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Culinary Science in Denmark: Molecular Gastronomy and Beyond

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Noting that Denmark is traditionally an agricultural country and that a large part of the gross national product derives from the export of meat and processed food products, this article points out the paradox that only during the last decade has some Danish food-related research been genuinely driven by gastronomy and gastronomic innovation, and only recently have research activities and academic educational programs that include aspects of molecular gastronomy and other culinary sciences been initiated. At the same time, Denmark has placed itself on the international map due to innovative chefs winning top international awards and celebrated positions on lists of the best restaurants worldwide. Moreover, the New Nordic Cuisine movement has released novel driving forces and instigated new types of collaborations between chefs and scientists. Danish scientists of different orientations are being stimulated by the empirical world of gastronomy and cooking and are maturing molecular gastronomy as a science, and others have become proliferate writers and communicators of gastronomically inspired science; for example, within gastrophysics.

KEYWORDS Food science, molecular gastronomy, gastrophysics, education, research communication, publication, Denmark

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A BRIEF HISTORY OF FOOD SCIENCE IN DENMARK

Denmark is an agricultural country and has long been producing more food than its inhabitants consume. Historically, due to increasing competition from the North American countries, Danish agricultural production, as in many other countries across Europe, developed toward more animal-based production from the last half of the 18th century to the late 19th century. In response to this shift, farmers organized cooperative abattoirs and dairies and the Danish government founded a number of scientific institutions, including, among others, the Royal Agricultural and Veterinary University of Denmark (KVL, founded in 1856), the Danish Institute of Animal Science (Staten Husdyrbrugsforsøg, 1883), and the Danish Experimental Dairy Research Station (Statens Mejeriforsøg, 1923). The first university-level food science education, the so-called dairy engineer education, was inaugurated in 1921, followed 50 years later by a more general food science education (Bromatolog) in 1971. Both educations were provided by KVL. Aspects of food technology were built into the master of science in engineering curriculum that was taught at the Technical University of Denmark.

Although the foundation of these institutions and educations initially had tremendous impact on the Danish food and agricultural sector, the effect leveled off completely toward the end of the 20th century. Food science came to concern itself almost exclusively with simplification and standardization, focusing on primary production, such as securing a high yield of crops, and a quite narrow range of food science topics, such as microbiological safety of milk and consistent quality of standard commodities for export products like butter and bacon. Food science in Denmark was clearly not developing along with other sciences such as chemistry and physics.

Around 1990, a number of businesspeople in the food sector together with politicians realized a disjunction between the existing range of food science activities in Denmark and the importance and potential of this kind of science in Denmark as a food-producing country. All food science activities in Denmark were subsequently reviewed and evaluated by the government research council, and publicly funded food science programs were estimated to support a meager 17.6 full-time research personnel. Based on this review, the government recommended the rejuvenation of food science activities in Denmark. In response to this recommendation, the Danish Centre for Advanced Food Research was founded in 1992, an umbrella organization coordinating most publicly funded food science programs in Denmark. The so-called FØTEK (The Danish Research and Development Programme for Food Technology) programs were initiated, and 525 million kroners (DKK) from public sources were made available for food science projects conducted predominantly in direct collaboration between and equally cofinanced by public and private partners. The field of food science in these programs was mostly associated with basic biotechnology, fast noninvasive analytical techniques, basic sensory science, nutritional science, and prediction of shelf

life. The FØTEK programs, followed by other research programs, boosted research activities to a high-performing level internationally—there are, for example, currently about 150 PhD students active in Denmark within food science-related subjects.

However, a side effect of this sweeping policy of funding food science caused by demanding a 50% cofinancing from external, mostly industrial, partners was that the majority of food science in Denmark became dominated by industrial thinking and subjects that were relevant primarily for large-scale production, whereas small-scale production of unique, artisanal products; curiosity-driven food research; gastronomic creation and innovation; as well as the procedures of domestic and restaurant kitchens were seldom considered subjects meriting scientific investigation and corresponding financial support. This early history of food science in Denmark has been reviewed in Danish by Skibsted (2008).

THE EMERGENCE OF MOLECULAR GASTRONOMY IN DENMARK

Influence from Great Britain and France—especially the activities of Peter Barham and Hervé This—reached Denmark in the beginning of the new millennium. KVL realized the potential of research and educational activities related to the emerging field of molecular gastronomy. The former environmental chemist of the Chemistry Department of University of Copenhagen, Thorvald Pedersen, was hired as the first professor of molecular gastronomy—a position he held for only one year until his retirement at age 70. Prior to that, Thorvald Pedersen had for many years been the proliferate author of monthly articles on chemical aspects of cooking in the magazine *Dansk Kemi* (*Chemistry in Denmark*; Pedersen, 2002, 2006, 2008). Thorvald Pedersen had attended some of the pioneering molecular gastronomy meetings in Erice, Sicily, in Italy and had made connection to the pioneers of molecular gastronomy.[1] As professor of molecular gastronomy, Thorvald Pedersen organized workshops and meetings bringing Danish chefs and scientists together with the founding fathers and advocates of molecular gastronomy Peter Barham and Hervé This. Before his retirement, Thorvald Pedersen was celebrated at a spectacular gastronomy event held at Theatre Avenu in Copenhagen where a number of head chefs prepared and presented food at the scene. Small dishes were served to the audience and a panel of scientists, including Thorvald Pedersen himself, entertained by explaining the relevant scientific phenomena involved in the dishes.

