The physical and mathematical sciences

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Introduction

1. Helge Kragh is the principal author of the chapter. Jesper Lützen is the author of the section on mathematics and Lars Birkedal is the author of the section on computer science.

This chapter is concerned with part of the broad spectrum of sciences represented in the Academy of Sciences: the subjects which are sometimes referred to as the exact sciences. With the exception of the mathematical sciences, the exact sciences are taken here to include natural sciences such as physics, astronomy and chemistry. Aspects of other disciplines will also be referred to, without any particular significance being attached to the categorization of the various sciences within the broader area of the mathematical and natural sciences. The primary orientation of this chapter is the contemporary period, from 1992 to 2017.

It goes without saying that a brief description of contemporary sciences within a particular national and institutional context is problematic. Not only is the definition of this context along national lines artificial in many ways; the association with the institution in question, the Royal Danish Academy of Sciences and Letters, is also fluid and without great inherent significance. What is more, most of the researchers referred to in this chapter are still alive, and many of them are very active. Finally, the nature of their contribution to science is so complex that it eludes popular summary. For these and other reasons, this chapter cannot be understood as a history of science in the classical sense, but rather as a fragmentary introduction to some of the research areas which the members of the Academy have been or are still involved in over the past quarter century. Obviously, this is an incomplete introduction characterized by a considerable degree of arbitrariness, as this chapter might have been structured in many other ways.

Even though the temporal perspective is contemporary, this period cannot be understood without reference to preceding history, insofar as it relates to the natural sciences in Denmark and the role of the Academy in its development. For this reason, the chapter begins with a very brief summary of the development of this relationship up to the middle of the twentieth century. To emphasize the absolutely crucial influence of both national and international research policy on the natural sciences in modern-day Denmark, this summary is followed by a sketch of the most important research policy initiatives since the 1950s. Although these two introductory chapters are oriented towards the physical and mathematical sciences, the conditions and possibilities described are naturally not limited to these sciences alone.

The long-term perspective

The Academy – or what was known as 'the academy of the sciences and letters in Copenhagen' (*Videnskabernes Societet i København*) at an early point in its history – was originally conceived as a historical-philological or antiquarian academy. And indeed, the new learned society was dominated by humanist scholars at that time. However, this dominance was short-lived, as the Academy rapidly gained members from the medical, mathematical and natural sciences. As described in a royal rescript of January 11th 1743, the Academy was also intended for those

> who in natural history, as well as who in the medical, mathematical and mechanical sciences are to present rare inventions, which could be considered worthy of revealing to the public, and contribute both to the increase of the aforementioned sciences as to the praise and fame of their authors.

Joachim Frederik Ramus was the first mathematician, Peder Horrebow was the first astronomer, and Jens Kraft was the first physicist to be elected within the first five years of the Academy's existence, which brought them praise and fame, at least on the national stage. On the other hand, it was not until 1796 that the first chemist was elected, the apothecary Nicolai Tychsen. As reflected by the number of treatises published in the *Writings* (Skrifter) of the Academy, the level of scientific activity among members from the mathematical and physical sciences was at about the same level as for members from the natural sciences. In the period 1745-1779, a total of 160 communications were published, 89 of which were concerned with the natural sciences in a general sense; the subjects of 45 of the articles were mathematical-physical (including astronomy, surveying and chemistry), while 44 were within natural history, including medicine and meteorology.

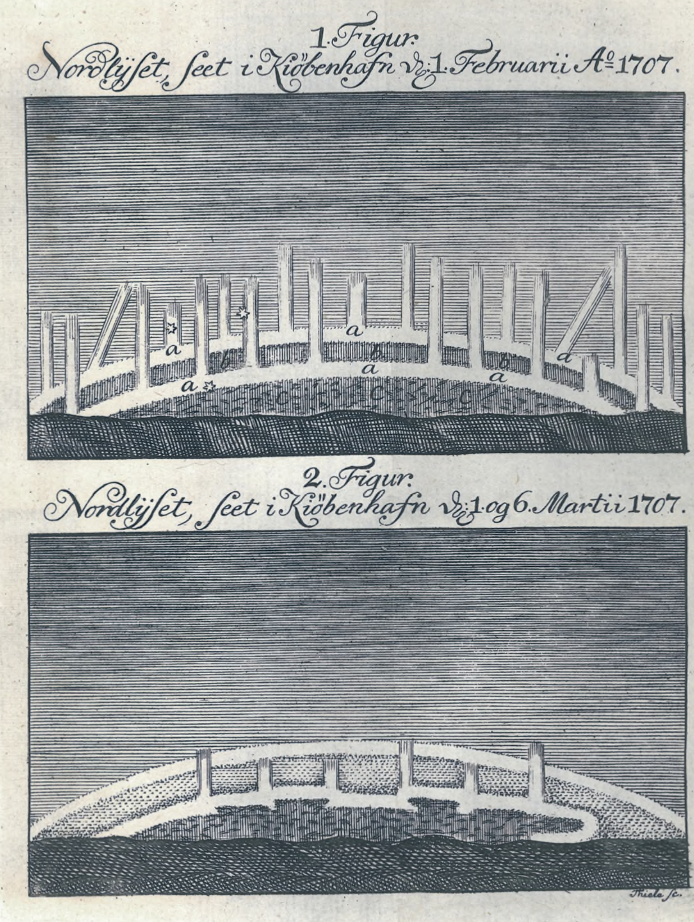
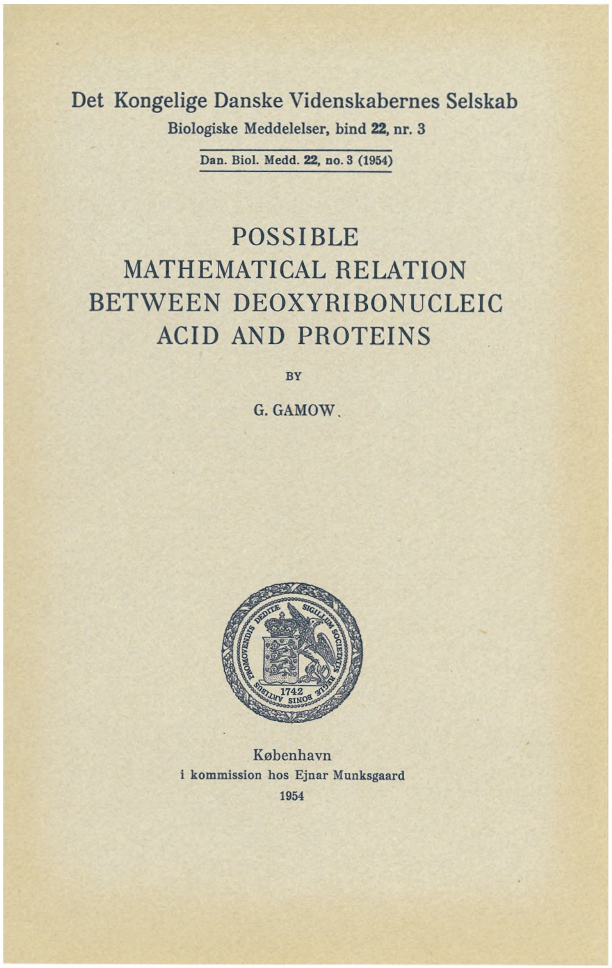


FIGURE 1. The Northern Lights, observed in Copenhagen in 1707. Plate in the first natural sciences treatise in the Academy's *Writings*, the mathematician Joachim Frederik Ramus' 1745 treatise *Historisk og Physisk Beskrivelse over Nordlysets forunderlige Skikkelse, Natur og Oprindelse* (Historical and physical description of the remarkable appearance, nature, and origin of the Northern Lights). The treatise is based on a number of new and older descriptions of the Northern Lights, and includes several illustrations of the Northern Lights, along with precise information on where and when they were observed. The plate reproduced here comes from a 1710 treatise by Ole Rømer in the first volume of *Miscellanea Berolinensia*, which was published by the academy of sciences and letters in Berlin.

Among the earliest and most active natural scientists in the early period was Christian Gottlieb Kratzenstein, who published papers on mechanics, physics, astronomy, chemistry, and medicine in the Academy's publications series. The prolific, versatile Kratzenstein was German, and as the *Writings* were published exclusively in Danish after 1748, his contributions had to be translated from German to Danish. Unavoidably, the result was that several of his studies remained unknown abroad. The unfortunate language policy of the Academy, which remained in force until 1902, had similar consequences in a number of cases.

