



CURIOSITY BENEFITS SOCIETY

Cover photo

Studies of eelgrass at Kertinge Nor on Funen
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PREFACE

The key question this publication addresses is: Does society benefit from highly educated citizens spending time and money on pursuing new ways to understand human behavior and how the world is organized down to the smallest molecules?

We want to show how science contributes to society's development in more ways than the obvious positive changes in our living conditions brought about by breakthroughs in research. Most people don't doubt the benefits gained from these breakthroughs; they know, for instance, that progress in the field of health care is driven by new scientific findings. Within the natural sciences we can look at, for example, Ørsted's and Faraday's discoveries of electromagnetism and induction, and see how these findings led to widespread electrification in a short amount of time. The quantum mechanics revolution in the 1920s, which largely took place in Copenhagen, much later led to significant insights into the semiconductor technologies that now form the core of all IT hardware. These are just a few examples of how curiosity-driven research has revolutionized society at different time scales.

The question about whether society is better off when scientists focus on specific problems or whether scientific endeavors should build a wider basic knowledge base in areas relevant to the further development of society is not new. In Egypt, 4000 years ago, people studied the night sky for practical reasons: To create calendars that could be used to establish when farmers should sow their crops and when the Nile would overflow its banks in the spring. Around 350 BC, Aristotle was the first person to talk about curiosity-driven research based on a desire to understand the world and human beings. He basically thought that all humans strive for knowledge and that society benefits from supporting this curiosity. His idea

turned out to be right for Athens, just as it would later be the driving force in the Renaissance and the Enlightenment, two periods upon which western civilization developed and thereby came to differ from many other cultures.

The Danish National Research Foundation (DNRF) supports curiosity-driven research and is convinced that as long as the research is of high quality, and the researchers can explain the significance of their visions, it will be one of the strongest forces in the development of society. It is essential that society understands and accepts that there most likely won't be breakthroughs unless the underpinning groundwork has been laid. Furthermore, society must accept that the time frame for breakthroughs is unpredictable and that the positive effects of such breakthroughs are manifold.

Soon after its founding, the DNRF supported research in, among other areas, green transition, food, and health care, areas that now, some 30 years later, present some of the main challenges facing society. In the same way, we expect that the research we currently support will affect society in the future. In fact, the research supported by the DNRF through its Centers of Excellence (hereinafter referred to as 'centers') is benefiting society every day, not least by way of training the next generation of top scientists by educating Ph.D. students, post-docs, and master's degree candidates, many of whom go on to high-level jobs in Danish businesses and public administration.

In this publication we will highlight some noteworthy activities undertaken by the centers of great importance to society. These activities, although they often take place outside of the public eye, paint a picture of people with an enormous commitment to society. We have chosen to focus on six areas:

1) Health care. Several centers have contributed to better diagnostics, improved therapy, new medicine, and counseling. The DNRF center PERSIMUNE has garnered a lot of attention during the COVID-19 pandemic and has made obvious the value of having a world-leading virology-immunology research environment.

2) Green transition. The centers doing research in this area work with new technologies to reduce energy consumption. They also study catalytic processes that are essential to storing energy without major energy losses.

3) Counseling of public and international institutions. The centers' leading employees mediate research knowledge to both Danish and large international institutions and governments. This information often forms the basis for political and financial decisions.

4) Cultural heritage. Danish museums are in a transition phase and are constantly pursuing new ways to disseminate their information and build their activities on the latest data and knowledge. Several centers have contributed to developing both the dissemination of knowledge and the collaboration between museums and researchers.

5) The second quantum revolution. The development of quantum-based technologies might revolutionize society over the long haul, and several Danish research institutions are currently working on this challenge.

6) New innovative companies. Researchers who seek new paths are often good at both creating research breakthroughs and finding immediate uses for their discoveries. Therefore, several companies have originated from basic research centers.

The intention of this publication is to show that curiosity-driven basic research provides a wealth of benefits to society both here and now and in the long run. It enriches society through activities that few people attribute to researchers. We hope to make this connection more apparent. The societal commitment of researchers is developing rapidly, helping to create a purpose for the generation of young researchers who, more and more, are seeking jobs through which they can contribute to society's progress and leave a positive mark behind.

Jens Kehlet Nørskov
Chair

Søren-Peter Olesen
CEO

SCIENTISTS

LAY THE FOUNDATION FOR FUTURE HEALTH CARE



Medical research is, by its nature, one of the most directly relevant research areas for the public because it is about improving health and the quality of life.

The output of Danish medical research is enormous, and a number of Centers of Excellence conduct research at the highest international level leveraging our world-class health sector. Four different examples of such centers are:



Centre for Personalized Medicine of Infectious Complications in Immune Deficiency (PERSIMUNE), Rigshospitalet

Center leader: Professor Jens Lundgren



Center for Hyperpolarization in Magnetic Resonance (HYPERMAG), Technical University of Denmark

Center leader: Professor Jan Ardenkjær-Larsen



Centre of Inflammation and Metabolism (CIM), Rigshospitalet

Center leader: Professor Bente Klarlund



Center for Epigenetics (EPI), University of Copenhagen

Center leader: Professor Kristian Helin



The picture shows double transgenic zebrafish larvae expressing red and green fluorescent proteins in the liver and pancreas, respectively, as captured by a fluorescent stereomicroscope. This tool is currently being used to illuminate how these organs are able to regenerate their structure after damage and fuel the development of new therapies for human diseases.

The biological understanding of the human organism

Basic research in medicine is about understanding human biology and the biological mechanisms that cause illness. Kristian Helin explains: *"It is about the fundamental questions of how the human organism works and why it works the way it does. And thereafter, what goes wrong when we develop diseases?"*

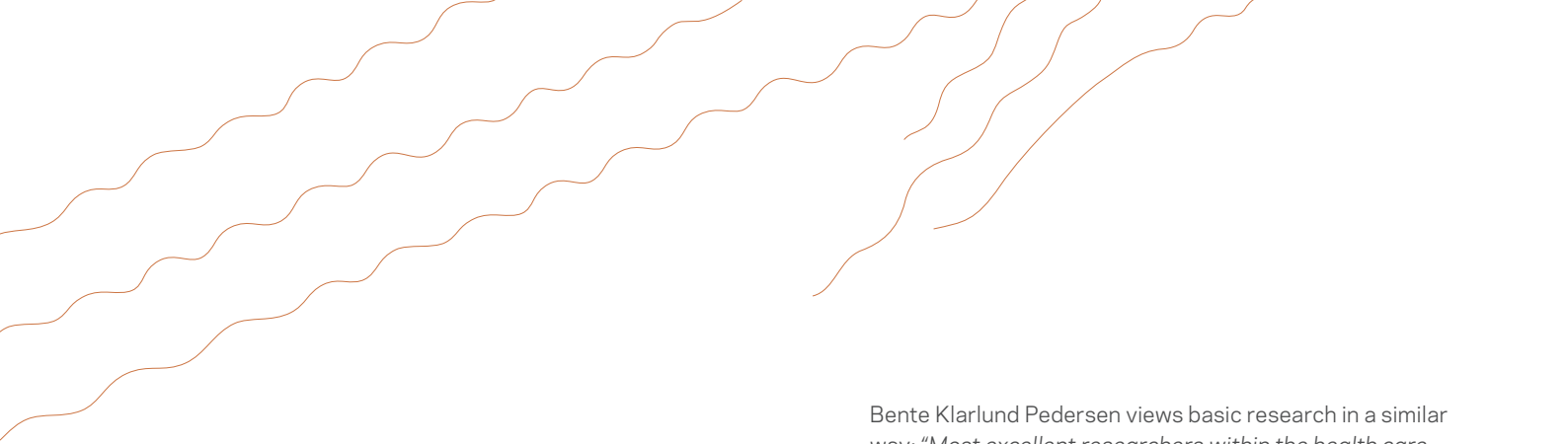
The centers specialize in biological heritage and are deeply immersed in the study of genetics and molecular biology. Their research address several common diseases such as cancer, diabetes, cardiovascular diseases, and brain diseases. And at his center, Jens Lundgren now also focuses on COVID-19, which hit the world at the end of 2019 and escalated into a pandemic in 2020.

Based on a method for analyzing huge patient data sets, which was developed during the first years of his center, Lundgren, in August 2020, was appointed to lead the trial protocol in a US-supported research project called ACTIV-3, in which a wide range of COVID medicines was tested. *"As a basic medical scientist, I am trying to understand why the response to an illness goes well for some people and less than well for others. One of the main challenges in resolving this issue is that it is difficult to determine whether people were infected by the exact same disease, that is, if the explanation for why it went well for one person but not for another is simply because what they were exposed to was different. This problem has been eliminated in relation to COVID-19 because everyone is infected with the same virus,"* explains Lundgren.

Basic research from a user's perspective

As a basic researcher in the field of health sciences, Jan Ardenkjær-Larsen notes that being able to make a difference for sick citizens is particularly important. He says that for a scientist to do that *"it always comes down to unravelling how nature works. We look at everything from the cellular to the medical implications. The fascinating part about the research we do is that it is translational, which means that by using model studies in cells or animals, we can develop a method that can be used on humans. It is very appealing that we have the opportunity to develop new techniques that may deliver better prognoses for patients with serious diseases."*

Jens Lundgren is also interested in the societal perspective. His experimental research uses other translational methods, which have led to his attaining a central place in the global research that will make the world more knowledgeable about the treatment of COVID-19. *"The center's multi-disciplinary research team consists of both researchers and clinicians, which means that we can not only analyze the patient data, but also understand the biological mechanisms that explain why there is a difference in how patients respond to treatments. As a result, we now have a central role in studies of the COVID-19 pandemic."*

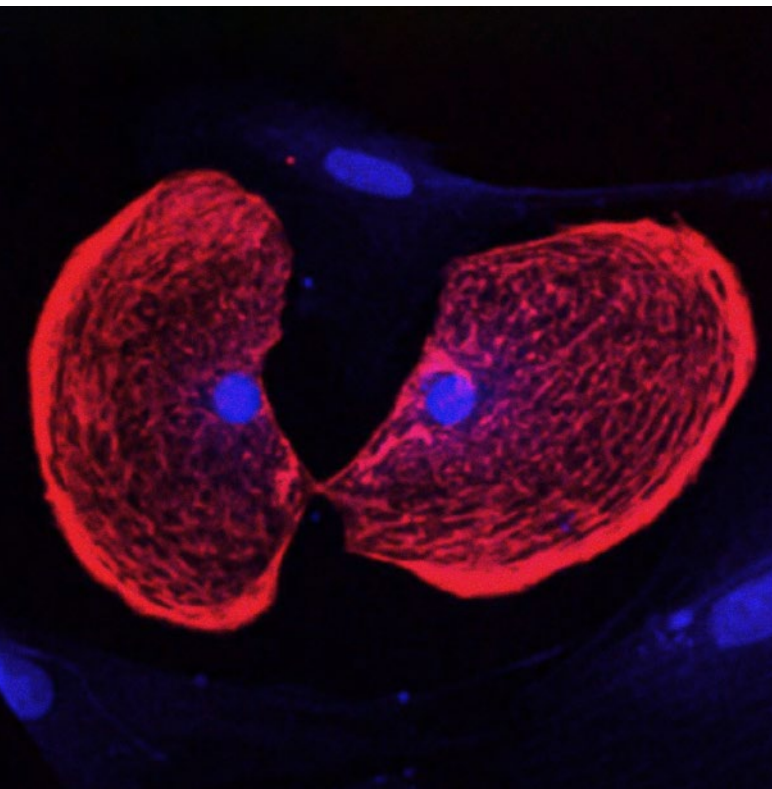


Bente Klarlund Pedersen views basic research in a similar way: *"Most excellent researchers within the health care field are inspired by a biological problem they try to understand."* Klarlund's center focused on trying to understand how we can minimize the risk of getting diseases like type 2 diabetes, dementia, cardiovascular diseases, and cancer. *"Overall, we were interested in how physical activity affects the immune system and thereby improves health. The starting point was a basic scientific discovery of how hormone-like substances are released to the blood following muscle contractions. Our hypothesis was that if these substances affect the organs, the muscle activity might also affect the disease processes. And if so, could the muscles even release substances that would affect the growth of tumors,"* Klarlund explains. Her center succeeded in identifying more than 100 substances that are generated by muscles and they demonstrated how these substances – called myokines – can contribute to repressing the growth of malignant nodules, affect glucose uptake and facilitate consumption of fat by the muscles.

Kristian Helin's center focused on how a person's surrounding environment and life can affect the activation of genes and the synthesis of proteins in the body. *"One of the things we discovered was a new class of enzymes that could erase some of the modifications that occur in our proteins. It turns out that many of these enzymes are altered in unhealthy cells. We also found another group of enzymes that modify DNA, and which are mutated in different cancer types,"* says Helin. Regarding his perspective on basic health care research, he adds: *"With respect to the development of new drugs, the knowledge from basic research as well as the insight into diseases gained from patient-centered research are both necessary, since it is the combination of the two that enables the discoveries that lead to new prevention and treatment methods."*

Diagnosis and personal medicine

The long-term vision in health care is personalized medicine. The dream scenario is that medication given to a specific individual corrects his or hers unique disease process, thus avoiding overmedication and side effects. The Danish health registers present a good opportunity to find connections between diseases and genetics; however, fulfilling the vision of personalized medicine, or precision medicine, demands, on one side, a theoretical and scientific knowledge of which genes and mutations lead to diseases, and on the other side, technologies and equipment that can be used for diagnosis, treatment, and control.



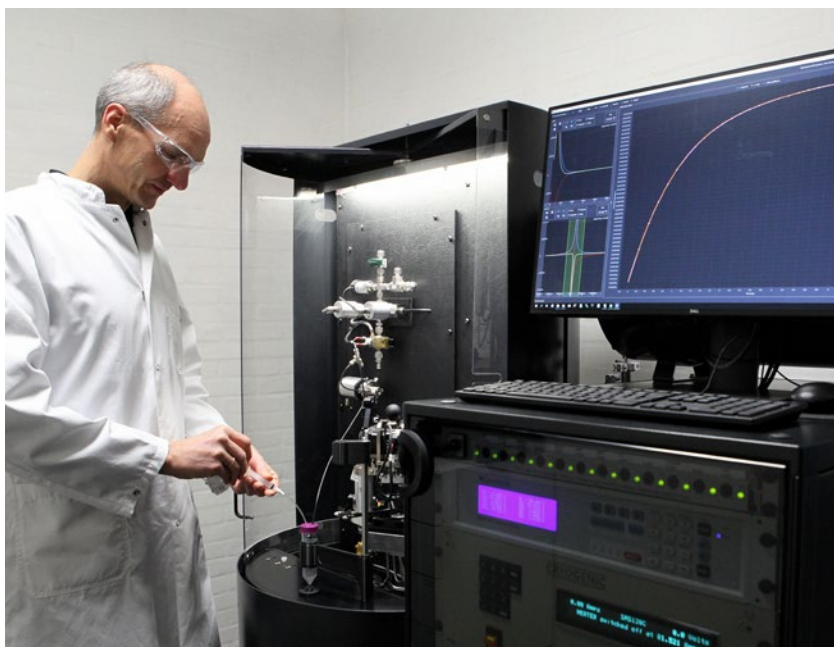
Cardiac muscle stem cells. Photo: Zoe Jenkins.

Our genomes contain a lot of material with an unknown function, and there are variations in genes that haven't yet been described as being the cause of diseases. With the development of gene technologies and omics technologies for molecular and microbial analysis, we have gotten closer. "In some areas we have reached our goal. For example, insulin is a precision medicine," says Kristian Helin. He adds: "But overall, we don't have a sufficient understanding of the human body to develop precision medicine for most diseases. We simply don't have enough tools in the toolbox yet." Jan Ardenkjær-Larsen agrees: "It might be decades to fulfill the vision about personalized medicine. We are just starting to build the platform for the needed diagnostics and therapeutics."

