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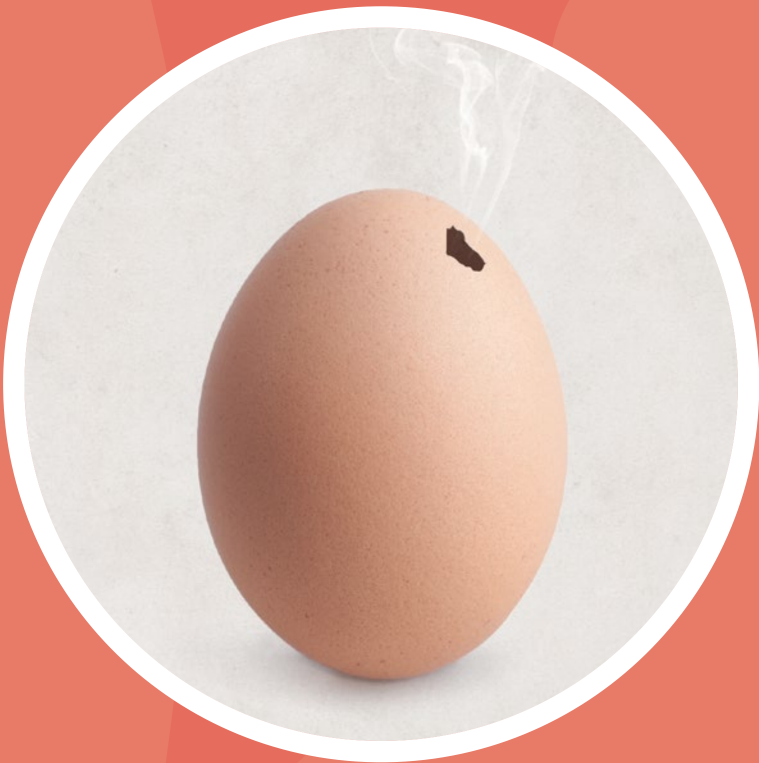

THE EMERGING SCIENCE OF GASTROPHYSICS

OLE G. MOURITSEN & JENS RISBO (red.)

SMAG #04 2015

skriftserie om smag

THE EMERGING SCIENCE OF GASTROPHYSICS

Af Ole G. Mouritsen & Jens Risbo (red.)

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The Emerging Science of Gastrophysics. **SMAG #04** 2015

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An International Interdisciplinary Symposium

The Emerging Science of Gastrophysics

The Royal Danish Academy of Sciences and Letters

Copenhagen, August 27-28, 2012

Invited speakers: Sebastian Ahnert UK + Peter Barham UK + Michael Bom Frøst Denmark
Erik van der Linden The Netherlands + Félix Gõni Spain + Martin Lersch Norway + Ole G. Mouritsen Denmark
Per Møller Denmark + Jens Risbo Denmark + Amy Rowat USA + Dana Small USA + Peter Schurtenberger Sweden
Thomas Vilgis Germany + Lars Williams Denmark

Organizers: Ole G. Mouritsen (University of Southern Denmark), Peter Kreiner (Nordic Food Lab), and Jens Risbo (University of Copenhagen)

Sponsors: Carlsberg Foundation & LMC-Centre for Advanced Food Studies & Nordic Food Lab. *Contact:* ogm@memphys.sdu.dk | www.memphys.sdu.dk

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EDITORIAL Open Access

Gastrophysics—do we need it?

Ole G Mouritsen[1*] and Jens Risbo[2]

Abstract

Applying science, scientific reasoning, and scientific methodologies to the study of food and cooking is an old trait that to a large extent is based on the chemical sciences. The focus has been on chemical compounds as well as chemical reactions and transformations involved in foodstuff, preparation techniques, and culinary precision. Gastrophysics is proposed as a generic term to characterize an emerging scientific discipline primarily based on the physical sciences underpinned by all three pillars of modern physics: theory, experiment, and modeling/simulation. Gastrophysics takes its inspiration from the world of cooking and gastronomy. It is our contention that gastrophysics is a science in its own right, not a discipline designed only to service chefs in interpreting and creating new dishes. Gastrophysics is physics, and its empirical basis of gastrophysics is gastronomy itself.

Physics or stamp collecting?

The British physicist Ernest Rutherford is quoted to have said 'All science is either physics or stamp collection.' A bold statement from a physicist, but probably meaningful in the sense that the history of physics is to have gone repeatedly into other disciplines and made them into modern, quantitative, and universal sciences—basically turning them into physics. Chemical physics, biophysics, geophysics, astrophysics, and econophysics are prominent examples. Hence, we suggest taking Rutherford's words as an invitation rather than an insult.

A recent international symposium entitled 'The Emerging Science of Gastrophysics' rallied a number of representatives of the physical, chemical, nutritional, psychological, and cognitive sciences as well as chefs, gastronomical entrepreneurs, and individuals working within gastronomical innovation. By bringing together 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 from stamp collection to physics, could well have a significant impact on both gastronomy and tomorrow's food sciences and how they develop in the 21st century.

In this special issue of *Flavour*, thirteen scientists present nine 'statements' on gastrophysics and expose their personal opinion on what gastrophysics may be and whether we need this new term at all.

* Correspondence: ogm@memphys.sdu.dk
[1]Department of Physics, Chemistry, and Pharmacy, MEMPHYS, Center for Biomembrane Physics, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark
Full list of author information is available at the end of the article

Molecular gastronomy, molecular cuisine, culinary chemistry, culinary precision, note-by-note cuisine . . . and all that

Very strong opinions have been put forward regarding differences and similarities between all these terms. This is not the place to flog that old horse. Clearly, molecular gastronomy relies heavily on well-established sciences, such as food chemistry, general food science, and food processing technology. In their authoritative review on molecular gastronomy, Barham and colleagues [1] present their definition of molecular gastronomy and how it differs from gastronomy, advocating 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.' In this definition there is no specific reference as to why the term molecular is invoked, although it is tacitly assumed that molecular gastronomy is based on a scientific and systematic study using molecularly based sciences, whereas nutrition and health are subdominant.

The use of physical principles to study foods from a materials science perspective is well established in food physics and food biophysics [2-4] with a focus on physical and physico-chemical properties, such as texture, foam stability, emulsification properties, phase transformations, the physical principles underlying cooking processes, and so on. These approaches are often less concerned with sensory perception and gastronomical considerations. McGee's encyclopedic monograph *On Food and Cooking: The Science and Lore of the Kitchen* [5] and Myhrvold's books on the *Modernist Cuisine* [6] are to date the most comprehensive accounts of the physical aspects of food and cooking (among other things) although these books are not claimed to be works of physics or gastrophysics. In fact, very little is written about gastrophysics from a scientific perspective and there appear to be only a few published scientific papers using the term gastrophysics [7,8].

What is gastrophysics good for?

Seen from the point of view of physics, the empirical world of cooking and gastronomy is a new promising territory for the application of state-of-the-art concepts and methodologies from the physical sciences. Gastrophysics may not only transform our study of this empirical world into new science but at the same time it may revitalize the physics of the kind of soft matter that foodstuff is made of. Gastronomy could well be a source of inspiration for posing new and interesting physics problems.

Seen from the point of view of gastronomy, gastrophysics may potentially lead to new fundamental insights that can be translated into a more scientifically inspired approach to gastronomy, without removing any of the craft, creativity, and art so characteristic of cooking.

In the same way as biology provides a focusing lens for the field of biophysics, gastronomy becomes 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 adsorption in the human body.

With a focus on fundamentals and universal phenomena, rather than nitty-gritty details and 'stamp collection', gastrophysics may become to gastronomy what astrophysics has come to be for astronomy.

Competing interests
The authors declare that they have no competing interests.

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Author details
[1]Department of Physics, Chemistry, and Pharmacy, MEMPHYS, Center for Biomembrane Physics, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark. [2]Department of Food Science, University of Copenhagen, Rolighedsvej 30, Frederiksberg C DK-1958, Denmark.

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Ahnert *Flavour* 2013, **2**:4
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OPINION Open Access

Network analysis and data mining in food science: the emergence of computational gastronomy

Sebastian E Ahnert

Abstract

The rapidly growing body of publicly available data on food chemistry and food usage can be analysed using data mining and network analysis methods. Here we discuss how these approaches can yield new insights both into the sensory perception of food and the anthropology of culinary practice. We also show that this development is part of a larger trend. Over the past two decades large-scale data analysis has revolutionized the biological sciences, which have experienced an explosion of experimental data as a result of the advent of high-throughput technology. Large datasets are also changing research methodologies in the social sciences due to the data generated by mobile communication technology and online social networks. Even the arts and humanities are seeing the establishment of 'digital humanities' research centres in order to cope with the increasing digitization of literary and historical sources. We argue that food science is likely to be one of the next beneficiaries of large-scale data analysis, perhaps resulting in fields such as 'computational gastronomy'.