Thorvald Pedersen's approach to molecular gastronomy is to a large extent that of a physical chemist, and his works could just as well be termed *culinary chemistry* or *chemical gastronomy*. A chemistry colleague of Thorvald Pedersen, the organic chemist Carl Th. Pedersen from the

University of Southern Demark, has also put his mark on the development of the culinary sciences in Denmark. His beautiful book on spices and cooking, written with the chef Torsten Vildgaard (Vildgaard & Pedersen, 2006), sets new standards for books combining gastronomy, recipes, chemistry, and cultural history.

MOLECULAR GASTRONOMY AS A SCIENCE IN DENMARK

After the retirement of Thorvald Pedersen, a group of food scientists at KVL made the observation that molecular gastronomy activities around the world so far had resulted mostly in books and articles addressing the broader public, whereas the publication of original experimental results in peer-reviewed journals was extremely scarce. It was also clear that making molecular gastronomy accepted as a real science would require funding of research activities leading to peer-reviewed articles and training of researchers within molecular gastronomy to the level of PhD degrees. Funding from the private Villum Kann Rasmussen Foundation made it possible to affiliate Peter Barham as visiting professor of molecular gastronomy at KVL. The Danish Research Council for Technology and Production subsequently granted 7 million DKK for a research project, Molecular Gastronomy—The Physical and Chemical Basis of Deliciousness, led by professor Leif Skibsted of KVL (KVL merged with the University of Copenhagen during the project period). The research group behind the project comprised both sensory scientists and food chemists in the Department of Food Science at KVL.

The first two Danish PhD students of molecular gastronomy were enrolled and dedicated to each of their projects. Pia Snitkjær Nielsen (married Bailey) studied the fundamental problems of reduction of meat stocks with and without the addition of wine (Bailey et al., 2011; Snitkjær, 2010; Snitkær, Frøst, Skibsted, & Risbo, 2010). In particular, she addressed the apparent paradox that the process of intensifying the flavor of a stock by boiling off water also inevitably drives off volatile aromatic components along with the steam. Using a combination of gas chromatography–mass spectrometry aroma analysis and descriptive sensory analysis of rediluted soups, a series of stages during stock reduction was identified. Each stage was dominated by different aroma components giving rise to distinct sensory properties. It was concluded that stock reduction is not only a process of intensifying flavor by increasing concentration of the various components but a continuous change in flavor due to loss of some volatile components and chemical generation of others. The balance between these two main processes can be shifted by the power input from the stove, and a fast reduction rate was found to give a stock that has less volatiles and a sensory profile that more resembles a less reduced stock.

The other PhD student, Louise Mørch Mortensen, addressed the new possibilities of low-temperature sous-vide cooking of beef with special emphasis on time and temperature as the parameters used by the chef to achieve the desired result. Descriptive sensory analysis showed that the descriptors could be arranged into two groups according to their time and temperature responses (Mortensen, Frøst, Skibsted, & Risbo, 2012). One group of descriptors (12 descriptors including juiciness), mainly flavor related, showed what could be called a chemical behavior, where time and temperature both either enhanced or diminished the impression related to the sensory descriptor. The other group of descriptors (6 descriptors including tenderness) was mostly related to the textural attributes of the meat and, for this group, time and temperature worked against each other. For example, perceived meat tenderness was diminished by increased temperature and enhanced by longer cooking times. This was attributed to a more complex mechanism involving at least two main processes: a fast toughening process promoted by temperature and a slower softening process mostly promoted by time. As a consequence of these two conflicting types of behavior, the chef cannot compensate for lower temperature by longer times (or vice versa) because different culinary results will be obtained. Properties related to the two descriptor groups (for example, juiciness in one group and tenderness in the other) cannot be optimized using the same combinations of time and temperature—and therefore the crucial role of the chef in this case lies in determining and executing the most appropriate compromise.

