from the very abstract to applied areas are central to this revolution. The wide mathematical competence at the 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 utilized by actors active in the field

Institut Mittag Leffler (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 VR funding directed to research institutes, and it is of critical importance that this continues.

Access to computing resources and storage capacities are 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, 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 (denoted VR grants below) 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 VR 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 program in 2013. Later, the Wallenberg AI, Autonomous Systems and Software Program (WASP), in 2017 launched a branch focused on the mathematical foundations of AI (WASP-AI/Math).

Despite these additional funding opportunities, the VR grants are of utmost importance. The WASP funding is directed towards math for AI, while the KAW mathematics funding is free in topic but available only to support postdoctoral and guest researchers. Apart from a few large excellence grants, VR is the only unconstrained external source for research and PhD 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 VR. 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

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

three largest areas according to the SCB code classification. An increasing share of the grant proposals has applications to data science (not well captured by the SCB codes), and the new panel NT-R is expected to grow.

The bar to obtain a VR grant in mathematics is very high, commonly perceived as too high. The average success rate in NT-1 panel between 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 VR. International collaborations are essential. Compared to other fields in the Natural and Engineering Sciences, the average number of authors on each publication is small but the ratio of the number of countries in the author addresses to the number of authors is large. There is an open access culture in the field and preprints are typically made available on ArXiv.org at time of submission, which has extra value since time to journal publication can be long in mathematics. The fraction of journal articles that are published with open access is increasing, but is currently about 30%, which is surprisingly low. The three-year citation window that is used when compiling data is way 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. The number of papers in these journals and speakers at the ICM are considerably larger than corresponding numbers for other Nordic countries.

2.5.4 Research trends and conclusions

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

The importance of mathematics as a language for the natural and technical 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 technical sciences use more and more advanced mathematics. This trend will lead to fundamental mathematical contributions to meeting our grand societal challenges, including sustainability and climate change.

The number of mathematics research groups at Swedish universities at the center 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 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 an increased investment in the free project grants through VR.

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 constitutes 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 e.g. fluid mechanics, tribology, material science, climate and geophysics, aerospace, biomechanics and paper production. In environmental engineering, research on energy efficient carbon capture and storage, and carbon capture and utilization, 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 on 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 utilized by actors active in the field

A large focus has been made 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) (neutron and X-ray scattering), SciLifeLab (Science for Life Laboratory) for large-scale multiomics (e.g. 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 groups often rely heavily on the use of small and middle-sized infrastructure available at the host institutions. Access to national high-performance computing resources, e.g. SNIC (the Swedish National Infrastructure for Computing), 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 KAW 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 & 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 e.g. China.

VR grants are essential for supporting fundamental, high-risk, high-quality research in these areas. The role of VR is even more important now as there is an obvious shift towards more applied research. The excellent fundamental research funded by VR is of highest importance and it can be employed later in more applied research projects funded by other agencies (e.g. Formas, SSF, Vinnova, the Swedish Energy Agency, 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, i.e. “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 homogenization 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 optimized design for selected properties and applications. Phase-field modelling also has emerged as an important research field, used e.g. to model and simulate complex fracture patterns, and to simulate the evolution of microstructural phases due to changing temperature and environment. Additive manufacturing (3D-printing) continues to attract technological interest with extension to e.g. 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 on the sustainability of processes, powered by the changes in the resource availability and the challenges from waste management and climate change. The design and implementation of biorefineries 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 utilization (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 (e.g. 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 large trend for all the research areas is an increased multidisciplinarity of the projects that is needed to tackle the challenges, which reflects on the large connections to other scientific areas 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 length 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, geosciences, and 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 degree organized into large international collaborations. This community has thereby one of the largest incidences of international collaborations in the field of natural sciences.

The field of astronomy comprises also astrophysics, cosmology, and space physics. Even this field is organized 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.

The field of physics of light and matter encompasses primarily the fields of atomic, molecular, and optical (AMO) physics and quantum optics in which fundamental structures and processes are under scrutiny, often by spectroscopic investigations. Sweden has strong research activities in these fields, involving experimental studies based on advanced light sources, e.g. those producing synchrotron or x-ray radiation, attosecond pulses, and frequency combs, including studies of ion collisions and reaction dynamics and non-linear optics.

The field of materials science and engineering comprises primarily the study of structure-processing-property relationships of substances, with strong connections to condensed matter physics, 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 e.g. automotive, chemical and forest industries.

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. Subfields that currently are in fast development include the development and utilization of emerging quantum- and meta-materials, design and fabrication of advanced electronic and photonic devices and systems, and realization and improvement of energy conversion and storage technologies.