Keywords: Networks, Data mining, Sensory science, Computational gastronomy, Flavour compounds

Large-scale data analysis

The past two decades have seen the advent of high-throughput technologies in biology, making it possible to sequence genomes cheaply and quickly, to measure gene expression for thousands of genes in parallel, and to test large numbers of potential regulatory interactions between genes in a single experiment. The large amounts of data created by these technologies have given rise to entire new research areas in biology, such as computational biology and systems biology. The latter, which attempts to understand biological processes at a 'systems' level, is particularly indicative of the potential advantage that large datasets and their analysis can offer to biology, and to other fields of research. This advantage is a 'birds-eye' perspective, which, with the right kind of analysis, can complement the more established research methods that take place 'on the ground' and investigate the system in much more detail. An example would be the analysis of high-throughput gene expression data of tumour tissues in order to highlight a set of potential candidate genes that may play a role in causing a particular cancer. These candidates would then be investigated one by one, for instance by creating mutant organisms in which one of these genes is deactivated.

Similar large-scale data analysis methods have more recently arrived in the social sciences as a result of rapidly growing mobile communications networks and online social networking sites. Here too data analysis offers a birds-eye perspective of large social networks and the opportunity to study social dynamics and human mobility on an unprecedented scale. The most recent research areas to be transformed by information technology are the Arts and Humanities, which have witnessed the emergence of 'digital humanities'. As more and more literary and historical documents are digitized, it becomes possible to uncover fundamental relationships that underlie large corpora of literary texts, or long-term historical and political developments. A striking example is the discovery by Lieberman *et al.* [1] that the regularisation of verbs across 12 centuries of English is governed by a simple quantitative relationship between the frequency of verb usage and the speed at which it is regularised.

Correspondence: sea31@cam.ac.uk
Theory of Condensed Matter Group, Cavendish Laboratory, University of Cambridge, JJ Thomson Avenue, Cambridge CB3 0HE, UK

Network analysis of flavour compounds

The growing availability of network data in a wide variety of research disciplines has made complex network analysis a rapidly growing research area ever since two seminal publications in the late 1990s uncovered fundamental principles that underlie many real-world networks such as social networks, power grids, neural networks and genetic regulatory networks [2,3]. In recent work [4] we construct a bipartite network of chemical flavour compounds and food ingredients in which a link signifies the natural occurrence of a compound in an ingredient. These data were derived from *Fenaroli's Handbook of Flavour Ingredients* [5]. Using a one-mode projection the bipartite network is converted into a weighted network of ingredients only, in which the weight of a link between two ingredients is given by the number of flavour compounds they share. This weighted network shows a modular organization, with modules corresponding to food types such as fruits, vegetables and meats. While this might be expected, it is particularly interesting to see the location of these modules with respect to each other. Meats for instance lie between fruits and vegetables, and closer to spices and herbs than seafood does. The backbone of this network, extracted using the method described in [6], is shown in Figure 1.

The chef Heston Blumenthal, together with flavour scientists, has suggested that two foods that share chemical flavour compounds are more likely to taste good in combination [7]. By comparing the network of ingredients to a body of 56,498 online recipes, downloaded from epicurious.com, allrecipes.com, and menupan.com, we were able to show that this hypothesis is confirmed in most Western cuisines, but not in Eastern ones. This result indicates that shared compounds may offer one of several possible mechanisms that can make two ingredients compatible.

Our network of ingredients and flavour compounds is just a first step towards a true network of shared flavour compound perception, which would have to include compound concentrations [8] and detection thresholds [9] in order to further investigate the shared compound hypothesis. Its most important purpose is to open up a

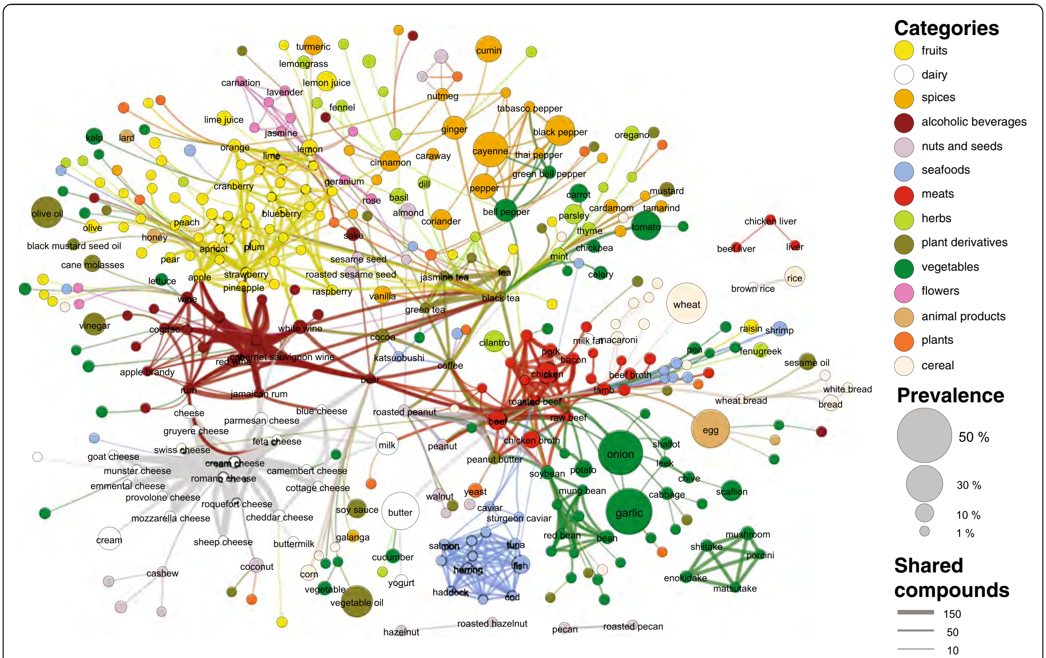

Figure 1 Flavour network . Culinary ingredients (circles) and their chemical relationship are illustrated [4]. The colour of each ingredient represents the food category that the ingredient belongs to, and the size of an ingredient is proportional to the usage frequency (collected from online recipe databases: epicurious.com, allrecipes.com, menupan.com). Two culinary ingredients are connected if they share many flavour compounds. We extracted the list of flavor compounds in each ingredient from them and then applied a backbone extraction method by Serrano *et al.* [6] to pick statistically significant links between ingredients. The thickness of an edge represents the number of shared flavour compounds. To reduce clutter, edges are bundled based on the algorithm by Danny Holten (http://www.win.tue.nl/~dholten/). © Yong-Yeol Ahn, Sebastian E Ahnert, James P. Bagrow, and Albert-László Barabási.

new way in which data analysis can aid sensory science and the study of culinary practice.

In a broader development the increasing availability of data on food usage, food chemistry and sensory biology is likely to result in the establishment of new research disciplines, such as 'computational gastronomy'.

Competing interests
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Flavour

OPINION Open Access

Physics in the kitchen

Peter Barham

Abstract

The kitchen is a laboratory and cooking is an experimental science. When we cook we generally follow a recipe (either written or from memory); we select, quantify and process the ingredients and then serve the food to our friends, family or guests. A good cook (or scientist) will keep records in a notebook of exactly what they do so that they can repeat the experiment (recipe) as required.

During the meal, as we eat we note how good the food is, where there is room for improvement and what is particularly liked. In effect we analyse the results of the experiment – the good scientific cook will keep notes of these discussions and use them to draw preliminary conclusions about how to improve the recipe. After several more tests of the recipe, we may then begin to derive a model to explain our results and to understand how and why making small changes to the recipe produces different qualities in the final dish – we can then use that understanding and apply it to other recipes, so continually improving our cooking skills.

This is nothing more than the application of the scientific method to cookery – simple but highly effective. If taken seriously and applied properly there is no excuse for any scientifically trained person not to become a superb cook.

But is there more to physics in the kitchen than ensuring physicists are good cooks? Can physics help chefs with no scientific background improve their own cooking? Is this really an area that is worth the attention of serious physicists? Is there new physics to be learned from the study of gastronomy? My unsurprising opinion is that there is good physics to be learned in the kitchen and that investigating the science of cooking is a worthwhile academic pursuit – but of course I would believe that as I have been doing it for more than 25 years now. So perhaps it is time to examine more critically whether it is indeed a worthwhile occupation.