Part of the funding of the project Molecular Gastronomy—The Physical and Chemical Basis of Deliciousness was allocated to hire the chef Torsten Vildgaard (at the time deputy head chef of Restaurant Noma in Copenhagen). Torsten Vildgaard was assigned by the scientific staff to create a series of dishes to be used for so-called restaurant experiments. Being under same roof as food scientists, Torsten Vildgaard could draw on a range of different expertise and was thereby able to overcome many technical difficulties; for example, consistently manufacturing a milk skin of adequate strength and taste or controlling the moisture content of seeds before popping by incubation in an atmosphere determined by saturated salt solutions. These restaurant experiments were conducted in real restaurant contexts (at Meyers Madhus and in Noma's function room). The experiments investigated a number of topics in relation to restaurant meal experiences.

In one experiment, the main purpose was to study the effect that verbal presentations have on the various aspects of perception of the dishes (Mielby & Frøst, 2010). Furthermore, the guests' psychographic backgrounds were used to elucidate whether different types of restaurant guests or consumer segments react differently to dishes and presentations. The results showed that the least-liked dishes were also the most novel and unusual dishes. Guests' psychographic backgrounds affected how challenging and how liked the dishes were and, in both cases, the most neophilic guests

gave the highest ratings. Moreover, the type of presentation was found to change both the hedonic evaluation (the liking) as well as how surprising and challenging the guests found the dishes, but not in a straightforward manner. There is a complex interplay between type of presentation and the dish that needs to be considered by restaurateurs. It appears that presentations that contain the technical details of the culinary processes used to create the dish are most successful in increasing the hedonic response to the dish. Mielby and Frøst (2010) concluded that presentations that best link the raw materials with the finished result also give a better understanding of the dish, and this may be a reason for the increased liking.

In two other experiments, the relationship between collative properties, like complexity, familiarity, and novelty, and their link to hedonic responses were explored. The studies also included guests' psychographic backgrounds. The results showed that increased complexity leads to higher liking (Frøst & Mielby, 2010). This is similar to the relationship observed in artworks (Hekkert & Leder, 2008) and thus hints that the perception of high-end restaurant meals may have some of the same symbolic functions as art. Further, the studies showed that the hedonic response as a function of the collative properties could be modeled well by multivariate data analysis (Frøst & Mortensen, 2011).

Another topic that was investigated as part of the sensory research was flavor pairing. Initially, an experiment with 19 common foods and 53 binary pairs of these foods was carried out (Bredie, Hartvig, Frøst, & Møller, 2011). Several interesting results were observed in the study. The majority of the pairs showed intensity suppression, such that the intensity of the food pair was lower than the strongest of the individual foods. The hedonic responses were more diverse, but one half of the pairs showed compromise behavior, such that the hedonic response to the mixture of the two foods was perceived as less liked than the more liked of the two. The experiment led to the conclusion that more sophisticated analytical chemistry approaches are needed to evaluate the level to which the composition of aroma volatiles and taste components can predict the hedonic response to food pairings. The topic of flavor pairing has since been investigated in a number of MSc theses (Claes, 2012; Lyse-Petersen, 2012; Malnor, 2012; Rasmusen, 2012).

With the additional possibilities provided by the visiting professor grant, the group at the University of Copenhagen decided that Peter Barham should take the leading role in composing a major scientific article with the dual purpose of reviewing, among other things, the chemistry, physics, sensory science, and neuroscience relevant for cookery and the appreciation of good food but also defining molecular gastronomy as a science. The article was published in *Chemical Reviews* and was entitled "Molecular Gastronomy: A New Emerging Scientific Discipline" (Barham et al., 2010). The article proposed, as a definition, that molecular gastronomy "should be considered as

the scientific study of why some food tastes terrible, some is mediocre, some good, and occasionally some absolutely delicious" (p. 2315). It is noteworthy that the term *molecular* does not enter directly into this definition, although it is understood that the sciences that are invoked to underpin this interdisciplinary inquiry are molecular-based sciences such as chemistry and physics. The key to the definition is its insistence that molecular gastronomy must take a starting point in the fact we all have passionate feelings associated with food and eating. The 53-page article reviews a range of subjects: the senses, the chemistry behind the color of foods, the effects of food production techniques on flavor and texture, food as colloidal systems, the principles of cooking methods, and the enjoyment and pleasure of eating. In conclusion, it presents a vision of where the science of molecular gastronomy is leading us and it suggests that in the future it may be possible to provide some quantitative measure of just how delicious a particular dish will be to a particular individual.

The research activities in Copenhagen led to collaboration with the culinary institutes of Norway and Nofima (a Norwegian governmental food science institute), both situated in Stavanger, Norway. The collaboration involves supervision of a PhD study on classical emulsion sauces.