2.7.2 Research infrastructure often utilized in the field

Swedish scientists are strongly dependent on access to both national and international infrastructures. Synchrotron scattering facilities (e.g. MAX IV, ESRF, Petra III) and Neutron scattering facilities (e.g. ILL, PSI and in the future also ESS) are of outmost 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 ion storage rings (e.g. DESIREE) which allow for detailed studies of ion-ion interactions in well-defined quantum states.

Within the field of subatomic physics, astrophysics, astronomy, and particle- and high-energy physics, Swedish scientists frequently utilize large-scale international infrastructures such as CERN (including the LHC), XFEL, EISCAT_3D, and ALMA.

Swedish researchers are also frequently using a number of important distributed and local infrastructures, in particular computational infrastructures (e.g. SNIC), nanofabrication facilities (e.g. 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 the Swedish physical sciences are strongly dependent on access to research infrastructures on 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 years. The total number of publications is fairly constant, although there may be a beginning trend of a decrease in output (which though is not yet reflected in the number of highly cited papers). The proportion of the Swedish contribution to the world output in physical sciences has decreased over the last years, similar to most research areas, which probably can largely be attributed to the rise in scientific impact of China and other emerging nations that lately have made significant investments in science and technology. Considering 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, 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 highest importance for the prosperous and multifaceted applied research that is being pursued in Sweden. In addition, and importantly, VR also serves as an unofficial quality stamp for researchers in Sweden thanks to the rigorous grant peer-review process.

Other sources of funding for the field of the physical sciences in Sweden are KAW (the Knut and Alice Wallenberg) foundation and SSF (the Swedish Foundation for Strategic Research). While the former plays an important role in financing research with medium size project grants awarded to consortia promoting innovative research outside the beaten tracks, and with larger, longer term grants (above 1 billion SEK) allocated to specific research field, e.g. by the WISE (the Wallenberg Initiative Materials Science for Sustainability), the WACQT (the Wallenberg Centre for Quantum Technology) and the WASP (the Wallenberg AI, Autonomous Systems and Software Program) programs, the latter supports research in natural science, engineering, and medicine with the aim of strengthening Sweden's competitiveness.

2.7.4 Research trends and conclusions

It is anticipated that in several areas of physics more science will be done in the future within large international collaborations, using national or international research facilities. For example, within the field of high-energy subatomic physics and particle physics, Swedish researchers will use upgraded versions of LHC and the upcoming FAIR (the Facility for Antiproton and Ion Research) facility. The latter will be accessible to Swedish scientists also in fields of atomic and anti-matter physics, and high-density plasma physics, condensed matter physics, biology, and the bio-medical sciences. Within the fields of materials science and engineering, our scientists will use new beam-lines at MAX IV and the upcoming ESS (the European Spallation Source, which is based on the most powerful pulsed neutron source in the world). This is expected to provide unprecedented research opportunities for Swedish scientists.

Regarding the field of astronomy research performed at the EISCAT-3D facility, e.g. for studies of aurora borealis, as well as, at international telescope facilities, e.g. for detection of exoplanets, have increased significantly during the last years. This growth is expected to continue over the coming years. The former activity is expected to yield better forecasts of space weather while the latter is expected to shift into a characterization of exoplanets, with the goals of finding "earth"-like planets and improving on our understanding of our universe. Swedish scientists within this field are also expected to utilize the SKA (the Square Kilometre Array) telescope, which will exploit radio astronomy's ability to provide the high resolution images of our universe by 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.

The field of AMO sciences, in which the most recent scientific advances have been (and is still) 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 ultrafast light sources (from attosecond lasers to XFELS) that are allowing the probing of dynamical behaviour at the atomic level in unprecedented detail. Within this field, there is also a pronounced “opposite” trend, viz. towards small-scale, high precision experiments, e.g. for investigations of fundamental physics or to advance the field of metrology, in particular using emerging quantum technologies.

In materials science and engineering, the major trend is materials for sustainability. This is pursued by research based on fundamental phenomena at the nanoscale, including synthesis, characterization, and computer modelling of nanomaterials and nanodevices, the design of new materials and structures from the atomic to the structural scale, and the transformation of bio-based raw materials into high-value products, e.g. 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 bioinspired 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 metamaterials, with the promise of quantum computing and for the realization of various improved and novel "quantum" applications, based on novel effects, e.g. the shrinking of the active part of electronic devices to the atomic and even subatomic level for the emergence of novel quantum phenomena. The research on energy conversion and energy storage, utilizing new advanced material systems, is also growing.

Theoretical physics and modelling have strengthened their role in the physical sciences during the last period and this will continue into the near future, in particular in fields where experiments or observations are lacking or difficult to perform. In addition, the field of artificial intelligence is expected to continue its way into various sub-fields of physical sciences, not least applied and engineering physics. For data interpretation, the cross fertilization with the fields of computer science and machine learning will continue to be important.