Heat and thermodynamics

One of the most basic kitchen operations is to heat food to change its texture or chemical make-up (or both). To ensure some degree of consistency between cooks there is a need to have some assurance that the temperatures used in different kitchens are closely similar (if not the same). Without the use of expensive scientific equipment the only easy way is to use a phase transition that occurs at a fixed temperature – and the simplest and most accessible of these is to use boiling water. Common practice when cooking vegetables, for example, is therefore simply to put them in boiling water for a fixed time. This can provide a system which is sufficiently reproducible that the same recipes can be used by cooks around the world and ensure they get similar results. But is it? We teach our children that water boils at 100°C, but it is only much later when those who progress on to higher levels of education begin to learn that the boiling point of water is not fixed, but actually quite variable – for example, in Denver, Colorado, which is about 1.6 km above sea level and where the atmospheric pressure is around 85 kPa, water boils at around 94°C.

But there is a further problem – water is not itself consistent from place to place. We do not cook with pure distilled water, but rather with the local tap or spring water; the concentration and types of salts present in the water also affect the boiling point. Although the increase in boiling point due to adding even quite large amounts of salts is much smaller than the effect of altitude, salts can have quite different effects on the food that is being cooked – for example, if divalent salts (such as magnesium or calcium) are present they can affect the colour of green vegetables – making them appear a brighter green after cooking [1] – as they interact with chlorophyll molecules to change their shape and hence their vibrational spectra.

A trained scientist will readily understand these issues and be able to adapt their cooking to accommodate the

Correspondence: Peter.Barham@bristol.ac.uk
H H Wills Physics Laboratory, University of Bristol, Tyndall Avenue, Bristol BS8 1TL, UK

water quality and the altitude. A cook may be baffled that it takes longer to boil an egg in Johannesburg than in Cape Town without hearing the simple explanation – indeed, I have even heard it said that the eggs are different in these two cities (which of course may be true as the hens are kept at quite different altitudes – but that should be the subject of a quite separate investigation).

Potatoes

Once we can establish a precise control over the water quality and the pressure we can begin to investigate how food immersed in hot water cooks. Perhaps the best example is potatoes. I could write an entire thesis on the structure and cooking of potatoes, but to keep it short and simple here all you need to know is that the starch granules in the potatoes 'melt' or 'gelatinise' at a reasonably well-defined temperature of approximately 60°C – this change is clearly visible as the texture changes from a wet milky creamy colour to a translucent gel-like sticky texture (this is also an indication that the potato is now edible).

We can use this gel transition to investigate heat transfer through a cooking potato [2]; this approach makes an excellent demonstration experiment for teaching the physics of heat transfer. Basically all that is needed is to place a potato in a temperature-controlled bath for a fixed time and then cut it open and measure the width of the cooked region. The experimental design is challenging; for example, a sufficiently large heat bath is necessary so that the temperature is not significantly reduced by the addition of the potatoes; and the measurement of the width of the cooked region poses some problems as the interface is not necessarily sharp and the cutting may not be exactly perpendicular to the surface; and so forth. However, these difficulties can be overcome (indeed, it is a good test of an experimental physics student to see whether they can meet them).

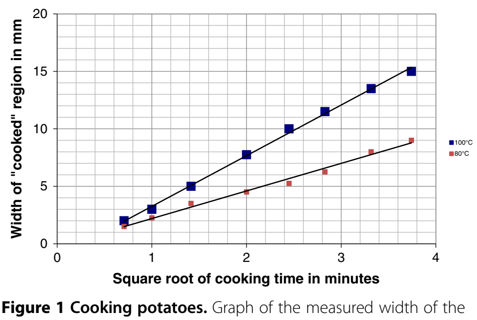

Figure 1 Cooking potatoes. Graph of the measured width of the cooked region of a potato as a function of the square root of the cooking time in minutes at two different temperatures.

Figure 1 shows the results of one such carefully controlled set of experiments. The data in the figure illustrate that the heat flowing into a potato in a constant temperature bath does indeed follow the expectations of thermal diffusion – the width of the cooked region increases as the square root of the cooking time; and the rate at which this width increases depends on the temperature difference between the potato before immersion and the temperature of the heat bath.

Meat cookery

Potatoes are roughly spherical and have thermal properties that are more or less constant over the temperature range of interest, and the heat of the gel transition is small enough to be ignored so that these properties can be readily modelled using straightforward thermal diffusivity. Other foods are not so simple. Consider a piece of meat; a steak, for example. The structure of meat is complex; therefore, as well as diffusion of heat, there is mass transport within the meat as it is cooked (we can see and hear water being expelled from the meat as it is being cooked). As the muscle proteins are denatured by the heat and shrink, so the composition of the meat and its thermal properties change; chemical reactions at the surface also affect the permeability of the meat and affect its thermal contact with the pan in which it is being cooked and to make matters more complex all these changes depend on both time and temperature – in short, we are not in a position as yet to be able to model sensibly the heat transfer processes in the cooking of a steak. This is an area where finite element modelling combining heat flow, chemical changes and mass transport might in the future be able to provide new insights – it is, in short, an area ripe for curiosity-driven research that could lead to new developments in modelling complex systems in general.

Ice cream

Everyone loves ice cream (well almost everyone). But what makes good ice cream? For most people the answer seems to be how smooth and creamy it is. The perceived smoothness seems to increase as the size of any solid particles in the ice cream decreases; this is especially true of the ice crystals. So a good ice cream has the smallest possible ice crystals.

This leads to many questions; for example, how can we avoid ice crystals growing larger during storage and transport in commercial ices? Simple thermodynamics tells us that smaller crystals are less stable and will slowly disappear as larger crystals grow steadily larger – this process (known as Ostwald ripening) is well documented and understood in model systems, but as yet little work has been done on actual ice cream. Commercial ice cream manufacturers have to find ways to slow down the ripening process [3-5] – some of the best solutions come from the use of additives that coat the surfaces of ice crystals and act to reduce the growth rates as they effectively reduce the liquid solid surface energy stabilising small crystals with a high surface-to-volume ratio [6,7]. Such anti-freeze proteins are found in fish that live in the cold polar waters – so the understanding of how fish evolved and survive in such cold water where they risk death from the formation of ice crystals in their bodies has a direct link to the production of ice cream.

In a restaurant or domestic environment, the storage of ice cream is not a major issue – it gets eaten as soon as it is ready! So all that is required (apart from the flavour and so forth) is to ensure the ice crystals are as small as possible. But how to do that? Traditional machines simply scrape growing crystals form the cold outer surface to stop them growing – the crystal size then depends on how well the scraper fits the surface, how stiff and sharp it is, how fast it rotates, how quickly the mixture is freezing and how long it is held before serving. A newer type of machine, the Pacojet, drives a rapidly rotating scraping blade into a solid block of ice cream mixture at a low temperature (approximately −20°C) to so that it advances around 0.001 mm per revolution – this shaves crystal fragments that have a size typically around 0.005 mm. Even smoother ice cream can be made by freezing at very low temperatures using liquid nitrogen as the coolant – by nucleating crystals at very low temperatures, very small crystals can be stable so it is possible to have an ice cream with ice crystals that are smaller than 0.001 mm, although it is very difficult to find experimental methods to measure the sizes of such ice crystals. In fact, the attempt to measure the sizes of such crystals has the potential to develop new methods of investigating the physics of phase transitions in confined spaces.

Gastrophysics: what is it and do we need it?

If the science of the kitchen is worthy of study, it is worthy of a name as well. Many have been suggested: culinary science, molecular gastronomy, kitchen science and now gastrophysics. These names each have connotations that may or may not be helpful and it is not my place to promote any of them – in fact I dislike them all for different reasons, but I shall not elaborate here on any except gastrophysics as that was the topic of the meeting that led to this article.

I first came across the name gastrophysics in the 1980s when it was noted by Nicolas Kurti as one of the possible, but discarded, names for the International Workshop on Physical and Molecular Gastronomy that he and Elizabeth Thomas organised in Erice (these eventually gave rise to the term molecular gastronomy). Later, gastrophysics was rejected as the title of a series of public lectures I gave in Bristol on the science of food and cooking and then was also rejected as the title of my book *The Science of Cooking* [2], and even as the title of one of the chapters of that book – eventually entitled 'Heating and Eating – Physical Gastronomy'. In all these cases the reason for rejecting gastrophysics as a name was that it would make people think of gastric problems – the echo of gastroenteritis is unlikely to persuade people to buy a book or attend a lecture!

My own arguments in favour of gastrophysics came from an analogy: gastrophysics should be to gastronomy as astrophysics is to astronomy. Astronomers observe the planets and stars, they note how they move and even predict future movements; but astrophysicists explain why the stars are where they are and how they got there, and they also supply the sound scientific basis for the whole subject.