The molecular gastronomy research project at the University of Copenhagen also organized and hosted a series of workshops with the purpose of bringing together scientists and chefs. In one workshop, four chefs were paired one-to-one with four scientists to collaborate on the development of a specific dish. In this way, for example, one pair evaluated the gastronomic potential of high-pressure-treated beef, chicken, and tuna, and another pair worked to create dishes centered on corn. They succeeded with two dishes: one had an intended pun on the similarity between the Danish word for corn—*majs*—and the first part of the word *marshmallow*. The dish was marshmallow based on corn syrup, rolled in a popcorn crumble. The second dish was a remake of the Danish child-friendly breakfast staple *guldkorn*, a puffed wheat grain rolled in honey and served with milk. The dessert dish was based on corn syrup, milk sorbet, gold dust, and freeze-dried corn. The last two pairs worked on the development of an edible candle and blood soup, respectively.

The last workshop was held just before the end of the project and included talks summarizing the obtained scientific results and how to make use of concepts of molecular gastronomy in university teaching of physical chemistry. The food science blogger Martin Lersch from Norway (Lersch, 2013) contributed with a lecture on how the Internet can be used to disseminate science about gastronomy and molecular gastronomy. In his blog he has reported extensively from the workshop. As an example of molecular gastronomy's power for activating the popular imagination, an attempt was made to break the world record for the fastest making of vanilla ice cream by use of liquid nitrogen.

Independent of the pioneering molecular gastronomy activities at the University of Copenhagen, and certainly arising from a different and initially much less rational approach, are the activities in a community of mostly physicists at the University of Southern Denmark in Odense. In 2001, this small group of physicists playfully described their combined interest in cooking, eating, gastronomy, and the physical sciences as *gastrophysics*, and they founded the infamous Gastrophysical Society. Gradually these scientists translated some of their amateur interests in gastronomy into more well-defined questions that could be addressed by rigorous physical experimentation, molecular simulation, and theory. Steeped in a tradition of the physics of complex liquids, soft matter, and biological systems, the view on science-related gastronomy formulated by these scientists is rooted in the molecular world and in concepts of universality and generic behavior. Some examples of works deriving from these activities pertain to seaweeds in gastronomy (Mouritsen, 2012, 2013), dashi production and umami taste from Nordic seaweeds (Mouritsen, Williams, Bjerregaard, & Duelund, 2012), the molecular mechanism behind the synergy in umami sensation (Mouritsen & Khandelia, 2012), and the science of deliciousness (Mouritsen, Duelund, Bagatolli, & Khandelia, 2013; Mouritsen & Styrbæk, 2011). It is interesting to note that whereas there is little, if any, rational science behind the so-called food-pairing hypothesis as demonstrated by an extensive flavor network analysis (Ahn, Ahnert, Bagrow, & Barabási, 2011), there is now a firm molecular basis behind taste pairing in umami as described by an allosteric action of free glutamate and certain 5′-ribonucleotiodes at the umami receptor (Mouritsen & Khandelia, 2012). Using this molecular insight into gastronomy is thus truly molecular gastronomy (Mouritsen & Styrbæk, 2011). Hence, linking the fate of molecular gastronomy to the fate of the conventional flavor-pairing hypothesis is ill founded (Humphries, 2012). As we shall return to below, the activities of the group at the University of Southern Denmark are also closely tied to research communication and popular science writing.

SCIENTIFIC ENVIRONMENTS IN DENMARK RELATED TO MOLECULAR GASTRONOMY

In a broader perspective, molecular gastronomy–related scientific environments in Denmark cover university partners with activities in sensory science and meat cooking at the Danish Meat Research Institute (DMRI), now part of the Danish Institute of Technology. This institution has for a long time applied gastronomically oriented science directed at offering know-how to consumers and chefs working in the catering sector. Topics of such research and outreach activities address questions such as whether steak should be salted before or after frying and whether steak should rest before being cut. The DMRI is also involved in scientific projects concerning low-temperature

long-time cooking of meat with the Department of Food Science at the University of Copenhagen.

In connection with a shared interest in sensory interactions during eating, researchers from the DMRI and the sensory science group at University of Copenhagen have investigated food-sensory interactions between meats and accompaniments with different basic tastes (Aaslyng & Frøst, 2008, 2010). They found that as well as an increase in the basic taste of the accompaniment, the interaction included reduction of several other flavors, such as porcine and metallic/liver flavors. In addition, they studied how gravy with different fat contents can be used to decrease bitter and acidic tastes in broccoli and cauliflower. A 5% fat content in gravy is enough to decrease the brassica flavor. Although there is some retention of key cabbage compounds, there is also a sensory-masking effect (Meinert, Frøst, Bejerholm, & Aaslyng, 2011).

