Research overview 2019

Natural and engineering sciences
Trends, impact and challenges

Swedish Research Council

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Foreword

The 2019 Research Overview in Natural and Engineering Sciences represents a natural extension of the 2014 research overview. The previous version was based on detailed descriptions of several subjects in the scientific area and can be regarded as still being relevant. The current overview has the ambition to highlight 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. These are included as appendices to the current overview.

Research in natural and engineering sciences has a very strong emphasis on fundamental scientific questions that push the frontiers of human knowledge forward. Historically, breakthroughs in fundamental natural and engineering sciences have irreversibly shaped our society and our lives. 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, including the origin of life, to the conversion of knowledge into technological advances. In addition, research in natural and engineering sciences is extremely international and recognises no borders. This is also the reason why this overview is in English, as this is the international language of science.

The Scientific Council for Natural and Engineering Sciences has compiled this overview. An early draft of the overview was published online for comments in a web forum. Several insightful and helpful comments contributed to a more balanced and representative report. 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 2020 research bill, and finally to serve as a source of information for anyone interested.

Lars Kloo
Secretary General, Natural and Engineering Sciences

Summary

This research overview of Swedish natural and engineering sciences is based on information provided in Appendices 1-3, complemented by the previous research overview from 2014 in Appendix 4. This information has been interpreted on the basis of the collective experience of the Scientific Council for Natural and Engineering Sciences together with input from the chairs of the review panels and from the scientific community via a web forum. 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 into natural and engineering sciences at the highest international level, which is vital to address societal challenges of today and in the future, a number of central research initiatives and structural reforms have been identified. We propose to:

- Strengthen the support to undirected project grants, which are the main tool for meeting future needs for new knowledge.
- Initiate national programs focused on basic research of strategic relevance.
- Develop national strategies for scientific infrastructure at all levels, from local laboratory instrumentation to large national or multinational facilities. These strategies should be based on priorities that are intimately linked to research of the highest quality.
- Develop a strategy and new funding initiatives for the research and technical challenges of large data sets and associated extensive computing and storage resources that require machine learning, artificial intelligence tools and new computational methods.
- Promote a structural reform to minimise the dependence on external funding for salaries and/or time for research by academic staff, i.e. associate senior lecturers, senior lecturers and professors.
- Analyse the causes of gender imbalance at Swedish higher education institutions, and formulate mitigating strategies.

Background and Recommendations

Background

The current research overview is based on the one performed in 2014, covering almost 50 separate subjects in natural and engineering sciences.[1] This overview was made just four years ago, and the timeline for changes in natural and engineering sciences is significantly longer. Thus, the extensive subject-based research surveys made in 2014 are to a large extent still valid. However, the texts from 2014 contain many statements, the validity of which cannot be verified. The ambition of the current research overview is therefore to offer a background for the statements made, in terms of statistics from 10 years of applications to the Swedish Research Council, investigations of the impact of research performed in Sweden, and answers from a survey directed to the Swedish research community (Appendices 1-3). The structure of the statistical results follows the division of the Research Council's review panels. This is why the different research fields presented in Chapter 3 also roughly follow this order, but is grouped into larger subject areas. The objective is not to provide a complete overview of all research activities in Swedish natural and engineering sciences, but to identify major and general trends, impacts and challenges revealed in the statistical material.

Based on the answers to the questionnaire, there are some important general themes to be pointed out. For instance, it is very clear that research in natural and engineering sciences is technology-driven. Breakthroughs in new experimental techniques or methods, such as free-electron lasers (FELs), cryo-electron microscopy (cryo-EM) or the next-generation of sequencing, have made a significant impact. This highlights the strong inter-dependence between science and research infrastructure, and the necessity to handle research and infrastructure priorities in close conjunction. The lack of long-term positions for researchers at the universities also emerges as *the* predominant system problem. This involves both the existing dependence on short-term, external project funding to support salaries of project leaders, as well as the lack of a clear tenure-track system for junior scientists. The reasons for this cannot directly be extracted from the current overview. However, these issues are central for the long-term quality of Swedish research. A noticeable trend is that the total number of scientific publications and the fraction involving international collaboration have steadily increased. This reflects the highly international character of natural and engineering sciences, where international collaboration often results in increased attention in terms of citation levels.

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1 Forskningens framtid! Ämnesöversikt 2014 Naturvetenskap och teknikvetenskap, Vetenskapsrådets rapporter 2015. ISBN 978-91-7307-255-7.

The statistical analysis shows some variation in the total number of submitted proposals over the 10-year period investigated, where the decreasing number of proposals the last few years can mainly be attributed to a decline in the number of proposals from junior researchers. This is likely to be caused by universities becoming more restrictive in their academic recruitment, as well as the newly imposed requirement of active approval of proposals to the Swedish Research Council. It is also noticeable that the funding level, in absolute amounts, to natural and engineering sciences at the Research Council (not counting research infrastructure) has not increased, despite the increasing costs for performing research. Changes in the number of submitted proposals within specific subject areas (referring to the 50 subjects in the 2014 research overview) involve too few data points to identify obvious patterns. However, changes over the last 10 years at broad subject level, such as chemistry, physics, mathematics, etc., show clear trends, and these trends are not general for all scientific areas.

In physics, the basic subjects show declining numbers of applications and, for instance, the number of applications for condensed matter physics has moved close towards the number for applied physics/engineering and material sciences. Analogously, organic and inorganic chemistry have become considerably smaller fields, whereas materials chemistry has increased correspondingly. Developments within analytical chemistry have moved into scientific areas where the performance of some analytical techniques has become essential, such as environmental science and molecular biology. A similar tendency can be observed in mathematics, where applied mathematics (especially statistics) has grown significantly over the last 10-year period. The movement in computer science appears to be towards software, and in geo-related subjects, climate and environmental science have emerged as expanding fields. Biology is more invariant, although structural biology and evolutionary biology have gained in importance. Among the pure engineering disciplines, the number of proposals from engineering mechanics has increased significantly. Other areas, such as biomedical engineering, are characterised by diversity where many new and currently quite small areas of interdisciplinary character have emerged. In general, basic engineering research and natural sciences are closely connected, and a sharp borderline is virtually impossible to define, and similar proposals have therefore been listed either as engineering or as natural science. This is particularly true for biotechnology, engineering physics of various types, and also applied mathematics.

There is an ongoing shift in research funding in Sweden towards more applied subjects, characterised (and even driven) by extensive national and international external funding from agencies other than the Swedish Research Council. The reason for these research investments is often the need to address societal challenges. However, analyses of basic research aimed at these societal challenges, exemplified below by climate change-related research, show clearly that individual researchers address these challenges earlier and more efficiently via undirected project grants than do political initiatives looking for fast and simple solutions to complex problems. In this overview, it is argued that new efforts should also be aimed at investments in basic research offering sustainable solutions to known and hitherto unknown societal challenges in order to achieve a healthy balance between basic and applied sciences.