The future

At the start of this article I asked whether there can be more to physics in the kitchen than ensuring physicists are good cooks? Or whether physics can help chefs with no scientific background improve their own cooking? And if this really is an area that is worth the attention of serious physicists, whether there is new physics to be learned from the study of gastronomy?

I contend that the answer to all these questions is yes. The almost trivial examples I have given above should serve to illustrate that even a rudimentary knowledge of physics can assist the cook in the kitchen. There are numerous areas where researching the physics in the kitchen can lead to new techniques that can be applied to more conventional branches of physics – indeed, I believe we can look forward to seeing this happen in the near future.

To me, however, by far the most important aspect of using the kitchen as an experimental laboratory is that is provides a route to encourage people of all ages to engage with science in a way that is not otherwise possible. We can use examples of what happens when we cook to teach science at all levels. In an ideal world, school students would have at least some of their science lessons in the school kitchens and would learn both basic cooking skills and basic science at the same time. If they can take their experiments home and talk about them while eating them over a family dinner, then the potential benefits to society are incalculable – improving diet to reduce obesity and improve health, bettering social cohesion though combined family activities, and creating a more scientific-literate society are all within the bounds of possibility.

Whatever we call the field, this is something we should strive towards.

Competing interests
The author declares that he has no competing interests.

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OPINION Open Access

Culinary precisions as a platform for interdisciplinary dialogue

Erik Fooladi[1*] and Anu Hopia[2]

Abstract

Claims or specifications about cooking (in some literature referred to as 'culinary precisions') as found in recipes or as generally shared knowledge, permeate the world of food and cooking. The collection and study of these culinary precisions carries with it potential as a framework for research, not only in food science, but also in other disciplines such as social sciences and humanities, allowing for multidisciplinary approaches and cross-fertilization between a broad range of sciences. These precisions also allow for novel approaches to education at all levels, as shown through educational efforts in several countries as well as educational research. Finally, they provide a unique arena for the interaction between science and society. In the present report, we describe a recent initiative, 'The Kitchen Stories Network', with an open invitation for interested parties to collaborate across disciplines and across societal boundaries in order to collect and study such culinary precisions for the common benefit of sciences, education, other stakeholders such as businesses and non-governmental organizations, and society in general.

Keywords: Cooking, Culinary precisions, Education, Food, Interdisciplinary, Kitchen stories, Molecular gastronomy, Natural sciences, Network, Science in society, Social sciences and humanities

Claims and specifications about cooking

The world of food and cooking is full of specifications on how to perform tasks and occasionally why one should adhere to this advice. Many of these specifications are rooted in tradition, while others are more recent, and these sometimes appear to us like modern urban myths. Some are rooted in the long experience of kitchen professionals or home cooks, and some originate from science. Such culinary 'claims', 'instructions', 'specifications' or 'precisions' (various terms have been used) are the shared common knowledge of societies about the techniques and practices of food and cooking. Often they are shared orally as knowledge is handed down through generations, or in written form, for example, as part of recipes. As described previously [1], this knowledge may come in the form of hints, advice, 'tricks', or 'old wives' tales'. In this paper, we use the term 'culinary precisions' to describe the technical or procedural information present in a recipe (oral or written), which provides added value in terms of improved quality and greater chance of a successful product, although, to our knowledge, this term has not yet been adopted as a formal term in the international scientific community. A typical example of a culinary precision is 'When preparing *beurre blanc* sauce, butter should be added as ice-cold cubes'. The understanding that temperature affects the structure and taste of the sauce has probably developed through generations of skillful chefs making thousands of *beurre blanc* sauces collecting their experiences and sharing best practice. If the claim is studied scientifically, phenomena such as melting, emulsion, droplet size, and water/fat solubility can be taken under the scope of research, science education, and science dissemination. Culinary precisions are already being collected and studied by scientists as well as food professionals and devotees. The widest collection is in France, where Hervé This has collected around 25,000 culinary precisions, some of which have been published in French on the internet [2] and in a book [3]. Smaller collections are also available in other languages [4,5].

To date, there have been several efforts to study the chemical and physical phenomena of such culinary claims, and since publication of *The Curious Cook* [6],

* Correspondence: ef@hivolda.no
[1]Volda University College, P.O. Box 500, Volda N-6101, Norway
Full list of author information is available at the end of the article

several publications have mentioned such claims as part of the field of molecular gastronomy [7-9]. Examples of scientific studies on such culinary claims are research into cooking of beef stock [10-12] and the effect on flavor of separating the peel and seeds from the flesh of tomatoes when preparing a tomato-based dish [13]. Even though culinary precisions have been studied within food science, we are not aware of any studies based on such claims in other disciplines such as ethnology, food history, or sociology (however, we do not claim that such research does not exist, and would be delighted to see any studies).

Culinary precisions: properties, purpose, and potential

In addition to providing material for research, culinary precisions contain questions and deal with phenomena that are by their nature multidisciplinary (Figure 1). These culinary precisions represent valuable parts of a society's cultural heritage and provide rich research material for various scientific fields, including cultural history and sociology. In some cases, the phenomenon in question is well described within one field of science but is less so in another, suggesting potential for multidisciplinary research and cross-fertilization/-pollination between disciplines.

Secondly, culinary precisions provide a unique arena in epistemological terms. These claims about food and cooking occur in the intersection between, on the one hand, the natural sciences, and on the other hand, practice-derived knowledge gained through experiential learning and sharing. This apparent gap might carry a potential tension between 'different ways of knowing', but it also opens up possibilities for interaction and exchange between science and society, in both directions.

Figure 1 Culinary precisions deal with questions and phenomena that by nature are multidisciplinary.

Thirdly, culinary precisions provide valuable opportunities for education and dissemination at various levels, not only in dealing with scientific facts, but also in matters pertaining to scientific methods, processes, and ways of thinking. In France, such educational efforts have been carried out in schools at both primary and secondary level [14,15]. In two linked research projects in Finland [16] and Norway [5,17], we have set out to unveil the potential this might have in science and home economics education, and preliminary results from these projects were presented at an interdisciplinary symposium in Helsinki in 2012 [18,19]. Efforts representing informal life-long learning perspectives also exist, including those directed towards chefs and the general public, such as seminars (e.g. in Argentina, Finland and France), blogs [4], TV [20] and radio shows, and podcasts [21].

Finally, because of their universal nature culinary precisions might be collected and studied by the public, craftsmen (chefs, artisans) or even schoolchildren, and these precisions could in turn prompt relevant research topics to be studied within the various sciences. Research projects involving contributions from the public exist in other disciplines such as weather and climate studies [22], ecology and biodiversity [23], and school meals/diet [24]. Thus, the concept of culinary precisions provides a possible framework to include contributions from various groups, such as students from primary through tertiary education, food professionals, and the general public.

Culinary precisions versus science in society

Even though science probably is closer to people's lives than it has ever been throughout human history, there is a perception among the general public that much science is difficult to understand, and even not relevant to their everyday life. To safeguard the development of a democratic knowledge-based society, wider public involvement with science should be encouraged [25]. In order for the public to be able to make qualified decisions on science-based topics that often use specialized and unfamiliar language and methods (e.g. healthcare, biotechnology, nutrition), it is necessary to stimulate the public to develop their understanding of science and particularly of the processes underlying scientific endeavor. Using culinary precisions, ordinary, everyday food can be an arena that makes the complexities of science accessible to the public, and the public can contribute back to science by generating research questions, collecting data, and contributing their practical and heritage-derived knowledge and experience. Thus, when knowledge is seen as shared (applying a transmission analogy with a more symmetric notion of communication between science and society), traditional knowledge based on cultural heritage may be preserved and also make a contribution to elucidate scientific questions.

Two examples of culinary precisions applied to science in society and education

In order to obtain material for molecular gastronomic research and activities to integrate science into society, the Finnish–Norwegian collaboration project has been collecting culinary narratives since 2009. The aim of the project is to expand and develop the current collection (a selection of a few hundred 'kitchen stories' in Finnish and Norwegian) into an international database to stimulate and activate researchers, professionals, and food devotees in different fields. The current collection is being used in Finland and Norway both for educational purposes and for science in society-related efforts. Inspired by initiatives in France [3,7], food devotees in Finland assemble in monthly informal meetings as a 'molecular gastronomy club', with the meetings run by a scientist and a chef, and debate mutually agreed topics. In this club, culinary precisions such as 'the best fish stock is achieved when it is prepared without fish heads and tails' are explored. Short theoretical presentations and a carefully planned experimental setup with blind tastings stimulate participants to share their knowledge and experience [4]. In addition to learning about the science and craftsmanship involved, participants thus learn about the culture and history of the food. In both Finland [16] and Norway [5,17], educational efforts include collection and analysis of culinary precisions by classes in lower secondary schools (Finland) and by students in pre-service teacher education (university college level). Here the focus lies on using culinary precisions as a framework for teaching scientific inquiry and argumentation in cross-curricular settings. Through the inquiry process, other topics occur naturally and are taught accordingly, with examples being scientific documentation, peer review, food science, chemistry, physics, biology, food culture, history, and epistemology.