NORDIC FOOD LAB

The Nordic Food Lab was born from horseradish. The head chef of Restaurant Noma, René Redzepi, was working on a dish with the peppery root and was confounded because the deliveries from a local farmer tasted different every time. Some were sweet and mild, some grassy and bitter, some moist, some dry, some spicy beyond belief. It was impossible to build a dish with such a protean ingredient. When he began to explore this unexpected diversity, he discovered that horseradish (*Amoracia rusticana*) actually includes over one hundred different subspecies, each with slightly different taste qualities. This was knowledge that had implications not only in the kitchen but also within the larger context of Nordic cuisine and its impulse to understand our relationship with the edible landscape more deeply.

This realization led Redzepi, along with Claus Meyer, the other cofounder of Noma, to imagine a space outside the constraints of the restaurant that could be devoted to conducting gastronomic research through scientific methodology for the benefit of the entire Nordic region. They established the Nordic Food Lab in 2008 as a place where chefs, scientists, academics, and producers could collaborate to explore the building blocks of Nordic gastronomy—raw materials, traditional processes, and modern techniques—and share these results with other chefs, industry, and the public.

The Nordic Food Lab is a nonprofit, self-governing institution whose driving force is the pursuit of deliciousness. The power of this goal, however, is that it leads to other implicit and interconnected pursuits: the search for flavors old and new, the rediscovery and reinvigoration of tradition, the preservation and cultivation of biodiversity, and the construction of sustainable food systems. The simple and seemingly trivial pursuit of good taste

(diverse, compelling, meaningful taste) can have a great impact on other issues and aspects of society, and it starts with deliciousness as the result of craft and knowledge, science, and gastronomy (Evans, 2012).

The Nordic Food Lab has a keen interest in the development of the New Nordic Cuisine and its expression of a Nordic identity (Hermansen, 2012). The ongoing concrete projects include broadening our sources of Nordic acidity through lactic, acetic, and mixed fermentations; cataloging wild edible plants for diversifying flavor and exploring better land use management; investigating the umami taste, how it functions biochemically, and how to employ it in the kitchen; and experimenting with underutilized food resources like seaweeds, insects, shellfish, and wild game. See the Nordic Food Lab's web-based blog (Nordic Food Lab, 2013) for more information on these subjects.

PUBLISHING ON MOLECULAR GASTRONOMY AS A SCIENCE—SOME REFLECTIONS

By deciding to advance molecular gastronomy as a so-called real science, one faces all of the challenges of real science, in particular, the constant quest for research funding and the publication of original research in peer-reviewed journals. The first challenge amounts to persuading government research councils and private foundations that science-based gastronomy is equally serious and important for research as, for example, nanoscience and toxicology. The second challenge arises after the research results are obtained and the writing of the scientific article begins, leading to a cascade of questions: Where to submit the article? Does research in gastronomy results in articles that are markedly differently from other articles? Are the scientific criteria for relevance and novelty different from those of other kinds of science? Do we need specialized journals for publication of molecular gastronomy? And if so, do we want them?

Some of these issues are well known from other emerging scientific disciplines. For example, in the early days of molecular biophysics and biological physics, scientists who approached biological phenomena or studied biologically inspired materials using hard physical techniques and concepts found that their papers were often rejected from physics journals because the work was considered to be in biology and not as presenting real physics. Similarly, the papers were often rejected from life science journals because the work was considered to be physics and not dealing with real biology. One way out of this dilemma is to divide the paper into physics and biology parts and publish these separately, with the obvious risk of losing the whole point and power of interdisciplinary work. However, once an emerging field matures, the community of its disciples has grown sufficiently large, and the field has demonstrated its viability, two things usually happen: new

specialized journals arise, thus formalizing the new field, and conventional journals broaden their scope, in some cases even to revive a withering field. This is what is about to happen within the broad field of science-based gastronomy.

There is an interesting corollary to this observation. Research and communication in molecular gastronomy can sometimes pay dividends back to its underpinning sciences. One example is work on umami taste from seaweeds that stimulated work on the molecular physics of the allosteric mechanism of the T1R1/T1R2 taste receptor, a piece of work that was published in a traditional mainstream science journal (Mouritsen & Khandelia, 2012). Another recent example is the impact of gastronomic experimentation with nitrous oxide pressurization for generating foams on development of new techniques for subcellular fractionation and isolation of cell nuclei (Rowat, 2013).

As products of a relatively newly established scientific field, papers derived from research within molecular gastronomy are not infrequently met with a bit of skepticism during the review process, particularly in more established and conventional food science journals. As an example from our own experience, when pursuing publication of a study on reduction of beef stocks, a referee commented that "the authors should rather communicate directly with the chefs" (personal communication, anonymous), thereby indicating that the subject was not a valid subject for a scientific publication in a food science journal.