Throughout the first century of the Academy's history, its role was not only to facilitate the exchange of new knowledge, but also to initiate its own research and publication projects. While most of the projects the Academy initiated or was involved in were oriented towards scientific expeditions and descriptive natural history, a few were related to the exact and experimental sciences. Thus at the end of the 18th century, the Academy devoted considerable resources to projects concerning longitudinal reckoning at sea, and was also deeply engaged in the Danish state's extensive project of geographical and trigonometric surveying of the Kingdom of Denmark (read more pp. 26-30 and 64-65). The leading figure in the latter project was the astronomer Thomas Bugge, who was able to involve the Academy deeply in the geodetic-topographical venture by virtue of his position as secretary of the Academy in the period 1801-1815. The Academy's responsibility for the project ceased in 1830, when it was decided that the Ministry of War was to oversee all subsequent topographical work.

Bugge was succeeded as secretary by H.C. Ørsted, who also used his position to initiate two larger projects, which were not, however, of any particular scientific importance. The first of Ørsted's projects concerned geomagnetic measurements in connection with the establishment of a new "magnetic observatory" at the Polytechnic College (*Den Polytekniske Læreanstalt*).



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Dan. Biol. Medd. **22**, no. 3 (1954)

POSSIBLE
MATHEMATICAL RELATION
BETWEEN DEOXYRIBONUCLEIC
ACID AND PROTEINS

BY

G. GAMOW

København
i kommission hos Ejnar Munksgaard
1954

FIGURE 2. One of Gamow's treatises in the *Communications* of the Royal Danish Academy of Sciences and Letters, in this case in the biological rather than the mathematical-physical series.

On the strength of the new observatory and its measurements, Denmark became a member of a formalized international research collaboration for the first time, the Magnetic Union (*Magnetischer Verein*), which originated in Germany. The second project initiated by Ørsted was a costly and rather controversial artesian well drilling project which lasted from 1831 to 1848. While the project had a degree of geological and hygienic significance, it was criticized for its narrow focus on utility and lack of fundamental scientific relevance.

Primarily for financial reasons, the Academy ceased to initiate major physical-mathematical research projects after this time. On the other hand, representatives of these branches of science had a major influence on the Academy, which is reflected in the list of the Academy's presidents. In the century 1888-1988, the office of president was held by a series of eminent scientists, including Julius Thomsen (chemistry), 1888-1909), Niels Erik Nørlund (mathematics, 1928-1933), S. P. L. Sørensen (chemistry, 1938-1939), Niels Bohr (physics, 1939-1962), Bengt Strömgren (astronomy, 1969-1975), and Jens Lindhard (physics, 1982-1988). Throughout the 1800s, the Academy awarded smaller grants to subsidize instruments, publications, and travel to young researchers, a number of whom later became members of the Academy. Some of the scientists who benefited from this support include Ludvig August Colding and Julius Thomsen from the middle of the century.

Although not itself in a position to provide support for the natural sciences in Denmark in the 20th century, the Academy was indirectly involved in many research projects. In some periods, the grant policy of the Carlsberg Foundation had a decisive influence on what kinds of science could be pursued in Denmark, and the executive board of the foundation was appointed by the Academy, which in this way gained influence on developments and contributed to keeping the Carlsberg Foundation focussed on basic research.

In addition, the Academy's publications series had an indirect scientific significance, as several extremely important contributions to the physical and mathematical sciences were published in this way in the period from about 1915 to 1970. For example, the young Niels Bohr published a groundbreaking treatise on quantum theory in the natural science-mathematics section of the *Writings* in 1918. Later, several works of Bohr and his co-investigators were published in the Academy's mathematical-physical *Communications*. In addition, Niels Bohr's younger brother, the mathematician Harald Bohr, published important communications in this series in the 1930s and 1940s on almost periodic functions and Dirichlet series. Among the very few foreign members who contributed to the Academy's publications was the versatile Russian-American physicist George Gamow, who wrote several treatises on cosmology and other topics in *Communications*. Finally, Bengt Strömgren also availed himself of this publication opportunity on occasion. From 1917 to 1990, a total of 41 treatises were published in the mathematical-physical *Communications*.

Changes in the conditions for research

In the post-war years, issues of research policy became an increasingly important aspect of the discussions and activities which took place under the aegis of the Academy. In harmony with the spirit and aims of the Academy, these issues covered the entire scientific and scholarly spectrum, and some of them arose out of or were motivated by developments in the physical sciences. By way of background, a brief overview of some of the important phases in Danish research policy in the years between 1945 and 1992 may be helpful here.

The need for a fully articulated research policy did not arise until the emergence of the new world order after the end of the war – a research policy which was not simply left in the hands of private organizations, but which to a very high degree was considered to be a task for the state. The most important of the new institutions established in the first decade was the national science foundation (*Statens Almindelige Videnskabsfond*) in 1952. Characteristically, the foundation was often referred to as 'the national Carlsberg Foundation', and the funds at its disposal were of the same relatively modest proportions. The distribution of the foundation's funds was handled by subject-specific five-member commissions, and the Academy was assured two seats on the natural sciences commission. And as the other three members of the commission were also members of the Academy, it exercised considerable influence in the foundation, which in many ways was the extended arm of the established university research world. However, the national science foundation could not itself initiate research projects, but was limited to allocating grants on the background of applications.

This situation changed in 1968, when five research councils were established as a replacement for the earlier commissions on the recommendation of the new joint research committee (*Forskningens Fællesudvalg*). The agenda for the research councils was set by politicians and civil servants rather than by the scientific and scholarly communities, and the councils could launch independent initiatives, unlike the commissions they replaced. The Academy was still involved, but only with a right of nomination. For example, in 1968 the Academy nominated biochemist Heinz Holter and nuclear physicist Ben Mottelson to the national natural sciences research council (*Statens Naturvidenskabelige Forskningsråd*), and the ministry selected the former candidate. In 1972, the planning council for research (*Planlægningsrådet for Forskningen*) was established as an advisory body for the government and the Danish Parliament (*Folketinget*). While the Academy did not have a privileged position in this body, several of the Academy's members were members.

In 1989, the planning council was replaced by a new research policy council (*Forskningspolitisk Råd*) with an associated representative council. The Academy was granted a single seat on the representative council, which however was shared with the Danish Academy of Technical Sciences. Perhaps the most important innovation in the research policy of this period followed two years later with the establishment of the Danish National Research Foundation as an independent and extremely well-capitalized organization. The first director of the foundation and chairman of the board until 1998 was the biochemist Peder Olesen Larsen, who was a former member of the planning council for research in addition to the Nordic research policy council (*Nordisk Forskningspolitisk Råd*). The foundation's initial capital was DKK 2 billion, and it received an additional DKK 3 billion in 2008. The new foundation was to exercise its influence primarily through the establishment of Centres of Excellence, and secondarily by attracting outstanding international researchers to Niels Bohr professorships.

This was neither the first nor the last time Niels Bohr's name and reputation would be used for research policy ends. As a kind of prelude to the celebration of the centennial of Bohr's birth, a private committee of scientists and industrialists collected DKK 12 million to finance stipends for promising young natural science researchers without permanent positions. The funds were administered by the Academy, which was also responsible for the selection of the 16 stipend recipients in the fields of mathematics, zoology, geology, physiology, astronomy, and chemistry. Although the Niels Bohr stipends were important in this period, the program ended in 1987. In any case, the centennial of Bohr's birth was celebrated with due pomp and circumstance in 1985, not least by the Academy. A similar though more modest celebration was held when Aage Bohr and Ben Mottelson received the Nobel Prize in Physics in 1975.

The conditions under which natural sciences research was performed in the last half of the 20th century were very different from those which prevailed at mid-century. Naturally enough, developments in Denmark reflected international tendencies, which can be summarized in terms of a few main trends: growth, collectivization, bureaucratization, globalization, increased competition, and a tendency towards applied and international research. The tendency towards 'big science' in the experimental sciences was confirmed by a number of international projects and research organizations in which participation on the part of Danish natural sciences research was a necessity.

Among the first and largest of these international organizations was CERN, the joint European laboratory for nuclear and particle physics, which Denmark joined in 1954 after having proposed Copenhagen as the location of the laboratory. Although the candidacy was unsuccessful, these efforts did indirectly lead to the establishment of NORDITA (the Nordic Institute for Theoretical Physics) in 1957. At the end of the 1960s, Denmark also joined two big science astronomy projects, ESRO (the European Space Research Organization) and ESO (the European Southern Observatory). Bengt Strömgren was active in the organization of ESO and served as president of the ESO Council from 1975 to 1977. In addition, Denmark joined the European Science Foundation (ESF) in 1975, a development of greater and more general significance, as it soon became clear that ESF would become a very important source of research funding.