The Kitchen Stories Network initiative: a multidisciplinary network around culinary precisions

An open 'Kitchen Stories Network' was initiated in December 2011 by an open invitation, using networks of professionals, blogs [26,27], and word of mouth. The network is open to all, and has set no limits (for example, age, profession, nationality, educational level) for affiliate members. The members share an overall interest in culinary stories, narratives, and claims as a source of shared knowledge and cultural identity. To date, the network consists of more than 80 participants from 17 different countries from Europe, Americas (North and South) and Africa. The members represent scientists (natural sciences, social sciences, humanities), teachers and educators, food writers and communicators, chefs, students, industry and businesses, and food devotees. We believe that this network, and the projects initiated within it, can involve and perhaps even integrate a multitude of disciplines as well as various research methods and paradigms. With culinary precisions as the centerpiece, the various disciplines are allowed to maintain their distinctive features while at the same time meeting at a common point of interest (Figure 1). The ultimate goal is to build an international internet-based collection of 'kitchen stories'/ culinary precisions to be developed by and to benefit researchers in different fields as well as society at large.

Anyone interested in joining the network, currently in the shape of a mailing list, are cordially invited to contact us. Efforts have been initiated within the network to apply for funding to expand the project.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

The idea for the contribution was conceived collectively by both authors, and both are responsible for the Kitchen Stories Network, which is mainly organized by EF. Both authors were involved in developing the first draft of the manuscript into the final version suitable for publication. Both authors have read and approved the final manuscript.

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Author details

[1]Volda University College, P.O. Box 500, Volda N-6101, Norway. [2]Functional Foods Forum, University of Turku, Turku FIN 20014, Finland.

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OPINION Open Access

A biophysicist in the kitchen

Félix M Goñi

Abstract

This paper originates from the reflections of a practicing biophysicist, that is, the author, while cooking at home, either everyday or at festive dinners. Both the activities, biophysics and cooking, were independently learned and incorporated into the author's life at different stages. Yet at some point, the biophysical reasoning permeated into the cooking of recipes. The biophysical interpretation of cooking has evolved to include other main subjects, such as the survival of vitalism in the mirage of 'natural food', the formalization of cooking as a pre-digestion and the democratization of good food through food technology.

Keywords: Biophysics, Biochemistry, Physical chemistry, Food technology, Cooking, Cuisine, Digestion, Vitalism

Introduction

It often happens that, when someone knows of my profession as a biophysicist and of my main domestic chore, that is, cooking, I am asked: "But, how do you cook?" I invariably detect an edge of suspicion in that question. What most of them ache to ask is: "Do you put chemistry into your cooking?" When, after a few polite exchanges, they confess to their poorly concealed real question, my reply is: "No, I don't put any chemistry into my cooking; cooking is chemistry and mostly biophysical chemistry at that." This is the main message of this paper, namely that it is a good time for vitalism to die, that there is no real difference between the chemical, biological and culinary processes, and that gastrophysics may help everybody to eat better.

Science is not against traditional cuisine

Science and cuisine are two activities which are often presented as opposing each other; cuisine would be a handcraft, kept as remote as possible from the ever-suspicious activities carried out by mad, if not venal, scientists in their laboratories. Grandma's food will always be superior to any of the new concoctions. Needless to say this is a pure mirage, owing to the fantastic ability of the human mind to suppress negative aspects of our memories. In a world of no electric fridges, slow transport, very short seasons for most vegetables, when food took away a much larger fraction of family incomes than now, it is difficult to explain how food was so much better. In the absence of any 'time machine' experiment to take us back there, it is enough to use our memory in a more objective manner to find out that we eat, qualitatively and quantitatively, far better than our forefathers (albeit we do it in excess, but that is another problem).

Yet the nostalgia of an inexistent past fuels most of the food business today. The greengrocer will offer us 'biologically grown' lettuces, the butcher will tell us that this particular veal was fed 'naturally' and the wine supplier will boast, in all honesty, of a wine made 'without any chemistry'. In short, we believed that the death of vitalism was initiated with the 1828 synthesis of urea from ammonium cyanate by Friedrich Wöhler [1], and fully completed with the *in vitro* synthesis of nucleic acids by Severo Ochoa and Marianne Grünberg-Manago in 1955 [2]; but, apparently, vitalism never dies. Perhaps the 'death of vitalism' is a contradiction in itself.

The way to overcome the artificial 'science vs. cuisine' debate is through education. Only scientific education at school-level can change our children's understanding. Nowadays, none of them believes that the Earth is flat or that the Sun moves around the Earth. For the same reason, none of our fellow citizens should believe that living organisms contain components undetectable to chemical analysis.

Physics and chemistry as the foundations of food technology

It should be clear that in our age, improvements in cooking should come from the experimental sciences,

Correspondence: felix.goni@ehu.es
Unidad de Biofísica (CSIC-UPV/EHU), Barrio Sarriena s/n, Leioa, Bizkaia 48940, Spain

rather than from pure empiricism or supposed folk traditions. This should be valid for both 'haute cuisine' restaurants and for collective restauration. Food technology is, in the author's opinion, in its infancy and largely devoted to the preservation of foods. This is a plausible aim but, in a society in which more people find the preparation of home-made meals impracticable and simultaneously the same people fall prey to obesity, type II diabetes and vascular diseases, food technology must make an effort to shift its main attention to food cooking, rather than to food preservation. The aim is to help all to eat better, to improve all our meals, making them appetizing and healthy.

In the pathway from empiricism to rational cooking, it is interesting to note that some of the avant-garde restaurants in the world [3,4] are already moving in this direction. Not only are physicochemical parameters (temperature, pressure, salt concentration and time) meticulously measured and respected, but also the raw materials (vegetables, fish and meat) are standardized as much as possible, the result of long and costly collaborative works with the suppliers. In this way, foods whose physical and chemical properties are almost exactly reproducible are treated in the same way, invariably giving rise to an optimum result. The famous, semi-magical point of the great chefs now gives way to technology. However, as mentioned above, the idea is that this culinary revolution does not stop at the Michelin star restaurants, but is extended to our homes, passing through schools, hospitals, prisons, convents and similar painful institutions. The motto is good food for all.

It is almost impossible in this context to avoid mentioning, at least in passing, the role of genetically modified organisms (GMOs) (plants, animals, micro-organisms) in the new food technology. The author is fully aware of the strong and active advocates against GMOs. So were the opponents to railways and to electricity. GMOs will prevail, just because they are better in so many senses, not to mention that all of our food has been genetically modified by agriculture or animal breeding in the last five millennia. When GMOs are accepted, as we accept electric light today, then the role of another science, biotechnology, will be recognized for its role in the marvelous endeavor of providing good food for all.

An example: cooking as a pre-digestion

Some of the above concepts, and particularly the oneness of chemistry and biology, are exemplified by the observation that cooking reproduces essentially the same processes occurring in food digestion [5], that cooking in some way anticipates digestion. Let us examine briefly the fate, in the kitchen and in the digestive tract, of the three most abundant components of food, namely carbohydrates, proteins and lipids.

Carbohydrates in our diet are particularly frequent in the form of starch (bread, pasta, rice, and so on). The cooking of pasta, or rice, or peas and the like, invariably includes a step of boiling. With this we can achieve two main effects. One is the hydration of the starch molecules, which are kept in the plant cell with a minimum of water to facilitate storage. The second effect is the partial hydrolysis of starch, a polysaccharide, which must be broken down into its component glucose units for intestinal absorption. But these two actions of carbohydrate cooking are essentially the same as those performed by saliva in our mouths. Insalivation moistures our bread and the saliva amylase partially breaks down the starch into smaller molecules. Cooking helps digestion, by contributing to some of its degradative steps.