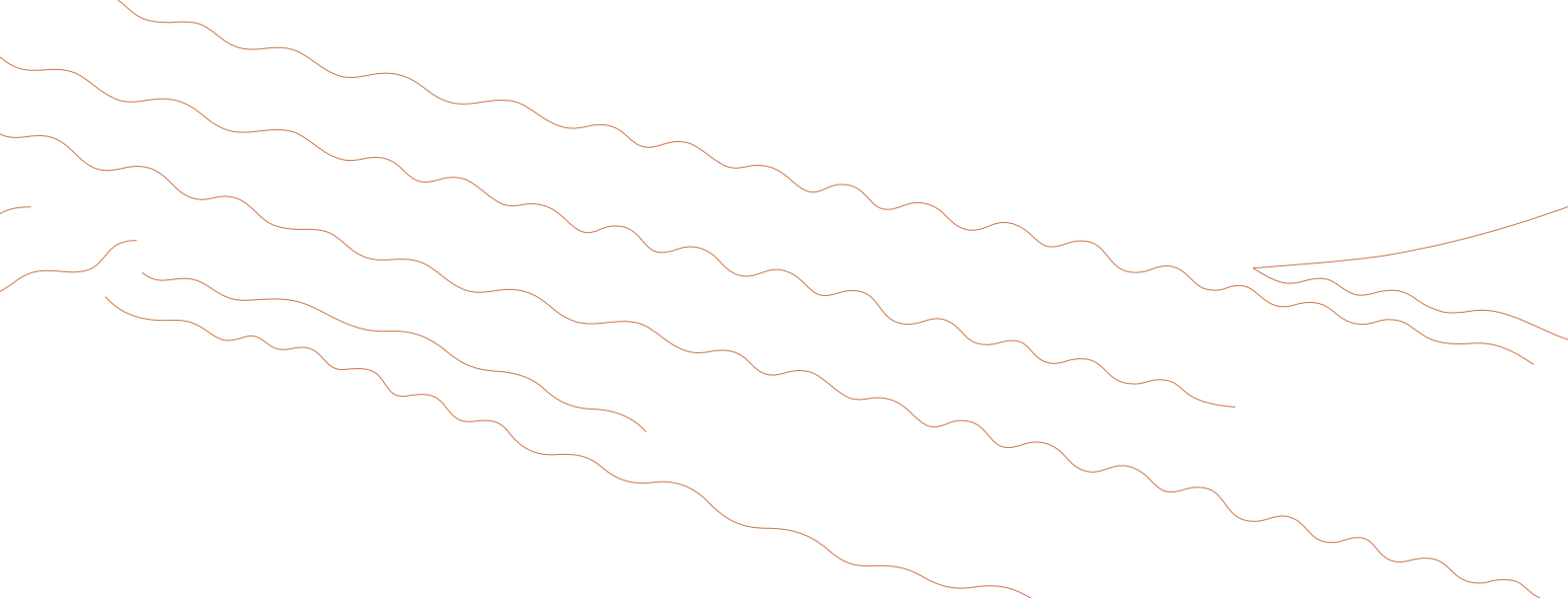
The scope of Ardenkjær-Larsen's research is a mechanical understanding of diseases, that is, an understanding of the mechanisms and the signals at the molecular level regarding early detection and diagnosis. "It would be even better if we could prevent diseases than to treat them. We primarily work on early diagnosis, which means we are trying to achieve a more precise diagnosis so the individual patient can get the best treatment."

Ardenkjær-Larsen's focus is on optimizing medical imaging, that is, scans that can be used to understand both disease processes and the effect of treatments. He explains: "Our research is about improving the signals of magnetic resonance by hyperpolarization, which is a technique for magnetization of trace elements. Magnetic resonance is a natural phenomenon and hyperpolarizing can heighten signals significantly. Unlike anatomical images that you get from X-ray examinations, imaging through magnetic resonance can generate molecular information. This means that we can both see where the disease is in the body and characterize it. It can also be used to evaluate the response to treatments, for example, chemotherapy. If the chemotherapy is effective and kills

the cancer cells, there will be changes in the metabolism that can be measured, and in that way, the doctor can decide if the treatment should be continued or if another treatment should be initiated. We also use the method to understand some fundamental questions about neuro-generative diseases that we don't yet know the answer to. There are a lot of hypotheses about what happens in our brain once we develop dementia, for example, and with our techniques for imaging, we can examine it in a unique way that is not otherwise possible."



Hyperpolarization of a metabolic contrast agent in the purpose built MR scanner developed by HYPERMAG.



For Bente Klarlund it goes without saying that her research results should be tailored to the treatment of the individual person. *"We cannot treat patients using physical activity if we don't know what happens inside the cell. To put it more simply, we can't expect all chemo patients to benefit from going for walks or bike rides. We need to find out which signal routes we have to activate. Only when we know this can we determine the appropriate training for the individual patient, so that we strengthen exactly that part of the biology, which in their organism might work against a tumor and can improve the blood supply. This is basic science in its truest sense, where we study the fundamentals of cells and cell lines at the molecular level."*

According to Jens Lundgren, one of the preconditions for using precision treatment is using basic knowledge about disease processes and studies of how treatments actually work, and then bringing this knowledge back to the basic research laboratories to analyze the data and the biological material from patients in what is called reverse translation. *"This is how we can reproduce and validate our research results and move our understanding to a higher level. We are becoming increasingly wiser about which new biologically founded mechanisms explain the difference in treatment responses,"* Lundgren observes.

Another aspect of better diagnostics is the way in which diseases are classified. *"We spend a lot of time redefining diseases based on contemporary understandings of which biological mechanisms are involved,"* notes Lundgren and adds: *"This is a central element of creating the treatment of the future, where every detailed diagnosis will lead to targeted therapies. If you look 10 or 20 years forward, the number of sub-diagnoses you can give a patient may increase by a thousand-fold."*

Training of specialists

All the centers are multi-disciplinary. The centers' success builds on collaborations between different professional fields as well as the fact that they can attract talented researchers to Denmark because of the centers' strong international standing. Kristian Helin points out that *"as a leader of a Center of Excellence, you create a top international scientific environment where you train new researchers who subsequently become academic leaders or get top jobs in industry. They wish to make a clear difference at their future workplaces."*

Strong research environments and access to specialists are important parameters for attracting companies that can use the discoveries made in basic research to develop new medication. *"From a socio-economic perspective, the centers are extremely good at delivering candidates to highly specialized workplaces within, for example, the medical industry, which you would want to create in Denmark,"* says Helin. He continues: *"Most medication is developed based on research from academia. Some of the models we used in my center to study genetic changes in cancer cells, which lead to uncontrolled cell growth, have resulted in new drugs for various forms of leukemia."*

Random breakthroughs in basic research

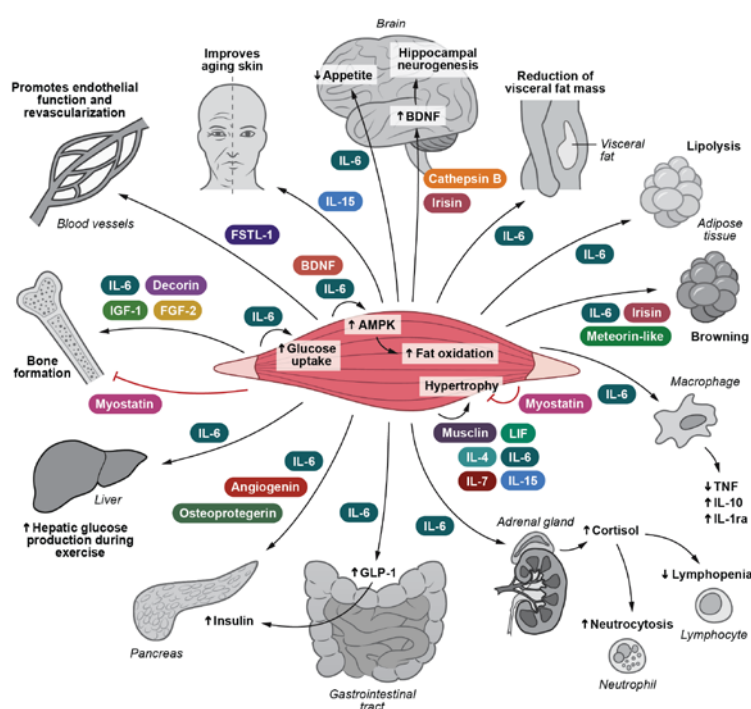
All center leaders wish to benefit society, broadly understood, but they also point out that the most important value of research is usually realized in the long haul.

Jan Ardenkjær-Larsen and Kristian Helin both emphasize that it is the basic research that leads to the surprising innovations, and it is typically these that move society forward in quantum leaps. It is important to ask open-ended questions about how our nature works. *"In biomedical research, the quantum jumps often come from places we do not expect. But it is exactly those leaps that revolutionize the very way we do research, and thereby also how to make new medicine. As an example, the latest genetic research comes from basic research,"* says Helin.

Bente Klarlund elaborates on this point of view: *"There are numerous examples of how basic research within my field, infectious medicine, has been applied out of the blue. For example, at one point, researchers found the so-called monoclonal antibodies, which they didn't know had any use. Unexpectedly, it turned out to be the basis*

for diagnosing the absence of a special immune cell, which led to the identification of HIV." She continues: *"As a society, we must prioritize funding for basic research. Otherwise, we will get poorer. There is a lot of knowledge available right now that we could implement, but if we want new knowledge, then we need the basic research as well."*

The dissemination of new knowledge has been a central part of Klarlund's work for many years: *"Mediation of our research was initially sort of a hobby for me. Now it has become fully integrated into my research plan. To me, dissemination of research is as much about being visible in society by giving people new insights about physical activity as it is about publishing in a prestigious journal. The research results need to be of use for the public, the patients, and the health-care staff. I also believe you are mediating research when you get politicians to speak about different aspects of health care and when you become involved in committees under the auspices of the National Health Board. As an example, I was part of a team that developed instructions for physical activity in schools and thereby influenced public health."*



The muscles produce hundreds of substances (myokines) influencing other organs.
Photo: Susanne Husted Nielsen.

WITH CONTRIBUTIONS FROM THESE CENTERS OF EXCELLENCE

Center for Epigenetics (EPI)

(2007-2017)

EPI studied human DNA to characterize environmentally-induced modifications of the genetic code. The research revolutionized the understanding of how some diseases arise, including why a healthy cell develops into a cancer cell. The research has resulted in the development of new drugs in a company that was a spin-off from the center, and the research has thus led to a variety of treatment options.

Centre of Inflammation and Metabolism (CIM)

(2005-2015)

CIM's overall purpose was the treatment of lifestyle-related disorders. CIM discovered that muscles can act as hormone-producing organs and thereby affect other organs, for example, the brain and adipose tissue. The research results have led to a better understanding of how muscle activity through exercise can contribute to an effective treatment of lifestyle-related diseases.

Centre for Personalized Medicine of Infectious Complications in Immune Deficiency (PERSIMUNE)

(from 2015)

PERSIMUNE uncovers the significance of a person's genetic background for the development of immune diseases in order to target medical treatment for the individual patient. PERSIMUNE has also developed a new model to analyze large sets of patient data, a method that is used to characterize previously unknown connections between diseases and side effects of drugs. Jens Lundgren is a member of the COVID-19 reference group that advises the government about the re-opening of society following the lockdown.

Center for Hyperpolarization in Magnetic Resonance (HYPERMAG)

(from 2015)

HYPERMAG's focus is on improving MR imaging of the body for the diagnosis of disease and to measure the effect of treatments. HYPERMAG has made particularly great progress with a groundbreaking scanning technology based on contrast substances that can reflect the metabolism in the body's cells and has been tested on cancer patients with promising results. The center leader has started a company that sells these new types of scanners for research purposes.



SCIENTISTS

GENERATE FUNDAMENTAL KNOWLEDGE TO THE GREEN TRANSITION



A key element of a green transition is the reduction of greenhouse gas emissions. The Danish government aims to reduce emissions in Denmark by 70% by 2030 and be carbon neutral by 2050. The reduction in greenhouse gas will be achieved by reducing energy consumption and by switching to the sustainable production of energy.

Several Centers of Excellence are working on a decarbonized and efficient energy system, including:



Center for Silicon Photonics for Optical Communications (SPOC), Technical University of Denmark

Center leader: Professor Leif Katsuo Oxenløwe



Center for High Entropy Alloy Catalysis (CHEAC), University of Copenhagen

Center leader: Professor Jan Rossmeisl



Center for Individual Nanoparticle Functionality (CINF), Technical University of Denmark

Center leader: Professor Ib Chorkendorff



The picture shows a common blue butterfly on bird's-foot trefoil. Bird's-foot trefoil interacts with many organisms, including nitrogen-fixing rhizobia bacteria and mycorrhiza fungi, which help the plant with phosphorus fertilizer.

Sustainability as the driving force

The centers' vision is to provide the theoretical and technological building blocks necessary for a more energy-efficient society. It basically means a future society where we can get the same services we get today but using far less energy.

Ib Chorkendorff describes the main challenge in the energy area: *"The green transition means we will use renewable energy, which must mainly come in the form of electricity from solar cells and windmills. So, if we are to be fossil-fuel free in 2050, everything that can be electrified must be electrified. But if we want a comfortable life like we have today, we still need fuel and chemicals, for example, if we want to keep flying. Therefore, we need to convert a major part of the electricity to chemical energy, which can then be stored and pulled out again. This is exactly what we worked on in my center: Finding new ways to make electricity as well as storing it as chemical energy."*

Jan Rossmeisl explains: *"Chemistry and knowledge about chemical processes are absolutely central when it comes to developing technologies for the production of climate-neutral fuel and storage of green energy. Therefore, there must also be a green transition in the chemical industry. The long-term vision for my basic research targets exactly that: to 'green' the chemical industry."*

Leif Oxenløwe's research aims to reduce the energy consumed in one of our era's most important infrastructures, namely, the internet. Globally, data transfers via the internet consume up to 10% of the electricity that can be produced today and leads to emission of about 2% of the CO₂. Oxenløwe explains: *"The data traffic is rising steadily year by year. Solutions are needed that, first of all, can support the increased need for data capacity and, secondly, are able to make the transfer of data more energy efficient, so that the increasing data traffic won't lead to increased energy consumption. And here we need to figure out something completely different than what we have today. We believe that optical communication technology may be the way forward. Our goal is to develop green IT for a green society."*

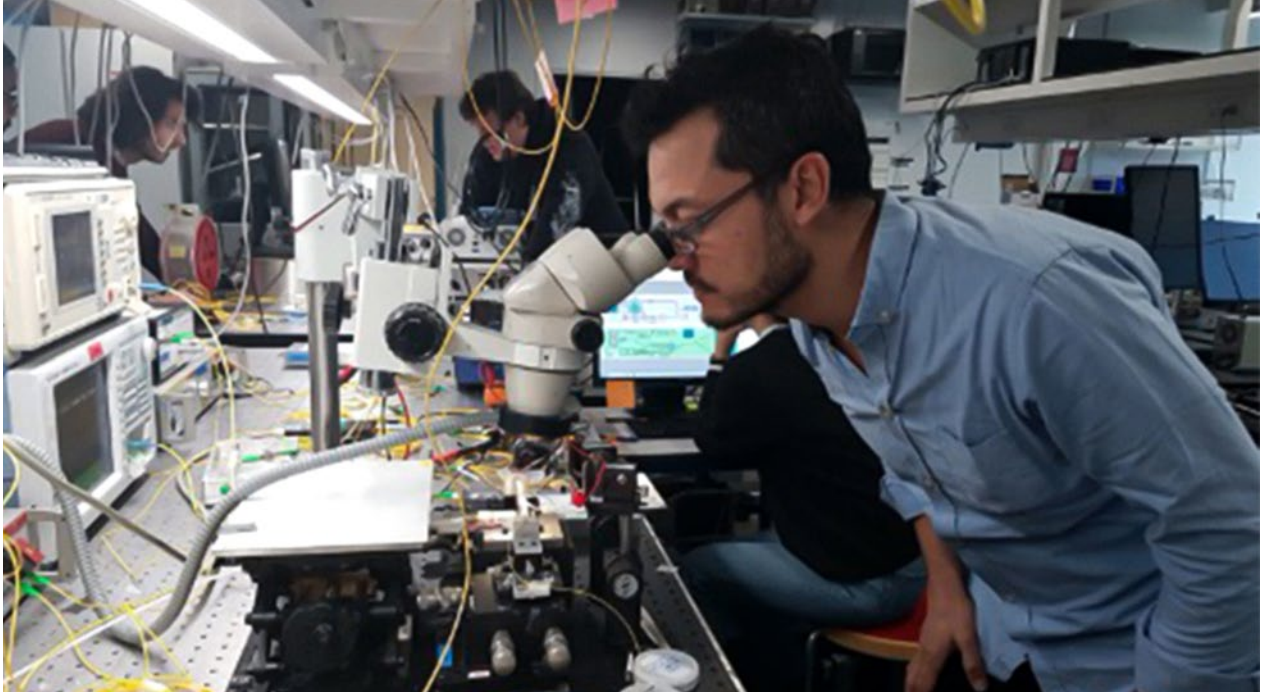
New materials = new possibilities

The common denominator for the centers is materials research. Fundamental innovations in this field are crucial for the development of new types of materials that can perform functions we previously never thought were possible.