Recommendations

Research initiatives

- *Undirected research*. It cannot be over-emphasised that scientific breakthroughs are virtually impossible to predict. It is also important to realise that even seemingly insignificant knowledge can form the solution to previously unforeseen societal challenges. History is full of examples illustrating the above phenomena. 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 crises, and for our fundamental understanding of the universe. 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.

- *A strategy and new funding initiatives for integrating research infrastructures and research.* There is an intimate relationship between major advances in terms of new methods and new technologies, and breakthroughs across all areas of natural and engineering sciences. This involves research infrastructures at all levels, from routine laboratory instrumentation to large national or multinational facilities. We are currently lacking a national strategy for linking necessary research infrastructure to research, and also a well-defined allocation of responsibilities between the government, funding agencies and institutions. A mitigating strategy is urgently needed, which if properly handled will significantly strengthen research in natural and engineering sciences. It is vital that a new strategy for infrastructure priorities is closely linked to Swedish research quality and needs, as defined by the research community. Moreover, new funding initiatives will be needed to secure optimal usage of and output from our current and future research infrastructures. Such initiatives would promote the interaction between users of advanced infrastructures and technical experts. These efforts, resulting in cross-disciplinary research environments, will be beneficial for many areas within natural and engineering sciences; for example, climate research, systems biology, palaeontology, and engineering mechanics.

- *A strategy and new funding initiatives for big data, computer resources and artificial intelligence.* The Big Data revolution has now reached all scientific areas, and most research disciplines in natural and engineering sciences generate increasing amounts of experimental and empirical data. There is also continuous development of advanced modelling tools. This calls for a national strategy concerning e-infrastructure, as well as necessary research into how to handle huge amounts of data. Such a strategy should include plans for data storage, transfer and usage, as well as for appropriately dimensioned computing resources. These issues are also closely linked to the successful development and application of machine learning and artificial intelligence, which have the potential to accelerate scientific progress in almost all areas. Moreover, these questions are closely related to issues of open access to research data, and research integrity. The current trend is towards a more unified platform for large-scale workflows, combining high-performance computing and data analyses, machine learning and artificial intelligence. The sheer size of simulated data demands infrastructures that minimise the need for data movement. This not only requires a convergence of hardware, but also of software environments. For Sweden, which has cutting-edge research teams and high ambitions in high-performance computing, data analytics, machine learning and artificial intelligence, it will be important to join forces and create multidisciplinary environments taking advantage of the new research opportunities. Researchers in all disciplines in natural and engineering sciences will be able to profit from a funding initiative in this area.

- *Interdisciplinary initiatives in basic research of strategic relevance*. The latest Government Research Bill (2016) was characterised by national programmes with a focus on societal challenges. These challenges will also need major efforts in fundamental science-generating new knowledge to avoid the implementation of uncertain or out-dated scientific results in large-scale applications. Therefore, it is urgent to launch new interdisciplinary initiatives in basic research of strategic relevance. These areas should be defined as broad efforts encompassing a large part of natural and engineering sciences; for example energy and climate research.

Structural reforms

- A structural reform is needed to encourage and ensure that Sweden's academic institutions take responsibility for minimising dependency on external funding for salaries of university associate senior lecturers, senior lecturers and professors. This would lower the dependence on 3- to 4-year project funding cycles and stimulate long-term and high-quality research. This is not only a matter of basic funding of institutions, but also a matter of how available resources are managed. The proposed reform is likely to increase the number of truly original research ideas with potential to generate a larger number of scientific breakthroughs, and increase the quality and quantity of output from grants awarded by the Swedish Research Council.

- It is important to increase funding for PhD students and postdoctoral research associates to safeguard future progress and increased impact of Swedish science. The reform proposed above may accomplish this, as it will release Swedish Research Council funding from being part of the basic funding of universities. This funding can instead be better used to support PhD students and postdoctoral research assistants involved in high-quality research projects submitted to peer review.

- In light of the importance of the invention of new methods and new technologies in science, it is essential that scientific merit is assessed in a manner that does not discriminate against scientists who engage in long-term and collaborative research. In this context, the criteria for assessing scientific merit need to be discussed and revised. The effects of review based primarily on bibliometrics may amplify a short-term perspective in science, and peer review focusing on long-term scientific quality should be employed as the main tool for review of project proposals, as well as for recruitment.

Measures to improve gender balance

- Gender equality is integrated at all levels of the Swedish Research Council. Although it cannot be claimed that complete gender equality has been achieved, major advances in terms of gender-balanced review panels and equal success rates, for example, have been made during the last 10 years. However, there are external phenomena that are more difficult to handle. Statistics for natural and engineering sciences show that a lower percentage of eligible female scientists than eligible male scientists apply for external funding, for example from the Swedish Research Council. The reasons for this are unknown, but the consequences are serious. This implies that, in absolute terms, female researchers are discriminated against. The Swedish Research Council will need to analyse the reasons for this imbalance, and, based on the results, take measures to mitigate the situation. Such measures may, for example, involve re-formulating call texts, changing funding instruments, and initiating an active dialogue with universities.

Research Impact

Biology

Review panels: Biochemistry and structural biology (NT-9); Cell and molecular biology (NT-10); Organism biology (NT-11); Ecology, systematics and evolution (NT-12)

Biology (sub-disciplines ecology, evolutionary biology and organism biology) is at the heart of our understanding of the concept of life. This includes our understanding of the complex past and present patterns and processes of natural ecosystems, as well as those involved in organisms that are closely linked to human society, such as farmed, hunted and fished species, pollinators, pests, diseases and invasive species.

A central theme in biology is the evolution of organisms adapting to the environment, and this is studied at every level of organisation, from the interactions of molecules to the interactions of species in an ecosystem including new fields of biology, such as systems biology and bioinformatics. How the molecular and genetic mechanisms shared among most life forms are managing these processes is of general importance. Linked to this is basic understanding of the systematic relationships between life-forms ("species") and the natural rate of turnover of species, as well as understanding of the increased risks of species extinction due to human activities.

Life sciences on cell to atom level can be divided into the closely linked disciplines of cell and molecular biology, biochemistry, structural biology and biophysics. Research into cell and molecular biology investigates how living organisms, ranging from bacteria to animals and plants, function on cellular and molecular levels. This, for example, involves clarification of molecular and cellular processes in reproduction, gene expression, development, signalling, and disease states. In biochemistry and structural biology, the structure and function of the molecules of life are studied. Biochemistry aims for molecular understanding of the interactions and transformations of small and large molecules within a living cell. Structural biology aims to clarify the three-dimensional structure of biological macromolecules and their assemblies to draw conclusions about their function. In biophysics, methods from physics are used to study biological samples and phenomena, overlapping with biochemistry, as well as cell and molecular biology. This involves studies of folding, binding and structure of single molecules or ensembles of molecules for example, as well as experiments within living cells. The whole area is dominated by experimental research, but there is also computational research ranging from structure-based computational biochemistry to modelling of phenomena within a cell.