Modern mathematics

In the first half of the 20th century, the dividing line between pure and applied mathematics became clearer, as a consequence of the reinterpretation of mathematics as the study of axiomatically defined structures by a group of French mathematicians under the pseudonym Bourbaki. In principle, the axioms in these structures are arbitrary as long as they do not contradict one another, and the objects have nothing to do with physical objects. By virtue of this reconceptualization, mathematics was severed from the physical reality which had inspired it, philosophically speaking. But at the same time, mathematics was finding more applications than ever before, both within traditional areas such as astronomy and physics and within new areas such as biology and economics.

During the second half of the 20th century, both pure and applied mathematics continued on the paths which had been marked out in the first half of the century, and the interplay between pure and applied mathematics was strengthened. Within the last 40 years, Danish mathematics has been recognized in particular for contributions in the areas of operator algebra, algebraic topology, statistics and probability theory; as well as mathematical physics, algebraic and arithmetic geometry, and discrete mathematics in recent years as well. Danish researchers have also made substantial contributions to other areas of analysis and algebra.

Research on analysis and algebra

Among the structures which mathematicians became interested in during the post-war period were the von Neumann algebras and C*-algebras, which were developed as a framework for quantum mechanics. The classification of the hyperfinite von Neumann algebras was completed in 1984 in a famous paper by Uffe Haagerup. The classification of general C*-algebras was originally thought to be impossible. But around 1990, George Elliot embarked on a project which involved dozens of mathematicians all over the world, and which culminated in 2015 with a complete classification of a natural class of simple C*-algebras. Several Danish mathematicians contributed to this effort, including Gert Kjærgaard Pedersen, Søren Eilers, Mikael Rørdam, and Klaus Thomsen, along with many of their PhD students and postdocs. The project as a whole comprised hundreds of articles and thousands of pages.

The above-mentioned classification results illustrate that although there are still more individual projects and publications in mathematics than in the natural sciences, the tendency is towards larger collaborative efforts here as well. In addition to the increasing complexity of mathematical problems, this development is also driven by the structure of research funding, which requires increasingly large research groups.

Additional Danish contributions to mathematical analysis include Bent Fuglede's studies of potential theory and Christian Berg's investigations of so-called indeterminate moment problems, which have an infinite number of solutions. The latter area combines complex analysis and classes of special functions, including orthogonal polynomials, and was the subject of an international symposium held by the Academy in 2012. Within the subject of geometrical analysis, Danish mathematicians have contributed to advancing the development of the analysis of symmetric spaces. In this connection, a mathematical problem naturally arises which is entirely analogous to the decomposition of a sound or light signal in pure oscillations or colors. This problem was completely solved in the period between 1980 and 2005 by an international group of mathematicians which included Mogens Flensted-Jensen and Henrik Schlichtkrull.

With support from a number of major grants from the EU and the Danish National Research Foundation, among others, Henning Haahr Andersen has headed a group of researchers at the Department of Mathematics, Aarhus University which specializes in representation theory since 1980. In the beginning, the group focussed on representations of Lie algebras and algebraic groups. In the mid-1980s, quantum groups arrived on the scene, which led to the solution of a 40-year-old fundamental problem within modular representation theory. The solution is valid for all sufficiently large prime numbers, and Haahr Andersen and many others have since worked to expand the result to apply to all prime numbers. This has involved a fundamental study of a new class of representations, the so-called tilting modules. In recent years, tilting theory has become the primary ingredient in an entirely new development within modular representation theory.

Traditionally, Danish algebraic topologists have focussed on two areas of study: algebraic K-theory and moduli spaces of manifolds. More recently, homotopy group theory has become an important research area. Ib Madsen and other Danish mathematicians have made a groundbreaking contribution to the understanding of algebraic K-theory through the introduction and development of topological cyclic homology. A major Danish result in this area is Lars Hesselholt's and Ib Madsen's proof of the so-called Quillen-Lichtenbaum conjecture for local number fields. Together with Michael Weiss and with the support of a grant from the European Research Council (ERC), Madsen also made a sensational contribution to the theory of the topological structure of Riemann's moduli spaces which occupies a central position in mathematics and physics. This contribution, which stems from the beginning of the 21st century, has given rise to intense international activity which continues to this day. As part of this activity, Søren Galatius was awarded the Academy's silver medal in 2009.

FIGURE 3. Algebraic topologists (Ib Madsen and Lars Hesselholt) at work. The old-fashioned blackboard is still popular among mathematicians. While intuitive geometrical figures are invaluable in the research process, they are seldom included in published papers.

Graph theory, statistics and mathematical physics

Graph theory is the branch of mathematics which investigates abstract networks. The Danish mathematician Julius Petersen was a pioneer in this field. Since then, the field has grown explosively, not least as a result of the interplay with other fields of mathematics as well asits applications in engineering (electrical networks), operations research (optimization), and theoretical computer science (algorithms). Carsten Thomassen's contribution to several topics within structural graph theory were supported by an ERC grant in 2013. Mikkel Thorup has made fundamental contributions to algorithmic graph theory, including the first undirected single-source shortest paths algorithm.

Within the past 40 years, most areas of mathematics, including graph theory, have been affected by the emergence of computers and their ever-increasing computational power. Computers permit mathematicians to do experiments resembling experiments in the natural sciences. Such experiments normally result in conjectures which mathematicians must prove in the traditional manner. However, in a few cases computers have also contributed to the solution of mathematical theorems, including the famous four-color theorem, which states that no more than four colors are required to color the regions of a map so that no two adjacent regions have the same color. Computer calculations are also central to most applications of mathematics and statistics.

One of the most important results in mathematical physics is the proof of the stability of matter on a macroscopic scale. Some of the most eminent mathematicians and physicists have been working on this problem for decades, including the pioneer Freeman Dyson. An important contribution to understanding this stability when magnetic forces are taken into account was provided by Jan Philip Solovej in 1995. In 2006, he was also able to prove one of Dyson's earlier conjectures concerning the stability of matter in relation to the superfluid state. His proof was not only significant for the understanding of macroscopic stability, but also provided mathematical verification of the theory of superfluidity for the first time. Since 2013, Solovej's research has been supported by an ERC grant.

Danish statisticians have made central contributions to the development of methods for the analysis of observations from stochastic processes and to the underlying theory. Such methods have been made possible by the great advances made in modern probability theory in the past 50 years. In research groups associated with Ole Barndorff-Nielsen and Michael Sørensen, there has been particular interest in stochastic differential equations, which are ordinary differential equations to which more or less complex types of random noise have been added. These models are central to modern finance theory, and are becoming increasingly widespread in many other fields. In recent years, there has been strong interest in the theory of high frequency asymptotics, which describes and exploits the extra information which is achieved when a stochastic process is observed very frequently.

Barndorff-Nielsen and a group of associated researchers developed the theory of ambit processes, for which the dynamic development is determined by the integral of random elements distributed in time and space in a so-called ambit set. This theory was in part developed as an alternative model of turbulence, and has required completely new developments in stochastic analysis.

In collaboration with the considerable research group she has built up, Susanne Ditlevsen has developed methods which make it possible to use stochastic differential equations for modelling and data analysis of many biological processes, not least in neuroscience and physiology. Research in statistics for stochastic processes has received considerable funding, for example from the EU. From 1998 to 2004, the Danish National Research Foundation funded a Center for Mathematical Physics and Stochastics, until 2003 headed by Barndorff-Nielsen.

Søren Johansen's contributions to the statistical theory of time series has received wide international recognition. In the period 1990-2000, he was the most-cited economist in the world, and is often referred to as the Danish researcher who has come closest to winning the Nobel Prize in Economics. Inspired by economic applications, Johansen has, jointly with Katarina Juselius, developed useful methods based on probability theory and mathematical statistics, which have found applications in central banks and financial institutions all over the world. Another topic in economics which is studied using mathematical methods is the modelling of credit risk. In the 1990s, David Lando formulated a class of models which are highly applicable to the study of corporate bonds. The models have also turned out to be useful in the study of financial frictions as they occurred in connection with the financial crisis which began in 2008. In 2012, Lando received a grant from the Danish National Research Foundation for a Centre of Excellence whose objective was precisely the study of the significance of financial frictions in financial markets.

In the last 20 years, mathematical and statistical methods have turned out to be relevant to risk management at banks and insurance companies. In this connection, Thomas Mikosch has developed models for extreme events in finance and insurance and their statistical analyses. His 1997 book on extreme events is a classic.