Because we have suggested a rather broad definition of molecular gastronomy (Barham et al., 2010) that covers subjects ranging from neural sciences to chemistry and physics, it is natural to attempt to publish molecular gastronomy research in a wide range of journals. The present authors have made use of journals ranging from ordinary food science journals (e.g., *Food Chemistry*), sensory science journals (*Journal of Sensory Studies, Food Quality and Preference*) to high-impact chemistry journals (*Chemical Reviews*), biochemical journals (*FEBS Journal*), and biophysics journals (*Biophysical Journal*). Turning then to more specialized journals, whose publication strategies also cover various aspects of molecular gastronomy, we encounter *Journal of Culinary Science & Technology* and the new journal *Flavour* launched in 2012. Both of these journals cover molecular gastronomy rather broadly and both appear to be less conventional and more open in their outlook on new developments in the sociology of science and research.

As an example, the journal *Flavour* has, since its inception, published a range of papers on topics that qualify under our working definition from Barham et al. (2010) as molecular gastronomy, and the Danish community has used it for original research papers as well as a series of topical papers on gastrophysics (Ahnert, 2013; Barham, 2013; Fooladi & Hopia, 2013; Goñi, 2013; Moller, 2013; Mountsen et al., 2013; Rowat, 2013; van der Linden, 2013;

Vilgis, 2013). As an example, we wish to mention our work on seaweeds for umami flavor in the New Nordic Cuisine (Mouritsen et al., 2012). This paper is unusual because of its group of authors, its topic, and its mode of presentation. The authors include a chemist, a physicist, a primary producer, and a chef. The topic is on using local and farmed Nordic seaweeds for dashi production and umami flavoring of a range of dishes. The mode of presentation includes scientific analysis of the chemical composition of seaweed extracts, practical cooking techniques, as well as concrete culinary precisions and recipes. The value of this interdisciplinary paper lies in its integration of disciplines and professions seldom put in dialogue, let alone joining together to publish the results in a scientific journal. It may be one model of how molecular gastronomy research can be presented in a scientific paper conforming to traditional scientific standards and at the same time being appealing and accessible to practitioners of the art.

A recent example of dissemination of science related to food and eating is the publication of the book *The Kitchen as Laboratory. Reflections on the Science of Food and Cooking*, edited by Cesar Vega, Job Ubbink, and Eric van der Linden (2012). It contains 33 chapters by selected scientists, with two contributions from Denmark. One chapter provides a description and explanation of the chemical processes occurring in preparing gravlax (Snitkjær & Mortensen, 2012). Another chapter addresses eating in the dark, with an elaboration of the sensory and psychological aspects related to this (Mielby & Frøst, 2012). Although these publications, aimed at a more general audience, may mean less in the meritocracy of academia, they are excellent outlets for works of general interest.

In any case, no matter which journal is used as the vehicle for dissemination, it is our contention that science-based gastronomy can and should develop into a science where the results of original experimental and theoretical work are presented in international peer-reviewed journals. This will take academic pursuits in gastronomy as such to the next level, allowing the field to address ever more advanced and complex research questions while also enabling researchers to reach increasingly wider audiences with their work.

MOLECULAR GASTRONOMY AND GASTROPHYSICS

There has been heated discussion about molecular gastronomy, what it is, and how it relates to other areas and trends in gastronomy such as molecular cuisine, culinary chemistry, culinary precision, note-by-note cuisine, etc. (This, 2013). We are not going to fuel this fire. In any case, as an example, we do not believe that the mere use of liquid nitrogen to cool complex fluids alone qualifies as molecular gastronomy. Only when the use of this type of cooling technique in gastronomy is invoked on the basis of scientific and

molecular reasoning—for example, a relationship between mouthfeel and the small-scale structure and properties of the frozen fluids—can it possibly qualify as science-based gastronomy. Science and molecules must somehow enter into the picture.

As an example of bringing molecules onto the scene, we would like to mention a Danish initiative to advocate the emergence of a subfield that has been coined gastrophysics. Gastrophysics places itself as an emerging new scientific and molecular-based (sub)discipline at borderlines between soft-matter physics and chemistry, culinary sciences, and food chemistry. Very little if anything scientific has been written about gastrophysics (Mouritsen, 2012), and there appear to be few, if any, published scientific papers claiming to be about gastrophysics. An early use of the term gastrophysics was found in 2001 among a group of gastronomically interested scientists, associates of MEMPHYS–Center for Biomembrane Physics at the University of Southern Denmark. One of these associates, Amy Rowat, then a PhD student at MEMPHYS, later brought some of the ideas to Harvard University where in 2010, she, as a postdoctoral researcher, and applied physics professor David Weitz and the celebrated *El Bulli* chef Ferran Adrià, ran the first of a series of courses entitled Science and Cooking: From Haute Cuisine to the Science of Soft Matter. Dr. Rowat has recently moved her activities in gastrophysics to the University of California Los Angeles where she is running an initiative called Science and Food (2013) that intends to promote knowledge of science through food and the knowledge of food through science (Rowat, 2013).