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

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

3 Future challenges

3.1 Basic research and societal challenges

It cannot be over-emphasised that scientific break-throughs are virtually impossible to predict. For this reason, and despite the predominant short-sighted demands for challenge-driven research, undirected 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 undirected project grant applications, with budgets that allow basic research of the highest quality. At present, both the grant amounts and numbers of research project grants are insufficient to promote the foundation for Swedish research. Moreover, in order to ensure that the potential societal impact of scientific breakthroughs is realised, incentives and processes need to be in place to facilitate this. Here, there is currently a gap in the Swedish research system. The latest Government Research Bill (2020) was characterized by an increase in the total research funding. Still, the resources for undirected scientist-initiated research in the field of the natural and engineering sciences was not significantly increased. The imbalance between funding for undirected and directed research will likely have long-term consequences for Swedish research, with a risk of falling behind the international forefront. This can have a severe impact both on scientific excellence, technical advancements and innovations as well as preparedness for future societal crises.

The interdisciplinary component of excellent research in the areas of natural and engineering sciences is becoming increasingly important. Research where theories, methodology, factual knowledge and/or data from differing disciplines are combined in ways that open up new research fields and research approaches often includes collaboration between several traditional subject areas. A major challenge is to encourage and support interdisciplinary research without losing the scientific depth within the different disciplines. This requires a spectrum of funding systems that both stimulate deepening of traditional subject-related competence and create opportunities for larger research constellations to adopt 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 interdisciplinary research as well as research falling at the interface 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 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. New funding initiatives could promote and secure optimal usage of and output from our 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 e.g. molecular biology, biochemistry, and environmental science that 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 (e.g. ILL and PSI) and will continue do so for several more years due to delays with the construction of ESS.

3.3 Artificial intelligence and machine learning

Vast investments have been made in AI and machine learning, both at a national and an 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 a huge potential for deploying these methods in almost all the research areas covered by the Natural Science and Engineering council. Each (sub)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 concerning e.g. 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 is now a capacity to generate vast amounts of data through a wide range of observational, experimental and numerical techniques, and there is a need to reexamine 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 in funding we risk being left behind at 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 at a small scale. How do we, as a nation, manage a collective strive towards the highest quality research, often funded through very stiff competition, at the same time as we give proper arrangements for long term efforts in order to strike the right balance? As mentioned, this also affects the way we prioritise and utilize 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. There are also challenges in the system that can reduce the attractiveness of doing academic research in Sweden, including high overhead costs and dependency on external funding for salaries of university lectures and professors. Many researchers need to use the project grants from the Swedish Research Council to (in part) finance their own salary rather than to employ PhD students or post docs. Many of these scientists end up leading small research constellations with limited possibilities. It is an important challenge to find means to mitigate this. The paradoxical connection between high university overhead costs, an expanded central administration, and increasing administrative load for the scientists is highlighted as a major challenge to Swedish research. In view of the increased administrative demands on scientists, the idea of establishing a more streamlined application process is relevant.

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 funding agencies is of great importance for the quality of Swedish research.

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 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 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 which are currently unknown. To be able to mitigate this situation, the Swedish Research Council is currently analysing the reasons for this imbalance.

Once applications reach the Swedish Research Council, they must be assessed objectively and thus gender-neutral. 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 percent of each gender, and an overall equal success rate for project applications. Still, there are risks of unconscious bias in all evaluation processes, and therefore a need to constantly raise awareness. The Swedish Research Council currently is doing a broad analysis of the assessment of researcher's merits, including analysis of the contemporary international environment, and effects of different CV formats. Although the analysis has a broader scope, it might also have an impact on the aspects of gender equality.

3.6 Graduate studies

Students graduating from a research education in natural and engineering sciences is 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 a role in this as the proverbial "tip of the spear", funding research of the highest quality that typically enables a PhD student or a postdoc to work at the absolute forefront of their field while being tutored by top researchers, often in an international environment. According to statistics from the Swedish Higher Education Authority, the number of Swedish citizens that start research studies have clearly decreased over the last ten years, which is alarming. The number of foreign doctoral students has increased over the same years, but after graduation too many of them leave Sweden to compensate. There is an apparent imbalance between the outflux of PhDs graduated in Sweden and the influx of PhDs graduated in another country, which on longer terms will have negative consequences for the supply of skills for Swedish industry, academia, large-scale infrastructures, etc.

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
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
IML	Institut Mittag-Leffler
KAW	Knut and Alice Wallenberg Foundation
LHC	Large Hadron Collider, CERN
MAX IV	MAX IV synchrotron, Lund University
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
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