In the 1980s, Steffen Lauritzen and others developed models based on concepts from graph theory for describing, understanding and analyzing the connections between systems of many stochastic variables. Graphic models of this type have found a wide variety of applications, for example in artificial intelligence and the discussion of causal structures, as well as in genetics and forensic genetics. Lauritzen's 1996 book has become a seminal reference work in this area.

Finally, mathematical biology has developed rapidly over the past decade. Topics in molecular biology have begun to interest pure mathematicians, who are able to apply the results from their own fields to understanding and describing biological phenomena on a general level. To a certain extent, it might be said that the focus of mathematical biology has shifted from

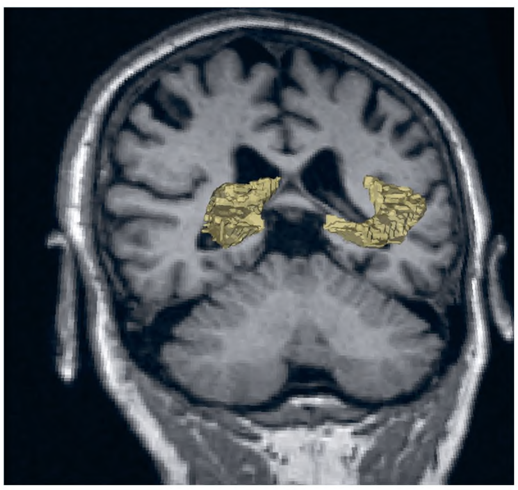


FIGURE 4. Segmentation of the hippocampus (left and right hippocampus), shown here as a three-dimensional rendering of a T1-weighted MRI slice (prepared by Lauge Sørensen, PhD). The segmentation was performed with the program FreeSurfer, which is a widely-used program for analyzing brain scans. Segmentation of MRI images can be used to calculate the volume of different parts of the brain. The technique can be used to detect cerebral atrophy, and is a common imaging biomarker in neurology, for example in connection with Alzheimer's disease, where hippocampal volume has been approved by the European Medicines Agency (EMA) as a predictive biomarker of Alzheimer's disease in clinical trials of subjects with a high probability of developing dementia.

modelling to theory formation. Carsten Wiuf from the University of Copenhagen has primarily contributed to applications of systems biology and the mathematical understanding of the connections within and between classes of deterministic and stochastic models of the same biological phenomenon. The large, complex volumes of data contained in electron microscope images of biological systems make stochastic analyses necessary. Danish research on steoreological methods of this type is the most advanced in the world. The Centre for Stochastic Geometry and Advanced Bioimaging at Aarhus University, which is headed by Eva Vedel Jensen, is one location for this type of research.

Computer science

Despite the brevity of the history of computer science in this context, Denmark has a strong and important research tradition in theoretical computer science which is derived from mathematics. The Center for Theoretical Computer Science (BRICS) was one of the centers which was established in 1993 in the first round of basic research centers. The center covered theoretical computer science in a very broad sense, and included complexity theory, algorithmics, logic, semantics, programming languages and cryptography. Denmark's strong position within complexity theory and algorithmics also led to the establishment of the Center for Massive Data Algorithmics (MADALGO) in 2007, as well as the Danish-Chinese Center for the Theory of Interactive Computation i 2011, which were funded by the Danish National Research Foundation. Both centers received funding until 2017. MADALGO is headed by Lars Arge, and the center focuses on the development of algorithms and data structures for efficient processing of extremely large amounts of data, for example by developing algorithms which are efficient in models which realistically reflect the memory hierarchies of modern machines. Not only has the center achieved considerable international recognition for its theoretical work, it has also worked in a more application-oriented manner, for example on biodiversity, in collaboration with Jens-Christian Svenning, and on the assessment of flood risk using very detailed (and therefore large) topographical models. The center's work on flood risk has resulted in the successful company SCALGO. In 2010, Arge received the Elite Research Prize for his research, and in 2012, he was appointed Fellow of the Association for Computing Machinery. Arge has been a member of the Presidium of the Royal Danish Academy of Sciences and Letters since 2015, and in 2016, he was elected general secretary of the Academy.

Another leading figure in Danish research on algorithms and data structures is Mikkel Thorup. Thorup has contributed many fundamental results, for example an extremely efficient algorithm for the solution of the shortest-path problem. From 1998 to 2013, Thorup worked at AT&T Labs – Research, where several of his algorithms found applications in internet routing. Since 1993, Thorup has headed the research group Efficient Algorithms and Data Structures at the University of Copenhagen. Thorup is a Fellow of the Association for Computing Machinery, and in 2015, he was awarded the Villum Kann Rasmussen Annual Award in Science and Technology.

Another important research area in relation to processing large amounts of data is database research, which Christian Søndergaard Jensen has been instrumental in developing at Aalborg University. Jensen defended his higher doctoral dissertation, *Temporal Data Management,* in 1999. Particularly noteworthy elements of this work include the exploration of a new temporal SQL language (Structured Query Language) and its effective realization in existing database systems. Later, Jensen's focus shifted to processing data with references to both place and time, known as spatiotemporal data. In this area, researchers from Aalborg University have made important contributions to the development of indexing techniques which make it possible to perform extremely efficient searches in enormous amounts of data. This research was among the achievements for which the Villum Kann Rasmussen Annual Award in Science and Technology was awarded to Christian S. Jensen. Most recently, a considerable part of this research has focussed on techniques which exploit position data from vehicles to enable the calculation of new types of routes in road networks. Jensen is a Fellow of the Association for Computing Machinery and a Fellow of the Institute of Electrical and Electronics Engineers (IEEE).

Denmark also has a strong research tradition within modelling, verification and analysis of embedded systems (cyber-physical systems). In this field, Kim Guldstrand Larsen has directed a wide variety of projects, both basic research and more applied research, at the Center for Embedded Systems at Aalborg University. Larsen is particularly well known for his work on UPAAL, a tool for the verification and analysis of real-time systems. In addition, he has developed new theoretical models and logics aimed at quantitative analysis of concurrent embedded systems. His re-

FIGURE 5. Two photos from the history of early computers in Denmark. To the right, Niels Ivar Bech, Willy Heise, Bent Scharøe Petersen and H. B. Hansen working in 1957 with DASK (Dansk Aritmetisk Sekvens-Kalkulator), the first computer that was developed in Denmark. The photo was taken in 1957 in Regnecentralen, the first Danish computer company. To the left, interior in Regnecentralen 1968. Dansk Datahistorisk Forening.

search has been supported by several foundations including the Danish National Research Foundation, which provided funding for the Sino-Danish center IDEA4CPS in 2011. Larsen also received an ERC Advanced Grant from the EU in 2015. He is an honorary doctor at Uppsala University in Sweden and at the École Normale Superieure Cachan (ENS Cachan) in France, and he received the Grundfos Prize in 2016.

One area in which Denmark has been at the forefront for a very long time is programming languages. As early as 1960, Peter Naur edited a report on the programming language ALGOL, (*Report on the Algorithmic Language ALGOL 60*), which became extremely important. He also contributed to the development of BNF (Backus-Naur Form), a notation technique for describing the syntax of programming languages. In 2005, he received the highest honor in computer science, the ACM Turing Award, for his fundamental contribution to the design of programming languages and program compilation.

In the early 1980s, Neil D. Jones initiated and directed research on the development of new methods for manipulating programs as data, together with the TOPPS group at the Department of Computer Science at the University of Copenhagen. The group became especially known for its work on partial evaluation, a form of automatic program optimization. A milestone in this field is the book *Partial Evaluation and Automatic Program Generation* (1993), by Neil D. Jones, Carsten K. Gomard and Peter Sestoft. Jones was named Fellow of the Association for Computing Machinery in 1998, and in 2014, he received the ACM SIGPLAN Programming Languages Award for his contributions to research on programming languages. Another significant contribution was related to the development of the programming language Standard ML: Mads Tofte co-authored the book *The Definition of Standard ML*, the first mathematical description of the semantics of a full programming language. Tofte also directed research on 'region-based memory management', a new implementation technique for ML which was implemented in the ML-Kit compiler, and to which Lars Birkedal also contributed.

In the 2000s, Birkedal headed the development of the Programming, Logic and Semantics research group at the IT University of Copenhagen, since 2013 at Aarhus University. Birkedal's group has focussed on the development of new mathematical models and logics for the description and analysis of programs and type theories. In recent years, the group has focussed on new program logics which can be used to reason about realistic programs written in modern programming languages which combine a variety of programming language elements which are challenging to model, but which are very important in programming in practice. Birkedal received the Elite Research Prize in 2013.