Rossmeisl elaborates: *"The understanding of materials is what, throughout history, has defined humans' living conditions. The Stone Age got its name because they used stone, the Iron Age because they used iron, etc. Once you find new materials, new ground opens, for example, silicon for electronic components and lithium oxide for rechargeable batteries. The chemistry we have now is almost exclusively based on oil and gas and is used for everything from medicine to paint. We cannot keep going that way. If we find the right catalyst materials for chemical reactions, we can completely change what we can do."*

Chorkendorff agrees and he explains: *"The way chemical energy is made from electricity today isn't very efficient, and it is often based on catalytic materials like platinum and iridium, which are scarce resources and very expensive. We need to find new materials to support the catalytic processes that are central for optimizing the production and storage, and the generation of green energy needed for transport."*

Oxenløwe shares the perception about the importance of materials and further stresses the key role of knowledge infrastructure solutions: *"The Age of Enlightenment, when philosophy and science expanded our knowledge about the world, really moved society forward. Having knowledge – and sharing it – made humans wiser. Knowledge is a fundamental element in the evolution of humanity, and I*



SPOC develops photonic chips for energy-efficient communication technologies.
Photo: Lisbeth Kirk Mynster.

view modern communication technologies as vessels that carry knowledge and enable information to be shared. In my center, we work on moving past the boundaries of what fundamental information theory and fundamental physical laws allow, that is, how much information can be sent per energy unit."

Transforming theory into practice:

The strength of the example

There is a need for research at all levels to develop the necessary breakthrough technologies to achieve the climate goals. There is also a need for a paradigm shift to get there: from using the materials we know exist to designing the materials we need.

Leif Oxenløwe has received international recognition for a number of research breakthroughs in the area of laser and optical technology: "We have developed a light transmitter that is able to send light in many different colors from a single laser, and an optical chip that can process all the light particles. A few years ago, we demonstrated how our laser and chip could transmit as much data as all the global internet traffic - using only the light from this one transmitter. Today, thousands of lasers are used to do the same."

Carrying out such large-scale experimental demonstrations demands a lot of resources, Oxenløwe emphasizes. One could settle for doing proof-of-principle experiments and publish the results in relevant journals, but as he says: *"We need these experimental demonstrations to make people believe in our work. By showcasing the potential of our technologies, we hope to catch the attention of politicians and IT companies. We are aware that our technology doesn't fit the market today, but it is a conscious strategy on our part to explicitly show the energy-saving potential. Our experiment speaks for itself: It showed that a single chip can carry the entire internet's traffic, and that is pretty wild. With basic research we can explain how it works. And hopefully someone else will use this knowledge to create products. That part is not the task of our center."*

Ib Chorkendorff and Jan Rossmeisl are investigating new materials for catalysis, which is the heart of chemical reactions to elements. When it comes to the production of green energy, electrocatalysis may play an essential role in converting electricity to energy stored in chemical bindings. The modern catchphrase is power-to-X.

"In catalysis you need to have two gasses reacting with each other. The most effective way to do this is to place the molecules on a surface, so you can control the process. In my center we looked at what configurations are needed at the atomic level on these surfaces to get the reactions to run optimally. We also experimented with developing alloys for the surfaces; for example, we showed that platinum alloys function ten times better than pure platinum as a catalyst for fuel cells," explains Chorkendorff.

He continues: *"The basis for electrocatalysis is a separation of water into hydrogen and oxygen, and for that platinum is really good for making hydrogen, and iridium is good for making the oxygen. As mentioned, however, there isn't much future in technology that is based on scarce resources. Therefore, we did some studies of molybdenum disulphide, which we grew on small nanoplates of gold, and we found that the hydrogen process runs well on the edges of such nanoparticles. It is still one of the best alternatives to platinum, and the publishing of this discovery is one of our most cited articles. It is a good example of studying something fundamental about atoms – how they sit on a surface, and how they absorb the gas – and then it turns out that the reaction on the edges is the new thing. And we demonstrated that it can be used for the conversion of renewable energy. This is what I call basic research with a technological perspective, and it is freely available for companies to exploit."*



The light from a laser beam spreads through a special fiber and creates a smiling face in the shape of a star. Photo: SPOC.

Jan Rossmeisl contributes to a completely new research field: *"We are researching a new class of catalyst materials for electrochemical reactions called high entropy alloys. These alloys consist of a mix of many different elements. There are millions of opportunities to mix elements together on a surface that haven't yet been explored, and thus countless combinations of how the atoms might behave and what their catalytic qualities may be. The idea is to construct surfaces based on these high entropy alloys and find the exact combinations of atoms that can do better than the catalysts available today. But because we are dealing with a completely new phase of materials and surfaces, we can't use the same theory that has been used for homogeneous surfaces over the last hundred years."*

The cost perspective

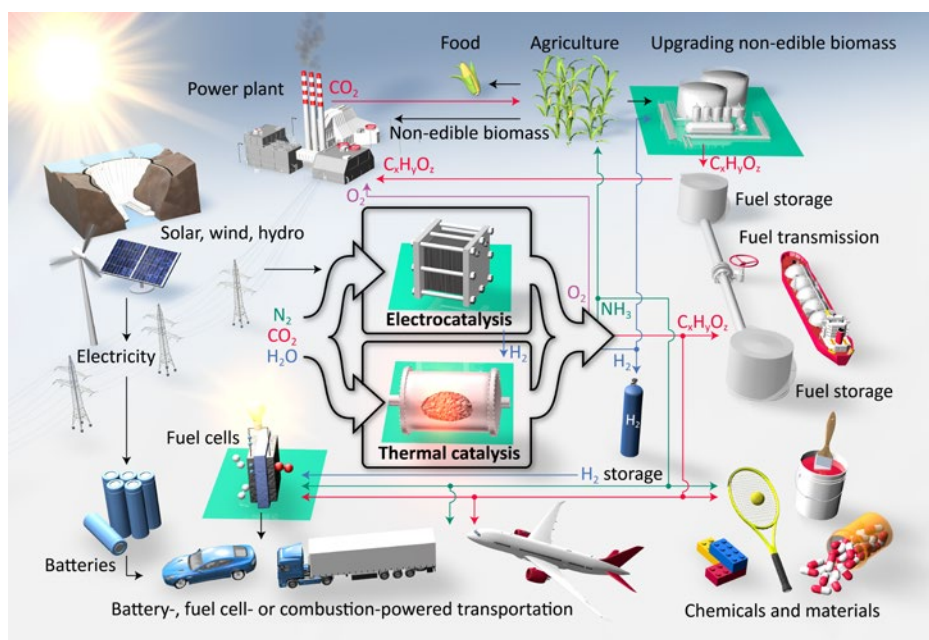
There are numerous aspects to the costs of the way we produce, transport, and consume energy. Leif Oxenløwe sums it up like this: *"Essentially, energy is the most relevant currency in everything we do on this planet."*

Electrocatalysis opens up a new way of making chemicals based on alternative starting molecules from water and air. Rossmeisl explains: “We are moving toward a future where you only need air (CO_2 or N_2), water, and electricity to produce chemical compounds and products. Today, chemicals are made at big factories that are often connected to oil refineries, but in the future, chemicals can be created in cells the size of a refrigerator. It opens up the possibility of producing chemicals on both big and small scales and close to where they are needed. Another aspect is that you can use them in whole new contexts because they don't necessarily need to be transported. This means that the entire chemical industry may look different in the future, also in Denmark, where our basic research may pave the way for the establishment of green chemical companies.”

Ib Chorkendorff points to the challenges surrounding energy storage. Energy needs to be stored because it must be available around the clock. “Electricity is very hard to store, and batteries aren't a real option on the scale that is needed. The best alternative is to store the

electricity as chemical energy. In other words, you convert electric energy into chemical energy in the form of hydrogen and oxygen, and then you can put the hydrogen back in a fuel cell and make electricity. You can also convert air molecules, water, and electricity to other gasses such as methane, which is compatible with our natural gas network. But each time you create a chemical transition such as a conversion from electricity to hydrogen, and from hydrogen to something else, you lose up to 30% of the energy. In a situation with several stages of conversions, you could end up with only half of the electricity's energy left. And that is due to poor catalysis.”

This highlights one of the challenges of electrifying most of our energy consumption with power-to-X technologies: Science isn't yet ready to upscale these technologies on a large scale, so massive investments are still needed to move forward. “There are costs to becoming fossil free. Otherwise, we would already be there,” says Chorkendorff. It should be noted that as of 2021, power-to-X is part of the government's green research strategy.



Our future society can be powered by sustainable CO_2 -neutral energy once the most important technologies have been developed. Photo: Jakob Kibsgaard.

Oxenløwe paints an encouraging picture of a growing paradigm shift in the IT world: "The dominant focus in terms of energy costs for data transfers, up until a few years ago, was 'dollars per bit.' Fortunately, there has been a shift in focus to 'energy per bit,' and in my center, we have done a lot to push for this. Naturally, cost is a central factor for both companies and society. Even with the change in focus from dollars to energy, cost will still be an important part of the equation, but it will be the cost of the energy. Big IT companies like Apple and Microsoft have already bought in on the 'energy per bit.' Smart people have said that Danish IT companies that hesitate to go green won't exist in a few years. It has become a strong competitive parameter." He continues: "The research perspective is to reduce the amount of energy needed to send one unit of data. We are working on developing technologies that are 100 and 1000 times more energy efficient than the technologies we have today."

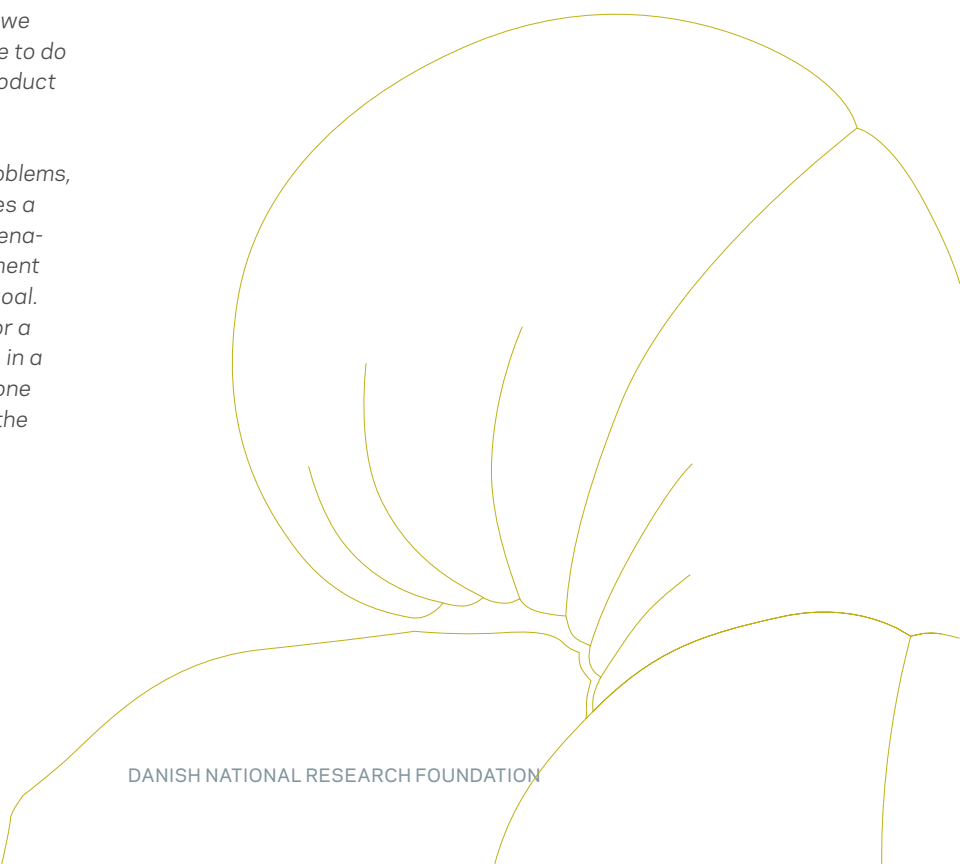
Long-term versus short-term research

The center leaders are committed to making their research work for society. In this context, Leif Oxenløwe says: "The distinction between basic and applied research is in many ways artificial. The research field I work in is very application-oriented, and many people are working toward specific products. But to see the bigger picture requires a long-term commitment to basic research such as it is possible in a Center of Excellence, which gives us time to take a step back and truly understand how we should address the challenges. We wouldn't be able to do that if our mission was applied research or pure product development."

Ib Chorkendorff agrees: "If you want to solve big problems, then you need to make big, focused efforts. It makes a huge difference to be funded by long-term grants, enabling you to build up an inspiring research environment where everyone is committed to the same overall goal. When you receive a grant of potentially 10 years for a Center of Excellence, you can take other risks than in a project where the grant only allows you to employ one Ph.D. student for three years. With the grant from the

Danish National Research Foundation, we were able to invest in equipment that opened up completely new research paths that weren't previously available, for example, how to manipulate the surface of nano particles and control reactivity. The value for society of grants from the Danish National Research Foundation comes both in the form of new theories as well as in new technologies that can mature outside the university and make a real difference."

Jan Rossmeisl describes the Centers of Excellence as incubators for talented people who, in their own way, become worth the investment: "What we do is basic research. But it is basic research with a commitment to changing society. This is important for the career development of the new generations. We are educating many people who get jobs in the private sector where they apply their skills to create something new, not least in the area of green transition."



WITH CONTRIBUTIONS FROM THESE CENTERS OF EXCELLENCE

Center for Silicon Photonics for Optical Communications (SPOC)

(from 2015)

SPOC is developing the building blocks for the communications infrastructure of the future, which is faster, uses less energy, and can send larger amounts of data in a completely secure way. The research is based on optical technology, which means using natural light. SPOC has demonstrated groundbreaking technology that can process information equivalent to the entire internet's data traffic at very low energy consumption.

Center for High Entropy Alloy Catalysis (CHEAC)

(from 2020)

CHEAC focuses on a green transformation of the chemical industry. This means that in the future, we will be able to use renewable energy and available molecules from water and air to produce chemicals. CHEAC is at the forefront of developing technology based on sustainable hydrogen that can be used to store energy, to create cleaner fuel for transportation, and to make chemical production greener.

Center for Individual Nanoparticle Functionality (CINF)

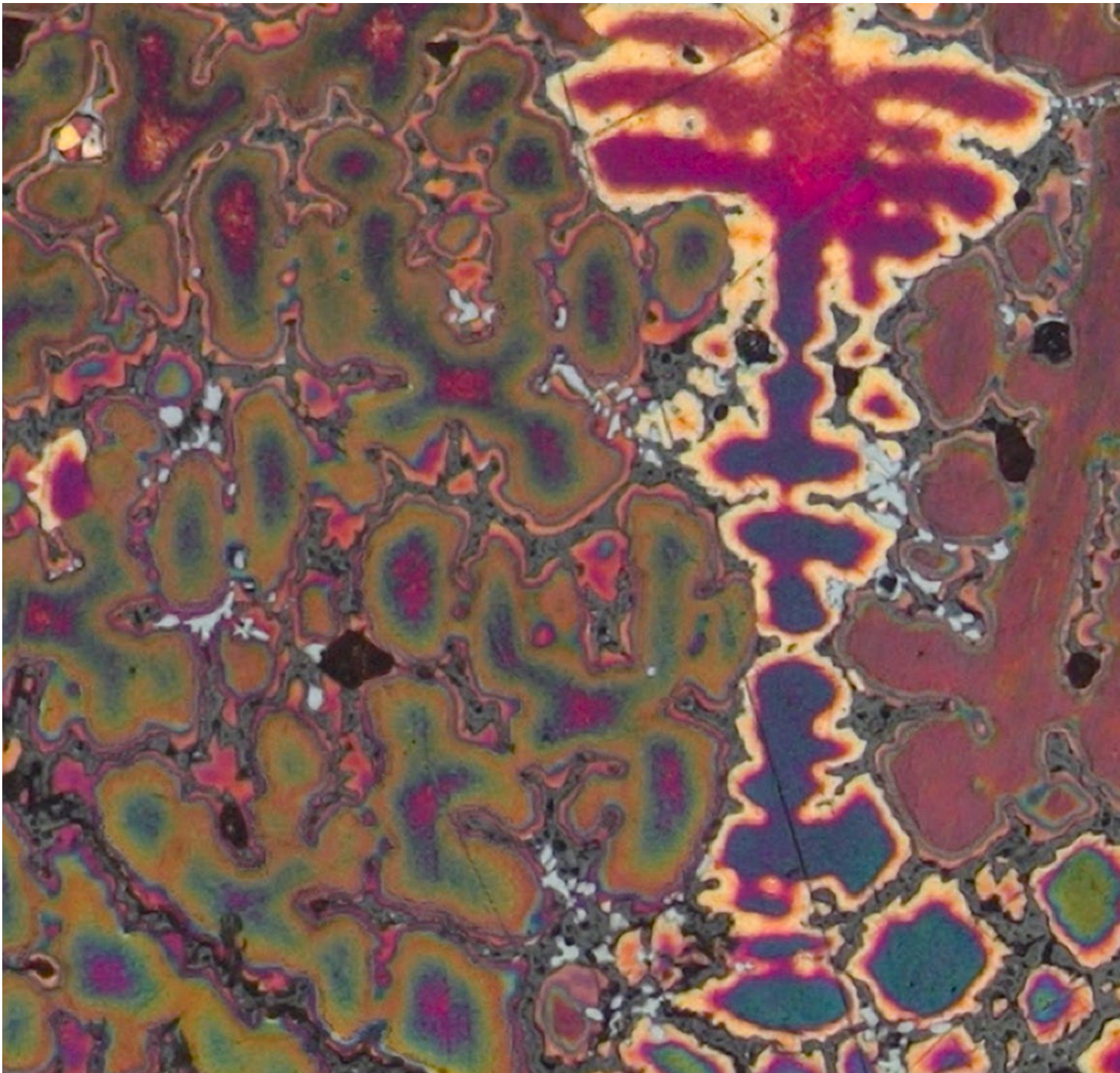
(2005 - 2015)

CINF characterized new catalytic nanomaterials and succeeded in developing a method for controlling the interaction of elements with different surfaces, which is a prerequisite for applying the technology outside the laboratories. The results have led to a number of innovations in the sustainable production of chemicals and energy. CINF's research forms the basis for the current efforts to realize a better protection of the environment and the green transformation of society.