Funding, publications and citations

Swedish research in biology has high international impact, and the quality of Swedish biological research is at the highest international level, with a much higher proportion of highly cited papers than the world average. Reflecting this strong trend, the area of evolutionary biology and genetics has increased its level of Swedish Research Council funding by 50% since 2013, at the expense of systematics, ethology, classical zoology and botany. Structural biology and biophysics are areas with slightly increased levels of Research Council funding, whereas biochemistry and molecular biology have remained at the same level. No specific publication data are available to judge the impact of the areas of cell and molecular biology, biochemistry, structural biology and biophysics; subjects that in the current statistics may be hidden within biology, chemistry, physics and medicine.

The Swedish Research Council is a very important funding source for the entire scientific area. Depending on the biological focus of the research and the potential applications of the results, some areas are also funded by a variety of medical funding agencies and yet others by FORMAS. The Swedish contribution in percentage terms to global research production in biology has decreased, despite a higher overall number of publications. The quality of Swedish research, as indicated by the number of highly cited papers, has been rather constant.

Research trends

The most important recent scientific advances in all of these scientific areas are technology-driven. Over the past 10 years, the new "omics" methods, genomics and transcriptomics in particular, have paved the way for completely new and important findings in the areas of genetics, system biology, evolutionary biology and cell and molecular biology. Some of these “omics” methods have recently been adapted to single-cell analyses. Rapid development of sequencing approaches, as well as new bioinformatics methods and gene editing (such as CRISPR/Cas9), promotes new trends and opens new doors for advanced studies of both traditional model systems and for species in the wild, the latter having high relevance for natural ecosystems. New technologies have partly changed the character of the research to become more dependent on large infrastructure facilities and data analysis support (such as bioinformatics) and require greater economic resources, making some of the research more descriptive. In addition, ecological network theory is currently being developed to understand species interactions, community dynamics and ecosystem functioning.

Parts of all these areas require large research infrastructures to stay competitive on an international level. The major techniques in structural biology, X-ray crystallography, NMR spectroscopy and cryo-EM, are complementary to each other, and, in order to stay competitive, it is very important for the Swedish community to have access to high-end research infrastructures. During the last 5 years, structural biology has been transformed by the developments in high-resolution cryo-EM. Through SciLifeLab, national facilities have been established that allow Swedish scientists access to state-of-the-art instruments for this technique. MAX IV, recently available for macromolecular crystallography, and the Swedish NMR centre are both important facilities and have benefitted from recent technology developments.

National infrastructures for modelling, computation, handling and storage of large data (such as provided by NBIS and SNIC, for example) are critical for modellers and experimentalists who produce very large data sets, as well as for the fields of computational biochemistry and bioinformatics. Some areas of biophysics are dependent on FELs. Apart from new technologies, a major trend in biology is that high-impact research and publications nowadays require the combination of a greater number of methods bridging the different sub-disciplines, and therefore often a greater number of participating scientists.

Chemistry

Review panels: Analytical, physical and theoretical chemistry (NT-5); Organic and inorganic chemistry (NT-6)

Chemistry is the molecular science, involving the design, synthesis, characterisation and theoretical modelling of molecular systems, substances and materials. Following advances in molecular biology, environmental and geo sciences, and materials physics towards an understanding of, and systems based on, molecular building blocks, chemistry has moved into these areas as a natural component. As a consequence, chemistry has to some extent lost its identity as an independent intra-scientific subject. Chemistry is divided into different sub-disciplines – analytical, inorganic, organic, physical and theoretical chemistry, as well as biochemistry. The strong trends towards multi-disciplinary chemistry and fuzzy interfaces towards other scientific areas make this sub-division less clear, and at the same time the intra-scientific advances are slowed down and in some cases even lost when chemistry is only used. Research in analytical chemistry focuses on new or improved methods for qualitative and quantitative analysis of 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, microfluidics and automation. Inorganic chemistry aims at an understanding of inorganic, metal-organic and bio-inorganic compounds and materials. 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. In organic chemistry and related research, NMR spectroscopy stands out as the single most central experimental technique. In physical chemistry, the focus of research is towards the understanding of molecular physical properties and processes. Important research areas involve spectroscopy, thermodynamics and kinetics, and electrochemical energy devices, as well as surface and colloidal chemistry. Theoretical chemistry research aims to study molecular structure, dynamics, binding properties, stability and reactivity using quantum mechanical and molecular modelling methodologies. There is a strong tradition in Sweden involving software development, such as MOLCAS and GROMACS. In recent years, research at the interfaces of these traditional disciplines has become more common, and has thereby made it possible to address new types of research questions. As noted above, more complex systems are studied, and at the same time there is a gap opening between fundamental understanding and the function of complex systems.

According to the questionnaire, recent important scientific advances in chemistry generally rely on new technologies and methodologies. In all traditional areas of chemistry, the importance of new methods for molecular analysis at nano and single-molecule level is highlighted. Analysis of single biological cells is also emerging as an important area. Development of such methods has become possible through technological advances, mainly within mass spectrometry (MS), but also via spatially-resolved spectroscopy based on fluorescent tags, for example.

The largest sub-areas of physical chemistry in Sweden include time-resolved laser spectroscopy for studies of energy-transfer and electron-transfer reactions, intermolecular interactions in self-assembled systems and at interfaces, and biophysical chemistry. Method development to study structure, molecular dynamics, kinetics and thermodynamics is also in focus; such as single-molecule spectroscopy and microscopy methods, scanning probe methods to investigate local material properties and local chemical compositions at the nm-scale, and also time-resolved spectroscopy for studies of ultrafast dynamics. Both physical and analytical chemistry are highly dependent on advanced experimental technologies, such as advanced spectroscopy and microscopy. ESS and MAX IV are considered to be very important for future advancements in many areas of physical chemistry.

The computational methods developed in theoretical chemistry include meta-dynamics to provide advanced sampling in molecular dynamics (MD) simulations, and to compute free energy related properties, multiscale modelling linking ab-initio and classical atomistic levels of description, as well as atomistic coarse-grained levels, advanced density functional theory (DFT) and quantum mechanical approaches, coarse-grained MD simulations, and protein-protein docking techniques. The development in GPU-based computing opens up possibilities for ab-initio MD modelling of much larger systems, of relevance in biochemistry and materials chemistry, for instance. For theoretical chemistry, easy access to supercomputing clusters is vital.

Core areas in Swedish organic chemistry research were earlier catalysis in various forms, natural product synthesis, and carbohydrate chemistry. Catalysis has remained a major topic, spanning from organo-catalysis to bio-catalysis in combination with transition-metal-based catalysis. However, research in natural product synthesis and carbohydrate chemistry has become smaller, and instead other areas, such as medicinal chemistry and chemical biology, have increased in size. Catalysis is a major scientific area within inorganic chemistry, as is research related to renewable energy involving new batteries, solar cells, heterogeneous catalysis, water splitting, and oxidation.