In order to clarify what gastrophysics could be and what future to chart for this emerging field, some of the authors of the present article organized the first international conference on gastrophysics in Copenhagen in August 2012 (Mouritsen & Risbo, 2013). The symposium, which was entitled "The Emerging Science of Gastrophysics," rallied a number of representatives of the physical, chemical, nutritional, psychological, and cognitive sciences as well as chefs, gastronomic entrepreneurs, and individuals working within gastronomic innovation. By bringing together these key actors, the purpose of the symposium was to help define, shape, and refine the preliminary and somewhat loose idea of gastrophysics. The symposium concluded that gastrophysics, by its designated move of gastro-sciences from stamp collection to physics,[2] could well have a significant impact on both gastronomy and tomorrow's food sciences and how they develop in the 21st century. A series of topical papers derived from the presentations at the symposium has been published (Ahnert, 2013; Barham, 2013; Fooladi & Hopia, 2013; Goñi, 2013; Moller, 2013; Mountsen et al., 2013; Rowat, 2013; van der Linden, 2013; Vilgis, 2013).

The following analogy may possibly best describe the vision from gastrophysics. In the same way as biology provides a focusing lens for the field of biophysics, gastronomy is the source of inspiration for gastrophysics.

In particular, gastrophysics aims to exploit, on all relevant time- and length scales, recent advances in the physical sciences to advance the scientific study of food, the raw materials, the effects of processing food, and quantitative aspects of the physical basis for food quality, flavor, appreciation, and absorption in the human body.

TEACHING, EDUCATIONAL ACTIVITIES, AND OUTREACH

As mentioned at the beginning of the article, the development of molecular gastronomy as an academic discipline in Denmark is closely tied to the rejuvenation of educational programs in food science at the University of Copenhagen, turning them into programs with elements of culinary arts and scientific aspects of gastronomy. This development has been dependent on the interaction with and direct involvement of creative chefs.

In terms of teaching, a gastronomic and culinary content has been most pronounced at an undergraduate level in the now defunct course Gastronomic Food Design and Consumer Preferences. The course was taught to food science students between 2007 and 2011 and offered in collaboration by the two research groups in Food Chemistry and Sensory Science. In 2007, as a result of the large research grant for molecular gastronomy, the Faculty of Life Science inaugurated a new MSc education titled Gastronomy and Health. This education includes a problem-based learning course (15 European credit transfer system units, equal to a quarter of a year's work) with a gastronomic focus. Since 2009, the course syllabus has increased the focus on innovation of healthy and palatable food. This development has included the involvement of organizations and companies that pose innovation challenges to students. Starting in 2012, the Nordic Food Lab is contributing to teaching, with exercises that increase the students' practical skills in a kitchen and their reflection on the sensory and chemical changes that the culinary processes lead to. In the last 6 weeks of the course, students work in groups with a challenge to develop and test consumer responses to a healthy and palatable food. The research activities in molecular gastronomy also rejuvenated teaching activities in more basic scientific fields in the bachelor's-level study of food science at the University of Copenhagen. It was acknowledged that the world of cookery constitutes a rich world of examples for teaching physical chemistry that most students can relate to. For example, the well-known stages for boiling syrups are used to illustrate glass formations of carbohydrates. Products like butter cream and fondants are used to discuss the concepts of thermodynamic phases. The well-known ideal gas equations and the vapor pressure curve of water are illustrated in a computer exercise exploring the expansion of a soufflé.

Other scientists with roots in the physical sciences, rather than food and sensory sciences, have also taken part in dissemination and outreach

activities in the area but from a different starting point: a passionate interest in eating and gastronomy. They have then gradually turned their interest into a science, so to speak, using the empirical world of cooking as a focusing lens for asking scientific questions. As described above, the concept of gastrophysics derives from this approach. It is interesting to note that science communication and public outreach have been the bridge that connects these passionate feelings about food to actual science. One of the present authors has, for example, used his long-time interest in Japanese cuisine and its use of foods from the sea (fish, shellfish, and algae), and hence an abundance of precious polyunsaturated fatty acids, as a medium to communicate lipid biophysics to the general public. This has gradually turned into a kind of popular sushi science that later materialized in a book (Mouritsen, 2009). This book is now the first in a series of three books so far that communicate aspects of molecular gastronomy to the general public. The books, which cover sushi (Mouritsen, 2009), seaweeds (Mouritsen, 2013), and umami (Mouritsen & Styrbæk, 2011), have developed a special style and mode of presentation whose starting point is peoples' fascination with good, nutritious, healthy, and beautiful food and from there delve into the science behind the foodstuff and its transformation in cooking and preparation of a meal. Part of the work behind the books was carried out with chefs (Mouritsen, Rasmussen, & Styrbæk, 2011; Mouritsen, Vildgaard, Westh, & Williams, 2010). These books are neither real cookbooks nor conventional science books, though they contain plenty of recipes and scientific explanations alike, often on a quantitative and molecular basis. Interestingly, from the point of view of molecular gastronomy as a science, the process behind producing the books and communicating the contents of the books to the public led to a number of scientific questions that were subsequently taken into the laboratory and ultimately led to rigorous scientific results and publications—see, for example, Mouritsen et al. (2012) and Mouritsen and Khandelia (2012).