BASIC RESEARCHERS

ACTUALIZE OUR CULTURAL HERITAGE



Museums carry out a variety of assignments that museum guests are often unaware of. Besides mounting exhibits, collecting and registering new artifacts, public-supported museums must also, according to law, conduct research.

Several Centers of Excellence contribute to the studies of the museums' valuable collections and help to turn museums into institutions of advanced knowledge. The centers engaged in this work are:



**Center for Medieval Literature (CML),
University of Southern Denmark**

Center leader: Professor Lars Boje Mortensen



**Center for Urban Network Evolutions
(UrbNet), Aarhus University**

Center leader: Professor Rubina Raja



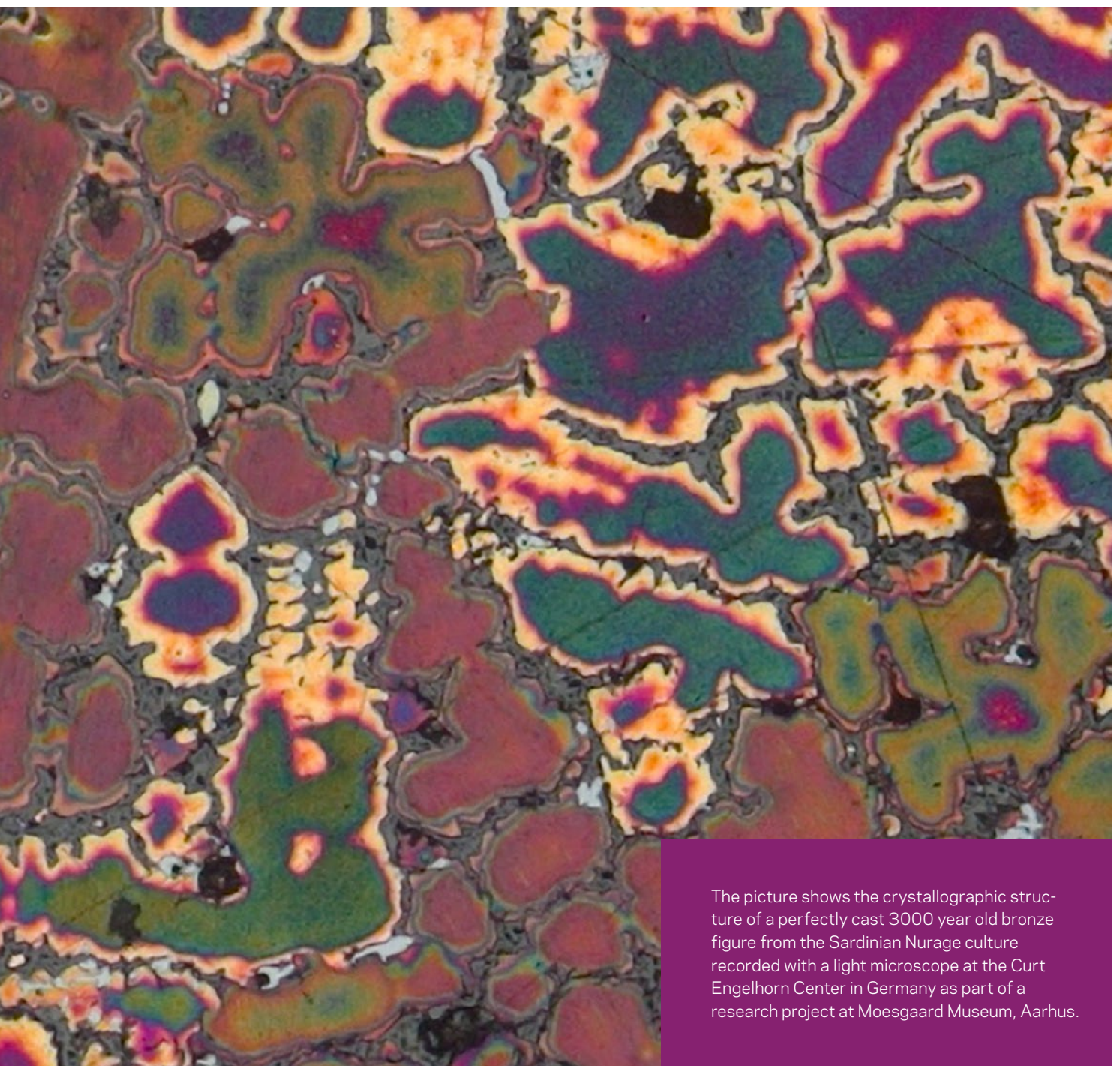
**Center for GeoGenetics (CGG),
University of Copenhagen**

Center leader: Professor Eske Willerslev



**Center for Macroecology, Evolution and
Climate (CMEC), University of Copenhagen**

Center leader: Professor Carsten Rahbek



The picture shows the crystallographic structure of a perfectly cast 3000 year old bronze figure from the Sardinian Nurage culture recorded with a light microscope at the Curt Engelhorn Center in Germany as part of a research project at Moesgaard Museum, Aarhus.

Museums as a source of updated and fact-based knowledge of the world

In Denmark and internationally, many museums possess huge collections within their respective cultural-historical, natural-historical, and art-historical areas, “though only a minimal part of the collections is used,” says Carsten Rahbek.

Museums vary greatly in terms of size and the resources available to them to carry out their tasks. It is therefore all the more relevant for museums to reach out to basic researchers to upgrade the museums’ research profile, and thereby prevent their collections from stagnating and their knowledge from becoming outdated. The collaboration between museums and researchers can bring to life objects that would otherwise be hidden away in drawers and closets, and which, on the one hand, can make us wiser and more knowledgeable about human life and living conditions from ancient times to today, and, on the other hand, can result in new and original material that museums can use to create exciting exhibits and catalogues.

“There are many opportunities, but it takes a lot of determination and effort realize them,” says Lars Boje Mortensen. Eske Willerslev has had the same experience: “Many people might wonder what we can do with old bones and objects that are lying around at the museums and taking up a lot of space. But suddenly, based on new research breakthroughs, such material can become priceless. As a result, museums’ collections are essential to supplementing our knowledge and they help us draw new conclusions.”

The prospects of finding “gold” in museums’ collections are endless, and the same goes for society’s gain. *“In the future one of the key findings we will see from museums is new knowledge about diseases that can be extracted from DNA found in old animal bones by using new research methods,”* Rahbek notes.

Center leaders are familiar with the newest and best techniques for examining archaeological findings and ancient monuments, exactly the type of expertise that can bolster museums’ relevance. Willerslev’s geogenetic research also uses DNA analysis and he has transformed research on remains from animals and people. He sees the same potential for contributing to our basic knowledge about diseases: “Our research will have a big impact on the basic understanding of infectious diseases, but also on obesity, cardiovascular diseases, etc. With new research methods, we can extract bacteria and viruses from bones, which means that we can verify that pandemics have ravaged populations far earlier than we thought before. This has changed the way we look at mutation rates and how viruses spread, and therefore, we can start to predict how viral diseases will develop in the future.”

Another aspect of the museums' enormous societal value is the fact that archaeological discoveries can help researchers gain new knowledge about the Earth's biological diversity. *"We are in the midst of a huge biodiversity crisis, which is connected to the crisis of the Earth's ecosystems and climate in general. With DNA mapping of the genome, we can renew our knowledge of evolutionary incidents and processes of the past, which are important for understanding the global situation today,"* says Rahbek. He continues: *"I couldn't do this kind of basic research were it not for the museums' collections."*

Basic research vitalizes dissemination of knowledge by museums

The center leaders have had positive experiences in collaborating with curators and specialists from museums, and these collaborations have inspired museum staff to look at their collections in new ways.

Rubina Raja had this to say about the research project "Urbanized Encounters and People," which was undertaken by the Museum of Copenhagen and her center: *"The two museum inspectors, who were also Ph.D. students at the center during the project, obtained an updating of the approach used in excavation and museum work. Besides allowing our researchers to work with the newest data from excavations in both Copenhagen and Odense, our research team was involved in organizing the excavation and the post-processing. It was a very productive collaboration, which may set completely new standards for the dissemination of urban archaeology by using the latest research methods and combining them with the museums' knowledge of local areas. To me, this is extremely interesting. The center will end one day, but if we can advance the way we approach research in excavations, we have reached one of my success criteria about making a difference."*

Researchers from the Center for Medieval Literature examine the famous illustrated manuscript Liber Floridus with colleagues from Gent University. Photo: CML.



The collaborations might be initiated by either the museums or the researchers, and sometimes they have perfect timing. Lars Boje Mortensen's center was at the right place at the right time when the Odense City Museum was preparing an exhibition with new findings from the Middle Ages in central Odense. Mortensen notes that *"we were brought in during the preparation of the exhibition and contributed our knowledge about Odense as the heart of Danish book culture, information that we had just acquired at the time. Without us, it would have been a purely archaeological exhibition, but our input made the exhibition better because it brought in a historical-literature and a historical-book perspective that no one else could deliver."* The center gave unique contributions to the exhibition, including the oldest copy of a Danish history book written by a monk named Ælnoth around the year 1100. This medieval book, which is about Canute IV's life and the birth of Christianity in Denmark, is owned by a library in Belgium and had never previously been exhibited in Denmark.

The collaborations are developed through dialogue between researchers and museum experts. The aim is to combine the researchers' approach with the museums' specialist knowledge. Rubina Raja explains: *"It isn't just about us going through the museums' catalogues and referring to their material. On the contrary, it is about us looking at the museums' material together with the curators and activating our respective methodologies and data. In this way, our basic research increases the knowledge that the museums gain and subsequently can profit from."*

Mortensen adds: *"Sometimes museums are surprised that we are interested in them. Our experience is that they like the attention that comes with it, and of course that they learn something new. They are excited that we can add to the knowledge about their collections."*

Maintenance of museum collections

Collections and data banks at museums are a good way to both build and channel new knowledge internationally. However, they must be maintained so as to not lose value in relation to current societal issues and challenges. In a situation with scarce financial and human resources, Carsten Rahbek stresses that *"the collaboration between research institutions and museums helps the museums make a qualified prioritization with regard to the collection of new data and items because we, as researchers, can offer our views about what is potentially important right now."*

Occasionally, coincidence plays a role in bringing new basic knowledge to an already well-examined area. Eske Willerslev was lucky enough to find a piece of hair in a soil sample from an excavation done by archeologists from the National Museum of Denmark. This strand of hair gave him and his research team an opportunity to characterize the oldest extinct human from Greenland, thereby uncovering the fact that the first Inuit didn't come from Canada, as previously thought, but from Siberia. In this way, basic research can pave the way for not particularly exhibition-worthy finds to provide new knowledge about our history.



Exceptionally well preserved fossil faunas provide fundamental insights into past ecosystems. The picture shows warm-water faunal assemblage on a 440 million-year-old rock from the Chaloupe River in Canada. Photo: Christian Mac Ørum Rasmussen.



Rubina Raja and a team of local excavators in Jerash, Jordan.
Photo: Danish-German Jerash Northwest Quarter Project.

The international angle

The work and the results of the centers' research build, to a large extent, on international partnerships with top researchers from all over the world, and many center leaders bring these partnerships into play with respect to exhibitions. For example, Lars Boje Mortensen established contact between the David Collection, a museum that houses a world-class collection of Islamic art, and international researchers who specialize in Arabic art of the Middle Ages. This contact motivated the museum to undertake new activities that benefitted both the public and the research world. The collaborations between museums and researchers can thus make Denmark interesting for foreign researchers while at the same time raising the quality of the exhibitions.

Rubina Raja agrees: *"The collaboration we had with the New Carlsberg Glyptotek regarding the Palmyra exhibition 'The Way to Palmyra' was the basis for placing the museum's collection in a broad global context. The exhibition was praised internationally because it was apparent that there was strong research behind it, and that it*

was lifted to a level which still managed to convey the substantial and detail-oriented research to the public."

Lars Boje Mortensen elaborates *"In my center, we are fortunate to have unique knowledge about the culture and literature of the Middle Ages. We offer our help with respect to updating and explaining the Danish part of this heritage based on international research on the Middle Ages and by applying the newest research trends on the Danish material. But we are only able to do this because the quality of our research is recognized internationally. The quality we can deliver to Danish museums only exists because of our international collaborations."*

Museums as culture-bearing institutions in a "fake news" era

Carsten Rahbek observes that center leaders focus extensively on bringing the results of their basic research to society as the foundation for new insights, especially at a time when more and more people choose for themselves what are facts. The scientific method as the basis for generating new knowledge is under pressure, as Rahbek notes. He sees an increasing and dangerous tendency to simplify the understanding of the biodiversity crisis without any root in research-based facts. *"Here, the museums have a unique position to disseminate research-based knowledge about our planet, which is of great importance for shaping our future. Their platforms for information and communication are becoming more and more important."*

Rubina Raja is also interested in the museums' potential role as learning institutions: *"The museum staff we have worked with have gained experience in a very important field that can still be developed and enhanced: the collaboration and interaction between research institutions and museums."*

When new research results emerge by revisiting old theories about agreed-upon contexts and offering new conceptual angles, it doesn't go unnoticed in the public debate. Eske Willerslev has often been at the center of such debates, for example, debates on identity and race concepts resulting from his research into past immigration patterns. *"The latest fossil DNA research we did on human history showed that immigration isn't a phenomenon only known to the present. Virtually all corners of the world have been affected by immigration as far back as we can look, and it has continuously happened. We can also see that immigration is absolutely essential for the cultural leaps that have taken place, for example, when hunters became farmers and when we went from the Bronze Age to the Iron Age, etc. This knowledge fundamentally changes the classical view that humans have consistently remained at the same location throughout history and developed more or less in isolation up to today. It is this type of basic research that changes our understanding of identity, that is, how we view ourselves through time and how we look at others. It also has an impact on our understanding of race because the long-term isolation which the concept of race basically presupposes has not taken place."*

The museums have a unique platform on which to educate new generations and shape historical consciousness based on research-driven information. Lars Boje Mortensen sums it up this way: *"It is all about what we want to teach the new generations. Should we teach them history as was done 40 years ago? Or should we give them the latest knowledge? The latter requires that there be people who are up to date with the latest knowledge and who both write specialized scientific articles and engage in contributing to cultural institutions such as museums."*

WITH CONTRIBUTIONS FROM THESE CENTERS OF EXCELLENCE

Center for GeoGenetics (CGG)

(2009 - 2019)

CGG researched fossil DNA from ancient times to get an understanding of how the genetic diversity found in humans and animals in different parts of the world was formed and how migrations took place. The research also mapped the processes behind the breeding of livestock and plants. The research can be used to understand the genetic basis of a number of diseases that challenge humanity today, including cancer and heart disease, as well as the fact that pandemics have existed for thousands of years.

Center for Medieval Literature (CML)

(from 2012)

CML places medieval literature in a new framework based on the geography, chronology, and typology of old texts. The center has described an interconnected European culture from before the emergence of states, a finding that has contributed to a new understanding and much needed strengthening of European identity. The center advises museums such as the David Collection.

Center for Macroecology, Evolution and Climate (CMEC)

(2009 - 2019)

CMEC researched the earth's biodiversity, that is, the diversity and variation found in nature. The center established new standards for the understanding of how different habitats and species emerged, and how their distribution patterns change as a result of environment and climate change. The research has modernized studies of the planet's ecosystems and is used in developing strategies for the conservation of biodiversity. The center leader advises national and international organizations on initiatives to conserve biodiversity.