Funding, publications and citations

The number of grant applications in chemistry has decreased over the years. However, the marks awarded in the Swedish Research Council's review process indicate that the quality of the applications is still very high. Physical chemistry is the largest sub-area in terms of number of applications, followed by organic chemistry. Theoretical and analytical chemistry show about half as many applications as physical chemistry, and inorganic chemistry is the smallest subject. A general observation is that applications outside the five core areas of chemistry clearly display lower funding levels.

As shown by the number of applications to the Swedish Research Council, physical chemistry is also the largest sub-area 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, and has decreased during the same period, whereas publications in inorganic chemistry has stayed fairly constant. The Swedish percentage of highly-cited publications is around 10% for all four areas. The decreasing number of publications mirrors the decrease in the number of researchers in analytical and organic chemistry in Sweden, although the statistics on highly-cited publications show that the research performed has high impact. No specific data are available for theoretical chemistry, possibly because most theoretical chemistry is performed in close collaboration with the experimental sub-disciplines, therefore losing its unique identity.

Research trends

Chemistry research targeting important fundamental problems in life science, biology, medicine, environmental science and physics has increased, and large collaborative efforts have emerged. One trend is that physical chemistry is moving towards other subjects, where physical chemistry methods and concepts are used as tools to understand physical chemistry processes in nano and material sciences, as well as in multicomponent systems. There is an obvious trend that research in analytical, organic and inorganic chemistry has become more directed towards societal challenges, spanning from sustainable energy and storage, green chemistry, new raw materials, to medicinal chemistry and chemical biology programs contributing to life science. Chemical research will also in the future be highly dependent on advanced experimental technologies, such as advanced spectroscopy and microscopy, and access to the experimental facilities at ESS and MAX IV is considered essential for advancements in many areas of chemistry. Finally, infrastructures for high-performance supercomputing will be vital for theoretical chemistry, as well as many other sub-disciplines within chemistry.

Computer and information sciences

Review panels: Computer science (NT-2); Signals and systems (NT-14)

These relatively young disciplines are experiencing rapid expansion and change, with a great many research advances in the field related to, or enabled by, technological advances and engineering progress. These technologies include GPUs and multicore computing for example, distributed large-scale data processing, high-speed wireless communication, and massive MIMO. It should be borne in mind that these technologies are the cumulative effect of decades of research and development work, as are many of the breakthroughs that build on them. For example, artificial neural networks, which form the basis for the recent breakthroughs in deep learning, were proposed in research from the 1950s, and owe their practical applicability to a range of technologies, such as the ability to handle vast amounts of data, the computational power of GPU processors, and software frameworks, such as TensorFlow and PyTorch.

Funding, publications and citations

Funding in the area of computer and information sciences has remained relatively constant in the period reported, 2011-2015, and makes up about 12% of the total NT

budget.
The bibliometric data for computer and information sciences is not reliable in absolute terms, due to lower coverage than in all other areas (less than 60% of referenced sources are included). The percentage of the world's production of research in the area shows no clear trend in the last 6 years, but the number of publications shows a steady but modest increase.

Research trends

The survey points to a range of advances and trends, and we highlight a few. One standout breakthrough and trend, mentioned more often than any other, is the broad success of machine learning. Machine learning is noted by more than a quarter of all respondents from both NT-2 and NT-14; in a relatively short space of time the success of machine learning, and deep learning in particular, has completely transformed diverse research areas, such as computer vision and natural language technology, and has had a significant impact on countless other fields. Rapid developments in reinforcement learning, with DeepMind's AlphaGo as a prime example, are seeing increasingly broad areas of application. There have also been significant developments in deep generative models, such as generative adversarial nets, and their potential application in unsupervised learning.

In theoretical computer science, "sum of squares" methods continue to be a powerful tool for producing new provably polynomial time algorithms in some cases, and in other cases efficient algorithms that are difficult to analyse. Several researchers mention the general trend in studying fine-grained complexity, hardness of approximation, and parameterised complexity. Recent breakthrough results on the problem of graph isomorphism, and the proof of a celebrated open problem on the complexity of constraint satisfaction problems are also noted. In the field of computational logic, and type theory in particular, the univalent foundations approach is mentioned by several as an important and influential trend. In the field of Human-Computer Interaction, the advent of computing devices that surround us has taken the focus away from user interfaces and directed it towards the total user experience. Software engineering research has seen a move towards evaluation of methods applied at scale in real-world scenarios. Breakthroughs in formal methods include the development of the first formally verified operating systems and optimising compilers, as well as powerful techniques for analysing and verifying software built on recent advances in software testing, constraint and SMT solving, and model checking. Looking to the broad area of computer systems engineering, cyber-physical systems and "internet of things", combining traditional embedded systems, networking, and interaction with an unpredictable physical environment face many challenges regarding how to develop software, and how to meet performance, power, and safety requirements. Several researchers note the general themes of security and privacy as being of increasing significance, and there have been a range of recent advances spanning the whole of the information and computational sciences area, from theoretical foundations of privacy to research in physical layer security. In computer systems and architecture there is increased focus on power and energy-efficient architectures and efficiency-aware compilers, with new challenges posed by heterogeneous architectures and programmable accelerators, and more advanced memory subsystems.

A number of breakthroughs and trends in the signals and systems areas have affected the focus and choice of proposed research topics in Sweden over the last ten years. Some specific examples follow, but by necessity this is not an exhaustive list. In computer vision, deep neural networks ("deep learning"), technology for object recognition in natural images and methods for structure-from-motion computation have undergone a revolution.

In communications, the emergence of rigorous analysis and design methodologies for massive and millimetre wave MIMO technology, non-asymptotic finite-block length information theory, advances in coding theory, and power-efficient implementations of sophisticated signal processing have revolutionised the field and fuelled new applications. In control engineering, the field of networked control has bloomed, and there has been progress in the system-theoretic understanding of biological principles in the human body, and in the application of "systems-level thinking" to many new interdisciplinary areas, for instance systems biology. In signal processing, emerging scalable tools for machine learning, estimation and detection (including Monte-Carlo methods), and advanced optimisation algorithms (especially convex optimisation), have enabled the solution of new classes of problems, and there is growing interest and progress in understanding non-convex optimisation and its application to neural networks.

Geosciences

Review panels: Geology and geophysics (NT-7); Soil, air and water processes (NT-8)

Geosciences encompass the knowledge of the history of the globe - from the formation of the Earth to today's world highly impacted by humans - and the processes that govern the development of and interaction between the global spheres, that is the geosphere, atmosphere, hydrosphere, cryosphere and biosphere. These processes are controlled by physical, chemical and biological factors and consequently physics, chemistry and biology, together with mathematics, constitute indispensable support sciences for geosciences. The development of a sustainable society is strongly linked to progress in geoscience research. This has increased the importance and interest in the subject area, and research into Earth’s climate, history, variability and sustainable exploitation has gained momentum. For example, the traditionally strong Swedish geoscience research in the polar regions has been highly recognised as a result of the sensitivity and significance of these areas for global climate change.