Danish researchers have also made a significant contribution to image processing research. One of the major challenges is that an image contains an incredible amount of information, which makes it difficult to process images automatically. This makes it important to develop techniques for extracting the information which is most relevant for a particular purpose. Since the 1970s, Peter Johansen has developed new mathematically-based techniques which can be used to scale down an image, which both makes it easier to find relevant information and also makes it possible to reconstruct the image with sufficient precision. Johansen's theoretical foundation for image processing has since been complemented by applications to medical image processing developed by Mads Nielsen's group.

Finally, there is reason to add cryptography to the list of fields in which Danish researchers are world leaders. In particular, Ivan Damgaard has developed a research group at Aarhus University which is known for its work on secure multiparty computation, which makes it possible to compute a common function based on private data from a range of different parties, without requiring these parties to make their private data public. In 2010, Damgaard was appointed Fellow of the International Association of Cryptologic Research, and in 2015, he received an ERC Advanced Grant from the EU.

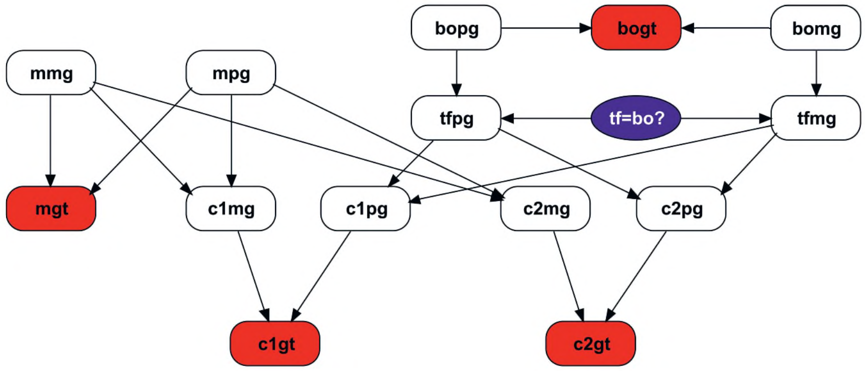


FIGURE 6. Graphical model in the form of a so-called object-oriented Bayesian network, which describes relationships among a group of individuals in which a missing person could potentially be identical to the father of two identified children (c1 and c2) whose mother (m) is also identified. Based on genotyping of the individuals involved (marked in red), the probability that the unknown individual is identical with the missing person (tf=bo?) can be calculated effectively. Each of the rounded boxes contains yet another Bayesian network of the same kind which describes a graphical model for the genetic processes involved.

Contemporary developments in the physical sciences

In this context, 'the physical sciences' is not a precisely defined concept; the term essentially refers to physics and to the sciences which draw on the laws, methods and results of physics to a significant degree, first and foremost astronomy and chemistry. Much of the research activity in the physical sciences is interdisciplinary and involves two or three of the classical disciplines, for example chemical physics, astrophysics and cosmology. But the diverse landscape of the physical sciences also includes aspects of fields traditionally belonging to natural history, such as geology and biology. Examples include biophysics, geochemistry, geophysics and even astrobiology.

An entirely different form of interdisciplinarity is cultivated in the history and philosophy of the mathematical-natural sciences. The first representatives of the history of science as an academic discipline in the Academy were Olaf Pedersen and more recently Jesper Lützen and Helge Kragh. As is perhaps characteristic of the intrinsically interdisciplinary nature of the history of science, Kragh is a member of the humanities class, while Lützen, whose primary field is the history of mathematics, is a member of the class of mathematics and natural sciences. In addition, the philosopher Carl Henrik Koch has also contributed works on the history of science, including not least a monumental biography of Isaac Newton which was published in 2013.

Some of the symposiums and larger events to which the Academy has contributed have focussed on the history of science, such as the 200th anniversary of Caspar Wessel's paper on the geometrical representation of complex numbers in 1998, which was commemorated with a symposium organized by the Academy in collaboration with Lützen. Another notable event was the international conference held in 2013 to mark the 100th anniversary of Niels Bohr's atomic theory, which was organized in collaboration between the Niels Bohr Archive (with Finn Aaserud) and the Academy. The conference papers were published by the Academy in a volume of the new series *Scientia Danica*, edited by Aaserud and Kragh. In 2016, the latter published a detailed biography of the chemist Julius Thomsen, who was president of the Academy from 1888 to his death in 1909, as previously mentioned. Another important publication on the history of science in the Academy's publication series was H.C.Ørsted's travel letters, which were published in Danish and English by Karen Jelved and the physicist Andrew Jackson. While the first two of the publications referred to here was published in the physical-mathematical section of *Scientia Danica*, the latter work was published in the humanities section. The contributions to the Wessel symposium of 1998 were published as an issue of the Academy's mathematical-physical *Communications*.

Physics

By about 1990, the fundamentals of the standard model of the three fundamental forces and their associated particles were in place. While the standard model is a unified theory, it is not a theory of 'everything', as it does not include gravity or the gravitational force. In Denmark, attempts to include gravity within the framework of quantum mechanics in the form of a theory of quantum gravity have been explored in various ways by researchers including Jan Ambjørn and Charlotte Fløe-Kristjansen, both of whom are affiliated with the Niels Bohr Institute. Ambjørn is working with a theory (Causal Dynamic Triangulation, CDT) which does not require supersymmetry or more than the standard four dimensions of space-time. In a number of ways, the theory resembles another better known alternative to quantum gravity, Loop Quantum Gravity (LQG). Although the CDT theory is rather unconventional, it is considered to be worth pursuing, as the large ERC grant Ambjørn was awarded in 2011 to support the theory's continued development attests.

Ambjørn's preferred theory is completely different than the popular string theory which was proposed around 1970, one of whose earliest contributors was Holger Bech Nielsen, who is also a member of the Norwegian Academy of Sciences and Letters. In 2001, he was awarded the Humboldt Research Award by the German Alexander von Humboldt-Foundation in recognition of his research on theoretical physics. In addition to his contributions to science, Bech Nielsen is also known to the general public for his original and engaging public lectures on physics and string theory. Kristjansen is investigating the possibility of integrating elements of particle theory and string theory in order to predict measurable consequences of string theory. She is also involved in Ambjørn's CDT research project.

There is a world of difference between string theory and the kind of physics Per Bak represented and advocated from about 1980 until his untimely death in 2002. Bak is perhaps the only Danish scientist of our time whose work has given rise to what some characterize as a new paradigm. His studies of critical phenomena and phase transitions led him to the dynamics of complex systems, and in 1987, to a general theory of 'self-organized criticality' which can be applied to a wide variety of natural phenomena. This theory won wide support and resulted in a veritable avalanche of new research, but it also encountered considerable criticism. Together with Kim Sneppen, in 1993 Bak developed a model of biological evolution on the basis of the idea of self-organized criticality. In 1996, he published a popular explanation of his ideas in the book *How Nature Works*, which quickly became a popular science bestseller. Bak was not only a charismatic and innovative physicist, he was also – like several other members of the Academy – a sharp critic of what he and others saw as the poor conditions for basic research in Denmark.

To a certain extent, Bak's focus on complex and chaotic systems in nature as well as in society has been continued by Mogen Høgh Jensen, Kim Sneppen, Tomas Bohr, Søren Brunak and others. Brunak has focussed on neural networks and bioinformatics in particular. After 25 years at the Technical University of Denmark (DTU), in 2015, he moved on to a principal investigator position at a new center for protein research at the University of Copenhagen financed by the Novo Nordisk Foundation. Another of Bak's colleagues in Copenhagen was Predrag Cvitanović, who was born in Croatia and educated in the United States. Until 2001, Cvitanović was the director of the Center for Chaos and Turbulence Studies (CATS) at the Niels Bohr Institute, and he has made important contributions to our understanding of the dynamics of chaotic systems.

Høegh Jensen has been extremely active, both as a scientist and as a member of the Academy. He became secretary of the Academy in 2011, and was elected president in 2016. He was the center director at CATS for a period, and since 2005, he has worked together with Sneppen as the head of the Center for Models of Life (CMOL). In a large number of articles, he and his fellow researchers have studied complex systems, including turbulence in liquids and fractal structures in biological systems. Høegh Jensen has received considerable recognition for his work, including the Norwegian Gunnar Randers Physics Prize in 2011. He shares his interest in biophysics, turbulence and complexity with Tomas Bohr from DTU, whose primary research focus has been on mathematical models for the behavior of liquids in natural systems. Together with Høegh Jensen and two Italian physicists, Tomas Bohr published the treatise *Dynamical Systems Approach to Turbulence* in 1998.