Center for Urban Network Evolutions (UrbNet),

(from 2015)

UrbNet has set new standards for archaeological fieldwork by embracing the possibilities of science in so-called "high-definition" archaeology. The results are used for a humanities-based rethinking of prehistoric urban communities, which can make us wiser about the cultural and environmental challenges of today. UrbNet creates exhibitions with, for example, the Moesgaard Museum and the New Carlsberg Glyptotek. The center leader advises Interpol and other international organizations about Middle Eastern cultures.



BASIC RESEARCHERS AND MUSEUMS ENRICH ONE ANOTHER

The National Museum of Denmark is Denmark's largest cultural-historical museum. Research is a core activity at the museum, which has been involved with three Centers of Excellence, most recently the Center for Textile Research (CTR) under the leadership of Professor Marie-Louise Nosch in collaboration with Ulla Mannering and Eva Andersson Strand, from 2005 to 2015.

In the following, Jesper Stub Johnsen, deputy director of Research, Collection and Conservation at the museum, and Ulla Mannering, research professor at the museum, tell what the collaboration with the Danish National Research Foundation has meant.

From basic research to dissemination

First and foremost, the museum sees the interaction with the centers as a way to realize the potential of interdisciplinary research. Due to their size and the length of their grant periods, the centers embrace a lot of different subjects. At the Center for Textile Research, people from the natural sciences and the humanities worked closely together in an equal and balanced interaction. "We are convinced that interdisciplinary collaboration is essential for the museum to place cultural-historical items and knowledge in a present-day context," says Jesper Stub Johnsen. "The museum hadn't planned this collaboration with the center, but suddenly the collaboration led us to see things in a different way."

The researchers can update the museum staff on developments in areas such as color analysis, protein analysis, DNA analysis, and nanotechnology. Ulla Mannering explains: "Obviously, it isn't new to use scientific analysis in archaeology. One thing that the Center for Textile Research brought to the museum was the use of analytical methods, which were developed over the last 10 to 20 years and the ability to test them on our materials."

Johnsen elaborates: "Objects that are dug up from the ground contain a surprising amount of information, and with new technology and methods, we can better examine those objects. Suddenly we become much wiser about what these objects might tell us."

The success of these collaborations has created new projects throughout the museum. The new knowledge is disseminated in exhibitions, catalogues, consultancy assignments, and teaching seminars. The museum has, for example, become more knowledgeable about the color palette of the Viking Age, found a new interpretation of the

Jelling Stone, and created a school project about the decomposition of plastic fibers in cigarette butts. It also offers guidance about microplastics in the oceans as well as the aging of iron drums with poisons found in Danish streams.

Both Johnsen and Mannering are interested in boosting the museum as an institution of information and mediation and also as one that participates in the public debate. Naturally, the latter would only be in areas based on their physical data and knowledge of the objects, so they can speak from a research-based perspective. *"We can quickly convey new research results in 1:1 communication activities, because every day we welcome new audiences. We also have 300 to 400 pupils visiting us daily through our educational programs. With the possibilities we have as a museum, we can make the natural and cultural sciences practical and relevant quite effortlessly,"* Johnsen emphasizes. The basic research inspires the museum to lift its dissemination to a higher level without it becoming a circus show, as Mannering puts it.

The interest goes both ways

The collaborations with the centers have helped to promote the museum as an interesting partner for researchers both internationally and nationally. And it is not only the museum that reaches out to researchers; researchers from a wide range of scientific areas approach the museum to work in the cultural-historical field, since it may give rise to new questions for them to answer.

"If you are a DNA scientist, it is very interesting to try something extraordinary, for example, testing your methods on a 3000-year-old skeleton. It is through these challenging undertakings that they can really push and advance their methods," says Mannering. She continues: *"I have worked with researchers who publish in the best scientific journals, and who tell us they get the best response on their articles when they collaborate with archeologists. A new relevance emerges and, with it, a novel awareness. Even though the prehistoric era seems distant, it is also very fascinating."*

Museum for the past and the future

Based on basic research in cultural-historical and nature-historical collections, museums around the world are taking on a new role: They don't want to be museums only of the past; they also want to offer views on how to shape today's society. *"We try to look at our collections with fresh eyes, so we don't appear as a mausoleum. You don't go to the National Museum of Denmark to just become wiser about the past; you want to take something from the experience with you that is relevant to the present. We claim that for any existing problem, whether big or small, societal or local, we can find parallels in the cultural history that can inspire us,"* says Johnsen.

The museum's knowledge may become an asset in many different areas. *"We can learn a lot from old technologies that speak to the interests of ecology and recycling, and therefore, our mission is potentially greater than previously,"* says Mannering. A concrete example of this can be found in the museum's involvement in a project about sustainable urban development at the Open Air Museum. The project involves building a modern contemporary farmhouse but using only local and sustainable materials and old technologies. Once the house is finished, it will look like any other farmhouse, but it will have all the same things a modern house has.

Johnsen concludes: *"When we do basic research, we normally don't know what we will do with the results. But we do contribute to the collective pool of knowledge that one day might become relevant. Also, the smarter we are in terms of basic research, the greater our chance of triggering an interest in cultural history that has benefits not only for the museum's guests today, but also for future guests. At the moment, the museum produces a lot of podcasts, where one of the main messages is that people may think that what is happening now is happening for the first time in history. But this isn't true. Everything has happened before. You just have to find it in our cultural history."*

Center for Textile Research (CTR)

(2005 – 2015)

CTR uncovered how textiles from a given time carry knowledge about the society in which they were used, in the same way as flint axes and other ancient findings. Textiles tell the story of tools, production methods, cultural interaction, language use, and general economic status. The center proved, among other things, that women in the Viking Age could create both canvas and fine clothes, which means that not everything was bought or stolen. Researchers and students from the center have become core employees at various museums.

BASIC RESEARCHERS

PROVIDE COUNSELLING TO PUBLIC INSTITUTIONS



Every day, politicians and other authorities make decisions that affect our society. Traditionally, the political system seeks counsel from and listens to researchers in order to act in accordance with the latest knowledge.

Research in the social sciences is important to maintaining an informed debate, and several Centers of Excellence focus on qualifying the basis on which political decisions are made, including:



**Center for Financial Frictions (FRIC),
Copenhagen Business School**

Center leader: Professor David Lando



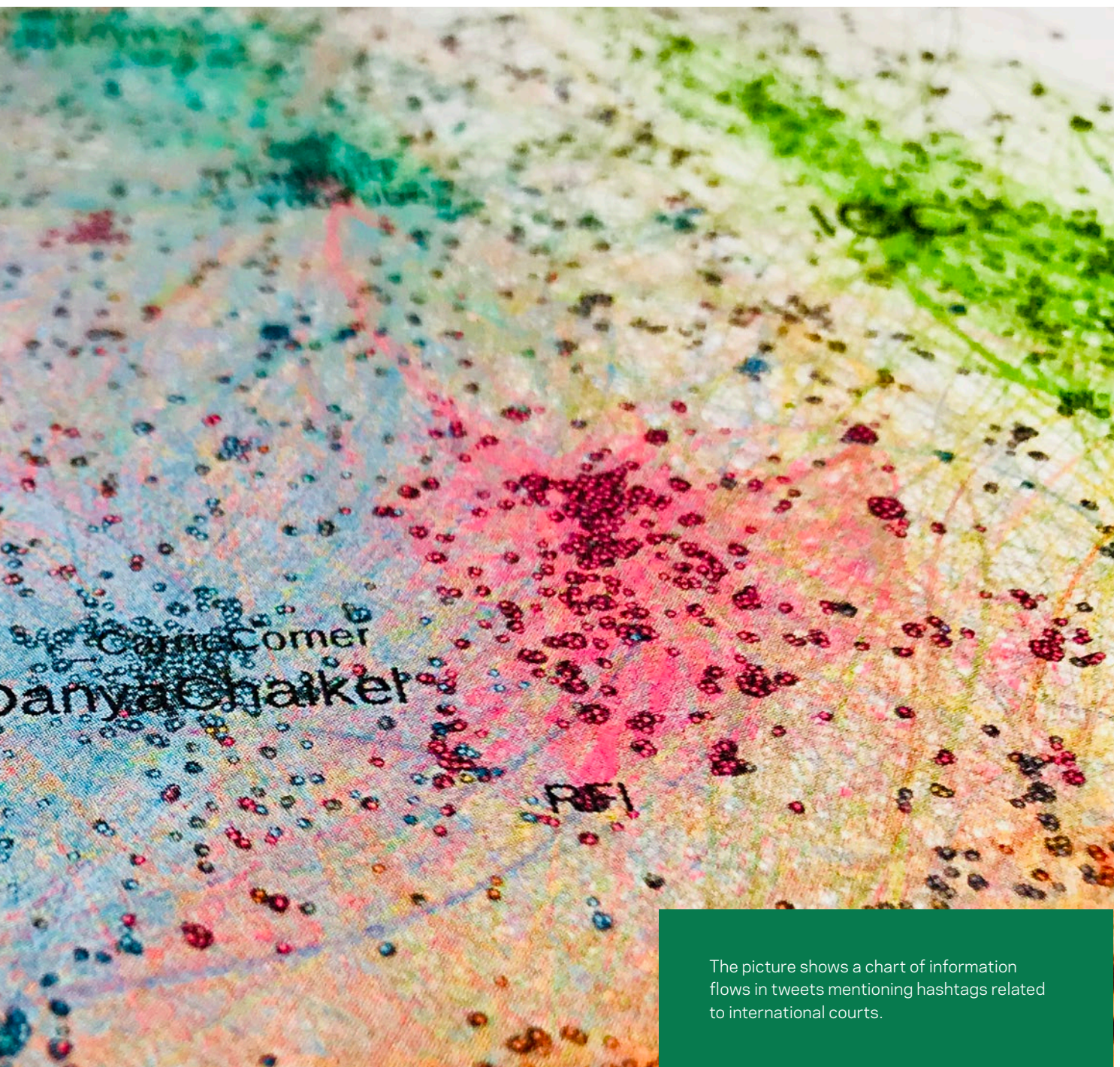
**Center for International Courts (iCourts),
University of Copenhagen**

Center leader: Professor Mikael Rask Madsen



**Center for Economic Behavior and Inequality
(CEBI), University of Copenhagen**

Center leader: Professor Claus Thustrup Kreiner



The picture shows a chart of information flows in tweets mentioning hashtags related to international courts.

Relevance-driven basic research

The centers' research focuses on basic societal structures, institutions, and the governing bodies of the judicial, financial, and economic sectors. The research is largely inspired by actual incidents and concrete political events.

"Our basic research is strongly driven by relevance, that is, by pressing societal challenges that call for explanations and a deeper understanding. It addresses issues we see here and now with new data, new models, and innovative ways to look at the problems," says David Lando.

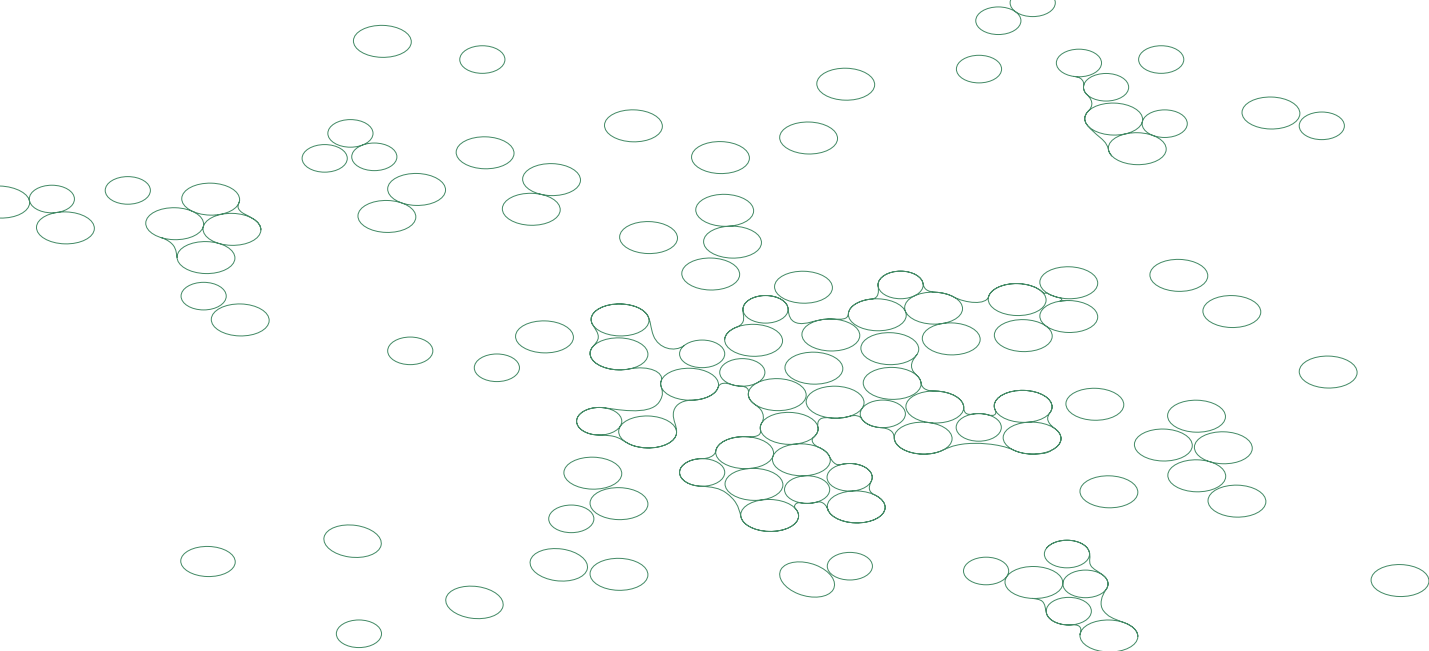
The focus of the center leaders is to enhance the competence of the authorities and politicians, in other words, those who are making important decisions about our society. Claus Thustrup Kreiner explains: *"The overall aim of our research is to improve decision-making in the context of*

political decisions. As far as redistribution policy goes, which is one of the areas we are looking at in my center, we can explain to the politicians which compromises in relation to different political measures they realistically need to decide on, and how the interventions may work out. And that is often different from what the politicians originally thought."

Mikael Rask Madsen elaborates: *"Our goal is basically to make the world more explicable. A Center of Excellence has a certain power to actualize a societal challenge by influencing the general insight in the field and in this way enlighten the decision makers. But we are not a policy center, and we don't intend to change anything specific."* He continues: *"My center has a standing invitation to participate in the United Nations' Commission on International Trade Law, where we contribute with our research results*



CEBI researcher Torben Heien Nielsen discusses inequality in society at Folkemødet on Bornholm 2019 with representatives from LEO Innovation Lab, Local Government Denmark, Danish Regions and the Danish Medical Association. Photo: Troels Heien.



and evidence-based knowledge about the reforms that are discussed. We also participate in meetings of the European Commission, most recently on the establishment of an international investment court. We presented our knowledge about how such a global court could be built up. We don't go out and say that it has to be done in a certain way; instead, we present comparative insights from similar institutions."

An ever-changing world

Globalization affects the basic rules in national decision-making processes and the financial room to maneuver, which is why a significant part of the centers' outlook is international.

Madsen explains: "Developments in the global community mean more power is moved to international institutions. It is this transformation of the world with strong supranational structures that we describe through juridical lenses, as well as the derived consequences on our democracy, which ultimately have a direct impact on citizens."

The focus of Madsen's research is the international courts. Understanding the international processes helps to explain how Danish law and jurisprudence can operate. *"Human rights, for example, are here to protect citizens from being ill-treated by the state. One traditionally looked at the Constitution to understand the human rights in a Danish context, but today, you also have to understand international law and human rights courts, because they tie national decisions to the supranational rules."*



Meeting between iCourts and representatives from various international courts.