There are several active and significant geoscience sub-disciplines in Sweden, as indicated by the number of proposals submitted during 2008-2017 to the Swedish Research Council. In atmospheric and climate research, the interactions between the atmosphere, surrounding landmasses, seas and even ecosystems are investigated. This holistic view is necessary for reliable weather forecasts and better understanding of climate variability, sensitivity and development. The understanding of atmospheric processes and their importance to the climate and their sensitivity to anthropogenic and altered natural emissions is paramount, for example in the Arctic. Geochemistry encompasses studies of key processes occurring at different inorganic and organic interfaces that control the global geochemical cycles of the elements. These processes determine the chemical composition of the sea, land

and air. The research is multi-scale, from molecular via ecosystem to global levels, covering most elements, their chemical forms and isotopes. Geology and geophysics focus on the physical and chemical composition of the Earth, as well as its physical properties and the phenomena associated with the Earth and its surroundings. The research is often characterised by collaboration over traditional subject boundaries in combination with initiatives to increase integration between laboratory processes and field-oriented studies and modelling. Access to advanced research platforms and participation in international sampling programs, such as IODP and ICDP, are also important for the development of the subject area. Swedish research in oceanography, hydrology and glaciology involves a combination of field activities, focusing on process understanding, in combination with remote sensing and modelling at various levels. The efforts are largely focused on fundamental issues both globally and regionally in Sweden, including the surrounding seas, sometimes with direct application to current issues in key sectors of society, such as households, agriculture and industry. A common theme in most geoscience research is that it is dependent on multi-year results from fieldwork, coupled with laboratory experiments. This requires long-term project funding and access to advanced laboratory equipment, as well as field instruments.

Funding, publications and citations

Clearly, our ability to tackle societal challenges, such as those related to climate change, depends on our understanding of the Earth's systems, and thus on research in geosciences and environmental science. It is therefore not surprising that public spending on research funding to geosciences and environmental science has increased; the support to this area of research increased by close to 70% between 2011 and 2015. The main sources of increase were public funding through sources other than the Swedish Research Council. Concomitant with the increase in research support is a significant increase in the number of publications in geoscience by Swedish researchers, and geoscience is one of the areas within natural and engineering sciences that has experienced the largest growth in research output during 2005-2017. However, this research area has also grown internationally, most likely due to a strong increase in publications from Asia (mainly China), and as a consequence the percentage of publications with contributions from Swedish research groups has decreased over the same period.

Within the broad definition of geosciences, environmental science is the dominating sub-discipline in terms of number of publications, followed by multidisciplinary geosciences and meteorology, as well as atmospheric sciences. These sub-disciplines are not only the largest by publication volume, but the papers in these areas are also well-cited and display a percentage of highly-cited articles clearly above the world average during 2014-2016. The same is true for smaller disciplines in Sweden, such as oceanography, palaeontology and remote sensing, and overall the international impact of Swedish geosciences is significant.

Research trends

Two overall trends in geosciences research can be identified. One includes efforts to understand, at a mechanistic level, the processes that govern the composition of and elemental cycles in our past, present and future environment. The other trend is a holistic approach to understand the climate and the Earth as complete systems, which is achieved by integrating modelling and experimental data across many different temporal and spatial scales. A common feature of recent breakthroughs in geosciences research is their dependence on technical advancements, such as new sensitive isotope techniques, chemical and structural analyses at micro- and nano-scales, including 2D and 3D imaging, genomics, and supercomputing.

Finally, an example of an upcoming research area is geobiology. This involves novel findings of life forms and processes in "extreme" environments, providing new important insights into how life evolved on our planet and how life has recovered from mass extinction events.

Mathematical sciences

Review panel: Mathematical sciences (NT-1)

Mathematics is considered as the language of science, where its methods and tools are indispensable. The interaction between mathematics and science is growing, and has been beneficial since it has led to the development of new mathematical areas. The exponential improvement in computing power has radically increased the importance of mathematics, making modelling possible in more realistic situations. But the modelling is based on theoretical insights, which have been applied in very different and unexpected areas. One example is the application of topological methods in program validation in computer science. Another example is the application of harmonic analysis in image compression using wavelets. Therefore, it is important to stimulate interaction, both between mathematicians and between mathematicians and other scientists.

It is claimed that we live in a golden age of mathematics, with major breakthroughs and rapid development of new fields. Great problems of many decades' or centuries' standing have been solved. Famous examples are the resolution of Fermat's last theorem, the Poincare conjecture and the weak Goldbach conjecture. But there are many more: the resolutions of the Yau-Tian-Donaldson conjecture, the Kadison-Singer problem, and the Onsager conjecture, and there has been great developments in percolation, and on the twin prime conjecture. Many of these advances have been made possible by combining methods from different areas of mathematics, and they have opened up new areas of research. On the applied side, there has also been great developments, for example in numerical analysis, such as the finite element method, optimisation, optimal transport, computational quantum physics and deep learning. Sweden has a long and proud tradition in mathematical excellence, traditionally in mathematical analysis and probability theory, but now also in other areas of mathematics, such as algebraic geometry, discrete mathematics, dynamic systems, and applied mathematics.

Funding, publications and citations

Mathematics is important in education. This results in heavy teaching loads for researchers, and often too little time for research. The importance of the Swedish Research Council's undirected project grants cannot be overestimated, and it is essential that Swedish academic institutions provide sufficient time for research so that these projects can be successfully carried out. To support the interaction between mathematicians and between mathematicians and other scientists, travel

support is also essential.
During the last 10 years, there has been an increase in funding for geometry and discrete mathematics, and a decline of funding for mathematical analysis. Research into mathematical analysis has historically been extremely strong in Sweden, and the decline of funding could be a sign of stronger competition from other research areas. However, one cannot draw too many conclusions from the data, since the division into research areas has changed during this period.

The average amount of funding for applications has decreased for the mathematics panel, and in the last years it has been 8% below the Swedish Research Council's average for natural and engineering sciences. The acceptance rate for applications has decreased from 25% in 2009 to 19% in 2017, which on a relative scale is 11% below the average. This is mostly due to a 40% increase in the number of applications, which goes against the trend of decreasing numbers of applications within science and technology at the Swedish Research Council.

In the last five years, the total number of publications in mathematics has increased by 25%, especially in applied mathematics, statistics and probability.
The Swedish percentage of the world's publications in mathematics has increased by 28% during this period. The number of citations has a large yearly variation, but shows an upward trend in the last 6 years, especially in applied mathematics. However, the database covers only 60% of the publications, which means the bibliometrical results are less reliable.

Research trends

The data on applications to the Swedish Research Council show a significant increase in the number of applications in probability and statistics, and a decrease in the number of applications in algebra and logics. The first phenomenon can be seen as a trend in mathematics to apply probabilistic aspects. Another factor could be the recent priority area supporting research projects that combined statistics with empirical sciences.