Like the study of complexity and chaos, nanophysics or nanoscience and nanotechnology in general are quite new fields in physics. The study of nanomaterials emerged in the 1980s, and has been developing explosively since then, not least on account of the extremely strong technological and financial interests invested in this field of research. Nanoscience is intrinsically interdisciplinary, and involves at least as much chemistry as physics. In fact, even biology and medicine have a stake in nanoscience.

In Denmark, Fleming Besenbacher at Aarhus University became the pioneer in this field in 1986, when he and a few members of his research team built a scanning tunnelling microscope, an advanced apparatus which is crucial to nanoresearch. He later went on to found the major center iNANO (the Interdisciplinary Nanoscience Center), which he directed from 2002 to 2012. Aside from an extremely active research career in nanoscience, Besenbacher has also been involved in research policy and industrial activities, including the establishment of close ties to research institutions in China. In 2005, the Academy appointed him to the board of the Carlsberg Foundation, and in 2012, he became chair of this wealthy and powerful foundation. But Aarhus is not the only place where nanoscience is flourishing. In Copenhagen, Thomas Bjørnholm has been the leading figure, and he directed a regional center for nanoscience and nanotechnology from 2003 to 2013. His background is in materials chemistry, not physics. Like Besenbacher, Bjørnholm has received numerous scientific awards and honors, and holds a number of positions related to research policy and business and industry. In 2010, he became pro-rector of the University of Copenhagen.

The close ties between nanoresearch and its practical applications are also evident in the careers of two of the Academy's younger female members, Anja Boisen and Lene B. Oddershede, who are professors at DTU and the Niels Bohr Institute respectively. As head of section at DTU Nanotech since 2005, Boisen has focussed on the development of nanotech sensors and their applications in a wide variety of areas. Oddershede's work in nanoscience is linked to cancer research, and more generally to the intersection between physics and biomedicine. Much of her work takes place under the aegis of the basic research center StemPhys (the Center for Stem Cell Decision Making), which was established in 2015 and which she directs, as well as the contemporaneous LANTERN (Laser-Activated Nanoparticles for Tumor Elimination) project, which is funded by the Novo Nordisk Foundation.

Materials research of a different type than in the nanosciences is taking place at Roskilde University (RUC), where Jeppe Dyre is the director of a successful research center, the Center for Viscous Liquid Dynamics (Glass and Time), founded in 2005. Dyre and his colleagues are leaders in glass research, which is concerned with understanding what happens at the molecular level when a viscous liquid is transformed into glass. This interdisciplinary work has been generously supported by the Danish National Research Foundation and has resulted in numerous scientific articles, including several in the journal *Nature*. In 2006, Innovation Fund Denmark contributed to a new project at the center, this time with a more application-oriented focus, aimed at reducing the rolling resistance of vehicles on asphalt pavement. By developing new surface treatments, Dyre and his group are working to reduce the resistance of cars on the road, which will also reduce fuel consumption.

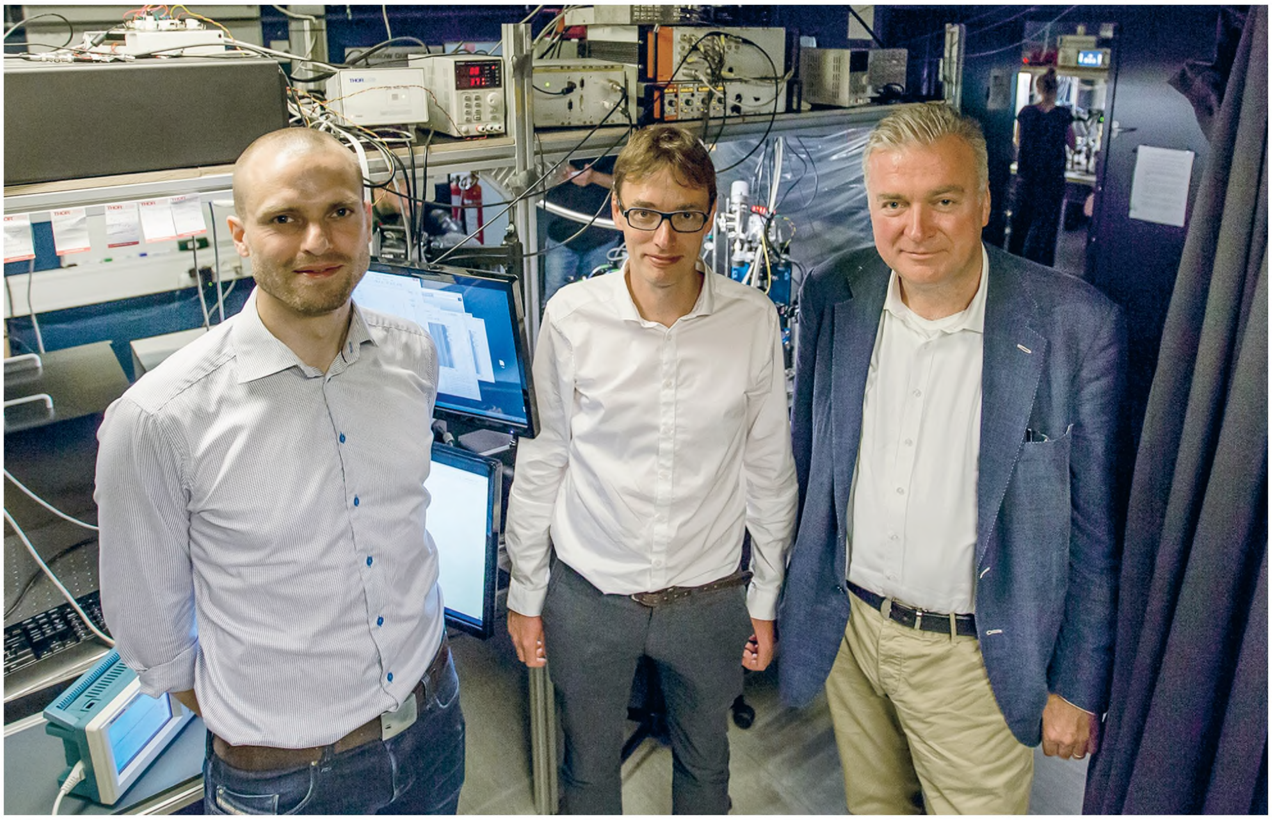
Much modern physics research, both in Denmark and internationally, focusses on light and the photons it consists of, which are described by quantum mechanics. Within this broad area of quantum optics and 'photonics', Lene Vestergaard Hau is perhaps the most well-known and successful Danish physicist. Hau received her PhD from Aarhus University in 1991, but has pursued her research career as a professor at Harvard University since 1999, where she and her colleagues created a minor sensation in 2001 by stopping light using an ultra-cold Bose-Einstein condensate. She became known as 'the woman who stopped light'. In experimental studies, Hau has explored the exchange of information between matter and light, which has enabled her to control and manipulate optical information. Hau's experiment was featured on the front cover of the February 8th 2007 issue of *Nature*. At a major event at the Carlsberg Academy in 2011, she was awarded the Carlsberg Foundation Research Prize, on the nomination of the Academy. Three years previously, she had been elected to the Swedish Academy of Sciences and Letters as a foreign member.

Much of the work on quantum optics and related fields taking place in Denmark is being performed by research groups in Copenhagen and Aarhus led by

FIGUR 7. From the conferral of the Carlsberg Foundation Research Prize to Lene Hau and the philosopher Dan Zahavi at the Carlsberg Academy in 2011. The latter (no. 2 from the right) received the humanities prize. Also pictured are Flemming Besenbacher (then member of the board of the Carlsberg Foundation), Søren-Peter Olesen (then secretary of the Academy), Kirsten Hastrup (then president of the Academy), and Povl Krogsgaard-Larsen (then chair of the board of the Carlsberg Foundation).

Eugene Polzik and Klaus Mølmer, among others. As head of the research center Quantop at the Niels Bohr Institute, Russian-born Polzik has played a central role in the study of quantum entanglement, a phenomenon in quantum mechanics which has to do with an interdependency of quantum particles (for example photons) even when separated by large distances. In 2013, Polzic received a DKK 18 million grant from the ERC for a new project which seeks to entangle quantum information in nano-electric circuits and ultimately to contribute to the development of a quantum computer. Another aspect of this research is quantum teleportation, the transfer of physical states between two physically separate systems of atoms. In 2013, Polzik's groups succeeded in demonstrating quantum teleportation between two containers which were two meters apart. Jesper Nygård at the Niels Bohr Institute works with quantum electronics, biosensors and nanophysics, and is also the co-founder of companies based on applying results from these research areas.