The same can be said of the proteins in our diet. With a few exceptions, for example, sushi and some seafood, in which raw meats are eaten in small amounts, proteins are denatured by heat and partially hydrolyzed during cooking. Both effects are again found in digestion, this time in the stomach. In this case denaturation does not occur by heat, but by acid (the gastric juice has a pH as low as 1). Note incidentally that in pickled herring, to mention one example, the proteins are denatured by acid (vinegar), just as it is done in the stomach by hydrochloric acid. Denaturation is meant to facilitate degradation to peptides and ultimately to amino acids, to be absorbed in the intestine. Cooking, especially cooking by heat, causes partial hydrolysis of proteins by activating proteases present in the cell lysosomes. In digestion, enzymes like pepsin, which can work under extremely acidic conditions, perform the partial hydrolysis of proteins in the stomach. It can be mentioned in this context that the food combination of meat with pineapple (Hawaii) or meat with papaya (Brazil) are excellent examples of this point. Both pineapple and papaya contain protease enzymes, respectively bromelain and papain, which are active at the low pH of the stomach, so these food combinations are somehow providing extra digestive power.

The case of fats is equally interesting. The primary enzymes involved in fat digestion are the lipases in the small intestine. However, lipases can only act in an aqueous environment. Therefore, fats must be fragmented into tiny particles, usually by mixing with non-fat substances, giving rise to microscopic droplets or micelles, amenable to digestion by lipases. In the small intestine, fat fragmentation (emulsion) is achieved by a special brand of detergents, the so-called bile salts, produced by the liver. Bile salts combine with the water-insoluble fats to produce a stable aqueous dispersion or emulsion of bile salt/fat-mixed micelles. The only source of fat in infancy, and a large source of fat for many humans throughout their lives, is milk. Milk is said to be easily digested. In fact, milk is a natural emulsion of fat in water, stabilized this time by proteins instead of bile salts. The cooking of fats normally includes their emulsion. Typical culinary emulsions are mayonnaise and béarnaise sauces, of a very complex physical chemistry. In the Basque Country, several fish preparations of cod and hake include sauces, which consist of olive oil and water emulsions stabilized by the fish proteins. In short, cooking anticipates the digestive fate of fats, that is emulsions, prior to their degradation and absorption in the small intestine.

This discussion probably explains the enormous evolutionary advantage of cooking for humans. Cooking is a purely human activity. The energy and time required to eat and digest cooked meals are much less than in the case of raw foods. Cooking liberated mankind for other activities, in addition to facilitating its feeding, the limiting step in animal reproduction. It is not an exaggeration to say that cooking has, to a large extent, made us human.

A future for gastrophysics

In conclusion, there is a need for a novel science, which has been called gastrophysics, and could be defined as the study of cooking on the basis of biophysical and physicochemical methods and paradigms. Gastrophysics will be aimed at:

– interpreting cooking in physical and chemical terms,
– conducting novel research within the above framework, and
– providing better food for all.

Abbreviation

GMO: Genetically modified organism.

Competing interests

The author declares that he has no competing interests.

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Flavour

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Gastrophysics in the brain and body

Per Møller

Abstract

In this short paper, a few important problems are highlighted that fall naturally within the emerging science of gastrophysics. This paper does not discuss how 'gastrophysics' is similar to or different from 'neurogastronomy' or 'molecular gastronomy'; but just notes that the time seems ripe for problems within these areas, as witnessed by the recent proposals of these as separate 'emergent' scientific fields centered at problems not covered by other traditional scientific disciplines.

Keywords: Pleasure, Preferences, Flavour pairing, Quantity vs. quality

Introduction

In my view, the new field of gastrophysics should include psychological, psychophysical and neuroscientific considerations in order to truly address fundamental problems related to human consumption of foods, no matter whether these are related to questions of pleasure and satisfaction, or are more concerned with health issues [1-3]. These fields, on the other hand, being mostly phenomenological and with very little predicting power, could greatly benefit from inspiration from theory and simulation of complex physical (and other) systems, as exercised mostly by physicists.

At the symposium, The Emerging Science of Gastrophysics (Copenhagen, August 27–28, 2012) Peter Barham suggested that gastronomy relates to gastrophysics in the same way that astronomy relates to astrophysics, the latter explaining the phenomena observed in the former. I fully agree with this view and hope that 'gastrophysics' will provide impetus for less phenomenology and more explanation and prediction in the psychological and neuroscientific areas that deal with food behaviour. In this paper, four groups of problems will be briefly described, which are very open and very relevant to 'gastrophysics'.

It is not all in the brain

Even though 'flavour is in the brain' [4], many more body and brain processes contribute to hunger, satiety, satisfaction and well-being after a meal [5-7]. A well-known effect, sensory specific satiety (SSS), describes that 'liking' of a food drops as intake increases and obviously plays a role in controlling the variety of food intake [8-10]. Despite extensive literature on SSS, any precise theory for prediction of 'transfer effects' (from one food to another) or for the number of sensory dimensions necessary to capture the effects has still to be formulated. The same applies to effects of induced sensory specific desire (SSD), which describes the non-random desire for other foods the eating of a given food induces [11]. SSDs might depend entirely on the food culture in which a measurement takes place, thereby being an indication of the strength of 'learning of food preferences'. There might, on the other hand, be elements of universality to SSDs, such that different foods in different cultures with similar sensory profiles will induce the same desires in different cultures. This would be highly interesting because it would demonstrate another level of universality of food preferences than what is usually described.

SSS and SSD are dynamic processes, which are dependent on neural and hormonal systems in the brain and body. At the phenomenological level they lend themselves to analysis by dynamic simulation, but to the best of my knowledge this has not been attempted yet.

Formation of preferences

All of our food preferences, with the notable exception of preferences for sweetness and fattiness, are learned. The types of learning responsible for food preference change are completely incidental and the memory systems involved are not semantic in nature. Learning takes

Correspondence: pem@life.ku.dk
Department of Food Science, University of Copenhagen, Rolighedsvej 30, Frederiksberg C DK-1958, Denmark

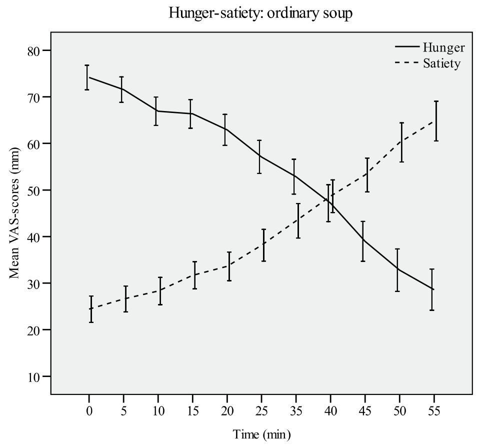

Figure 1 Development of hunger and satiety when eating ordinary tomato soup. Hunger and satiety scores as a function of time for ordinary tomato soup. Subjects were served 10 portions of 50 grams of soup each with 5 minute intervals.

place already in the fetal state [12,13] and a number of conditional learning types have been identified which help us to change our food preferences [14,15]. A better understanding of the mechanisms of preference formation has potential for both gastronomy and health. It has been found that children have specific sensitive periods for these types

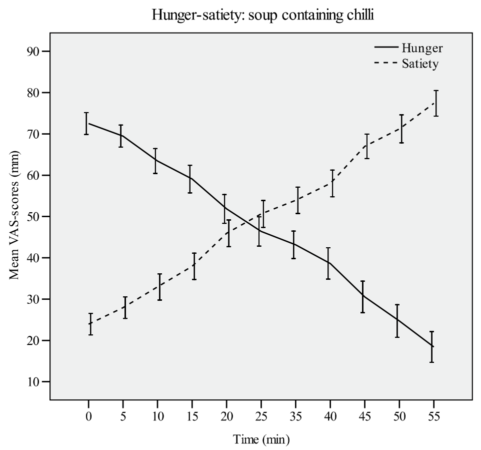

Figure 2 Development of hunger and satiety when eating ordinary tomato soup spiced with chili. Hunger and satiety scores as a function of time for ordinary tomato soup spiced with chili. Subjects were served 10 portions of 50 grams of soup each with 5 minute intervals.

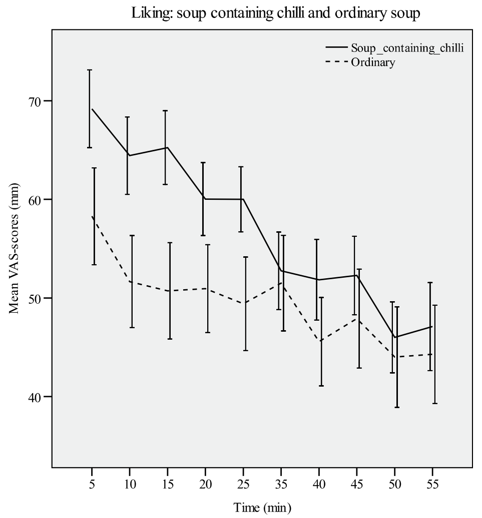

Figure 3 Does the soup spiced with chili taste worse than the ordinary soup? Liking scores of the two soups as a function of time for two eating conditions, ordinary tomato soup and the same tomato soup spiced with chili.

of learning. More information about these mechanisms in adults would be very useful, both from a health and from a food enjoyment or hedonistic perspective. Since it is virtually certain that sustainability concerns imply that we have to dramatically change the foods we eat, a better understanding of the neurobiological mechanisms responsible for preference formation and change could facilitate this necessary change of food habits.