In order to attack hard and long-standing problems, there is continuing interaction between different research areas, for example between algebra and geometry, between combinatorics and probability theory and between discrete mathematics and analysis. There is a growing interdisciplinary trend, especially concerning physics, where there are strong interactions. Examples are the study of critical behaviour, such as phase transitions, the role of geometry in the spectrum of partial differential equations and the cosmic censorship in mathematical relativity. This inspires developments in in many areas of mathematics, such as analysis, geometry, combinatorics and probability theory.

In applied and computational mathematics, the trend is toward studying large scale systems, for example interconnecting networks, and modelling multiscale physics, such as composites, stochastic modelling and large scale optimisation. There is also a strong trend towards machine learning and artificial intelligence, and towards developing algorithms and methods for handling big data sets. The number of applications is increasing, especially in material and life sciences. A remaining problem is that researchers in empirical sciences are often using outdated and even erroneous statistical methods.

Infrastructures for mathematicians are, in general, the research institutes, where mathematicians can meet and interact. Institut Mittag-Leffler was the first, is still world leading and is very important for Swedish mathematics, as it attracts many foreign visitors to its thematic programs. For applied mathematics, there is a need for hardware and support for large-scale computations, such as numerical and stochastic simulations, and for solving partial differential equations. There is also a need for resources for handling and storing big data sets. In this connection, it is also important to get access to observational data related to areas such as transportation, finance and climate.

Mechanical, chemical and biomedical engineering

Review panels: Mechanical engineering (NT-16); Bioprocess technology, chemical engineering and environmental engineering (NT-17); Biomedical engineering (NT-19)

The area of engineering mechanics has significant impact in different areas, such as fundamental fluid mechanics (turbulence and complex fluids), combustion research, materials design and modelling, and realisation of designed microstructures. Recent breakthroughs concern the fully resolved simulations of turbulence, as well as simulations of multiphase flows, including heat and mass transfer, as well as chemical reactions. There is a growing interest in the design of new materials and structures from atomic to structural scales. For assessment of structural reliability and for optimised material design, improved solid mechanics-based models are needed. Research efforts are growing in the areas of multi-scale modelling, advanced experimental techniques, deformation and failure mechanisms at micro and nano level. One important breakthrough is related to new bio-based materials involving wood fibres at nano level, resulting in new materials with unprecedented characteristics. Some scientific challenges are clearly identified: i) understanding and exploiting the possibilities offered by micro and nano fabrication by understanding the implications of macroscopic behaviour; ii) a need for competitive computational resources; iii) a need for medium-scale experimental infrastructures; iv) developing strategies to gain real physical understanding and predictive tools from in-depth analysis of vast amounts of data produced by large-scale simulations and experiments on complex systems.

Chemical engineering is the technological basis for the process industry, and, for bioprocess technology, the transformation of bio-based raw materials into valuable products is in focus. Separation techniques developed within chemistry represent important tools in chemical engineering and related subjects. In environmental engineering, the aim is to find processing solutions that are environmentally benign. In this field, there are also strong interfaces towards modelling and automation.

Biomedical engineering (BME) is a broad interdisciplinary research field, originating from engineering sciences that focus on solving medically and clinically oriented problems using engineering methods. Today, BME research involves a broad range of topics, such as biomaterials, biomechanics, biomedical optics, biomedical sensors, biomedical modelling and simulation, biomedical signal processing, E-Health, medical imaging, medical informatics, medical radiation physics, physiological measurements and instrumentation, prosthesis technology, sports technology, technical audiology, and tissue engineering.

Funding, publications and citations

The funding in the area of engineering sciences has remained approximately constant over the last five years.

Bibliometrics show that the number of Swedish publications in engineering mechanics (mechanical engineering) and biomedical engineering has increased by about 50% over the last decade, while the percentage of highly-cited publications has remained about the same.

The number of Swedish publications in chemical engineering has doubled over the last five years, and increased by about 50% for environmental engineering. The percentage of highly-cited publications from Swedish researchers in chemical engineering has decreased in the last 10-year period, but can still be considered high. The corresponding percentage remained constant for environmental engineering.

Research trends

Engineering mechanics and biomedical engineering have much in common in terms of advances and challenges. One clear trend is that the research questions addressed are becoming increasingly multidisciplinary. In engineering mechanics, the increase in research related to tribology, other physics (climate and geophysics), aerospace, biomechanics, paper production and biomaterials can be noted. These and other research questions require fundamental expertise in other areas, for example chemistry for tribology, or nanotechnology and applied mathematics for multi-scale modelling. In biomechanics, many research areas illustrate the broad palette of multidisciplinarity as noted above. The design of new materials with tailored properties, such as resistance to fatigue or optimised energy absorption, advances with the development of new optimisation methods. These materials have unique nano- or micro-scale structures, so research facilities such as MAX IV and ESS that can provide information at these length-scales are vital, both for characterisation of new materials and for validation of novel optimisation methods.

Advances in high-performance computing have led to major progress in complex dynamics (NT-16), and improved modelling (NT-19). The dependence on high-performance computing resources has increased, and is very high for projects handled in NT-16, which are clearly the most dependent on e-infrastructure of all the areas in engineering sciences.

Chemical engineering is undergoing a transformation, due to the change in raw materials in the chemical industry moving from fossil resources towards renewable resources. This gives rise to fundamental challenges in all processing steps, biochemical as well as chemical, but also offers opportunities in terms of novel functionality. The chemical or biochemical processing of biomass towards a range of products, including new materials, chemical building blocks and fuels, is a theme in many applications. A slight widening of feedstocks of interest can be seen in recent years, in which, apart from cellulose and hemicellulose, lignin and algae are also included. The issue of carbon dioxide fixation/capture/processing is also gaining in interest. A second trend affecting bioprocess technology is the advancements in molecular biology tools, as well as the rapidly increasing availability of “omics” data. A third trend is the access to ever better materials characterisation tools.

The focus on biomass as an expanding feedstock and biomass conversion to novel products is very strong today, as in 2014. New initiatives within the wood sector, such as. a second stage of the Wallenberg Wood Science Centre has been granted, and a new national research school related to forest industry (Treesearch) has been initiated. In terms of infrastructure, a new beam line specifically dedicated to materials derived from wood (ForMAX) will be constructed at MAX IV.

Physical sciences

Review panels: Subatomic physics, space physics and astronomy (NT-3); Atomic and molecular physics, optics and condensed matter physics (NT-4); Electronics, electrical engineering, semiconductor physics and photonics (NT-13); Applied physics (NT-15); Materials science (NT-18)

Physics is a fundamental scientific discipline that covers research from the smallest elementary particle all the way to the dynamics of the universe, and on timescales from attoseconds to billions of years. The field is developing through interplay between experimental efforts and the formulation of theoretical models. It is also integrated with engineering physics, where iterative processes generate both new techniques for characterisation and also new science.