The financial markets in Denmark are obviously affected by international circumstances, and they have a central place in David Lando's research. The research is about understanding how frictions in financial transactions affect the pricing of financial assets and the allocation of risk. In this context, frictions should be understood as

financial regulation, illiquidity, taxes, and other restrictions. *“The financial markets are tremendously important for the general prosperity of our society. The markets are huge, so we are talking about very large amounts of money. Therefore, it is important to understand the basic mechanisms of these markets,”* says Lando. He continues: *“Frictions are particularly relevant in crises, where you clearly see the importance of restrictions for market agents such as banks, credit institutions, pension funds, and other asset managers. After a crisis, there is typically a demand for financial regulation, which introduces certain frictions into the economy to prevent new crises from happening. Here we can contribute insights into the effects that different frictions may have and what possibilities there are to react when the crises come anyway.”*

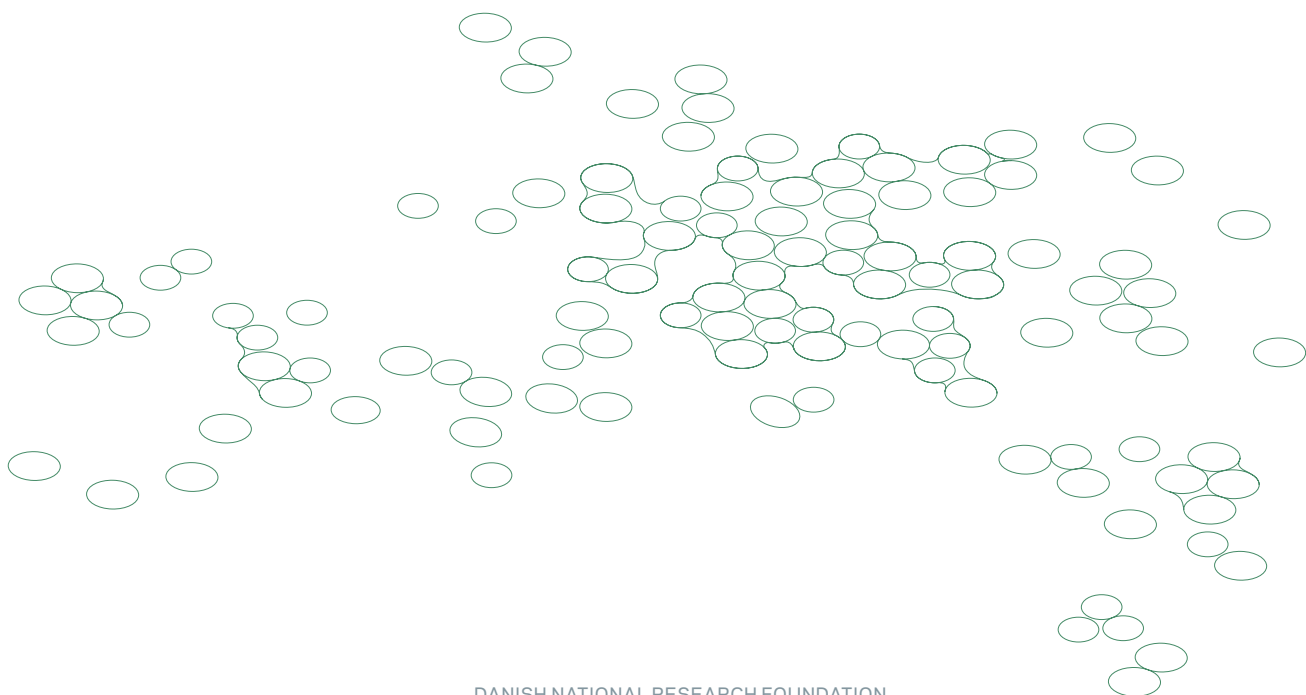
Claus Thustrup Kreiner's research revolves around gaining clarity about the degree of economic inequality in society and determining the causes of it. Therefore, a substantial part of the research is about the role that individual behavior plays in the big picture. He explains: *“The inequality between people in terms of income and wealth is partly due to differences in circumstances and partly to different behaviors. My center mainly focuses on the latter, that is, the role of human behavior in creating inequality.”*

Kreiner also includes other kinds of inequality in his research, for example, the expected life span. Presumptions about life expectancy for people with high and low incomes became relevant in the debate about the so-called Arne pension (an early retirement plan for people with long professional lives behind them). *“Generally, it is assumed that people continue to be either at the bottom or at the top in terms of income, but it isn't like that. There is a fairly large social mobility, which is important for how big the difference actually is between people with high or low incomes. Our research in this area shows that the inequality in a life span is only half as big as people generally think. The bad news is that inequality has been rising since the 1980s,”* Kreiner notes.

Development of new models and frameworks

Since they carry out basic research in the social sciences, the centers, for good reason, widely base their research on statistical data, empirical data, and case studies about phenomena and events in a real-world context. A large part of the centers' basic research is about the further development of theories and methods by combining classically delimited research fields in completely new ways and integrating them with new trends and research directions.

David Lando gives the following example of how his center has further developed Markowitz's classic portfolio theory about how financial investors act to minimize risks:





Niels Johannesen from CEBI was invited by Margrethe Vestager in 2019 to present his research results on tax evasion to the EU Tax Commissioner.

"When Markowitz published his theory in 1959, there was no talk of whether investors placed their funds based on socially ethical values (environmental and social governance [ESG]). But you do that now. We can ascertain that more and more investors are interested in ESG guidelines about responsible investments, either because they believe it has a value in itself, or because it may have an impact on the value of their assets. In my center, Lasse Heje Pedersen has developed a portfolio model that takes ESG into account. It is a fully operational mathematical model that is able to connect a potential value of using ESG and assess whether it has meaning for your earnings."

The research at Mikael Rask Madsen's center is groundbreaking in terms of the use of big data within the court system. "We examine how algorithmic analyses of large amounts of data can be used in public administration without undermining the legality or weakening people's trust in the authorities. The goal is to contribute with methods that can streamline judicial institutions and strengthen the legal confidence," says Madsen. Madsen's center has been involved in preparing arguments in

specific court cases where the evidence relied on a statistical analysis of a judicial development over several decades. He notes that "here we are definitely at the forefront by introducing new methods into the court system. It is exciting that a method we developed, and are still working on, ends up being presented to the Supreme Court,"

The research at Kreiner's center is also breaking new ground by incorporating behavioral theory into economic models. He explains: "Much of the theoretical foundation on which economic policy is analyzed is based on the assumption that people behave homogeneously, which means that if they are placed in the same situation, they would all make the same decision. But those differences that we know exist in people are potentially important when it comes to political decisions, and whether they will work or not. We seek to get a better picture of the systematic heterogeneity we observe and add the new information to the theoretical models. We do this by, among other things, working with preferences, a method that involves mathematical modelling of people's behavior in different situations."

Kreiner offers a concrete example of using preferences to nuance the understanding of economic behavior: *"The theory says that if you are an economically patient person, then you will save more and have a larger fortune than someone who isn't. So far, so good. But we go even deeper and look at the fundamental characteristics that may explain this difference and why some people end up in financial trouble, for example, by taking big chances by borrowing a lot of money. We go in and look at risk preferences and time preferences."*

He continues: *"Politicians often use information in different ways. In the context of getting into financial trouble, one could say it is people's own responsibility. On the other hand, you could say that there is a need for regulation to stop people from taking payday loans at exorbitant interest rates. But that isn't up to us. From our point of view, we are only interested in doing good research that provides the best foundation for decision-making. Naturally, we try as far as possible to bring something factual, but we are researching an area that is hard to measure, and there will often be a large margin of uncertainty about the results."*

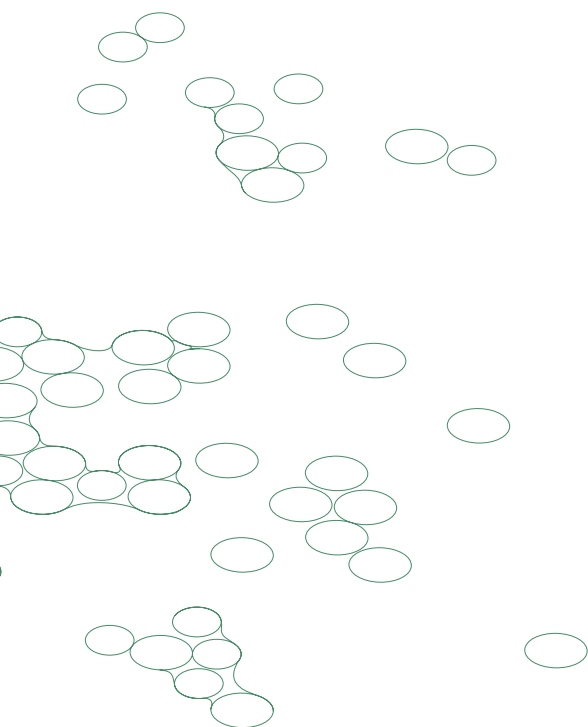
The imprint of the Centers of Excellence on society

The center leaders bring their knowledge into play in different ways. One way is by accepting invitations to give presentations to central banks, courts, interest groups, government committees, commissions, conferences, etc., all over the world.

Mikael Rask Madsen says: *"The value to citizens and society is largely related to our ability to communicate our research results about the principles of our rule of law and our democracy. It involves a great deal of explaining because the issues discussed in the academic world are far more complicated than when discussed by decision makers who have a real possibility of influencing the institutions,"* says Madsen. He adds: *"We are dealing with highly political issues, so it is important to maintain our legitimacy by focusing on structures and principles. When we make a statement, it is 100% based on our research, and we don't adapt it to a given audience. If we don't have research-based insight, we don't join in. Still, there is always a risk that you will be looked upon as someone who politicizes even though that is not the intention."*

Kreiner shares this experience: *"We are often asked for advice on topics that contain an inherent political conflict and where there is disagreement between different groups. If there was no disagreement, we wouldn't be asked."*

In relation to the overall value of the centers to society, David Lando doesn't hesitate: *"It is first and foremost the graduates whom we educate and send out into the world. We know what it takes to be successful, whether in the academic world, the business world, or the public sector. Some of the key qualities we teach our students are to identify new ideas and decide which ones are important. Of course, we as professors and center leaders also need to contribute to solving the challenges of the world. But for me it is just as important to train hundreds and thousands of skilled young people who will find all sorts of creative and innovative ways to push the world in a better direction. This is how we leverage our knowledge and impact society positively."*



WITH CONTRIBUTIONS FROM THESE CENTERS OF EXCELLENCE

Center for Financial Frictions (FRIC)

(from 2012)

FRIC's aim is to improve the understanding of how the financial markets work. The research results are used by authorities to assess the need for regulation and its consequences for economic activity in society. FRIC has, among other things, highlighted matters concerning capital requirements for banks and credit institutions in light of the financial crisis. Center leader David Lando has recently joined the think tank KRAKA, which provides professional knowledge about the economy.

Center for International Courts (iCourts)

(from 2012)

iCourts' research on international courts contributes to the systematic analysis of the courts' influence on national policies and societal structures. Results from iCourts have formed the basis for reforms of international institutions within the Council of Europe and the EU. iCourts also advises the Danish government and the civil society about human rights and the relationship between international and national law. Center leader Mikael Rask Madsen is a sought-after consultant by many governments and courts.

Center for Economic Behavior and Inequality (CEBI)

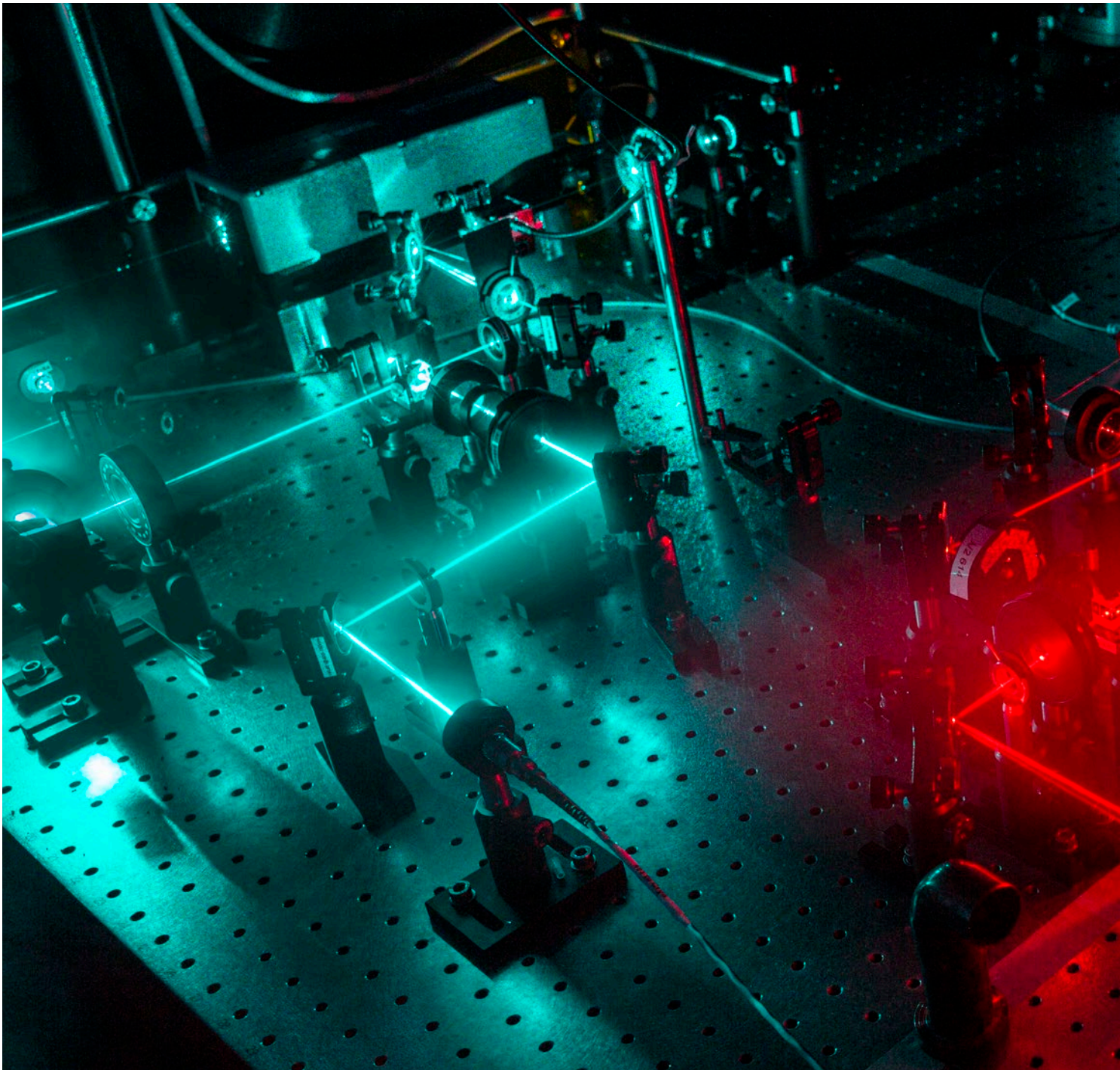
(from 2017)

CEBI's research is about how inequality in society occurs as a consequence of the way society is structured and of individuals' life conditions and personal behavior. The research results have direct relevance to national policy initiatives, for example, the formulation of tax policies and the EU's work in fighting tax evasion. Several CEBI employees have been appointed members of ministerial expert groups such as the Tax Commission and the Benefits Commission. Center leader Claus Thustrup Kreiner has been appointed a member of the commission that identifies initiatives needed to achieve the 2030 green goals.



SCIENTISTS

PAVE THE WAY FOR THE SECOND QUANTUM REVOLUTION



The first quantum revolution completely changed our understanding of the fundamental laws of nature. The second quantum revolution is about using nature's quantum properties to build new communication and sensor technologies. The world is looking for transformative technologies as reflected in billion-dollar investments by IT companies such as Microsoft, IBM, and Google as well as in research programs.