The flavour pairing problem

Even though a broader approach, including interoceptive states (the sensation of the physiological condition of the body) [16], is necessary to understand food appreciation, there are many important open problems of a less dynamic nature than those experienced during and after a meal, which are almost entirely the business of the brain. Flavour pairing, that is, which flavours will, if paired, produce an experience that is more appreciated than either of the two flavours alone, is one of these problems. Limiting the problem to odours only still presents major challenges. At present, no theory in olfaction can predict the non-linear effects implied in flavour pairing problems. There are many linear curve-fitting schemes available, but none with any power of predicting the interesting non-linear pairing results.

Solving the odour pairing problem would contribute greatly to hedonic psychology and affective neuroscience, as well as being a first step towards a less phenomenological science of flavour pairing.

The scientific literature on flavour pairing is surprisingly limited especially given the enormous progress, scientifically as well as commercially, a better understanding of flavour pairing would bring. A hypothesis that two foods that share volatile molecules should go well together has not received support [17,18]. Chefs collectively have a very large knowledge base of flavour pairing, which scientists should tap into, from an anthropological, psychophysical and neuroscientific perspective, to physicochemical investigations.

Quantity vs. quality

Will high gastronomic quality of foods consumed on a daily basis lead to overeating, thereby exacerbating problems of overweight and obesity? This view has indeed surfaced in certain scientific circles [19-21].

It might, to some, seem almost self-evident, but to others, like myself, not at all so. From a highly unscientific introspection and conversations with friends and colleagues about these matters, it seems that most of us eat far less high quality Parmesan cheese when offered it, than cheap, not so tasty hard cheeses. The same applies to wines and chocolate. Very few people can eat a whole 100g bar of Valrhona chocolate in one go, but easily perform this feat with chocolate of a lesser quality. From a more epidemiological point of view, one would wonder why the obesity problem in France is less severe than in other affluent countries with foods and meals generally of a lower quality than those served in France.

The question can be phrased as whether it is possible to replace 'quantity' with 'quality'. If this is indeed the case, gastrophysical/neurogastronomic/molecular gastronomic studies of delicious foods might have a major impact on how to tackle problems of overeating.

In an experiment on the effects of trigeminal stimulation (hot spices) on hunger and satiety, Hans H Reisfelt and I came across a result that is reported in Figures 1, 2 and 3. Subjects in the experiment attended the laboratory twice. On one of the visits they were served an ordinary tomato soup and were asked to report on hunger and satiety feelings, as well as on liking (and other measures which are not important in this context). On the other visit they were served the same base soup but this time spiced with chili.

Figures 1 and 2 illustrate that satiety increases faster and hunger decreases faster when subjects eat the soup spiced with chili. The faster satiation when eating the spiced soup might conceal a wish to stop eating, caused by a lower appreciation of the spiced soup than of the ordinary soup. In Figure 3, however, the opposite effect is seen. Subjects like better the spiced soup that satiated them faster (and more).

Concluding remark

At the symposium, Erik van der Linden proposed that gastrophysics is not just finding some piece of 'physics' to apply, not just 'physics to go', but new physics, in the broadest understanding of the phrase, needs to be developed. The four sets of problems described all need new fundamental insights and, in my view, fall naturally under the umbrella of 'gastrophysics'.

Abbreviations

SSD: Sensory specific desires; SSS: Sensory specific satiety.

Competing interests

The author declares that he has no competing interests.

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Flavour

OPINION Open Access

The name of deliciousness and the gastrophysics behind it

Ole G Mouritsen[1*], Lars Duelund[1], Luis A Bagatolli[2] and Himanshu Khandelia[1]

Abstract

The term 'gastrophysics' has been proposed to describe an emerging scientific discipline that employs an arsenal of the most powerful theoretical, simulational, and experimental techniques from the physical sciences to study the empirical world of cooking and gastronomy. In the same way that biology has inspired the field of biophysics, gastronomy is the source of inspiration for gastrophysics. In particular, gastrophysics aims at exploiting recent advances in the physical sciences to forward the scientific study of food, the raw materials used, the effects of processing food, and quantitative aspects of the physical basis for food quality, flavor, appreciation, and absorption in the human body. In this study, we focused on questions pertaining to the texture and flavor of a particular type of raw material, namely, the red seaweed, dulse (*Palmaria palmata*), and demonstrate how a combination of physical chemistry, biophotonics, and atomic-scale molecular simulation might shed some light on these questions, particularly in relation to the physical mechanism of the umami sensation.

Keywords: Gastrophysics, Umami, Seaweeds, Receptor, Synergy

Gastrophysics research program

We and our colleagues at the Center for Biomembrane Physics have a wide range of interests, competencies, and facilities in the broad field of biophysics, and in the physics and physical chemistry of biological materials. In particular, we are interested in lipids, proteins, and membranes, as well as of the different phenomena related to membranes, including membrane function, the action of drugs, and the effects of various processes on membranes. Moreover, we have available a large arsenal of theoretical, experimental, and simulational methods and instrumentation. Taken together with a keen interest in food and the enjoyment of food, a natural step was to apply all these capacities to study problems related to gastronomy. After all, the empirical world of cooking mostly uses materials of biological origin, the methods used in cooking involve some kind of chemical and physical processing [1-5], and the sensations of food, such as mouth-feel and flavor, are based on mechanisms obeying principles from physics and chemistry.

An initial interest in food from the sea, stimulated by the first author's passion for Japanese cuisine, particularly sushi [6], gradually developed into questions regarding the use of marine macroalgae (seaweeds) [7], and from there to the flavor of certain seaweeds, in particular the taste of deliciousness (umami) [8,9]. The work was greatly stimulated by collaboration with a range of inventive chefs.

We provide a brief preliminary report on the likely results to which such an approach can lead, and hence, by example, give an opinion on what gastrophysics could be.

Flavor of seaweeds

The history of flavor owes so much to a discovery made by Kikunae Ikeda, who in 1908 [10] studied the chemical composition of the large brown seaweed, konbu (*Saccharina japonica*). Konbu is used together with a highly processed fish product, katsuobushi, to produce dashi, the soup broth around which the entire Japanese cuisine revolves. Ikeda found that konbu contains very large amounts of free monosodium L-glutamate (MSG). He suggested that this compound is the primordial source, or the essence of deliciousness (umami), and he proposed it as a fifth basic taste

* Correspondence: ogm@memphys.sdu.dk
[1]MEMPHYS, Center for Biomembrane Physics, Department of Physics, Chemistry, and Pharmacy, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark
Full list of author information is available at the end of the article

quality, in addition to the existing four qualities of salt, sour, sweet, and bitter. However, it was only in the early part of this century, after the discovery of specific umami receptors located in the taste-cell membranes, that umami was fully recognized as a basic physiological taste sense [11-15].

Seaweeds are a common staple of Asian cuisine, not only in Japanese cooking, but they are rarely used nowadays in western cuisine [16]. We set out to explore whether Nordic seaweeds are equally flavorful, and discovered that the red seaweed species, dulse (*Palmaria palmata*), which has been used for centuries in traditional cuisine in Ireland, Brittany, and Iceland, also has large amounts of MSG [17]. To assess its flavor, we developed various extraction methods, inspired by processes in the kitchen, and used physicochemical techniques to assess the amino-acid profiles of the extracts under different conditions of temperature and composition (an example of the results of such an analysis is shown in Figure 1). We found that dulse has very large amounts of free MSG as well as other flavorful amino acids, such as aspartic acid (umami sensation); alanine, proline, glycine, and serine (all sweet); and measurable amounts of isoleucine, leucine, and valine (all bitter). Indeed, the umami capacity of dulse is comparable to that of good quality konbu [17,18]. Together with several chefs, we explored the possibilities of dulse-derived dashi in various dishes, including ice cream, bread dough, and fresh cheeses [17].

Texture of seaweeds

Seaweeds also play another important, but little-known role in cooking. Their contents of certain complex polysaccharides particularly alginate, agar, and carrageenan, readily form stable hydrogels and are highly valued as gelling agents, providing texture to foodstuffs and enhancing the mouth-feel of fluid materials. These polysaccharides are used by the seaweeds to bind together their cells that in most species are little specialized. The polysaccharides can be extracted from the seaweeds by chemical methods, thus alginate, agar, and carrageenan introduced into foodstuff have to be declared as food additives.