In sub-atomic physics, the discovery of the Higgs boson and the observation of neutrino oscillations made at the Ice-Cube experiment are two important recent discoveries. There is also continuous development of major experiments, including CERN and FAIR. Astronomy and astrophysics have seen dramatic increases in research possibilities driven by rapid technological developments. For these disciplines, the organisations ESA and ESO, as well as the national Onsala Space Observatory, Institute for Solar Physics and EISCAT are central infrastructures. The detection of the gravitational waves was a pivotal experiment, which provides the scientific community with tools to study a broad range of topics, including the nature of cosmic explosions, the properties of nuclear matter and the beginning of the universe. The operation of the fusion reactor JET and the new reactor ITER are of greatest importance for fusion, plasma and space physics. Within space and plasma physics, the successful missions to other solar system objects, such as the European Rosetta mission, has provided valuable observations.

Swedish atomic, molecular and optical physics are active in synchrotron radiation, X-ray laser, attosecond spectroscopy, and non-linear optics research, as well as in studies of ion collisions and reaction dynamics performed at the DESIREE facility. The development of infrastructures, such as XFEL, MAX IV and the Lund Laser Centre, contributes strongly to the scientific progress of the field. Furthermore, the area of quantum optics and quantum information is expanding, and this expansion is expected to continue.

From an international perspective, condensed matter physics is the largest areas in physics, and is closely related to engineering. Sweden has a strong tradition on the theoretical side. Experimental condensed matter physics is expected to increase, due to the interest in quantum materials displaying strong electronic correlations and aspects of electronic ordering, and in electronic properties linked to non-generic quantum effects.

Material sciences covers the design and discovery of new materials. The development of new technologies based on new materials is of strong societal relevance, and has direct implications for several societal challenges, for example in the energy sector. The same is true for rapidly developing research areas based on fundamental phenomena at nanoscale, including synthesis, characterisation and computer modelling of nanomaterials and nanodevices. Measuring, modelling, and manipulating low-dimensional forms of matter at the nanoscale are of vital importance in a wide range of new and emerging technologies.

Theoretical physics and modelling are fundamental to the physical sciences in order to rationalise, explain and predict physical phenomena. Realistic simulations of complex systems can be used to supplement experiments, which are often both expensive and time-consuming. This has had a major impact in hard and soft materials physics, nano-sciences, particle physics and atomic and molecular physics through increased precision, advanced energy mapping and improved lateral resolution.

Electrical and electronic engineering are now expanding and include electricity, electronics, and electromagnetism. Increased activity is expected in areas such as design and fundamental understanding of materials for medical and pharmaceutical applications, physical and medical engineering, biomaterials engineering, and medical imaging and visualisation.

Clearly, the progress and impact of Swedish physical sciences is strongly dependent on access to and development of experimental and computational infrastructures. The main new and emerging large-scale facilities in Sweden are the MAX IV Laboratory and ESS. These are of vital importance for strong national and international contribution to the fields of material sciences, condensed matter physics and engineering, among others. A range of distributed infrastructures, such as Myfab, is also essential for several disciplines within physical sciences. There are a number of important smaller national and local research infrastructures, including electron microscopes, larger laser systems, NMR spectroscopic facilities, advanced light microscopes and various instruments for material analysis. For theoreticians, access to large-scale computer resources, channeled through SNIC, is absolutely indispensable.

Funding, publications and citations

The financial support for research and development in physical sciences, measured in absolute numbers, shows an increase of 58% during the period 2011-2015, where the main part of the increase is in applied fields. Connected to this increase, there is also an increase in the number of publications in material sciences and engineering of more than 50% over the last 12 years (2005-2017). During the same period, fundamental physics shows a relatively constant level of funding, which is also manifested in a stable publication level. It is interesting to note that, based on international co-authorships, physical sciences are by far the area with the largest degree of internationalisation. Overall, the area of physical sciences (physics, engineering physics and materials science) delivers 50% of all publications within natural and engineering sciences.

Research trends

Many of the most challenging scientific problems that humans currently face will require breakthroughs in materials science. Future developments in materials science involve the design of hard, soft and hybrid materials, where organic and biological materials are included as adsorbed species. Other important scientific advancements are the use and design of artificial materials, for technological developments in the fields of photonics and quantum communication.

In theory and modelling, future central questions are related to the completeness and accuracy of the predicted properties of new, not yet produced, materials and quantum systems. At the same time, the development of refined techniques, experimental methods, and more sensitive detectors and faster processing of large experimental data sets are fields in rapid progress. The combination of this progress means that we are on the verge of acceleration in the field of materials science, from basic research to industrial applications.

In basic research fields, such as subatomic physics and astronomy, there is a tendency towards larger experimental facilities, with project times extending over decades. Swedish participation in such programs requires our funding systems to allow researchers to work with longer time perspectives than is currently the norm. This applies to funding of research infrastructures, the cost of Swedish participation in international facilities, as well as for project grants for participating researchers. At the same time, science at small-scale facilities is a driving force for the renewal of research efforts. Here, lead times are much shorter, allowing the development of ideas, methods and technologies that can later be implemented at large-scale facilities.

Overall, the total scientific activity within the field of physical sciences is increasing, and is expected to increase even further. Novel research infrastructures will open the door for new experiments, followed by front-line science and international breakthroughs and an increase in international scientific impact, both within physics and in other scientific areas.

Future Challenges

Gender equality

An important future challenge in many areas of natural and engineering sciences is to improve the gender balance. In several cases, gender imbalance is large already at PhD level, and increases yet more further up the academic career ladder. However, for some areas (such as biology), this bias is not present among junior scientists but remains a problem among senior researchers. An improved balance will require that we increase the number of female students and secure gender-neutral selection procedures throughout the academic career. This applies to both individual and collective reviews and evaluations, and gender aspects should permeate these procedures. In this respect, education, self-reflection and reliable statistics are important tools.

On top of this, an imbalance persists, which is highlighted by current statistics, showing that there are still significantly fewer eligible women than eligible men who apply for Swedish Research Council funding within natural and engineering sciences as a whole. This is a serious problem that urgently needs to be further analysed in order to identify effective measures.

Some sub-disciplines have in the last few years experienced an even greater drop in applications from women (such as organic and inorganic chemistry). Thus, there is an additional important challenge to investigate the underlying reasons for the decline, and to motivate women to take on research topics in these disciplines.

Research infrastructures and research

An obvious conclusion from the answers to the questionnaire is the strong correlation between scientific progress within most areas of natural and engineering sciences and the development of new experimental and computational methods and technologies. A major future challenge will be to secure access to and efficient use of necessary research infrastructures at all levels, as well as to prioritise among these infrastructures. An emerging problem with Swedish-based infrastructures is that, in several cases, they are underfinanced with respect to running costs and maintenance. In the long term, this will lead to deterioration of equipment and loss of performance.