Several Centers of Excellence are among the world's elite in the field of fundamental physics, on which the development of quantum-based technology is founded. These centers include:



Center for Macroscopic Quantum States (bigQ), Technical University of Denmark

Center leader: Professor Ulrik Lund Andersen



Center for Hybrid Quantum Networks (Hy-Q) University of Copenhagen

Center leader: Professor Peter Lodahl



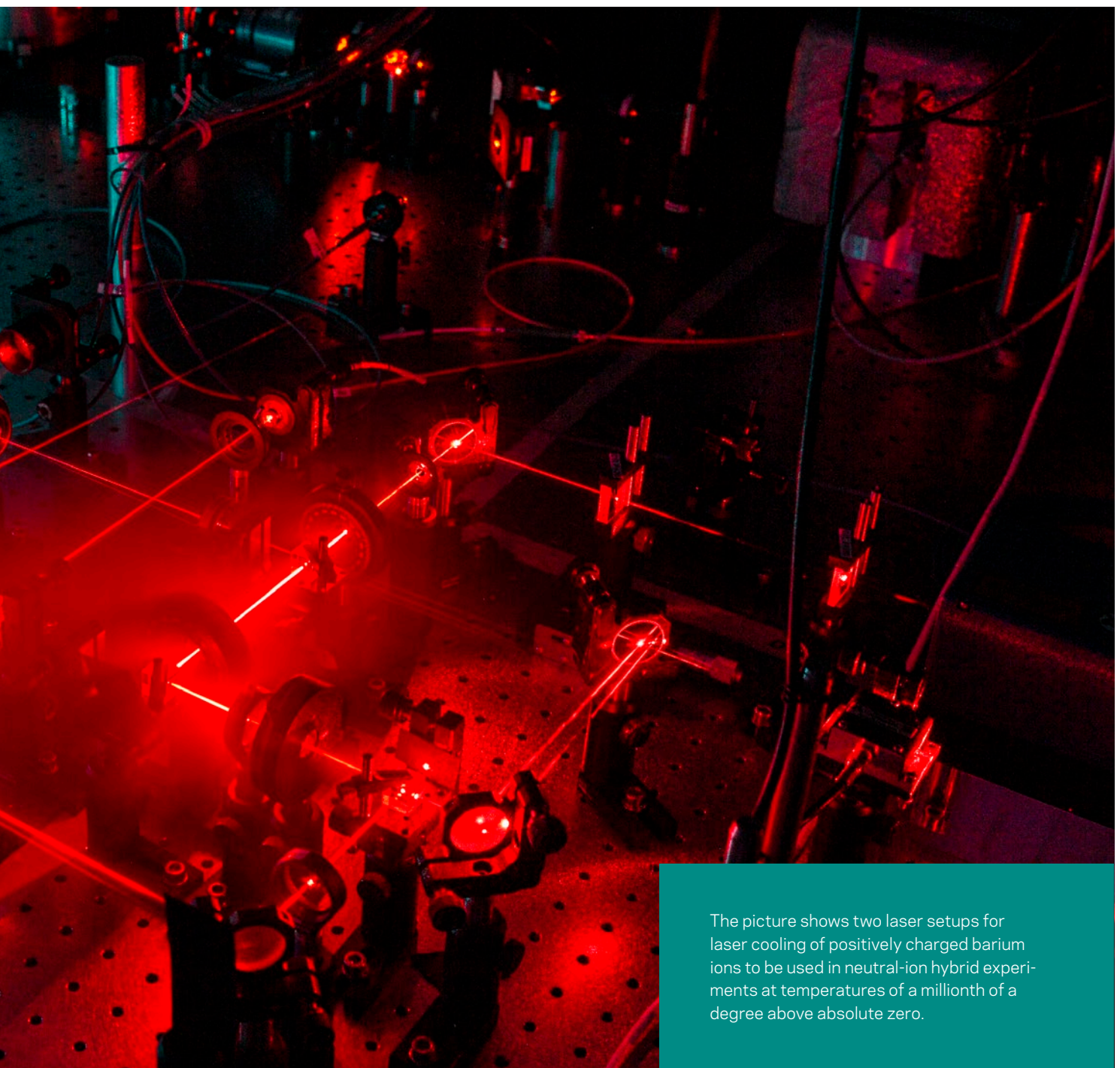
Center for Quantum Devices (QDev), University of Copenhagen

Center leader: Professor Karsten Flensburg

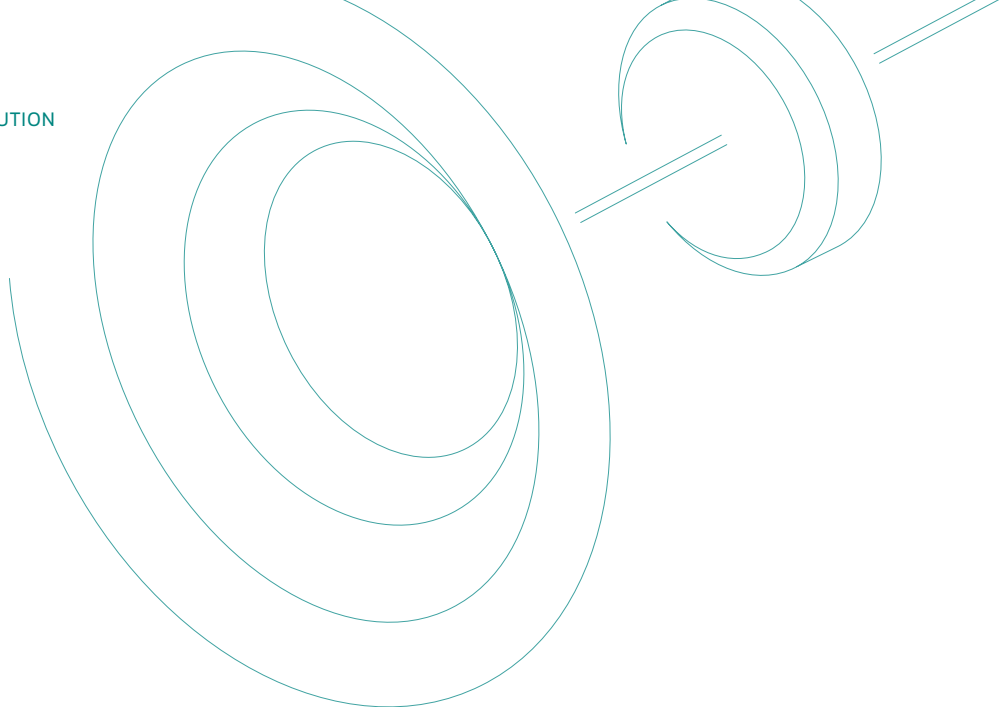


Center for Complex Quantum Systems (CCQ), Aarhus University

Center leader: Professor Thomas Pohl



The picture shows two laser setups for laser cooling of positively charged barium ions to be used in neutral-ion hybrid experiments at temperatures of a millionth of a degree above absolute zero.



Technology development based on quantum physics

The centers have different approaches to quantum science, but their united mission is to test new theories and develop the building blocks needed to transform theoretical algorithmics into practice and on a scale where they can be used to develop technology that is useful to society. The centers' focus is on quantum simulations, quantum computers, and a quantum internet.

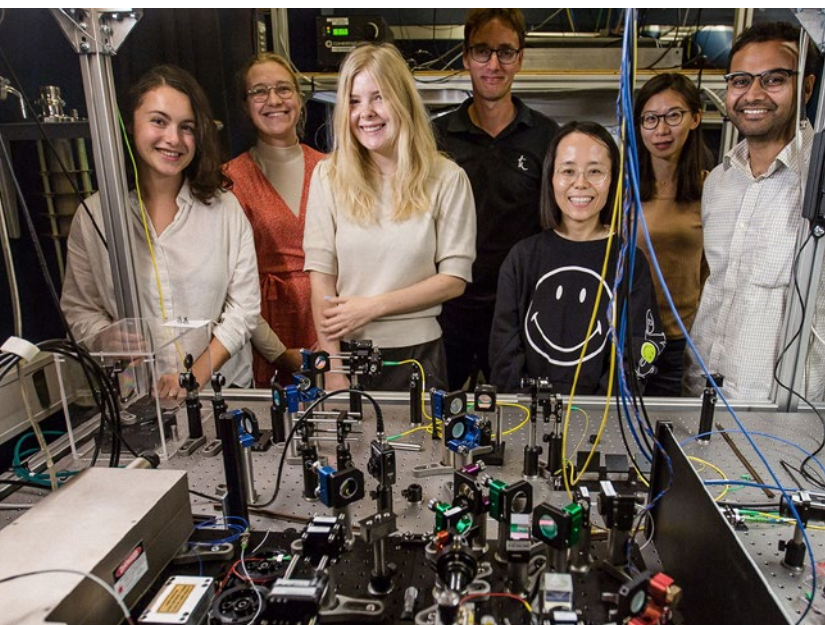
"We are beginning to have quantum resources available, whereby you can implement quantum algorithmics that can't be solved on ordinary computers," says Peter Lodahl.

A quantum is an atom's smallest energy packet that can be released as light (photons) when the electrons change energy state. As the limit for the size of computers' silicon chips is being reached, interest in using the properties of atoms in IT technologies is growing.

Last year, Google demonstrated the so-called "quantum superiority" by making a conventional supercomputer and a quantum computer with 53 quantum bits perform the same calculation. The experiment proved that the quantum computer was capable of solving a concrete problem and that it did so much faster than the conventional computer. In this way, one now knows with certainty that a quantum computer is capable of making calculations and thus solving a concrete problem. Up until now, researchers were only able to simulate the operations a quantum computer might be able to do.

"However, there are still technical barriers and fundamental challenges that must be solved before a full-blown quantum computer is ready. It is difficult to predict when it will be ready, which in particular depends on the extent to which we are able to attract financial support and talented people to the field," says Ulrik Lund Andersen. He elaborates: "The calculation made by Google cannot be used for anything concrete yet. But the principle of a quantum computer has been shown. It is a first step and a very important milestone. The next milestone is to make a quantum computer solve a practical problem."

All center leaders agree that Google's demonstration was a big step. *"If you can control about 50 photons, which we have already shown that our photon source can deliver, then you are in an area where a conventional computer will never enter," says Peter Lodahl.*



The Hy-Q team behind the demonstration of a deterministic one-photon light source. Photo: Ola Jakub Joensen.

One area of application that is closer to being realized is the use of quantum simulators to make calculations for answering biological, chemical, and molecular questions. One example is protein-folding processes, which are essential for the development of medicine. *"There is a wide range of sectors where applications based on quantum technology have the potential to transform the status quo, for example, in the pharmaceutical industry, the construction sector, and the transport sector,"* explains Thomas Pohl.

"The procedure is to start with simple calculations you know the answer to or questions you are able to verify with ordinary computer power, and then start putting more and more photons into play. But that is technologically difficult, because it requires scaling the quantum mechanical systems up to a hundred or a thousand photons, or even more. It may sound easy, because when we have a one-photon source, one would think that you just have to press the

button a hundred times. But the photons must be completely identical and inseparable, which is difficult to achieve. And one must not lose them. Quantum states are very fragile. The rules of the game in the quantum world are very different from the rules in the ordinary world," says Lodahl, adding: *"This means that we need to be smarter about how we build quantum systems."*

Ulrik Lund Andersen notes that *"if you want to simulate a relatively complex molecule like penicillin, for example, you have to go up to about 250-300 quantum bits, and you can't do that today. And it's not even ordinary quantum bits that are needed; it is error-corrected quantum bits. And to correct one quantum bit, you need hundreds of other quantum bits. So, you may need about a million physical quantum bits in a quantum computer to handle the large and complex molecules that are really interesting. And today we only have around 53 quantum bit systems, so there is still a long way to go."*

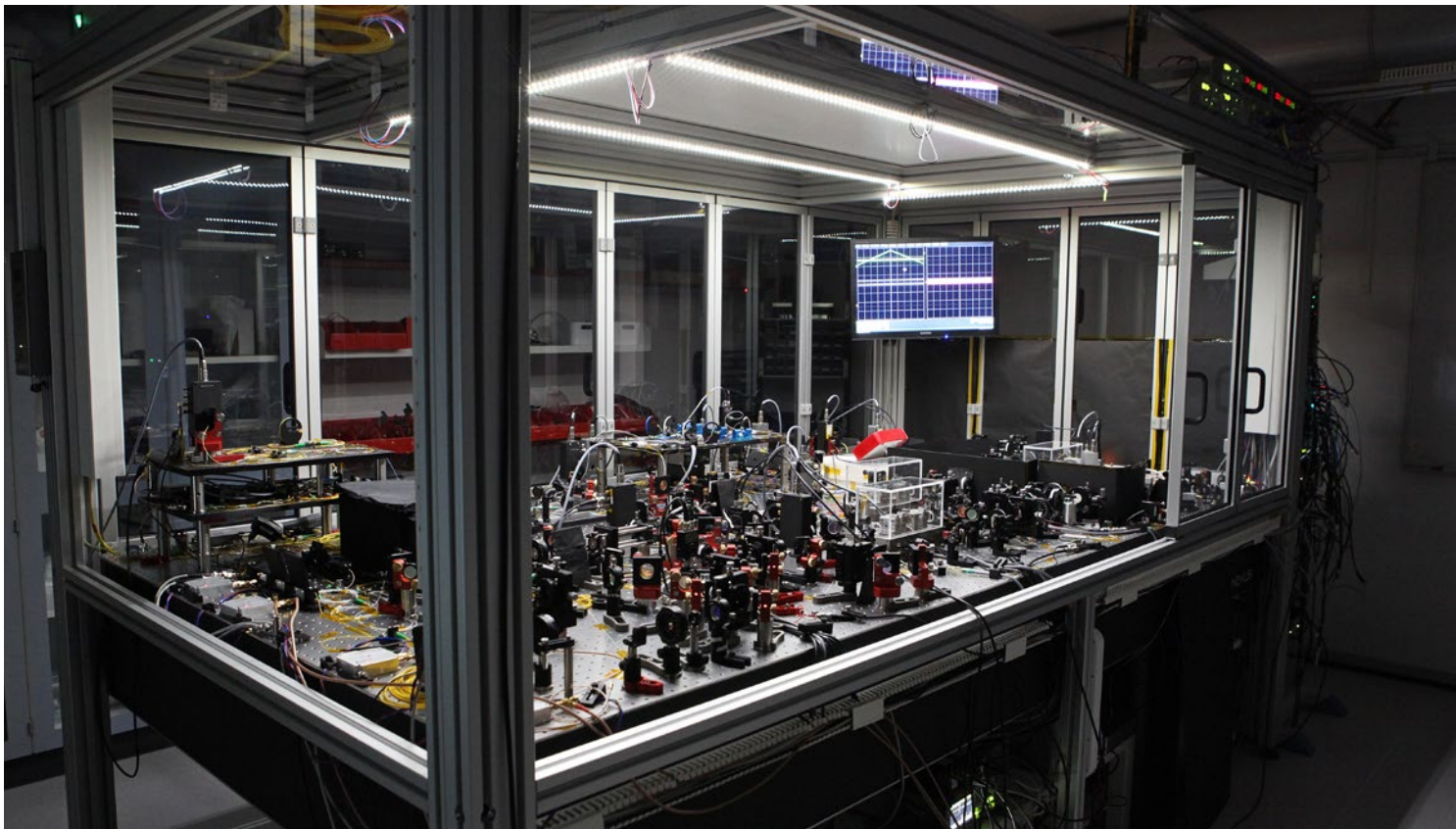
Basic research is essential for moving forward

The center leaders are excited about the exposure of quantum science in the media that is going on right now. Pohl notes that quantum technology has also found its way into the movie industry: *"One may be led to believe that the technological development process is brand new, but that is not the case. It has been around for a long time - since the late 1980s - which you could easily forget in the current hype about "quantum."*


Lodahl explains: *"The starting point in technology development is basic research because quantum physics is so fundamentally different. We understand the quantum mechanical rules, which have been tested with enormous precision. We begin to have control over individual atoms and photons that we can use for experiments, but what happens when we scale up? What are the limits of this upscaling? Here we still lack theoretical understanding. That is where the potential is and where there is a need for fundamental science."*

The most obvious sign that there are still many years to go before the realization of a second quantum revolution is that the IT giants still need basic scientists. If “quantum” was already a technology, the basic scientists would be out of the equation, and as Lodahl says: *“We are not yet in a place where you can leave it to the engineers to create technology based on quantum physics.”* Karsten Flensberg shares this view: *“If it was a mature technology, then things would have happened by themselves. But it has not happened!”*

Thomas Pohl agrees: *“It is important to keep in mind that we are in the middle of a process. We cannot say that we have carried out a new quantum revolution, even though a lot point in the right direction. There are high expectations about how quantum technology can change society, and the next 10 to 20 years will show if we are able to live up to them. Fundamental theoretical research is pivotal to moving forward and meeting those expectations.”* He continues: *“We do see profound breakthroughs in, for example, quantum cryptography for safe communication. Quantum*



From the inside of the Molecular Beam Epitaxy machine. Quantum computer setup.
Photo: Jesper Scheel.



cryptography builds on the principles of quantum physics and is unbreakable, unlike classical encryption, which is based on mathematics. Quantum encryption will eventually replace classical encryption."

Collaboration between basic researchers and companies

One of the characteristics of the second quantum revolution is investments from private companies. Most of the centers collaborate with industrial partners, either directly or through participation in international projects and networks. The researchers' motivation is to create new knowledge and to convey it to the world. Industry's motivation is the same, but of course, it has a more short-term goal of applying the new knowledge in services and products that can be sold.

"Numerous ties are being built between universities and the business community. It's interesting that right away you can see the technology being used for something. We clearly expect that we will be part of creating the foundation for the development of a whole new technology," says Ulrik Lund Andersen.

Part of the contact with industry partners comes from participation in EU programs such as the Quantum Technology Flagship and the Quantum Communication Infrastructure. The latter focuses on quantum cryptography

and is a follow-up to the first flagship program about developing quantum technology for communication, simulation, computers, metrology, and sensors. Almost half of the participants in the EU programs that the centers are involved in come from industry. *"Their role is to help us develop quantum technology and examine what use it may have in future communication and computer systems, and ultimately, to test the technology in the real world. This has resulted in an incredibly close and fruitful collaboration,"* says Andersen. *"The collaborations in these programs are generally profitable for all involved. Of course, the companies get knowledge from us, but in return, we get new electronics and many other things we can use in our experiments, which helps us to improve our basic research. It has been interesting to see how new, innovative ideas have been developed at the crossroads between basic research and commercial thinking."*

Karsten Flensberg adds: *"It is precisely in the synergy between basic researchers and companies that interesting developments happen. But within the quantum sciences, it is the basic research that sets the pace. So, the industrial partners have to be patient."*

At the national level, the Innovation Fund Denmark is an important player in getting the technology that the centers develop tested and matured to a level where there is a real commercial potential. *"The Innovation Fund's funding opportunities are absolutely essential for us to be able to move forward with our building blocks and commercialize them,"* says Peter Lodahl.