In 2011, Peter Lodahl became a professor at the Niels Bohr Institute, where he heads a research group on quantum photonics, which explores connections between quantum optics and nanophysics. The close ties between basic research and commercial technological interests in this area is highlighted by the company Sparrow Quantum, which Lodahl and his colleague Associate Professor Søren Stobbe founded in 2016 to develop and manufacture a new kind of optic chip. The expectation is that this single photon chip will be used in the quantum computer of the future, and for this reason, the new company has been able to attract considerable capital, not only from Innovation Fund Denmark but from private investors as well.

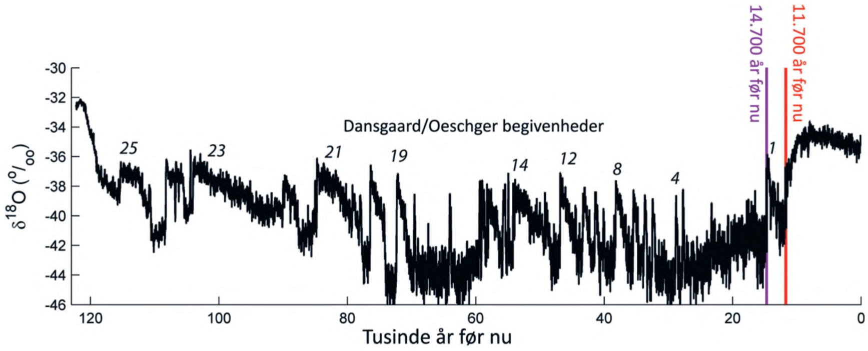


FIGUR 8. Peter Lodahl and Søren Stobbe from the Niels Bohr Institute's quantum photonics group made headlines when they formed the company Sparrow Quantum in 2016. Stobbe is on the left, Lodahl in the middle, and on the right is financier and bank CEO Lars Seier Christensen.

In Aarhus, similar research interests are pursued by Mølmer, who served as director of the Lundbeck Foundation Theoretical Center for Quantum System Research from 2006 to 2011. Like his colleagues in Copenhagen, Mølmer has won many awards, including the Elite Research Prize in 2017 and the Villum Kann Rasmussen Annual Award in Science and Technology. He is also very active in the dissemination and popularization of physics, and is much in demand as a speaker as a result.

The position of geophysics in Danish science changed with Willi Dansgaard's innovative method from the 1960s for dating ice cores using mass spectrometry to analyse the amount of the heavy oxygen isotope O-18 in a sample. His near colleague from the ice research of the 1960s, the American geologist Chester Langway, became a foreign member of the Academy in 1992. Dansgaard concluded his active career with the Danish-led Greenland Ice Core Project (GRIP), which was financed by the European Science Foundation and lasted from 1989 to 1992. On the basis of the 3029 meter-long ice core which was the main result of the project, researchers could map climate changes over 250,000 years. Some of these climate changes were already well-known, while others were new and unknown. Even though Dansgaard retired in 1992 and his most important scientific contributions belong to the earlier period of his career, he remained active. In 1995, he was the first Dane to receive the prestigious Swedish Craaford Prize for the geosciences. The Craaford Prize, which was established in 1980, is awarded in the categories astronomy, mathematics, biosciences and geosciences, and has almost the same status as the Nobel Prize.

Dansgaard passed away in 2011, at a time when his legacy was still as vibrant as ever. The young geophysicist Dorthe Dahl-Jensen, who was one of the researchers who worked on the GRIP project, published an important article in 1995 together with Dansgaard, Sigfus Johnsen and Niels Gundestrup about the temperature history of Greenland, based on results from GRIP. Dahl-Jensen became director of the Centre for Ice and Climate, a basic research centre at the Niels Bohr Institute in 2007, and in this capacity has been responsible for a number of ice coring projects, on Antarctica as well as in Greenland. In the period 2009-2011, the Greenlandic NEEM project corrected and improved some of the results from GRIP; the title NEEM refers to the last interglacial period, the Eemian, from about 130,000 to 115,000 years ago. In 2015, Dahl-



FIGUR 9. Variations in the content of the oxygen-18 isotope show that there were rapid and approximately periodic changes in Greenland's climate from about 15 to 120 million years ago. The changes are known as 'Dansgaard-Oeschger events,' a reference to Willi Dansgaard and his Swiss collaborator Hans Oeschger who discovered them in the 1980s.

Jensen received a major grant for the center from the A.P. Møller Foundation for a new project in Greenland which will focus on exploring the mobility of the Greenland Ice Sheet. This glaciological project is expected to be completed in 2020. Dahl-Jensen has participated in numerous international conferences on Greenland, climate research and global warming, and has received numerous awards for her work.

Astronomy and astrophysics

A considerable amount of modern Danish astronomical research takes place in an international context, for example in connection with international organizations like the European Southern Observatory (ESO) or under the aegis of centers established by the Danish National Research Foundation. Throughout its history, Danish astronomers have had a strong influence on the ESO, which was founded in 1962, an example of which is Johannes Andersen, who served as chair of the ESO's scientific-technical committee from 1993 to 1995. Danish astronomers have played an important role in the construction and use of the ESO's advanced astronomical instruments.

In particular, two basic research centers have contributed to the advanced level of contemporary Danish astronomy and astrophysics. One of these is the Dark Cosmology Centre (DARK), which was established at the Niels Bohr Institute in 2005 with a ten-year grant of DKK 114.20 million. The primary objective of the center is to advance our understanding of two of the greatest mysteries in contemporary cosmology: the nature of 'dark energy', and 'dark matter' which fill the universe. DARK is headed by the astrophysicist Jens Hjorth, who has contributed to the exploration of the gravitational lens effect and the extremely energetic explosions known as gamma-ray bursts. Much of DARK's research derives from the studies of supernovas which in 1998 led to the Nobel Prize-winning discovery of the accelerating expansion of the universe, which astronomers theorize is caused

FIGUR 10. Although there is much more 'dark matter' in the universe than ordinary matter, no one yet knows what dark matter actually is. Jens Hjorth and other scientists at the Dark Cosmology Centre are working to help solve one of the greatest mysteries of modern cosmology.

by dark energy. In this connection, it is worth mentioning that the methods which led to this discovery were developed as early as 1989 by Danish astronomers (in particular Hans Ulrik Nørgaard-Nielsen and Leif Madsen).

Since the mid-1960s, virtually all cosmological research has taken place within the framework of the Big Bang theory of the universe. In this connection, it is interesting that one of the primary architects of the theory, the Russian astrophysicist and cosmologist Igor Novikov, came to Copenhagen in 1991 for a professorship, first at NORDITA and later at the university. He continued in this position until his retirement in 2005. Since the 1960s, Novikov has been a central figure in the exploration of the early universe, black holes and other areas of relativistic astrophysics. In 1998, he published the popular book *The River of Time*, which explores the concept of time in modern physics. In 2007, he received the prestigious Eddington Medal from the Royal Astronomical Society. The award, which honors exceptional contributions to theoretical astrophysics, had never been awarded to a researcher from Denmark before.

A second basic research center was established at Aarhus University in 2012, the Stellar Astrophysics Centre (SAC). The center was established not least on account of Jørgen Christensen-Dalsgaard, the center director. Dalsgaard is recognized as one of the pioneers of a new branch of astrophysics research, helioseismology, or more generally asteroseismology. At SAC, researchers study 'starquakes' using more or less the same approach which geophysicists use to study earthquakes. Helioseismology emerged in the early 1970s, and Christensen-Dalsgaard has been a major figure in the field since then. In 2013, he received the Carlsberg Foundation Research Prize for his research on the sun and other stars. Christensen-Dalsgaard has also contributed to popularizing astronomy through his lectures and publications. For example, he coauthored a book on recent breakthroughs in astronomy which was published in 2016 to mark the 100th anniversary of the Danish Astronomical Society. Other members of the Academy also contributed to this anniversary publication, including Jens Hjorth and Helge Kragh.

FIGUR 11. The astrophysicist Jørgen Christensen-Dalsgaard, member of the Academy since 1990 and recipient of the Carlsberg Foundation Research Prize in 2013.