At Swedish research infrastructures, a large number of the researchers who bring their excellent science to the facilities are not technical experts and therefore rely on skilled support in order to get maximum output from the experimental and computational resources. A significant challenge is thus to establish and maintain efficient links from formulation of a scientific problem via an appropriate method to the final analysis. One example is the new sequencing methods, which have created an ever-growing need for infrastructure for sequencing, adequate bioinformatics support, computational power, as well as data and sample storage facilities.

Experimental natural and engineering sciences rely to a large extent on small laboratories operated by individual research groups. Here, direct access and control of the equipment allow innovative projects to be executed within short lead-times. This type of in-house equipment is also important for training students and post-doctoral research assistants, as well as for preparatory work for experiments at larger facilities. However, there is a lack of financial support for such medium-expensive equipment. This lack of funding affects the progress of research in most areas of natural and engineering sciences.

When science is mainly method-driven, theory building and modelling is at risk of lagging behind, weakening the conceptual basis for the use of all the data generated. Consequently, advanced mathematical description and modelling of systems under study is another challenge that demands opportunities for multidisciplinary collaboration. In this respect, both algorithmic and logical understanding of machine learning and artificial intelligence are broadly acknowledged, with numerous issues of fundamental limitations (such as transparency, fairness, and safety) that need to be addressed.

Big data and computer resources

The answers to the questionnaire indicate that, across many areas of natural and engineering sciences, access to sufficient high-performance computing power will be a future challenge. A variety of methods require and are to some extent driven by the availability of such computing resources. This is especially true in the expanding areas of machine learning and artificial intelligence, where huge amounts of data must be processed. Other examples are bioinformatics, climate modelling, mathematics, engineering mechanics and biomedical engineering. The latter are related to the huge amounts of data created from sources such as wearable devices and imaging of the human body, especially the brain, and we need to find ways to adapt and tailor diagnostics and therapies on an individual basis. Computer-intensive imaging techniques are also important in structural biology and geosciences.

Terms and use of research funding

A structural challenge for most areas within natural and engineering sciences is the current situation, where associate senior lecturers, senior lecturers, and professors are forced to use external funding to support their own salaries. It will be a major challenge for the Swedish academic system to make a transition from this situation to one where external project funding is used only for direct project costs, such as for PhD students, post-doctoral research assistants and research infrastructure. The need to support the salaries of project leaders, as well as scientific co-workers, via external funding, in combination with the high salaries for students and scientific co-workers, has become an increasing problem, not the least for junior researchers expected to establish independent research groups. On top of this, the questionnaire answers identified challenges related to increased administrative regulations and administrative work, often and paradoxically in combination with high university overhead costs.

It is obvious from “Section 3. Research impact” that much of the research within natural and engineering sciences is connected to existing societal challenges. However, in many cases the solutions are perceived to be mainly of an applied character, but for long-term future progress it is essential that there is a healthy balance between funding directed towards basic research and applied development projects. There is also a pedagogical challenge associated with challenge-driven research, where only applied research gains visibility, clearly linked to the challenges, but relying on existing knowledge. For example, the Swedish Research Council has supported basic climate-related research with more than 1 billion SEK over the last three years; research that is likely to provide the new knowledge necessary for handling the climate change challenge. This research has almost exclusively been initiated by individual researchers, and is not a result of challenge-driven and targeted efforts. This sole example shows the research community’s preparedness to tackle research questions related to societal challenges in a timely and efficient fashion, without the need of directed calls. Obviously, generating the new knowledge needed in the future, one challenge will be to secure sufficient funding for basic research in natural and engineering sciences, and in this respect the Swedish Research Council’s undirected project grants will play a crucial role.

Distinctive features of natural and engineering sciences are the interdisciplinary character of the research, and the need for long-term funding extending way beyond the 4-year funding cycle characteristic of external funding agencies. Some examples are the need to make temporal observations of ecosystems and environmental processes over extended periods of time, and in many areas, where large research infrastructures are required, with a time span from idea to a working infrastructure facility that may extend to several decades. Thus, a future challenge is to develop suitable funding instruments that allow a long-term perspective, and at the same time meet the requirement for thorough evaluation in order to secure scientific excellence and to maintain scientific relevance.

As pointed out above, scientific progress is strongly linked to the development of new research techniques and methods. At the same time, there must be a healthy balance between available project funding and infrastructure funding. This is a central task for future research funding systems.

Abbreviations

ALMA	Atacama Large Millimeter Array
BME	Biomedical engineering
Cryo-EM	Cryo-electron microscopy
CERN	European Organisation for Nuclear Research
DESIREE	Double ElectroStatic Ion Ring Experiment, Stockholm University
DFT	Density functional theory
ESS	European Spallation Source
EISCAT	European Incoherent Scatter Scientific Association
ESA	European Space Agency
ESO	European Southern Observatory
FAIR	Facility for Antiproton and Ion Research
FORMAS	Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning
GAIA	Space observatory; not an abbreviation
GPU	Graphics processing unit
GROMACS	Groningen Machine for Chemical Simulations
ICDP	International Continental Scientific Drilling Program
IODP	International Ocean Discovery Program
ITER	International Thermonuclear Experimental Reactor
JET	Joint European Torus
LHC	Large Hadron Collider, CERN
MAX IV	MAX IV synchrotron, Lund University
MD	Molecular dynamics
MIMO	Multiple input, multiple output
MOLCAS	An ab initio quantum chemistry software package
MS	Mass spectrometry
Myfab tion	The Swedish Research Infrastructure for Micro and Nano Fabrica-
NBIS	National Bioinformatics Infrastructure
NMR	Nuclear Magnetic Resonance
NT-X	The review panels within natural and engineering sciences are normally denoted NT-1, NT-2 etc., and the scientific areas they cover are explained in the link in the footnote below[2]
SNIC	Swedish National Infrastructure for Computing
VR	Swedish Research Council
XFEL	European X-Ray Free-Electron Laser Facility

2 https://www.vr.se/english/calls-and-decisions/assessment-of-applications/review-panels.html#?subject=-Natural%20and%20Engineering%20Sciences

List of Appendices

1. Statistics for applications to natural and engineering sciences 2008-2017
2. Research funding, personnel and impact - a research barometer for natural and engineering sciences in Sweden (in Swedish)
3. Questionnaire to scientists in natural and engineering sciences 2018 - a short summary of the answers
4. The 2014 Research Overview in Natural and Engineering Sciences (in Swedish).

The Swedish Research Council's research overview within natural and engineering sciences describes the current position of research and makes a forecast of developments over the next five to ten years. The overview also includes scientific and research policy recommendations for inputs to promote research in Sweden within the area.

This is one of seven research overviews in total, produced during 2018. The other overviews cover the areas of humanities and social sciences, clinical therapy research, artistic research, medicine and health, educational sciences and development research. The overviews form a central part of the Swedish Research Council's input into the upcoming Government Research Bill.

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