IMPACT OF MOLECULAR GASTRONOMY AND GASTROPHYSICS ON CULINARY INNOVATION IN DENMARK

Since the early 2000s, informal interactions have taken place between science and the culinary arts in Denmark. For a number of years, chefs and restaurants were not unhappy to be labeled as practicing molecular cuisine (in the Hervé This definition), in particular Bo Bech at Restaurant Paustian and Thorsten Schmidt at Restaurant Malling & Schmidt. However, with the culinary vanguard's increased focus on New Nordic Cuisine and its emphasis on purity, freshness, simplicity,[3] few restaurants claim to be practicing molecular cuisine any longer. Nonetheless, techniques such as temperature-controlled water baths that secure a consistently high quality of the end

product are increasingly used throughout the country in restaurants of a certain caliber. Similarly, these restaurants use vacuum packaging techniques as means to rapid infuse, acidify, and preserve a range of foods. These high-end restaurants also allocate more of their resources to development and innovation, investing in specialized equipment and staff that put the majority or even all of their time into developing new dishes. Lastly, Restaurant Relæ, headed by Christian Puglisi, a former sous-chef from Noma, has opened a specific table—Table 0 (Bord 0) where diners also are exposed to unfinished concepts and highly experimental menus (Buhl, 2012).

In 2012, the Nordic Food Lab formed a collaborative relationship with Madkulturen, an organization under the Danish Ministry of Food, Agriculture, and Fisheries. Madkulturen has the stated purpose of promoting better food for all Danes. The content of the collaboration is that Madkulturen helps the Nordic Food Lab to disseminate their innovations at the culinary front to organizations and enterprises in the food sector. The purpose is to increase innovation in the food and culinary sectors in Denmark. Strengthening the interaction between chefs, food scientists, and entrepreneurs will hopefully lead to more innovation in the food sector (Frøst & Jaeger, 2010).

The work on Nordic seaweeds (Mouritsen et al., 2012) serves as a specific example of activities in molecular gastronomy in Denmark that can lead to culinary innovation. Seaweeds are an underused resource in the Western cuisine (Mouritsen, 2013), including Danish and other Nordic cuisines. The use of local seaweeds in gastronomy is virtually virgin in Denmark and it holds great potential for culinary innovation. The dashi produced from Nordic dulse (*Palmaria palmata*) that was found to contain large amounts of free glutamate (Mouritsen et al., 2012; Mouritsen, Dawczynski, et al., 2013) and hence umami flavor has, among other things, been used to produce a dulse-flavored ice cream and an *aqua vitae*. Arla, a major Danish/Swedish dairy company, has also developed a prototype of a cheese with dulse. A number of small companies have consulted with the scientists behind the gastronomic seaweed projects concerning the uses of seaweeds in a range of products, such as mineral water, fruit gum, fish products, and ice cream, for cancer patients.

CONCLUSION AND OUTLOOK

Molecular gastronomy and culinary sciences in Denmark have evolved over the last decade into maturing scientific disciplines fueled and sustained by a strong tradition in food chemistry, sensory sciences, and biophysics. A close and fruitful collaboration between open-minded scientists of different orientations and creative chefs, innovative restaurants, and gastronomic entrepreneurs has been a main driving force for establishing and maturing the field. The results of the research work are to an increasing extent

published in the international peer-reviewed scientific literature. There are signs of an impact of the activities not only on Danish restaurants at large but also on industrial innovation in the food sector. The development of molecular gastronomy and related activities, such as gastrophysics, has gone hand in hand with educational programs on several levels as well as outreach and science communication to the general public. Though the initial spellbinding power of the term molecular gastronomy may have waned, the activities themselves—whatever the name—continue to grow and proliferate.

NOTES

1. A more comprehensive history of molecular gastronomy, its founders, and their relationship to each other can be found at Harold McGee's website, Curious Cook, at http://www.curiouscook.com/site/erice.html.

2. "All science is either physics or stamp-collecting." Attributed to Ernest Rutherford (Birks, 1962).

3. Quoting from the manifesto from New Nordic Cuisine (2004): To express the purity, freshness, simplicity and ethics that we would like to associate with our region and elaborated as:

- Uncomplicated preparations that bring out the flavors of the raw materials—food that can be both rustic as well as elegant.
- Honest food—that the food is made without superfluous exertions, complications, manipulations and transformations.

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