The physics and development of stars is one of the main research areas at SAC, while another is their immediate surroundings: the planets. Without a doubt, the biggest name in Danish planetary research in the 1990s was Jens Martin Knudsen, who was an associate professor of physics at the University of Copenhagen until his retirement in 2000, where he was particularly known for his contributions to the exploration of Mars. While this excellent communicator never became a member of the Academy, the Academy honored his contribution by awarding him a gold medal in 2004. Since the discovery of the first exoplanets in 1995, planets have been discovered around hundreds of other stars in the Milky Way, including a few with conditions which may support life. Hans Kjeldsen at SAC and other Danish astronomers have contributed to the discovery of exoplanets in several cases. Also, at the University of Copenhagen, there is a group under Astrophysics and Planetary Research which works on exoplanets.

Another Aarhus researcher who has contributed to the development of modern astrophysics is Jes Madsen, who was appointed professor of theoretical astrophysics at Aarhus University in 2006. He is internationally recognized for his research on quark matter or quark clumps and their role in the early universe and its cosmic radiation. Such plasma-like states of matter can be described by the theory of quarks, which are the particles which make up protons and neutrons. Together with other researchers, Madsen has investigated the possibility of demonstrating the existence of small quark clumps and other strange particles (like antimatter) in cosmic radiation with the help of an instrument at the International Space Station. The first results of this major project were produced in 2013. From 2000 to 2009, Madsen was a member of the Danish Council for Independent Research – Nature and Universe.

FIGUR 12. Jens Christian Skou, who received the Nobel Prize in Chemistry in 1997, is seen here examining nerves in crab legs.

Chemistry

Without a doubt, the most notable event in the history of Danish chemistry in the period after 1992 was the conferral of the 1997 Nobel Prize in Chemistry on Jens Christian Skou, who was 79 at the time. This was the first time the prize in chemistry had been awarded to a Danish researcher – who was, however, a biophysicist with a degree in medicine, not a chemist. Skou was a professor of biophysics at the Faculty of Medicine at Aarhus University, and his award-winning discovery of the enzyme Na,K-ATPase took place on the boundary between biophysics and biochemistry. It may be relevant to note here that the only Danish chemist to be awarded a Nobel Prize received the award for medicine. The biochemist Henrik Dam, who was trained as an engineer, was awarded the prize for his discovery of vitamin K.

Although the retired Skou received his Nobel Prize forty years after the fact, naturally, it generated considerable attention – not just scientific, but also in relation to research policy. When the former Minister of Science Helge Sander attempted to link the prize to the government's research policy, the president of the Academy, the marine biologist Tom Fenchel, responded in sharply critical terms. He characterized Sander's behavior as nothing less than "grotesque and absurd". Another member of the Academy drew critical attention to a Nobel Prize on a different occasion. In 2002, the leading Danish protein chemist Peter Roepstorff criticized the conferral of the Nobel Prize in Chemistry to one of the three award-winners, Japanese Koichi Tanaka. According to Roepstorff, the mass spectrometry method for the study of proteins for which Tanaka received the prize was not original, as it had been developed by German scientists earlier. Even though Roepstorff presented his critique internally to the Nobel Committee in Stockholm, the public got wind of it, and it was covered by Nordic and international media.

Roepstorff was not just anybody; as a professor of protein chemistry at the University of Southern Denmark in Odense, he was one of the pioneers in the use of mass spectrometry to analyze proteins and their transformations. Although mass spectrometry had been invented as early as 1920, the technique was not widely used for research applications outside physics until the 1950s. The research carried out by Roepstorff and his group in Odense demonstrated that mass spectrometry could be used to demonstrate genetic mutations, which meant that the technique had practical medical significance. Since Roepstorff's retirement, this work has been continued by other members of the group, including his student Martin Røssel Larsen.

Just as mass spectrometry has had a major influence on organic structural chemistry and its intersection with biochemistry, this is also the case with regard to another method based on physics, NMR spectrometry or nuclear magnetic resonance. Although NMR is over sixty years old, it was not developed into a precise, effective instrument until the 1970s, work which was recognized by a Nobel Prize in 1991. In Denmark, the organic chemist Klaus Bock had been working with NMR spectrometry for a number of years, and when he was appointed head of the Carlsberg Laboratory's chemistry division in 1998, he turned the lab into an international center for NMR studies of proteins, carbohydrates and other biochemically active molecules. Bock has received several scientific awards for his efforts, and has also played an important role in research policy, both in Denmark and internationally. In 2015, he was appointed one of the three vice-presidents of the ERC. In the same year, the major Danish Center for Ultrahigh-Field NMR Spectroscopy was inaugurated in Aarhus, where it is affiliated with iNANO and the Department of Chemistry. Among the founders of the center was the chemist Niels Christian Nielsen, who heads the laboratory for biomolecular NMR spectroscopy in Aarhus. Like Bock, Nielsen is a member of the Danish Academy of Technical Sciences (ATV).

With a grant of DKK 35 million, an interdisciplinary chemistry-physics-biology basic research center was established in 2001 at DTU headed by the biophysicist Henrik Bohr, the Quantum Protein Center (QuP). Over a ten-year period, the center studied the electron structure of proteins and their chemical reactions using quantum chemistry methods supplemented by molecular spectroscopy and other experimental techniques. This research has led to an understanding of how electromagnetic radiation can influence protein folding. The strong link between chemistry and biology, in addition to the role played by nanochemistry in the nanosciences, is also illustrated by the Centre for DNA Nanotechnology (CDNA), which was established in Aarhus with funding from the Danish National Research Foundation. The center, which is affiliated with iNANO, is headed by chemist Kurt Vesterager Gothelf, who is a leading organic nanochemistry researcher.

Although Jens Peder Dahl carried out the bulk of his scientific work in the fields of quantum chemistry and theoretical chemistry before 1992, he deserves mention here as perhaps Denmark's mos prominent and internationally recognized quantum chemist. He continued his research and teaching at DTU throughout the 1990s and received several awards, including the NKT Research Prize in Chemistry and the Humboldt Research Award. Dahl retired in 2001, and in the same year he published a comprehensive introduction to quantum mechanics and its applications in chemistry. His *Introduction to the Quantum World of Atoms and Molecules* is not only an innovative and systematic quantum chemistry textbook, it also provides a comprehensive historical perspective which is remarkable. Dahl, who remained active throughout his retirement, died in 2016.

Among the somewhat younger members of the Academy who have made outstanding contributions to chemistry research in a more classical sense, only Karl Anker Jørgensen will be referred to here, who has been a professor of chemistry at Aarhus University since 1992. Jørgensen has received numerous grants and awards (including the Bjerrum Medal, the Carlsberg Research Prize in Chemistry and the Lundbeck Foundation Nordic Research Prize). In 1997, he became the head of the Center for Catalysis under the Danish National Research Foundation, where he and his research team investigated chiral molecules (molecules which are non-superimposable on their mirror images), with a particular emphasis on the chemical reactions which resulted in just one of the chiral forms. This area has great importance for biochemistry and biotechnology, as this type of reaction occurs naturally in living cells.

One of the milestones of the center's research occurred in 2002, when its researchers became the first to describe a reaction in which an amino acid acted as the catalyst of a reaction which produced only one of an amino acid's chiral forms. This discovery drew considerable international attention, and was described by the journal *Chemical and Engineering News* as one of the scientific highlights of the year. Jørgensen's high status in chemistry research circles is illustrated by his appointment as Fellow of the British Royal Society of Chemistry in 2004 and as foreign member of the Swedish Academy in 2016. Perhaps more of a curiosity: another of Jørgensen's interests is culinary innovation and molecular gastronomy, an area in which the chemist Thorvald Pedersen and the biophysicist Ole G. Mourtisen have been particularly active in Denmark.

FIGUR 13. Karl Anker Jørgensen, professor of chemistry at Aarhus University, has carried out important research on the synthesis of molecules based on asymmetric catalysis. In 2017 he received the Carlsberg Foundation Research Prize.

Conclusion

The physical-mathematical sciences in the broad sense as described here have always played an important role in the Academy. This position has not become less prominent over the last 25 years, although the direct role played by the Academy itself has changed considerably. As this chapter has shown, the Academy has primarily served as a gathering place for researchers whose primary scientific activities take place elsewhere. It should be clear that the outline sketched out here does not provide a complete account of the activities in Danish science within the subjects covered, as this chapter focuses on the contributions of scientists who are members of the Academy or who are affiliated in some other way. Nonetheless, it is evident that the Academy's members over the last quarter of a century have been at the absolute forefront of innovative research in the physical-mathematical sciences. But there is nothing new in this. They stand on the shoulders of giants.

Source of citation

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