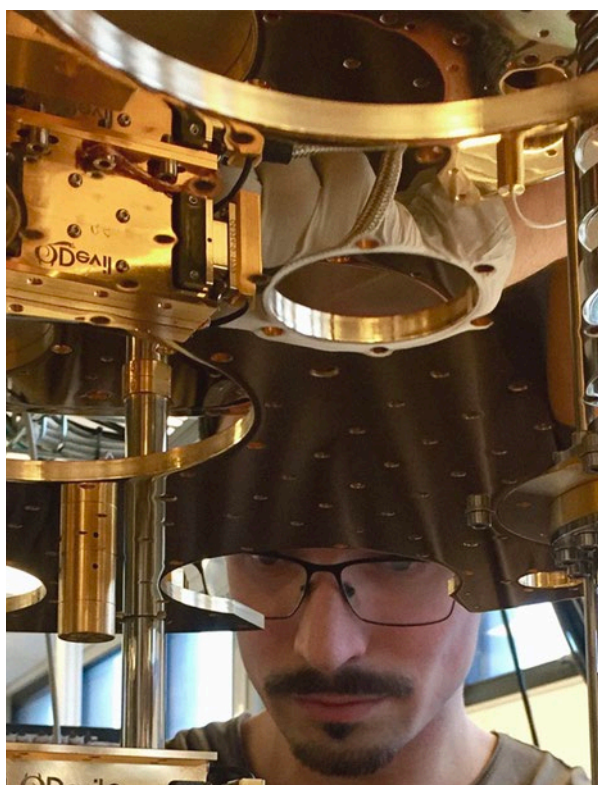
Motivation and societal relevance

All the center leaders are basic scientists at heart and would continue their research in quantum science even though this era does not represent a new quantum revolution. But of course, researchers are motivated by the possibility that they might be part of a breakthrough that can be useful for society.

"Relevance is an issue that must be taken seriously, but without making it the driving force," says Lodahl. He elaborates: *"It gives us a huge energy boost to know that we are part of creating something that is really meaningful for our society. Instead of just writing scientific articles, we have something that is valuable and possible to scale up in relation to quantum computers and a quantum internet. It is extremely exciting that our research might lead to real and useful technology."*

Concerning the societal relevance of basic research, the center leaders emphasize that one of their most important tasks as holders of DNRF grants is to educate a new generation of skilled people. And because there will not be room for all young researchers at the universities, they will create societal value elsewhere.

"We educate people who are on such a high level that they can take ideas that arise and work on them in the companies where they are employed. The ability to absorb new ideas requires that they have a high technical level. And they seem to be getting the right training from us. Even our theorists who have never touched a button don't have any problems getting jobs if they don't wish to continue in the research world," says Karsten Flensberg. *"It has become a prestigious mark for our graduates to be trained in quantum technology when they seek jobs in companies,"* Lodahl concludes.



QDev postdoc Asbjørn Drachmann at a BlueFors cryostat from QDev.
Photo: Niels Bohr Institutttet.

WITH CONTRIBUTIONS FROM THESE CENTERS OF EXCELLENCE

Center for Macroscopic Quantum States (bigQ)

(from 2018)

bigQ strives to understand and exploit macroscopic quantum phenomena. The center's research has resulted in a groundbreaking demonstration of entangled optical cluster states that can form the basis of a scalable, error-corrected optical quantum computer and long-distance quantum communication.

Center for Hybrid Quantum Networks (Hy-Q)

(from 2018)

Hy-Q researches optical technology for quantum computers of the future and a global quantum internet. Hy-Q is behind the development of a nanochip that can transmit one light particle at a time in a certain direction and at a certain time. An obvious potential use of the center's technology is an upgrade of the existing cryptography systems to support secure communications.

Center for Quantum Devices (QDev)

(from 2012)

QDev is researching quantum electronics that potentially can be integrated with traditional electronics. QDev has developed a quantum bit, which is an artificial atom, in which you can control the number of electrons and code them with information. The results can be used in future quantum computers and for complex calculations.

Center for Complex Quantum Systems (CCQ)

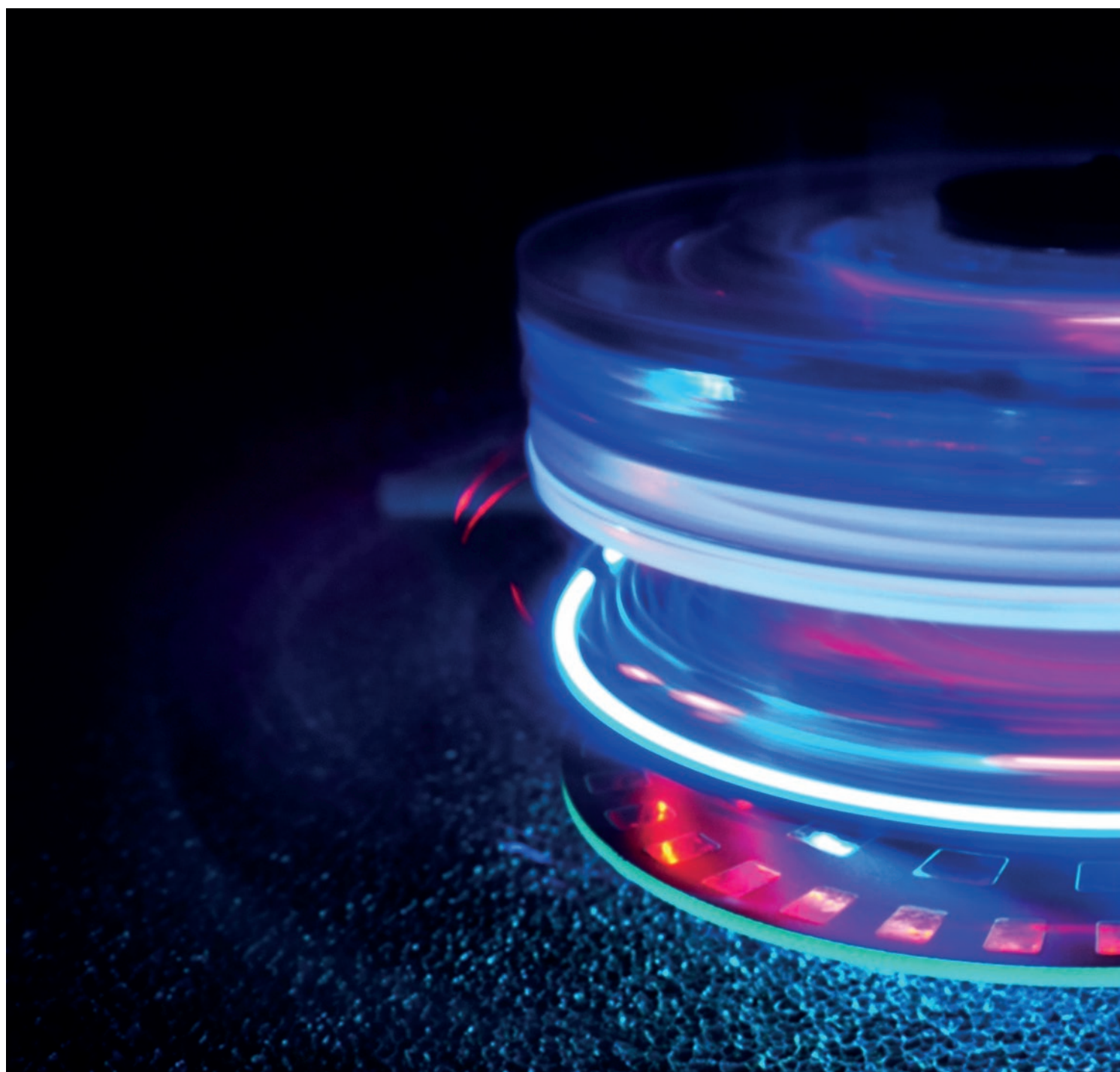
(from 2020)

CCQ researches the construction of quantum systems from the ground, i.e., atom by atom, and how to control the interactions between different quantum mechanical components. The results can be used for the development of quantum technology, e.g., for optimizing lasers and superconductors which might lead to the production of electricity without wasting energy.

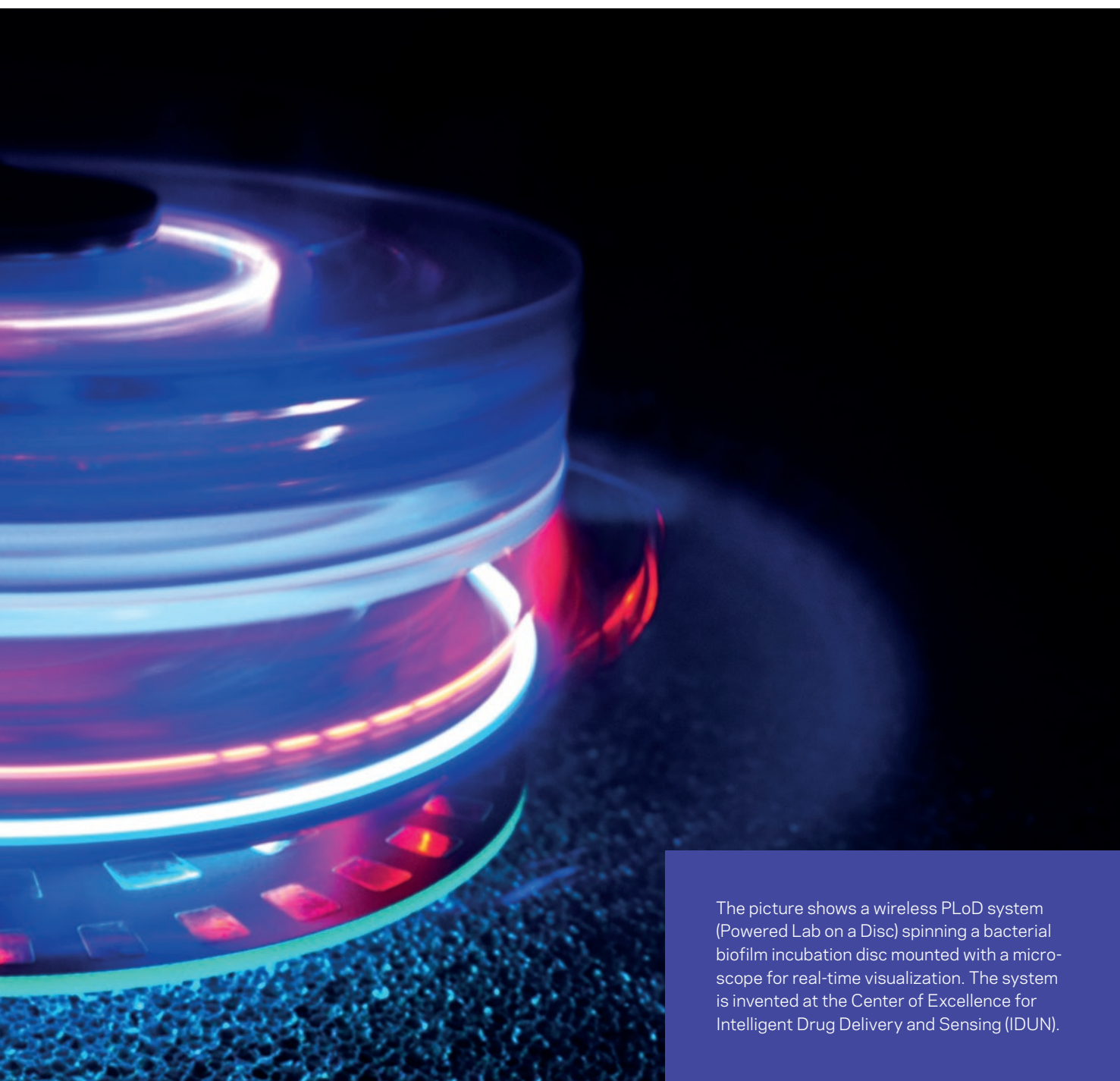


CENTERS OF EXCELLENCE

ARE INCUBATORS FOR INNOVATIVE COMPANIES



Many Centers of Excellence prioritize collaborations with companies to further bolster their usefulness to society, in terms of both their research and the graduates they teach at the master's, Ph.D., and post-doc levels. The collaborations are created through participation in national and international research programs as well as through networks or direct contact.



The picture shows a wireless PLoD system (Powered Lab on a Disc) spinning a bacterial biofilm incubation disc mounted with a microscope for real-time visualization. The system is invented at the Center of Excellence for Intelligent Drug Delivery and Sensing (IDUN).



In several of the centers, their scientific discoveries form a starting point for establishing companies – so-called spinoffs – created to commercialize one or more inventions derived from their research.

When comparing the Ministry of Higher Education and Science's commercialization statistics to the Danish National Research Foundation's own data on the centers' activities, it turns out that about a quarter of the spinoffs that came out of public research institutions in 2018 and 2019 originated from Centers of Excellence. The Centers of Excellence are often financed by other funding bodies as well, so the foundation alone cannot take credit for the commercialization results.

Naturally, it is not every year that the Danish National Research Foundation has this big a share in spinoff companies from the universities. Nonetheless, these spinoff companies demonstrate that top research and its real-life use go very well hand in hand.

The company EpiTherapeutics Aps, a spinoff from Professor Kristian Helin's Center for Epigenetics, is among one of the most remarkable spinoffs arising from previous Centers of Excellence. EpiTherapeutics developed new medicine for the treatment of cancer and other diseases and was sold a few years ago for half a billion DKK to an American pharmaceutical company.

Professor Ib Chorkendorff's Center for Individual Nanoparticle Functionality was the basis for the spinoff company HPNOW Aps. The company still has great success with the production of hydrogen peroxide based on water, air, and electricity, which is used for disinfection, for example, to keep irrigation systems free of algae growth.

Over the period 2005-2015, the Danish National Research Foundation's CEO Søren-Peter Olesen led the Center for Cardiac Arrhythmia. This center contributed to establishing the company Acesion Pharma, which is now conducting phase-2 clinical patient studies of a drug for the treatment of atrial fibrillation based on a completely new medical principle. The financing of the company originally came from the Innovation Fund Denmark and NovoNordisk Ventures, and later from the Wellcome Trust and other venture funds.

"There is no doubt that without the basic research in cardiac physiology conducted at the center, the company and this new approach to the treatment of atrial fibrillation would never have happened. It was a fortunate situation whereby pharmacological knowledge, clinical genetics, and animal experimental knowledge all came together in the center. The environment at the center was characterized by a keen interest in innovation. We also trained about 50 researchers who, for the most part, have moved on to work in the industry and have interesting careers here. The center, at its inception, had a wide network within the Danish biotech and pharmaceutical industries because that's where I came from, and naturally, this network has grown through the next generation of scientists and leaders," says Olesen.

Søren-Peter Olesen concludes with an important point that illustrates the Danish National Research Foundation's function and work ethic: *"I'm actually very content that, early on, we separated the company's activities from those of the center as the end goal is different in these two types of research activities, even though they have the same origin."*

EXAMPLES OF SPINOFF COMPANIES THAT EMERGED FROM CENTERS OF EXCELLENCE IN 2018 AND 2019:



Sparrow Quantum Aps produces single-photon chips for quantum and nanotechnology. The company is a spinoff from the Center for Hybrid Quantum Networks, led by Professor Peter Lodahl.



Lightnovo makes microscopes for diagnosis and spectrometers for the measurement of electromagnetic waves. The company is a spinoff from the Center for Intelligent Drug Delivery and Sensing Using Microcontainers and Nanomechanics, led by Professor Anja Boisen.



SiPhotonIC designs and manufactures advanced silicon photonic integrated circuits. The company is a spinoff from the Center for Silicon Photonics for Optical Communications, led by Professor Leif Katsuo Oxenløwe.



Polarize makes instruments for hyperpolarization, a new technique used to discover and examine metabolic changes in the body. The company is a spinoff from the Center for Hyperpolarization in Magnetic Resonance, led by Professor Jan Henrik Ardenkjær-Larsen.



TEGnology Aps develops materials for thermoelectric modules that convert waste heat from industrial processes to electricity. The company is a spinoff from the Center for Materials Crystallography, led by Professor Bo Brummerstedt.



Deliver Pharma Aps produces pharmaceuticals for microphages, which are a specific type of white blood cell in the immune system. The company is a spinoff from the Center for Functional Genomics and Tissue Plasticity, led by Professor Susanne Mandrup.



GlycoDisplay develops pharmaceuticals based on glycoprotein, which is a special transporter of medicine in the body. The company is a spinoff from the Copenhagen Center for Glycomics, led by Professor Henrik Clausen.



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