However, there is no reason why raw seaweeds that have been appropriately processed (for example, as a fine particulate material), could not be used as a whole ingredient in food. In this case, not only can the gelation properties of the seaweeds be exploited, but also their flavor characteristics. The gastrophysical questions that arise in this context pertain to seaweed structure and texture under different preparation methods. In this project, we used advanced bioimaging techniques to study the cellular structure of seaweed under different conditions of hydration and processing, such as aging and cooking. Figure 2 shows an example of a fully hydrated frond of dulse, in which the large intercellular space containing the polysaccharides can be clearly seen. Using various intrinsic and extrinsic fluorescence probes, we

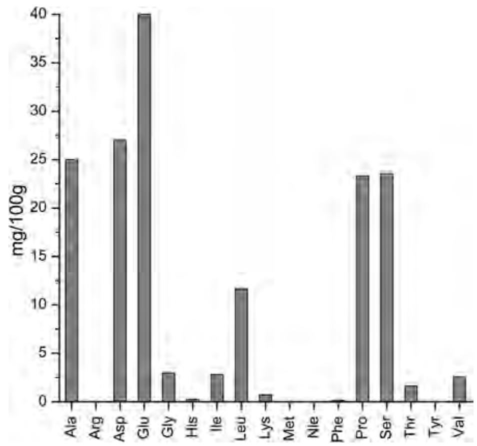

Figure 1 Amino-acid profile for dashi made from the red seaweed dulse. The dashi was produced by using the sous-vide technique at 60°C, resulting in an extract of 10 g dry dulse in 500 ml water, which was analyzed by mass spectrometry. Data from Mouritsen *et al.* [17].

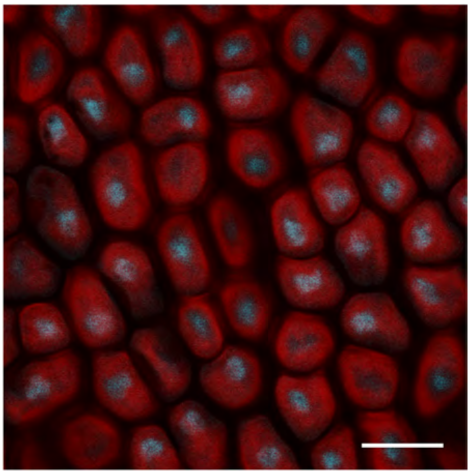

Figure 2 Bioimaging of seaweeds. Two-photon laser microscopy image of a rehydrated frond of the red seaweed dulse (*Palmaria palmata*), showing a single cross-section imaged by both intrinsic fluorescence and a label (4',6-diamidino-2-phenylindole; DAPI) that stains the DNA of the cell nuclei. The excitation wavelength was 780 nm. Scale bar 10 μm.

could image different parts of the cells and map out the structural and spectral properties of the intracellular water.

The molecular mechanism of the umami receptor

Our work on the flavor of seaweeds led to questions regarding the molecular mechanism of the umami sensation, particularly the special synergy that pertains to the simultaneous presence of glutamate and certain 5′-ribonucleotides. The unique aspect of the umami taste is that it can be enhanced many times by the presence of free nucleotides such as inosine 5′-monophosphate (IMP), guanosine 5′-monophosphate (GMP), and adenosine 5′-monophosphate (AMP). Free glutamate is found in large amounts in cured hams, anchovy paste, ripe tomatoes, walnuts, hard and mature cheeses, and soy and fish sauces, as well as certain brown seaweeds. Free nucleotides are abundant in meat broths, chicken, fish and shellfish, mollusks, and dried fungi. In the classical Japanese dashi, the seaweeds provide free glutamate and the katsuobushi free IMP. In *shojin ryori*, the vegan Japanese temple cuisine, the fish is replaced by shiitake mushrooms, which contain large amounts of free GMP [18-20].

A deeper understanding of this remarkable synergy in umami sensation requires insight into the structure and functioning of the umami receptors that reside in the taste-cell membranes [21]. Although three different kinds of umami receptors have been discovered since 2000, one particular heterodimer G-protein coupled receptor, T1R1/T1R3, is most likely to hold the key to the synergy in umami.

By using large-scale molecular dynamics simulation techniques, we recently studied the atomic-scale dynamics of the Venus-fly-trap domain (VFTD) of the T1R1/T1R3 umami receptor monomer, both in the presence and absence of glutamate and GMP, in order to unravel the molecular mechanism behind the synergistic effect of these two ligands on the dynamics of the receptor [22]. We found that the dynamics of the VFTD along the hinge-bending motion that activates signaling was dampened significantly after binding of glutamate. The dynamics were further slowed by binding of GMP at an allosteric site, thus suggesting a molecular mechanism of cooperativity between GMP and glutamate (this effect is illustrated schematically in Figure 3).

Conclusion and future outlook

We consider that gastrophysics has as its goal to demonstrate that fundamental principles of physics, in particular soft-matter physics, biophysical chemistry, and molecular biophysics, can be brought together to work within the sciences dealing with food. In this paper, we give examples of how questions stimulated by an interest in gastronomy can lead to new insights that both have scientific merit in themselves and can have an influence on gastronomy.

For this study, we focused attention on a little-explored material in the context of gastronomy, namely seaweed [16], and found that this material has very interesting flavor and texture properties. Moreover, using a detailed and well-defined molecular model, our molecular simulations have established, quantitative support for the proposed and putative mechanism [23] behind the ubiquitous synergy effect in the umami sensation. The power of this synergy for cooking delicious food has been known and used by cooks for centuries, and in 1960, it was shown that inosinate from fermented fish or guanylate from dried shiitake together with glutamate from dried seaweeds provided enhanced umami flavor in soup broths [24]. In this study, we have revealed that

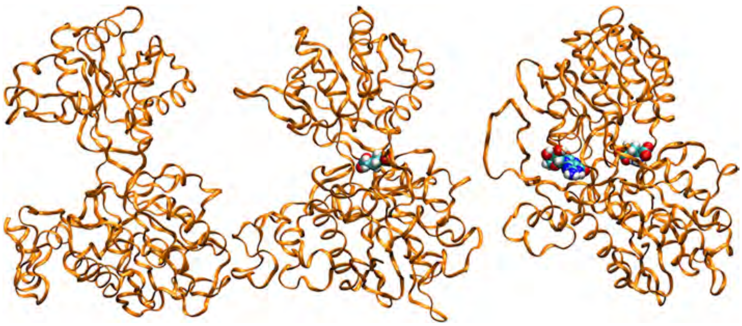

Figure 3 Molecular mechanism of the umami receptor. Ribbon-band representation of the Venus-fly trap motif on the T1R1/T1R3 umami receptor in three situations. From left: no bound ligands; binding of glutamate; binding of both glutamate and GMP. The images are snapshots obtained form molecular dynamics simulations on a receptor motif with 7,105 atoms in a box with 25,542 water molecules (not shown).

this exciting mechanism arises as a consequence of an allosteric molecular action at the receptor.

The findings of our gastrophysical research program on seaweeds and umami holds promise for the design of novel compounds to controlling the umami flavoring of foodstuffs. Furthermore, our findings regarding the mechanism of the umami taste at the receptor level may not only lead to inspiration for new delicious dishes but may indicate how best to use umami as a means to regulate food intake and to improve nutrition and health [25].

Competing interests
The authors declare that they have no competing interests.

Authors' contributions
OGM designed the study and wrote the paper. LD performed the analyses of glutamate contents in dashi. LAB made the fluorescence microscopy images of the red seaweed dulse. HK performed the Molecular Dynamics simulations of the umami receptor. All authors read and approved the final manuscript.

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Author details
[1]MEMPHYS, Center for Biomembrane Physics, Department of Physics, Chemistry, and Pharmacy, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark. [2]MEMPHYS, Center for Biomembrane Physics, Department of Biochemistry and Molecular Biology, University of Southern Denmark, Campusvej 55, Odense M DK-5230, Denmark.

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OPINION **Open Access**

The molecules we eat: Food as a medium to communicate science

Amy C Rowat

Abstract

Creative, inquiry-driven approaches in science education help to address the growing need to effectively engage students and promote the public understanding of science. Here we describe an interactive format using food that can be applied both in a course for undergraduate students, as well as in a lecture for the general public. Communicating science through food may also dispel fear of naturally occurring chemicals as well as scientific misconceptions that are propagated by the media.

Keywords: Science education, General education, Public understanding of science

Introduction

Each day we consume a very large quantity of molecules. For example, a glass of water and a serving of steak each contain over 10^{24} molecules. These molecules are major determinants of food texture and flavor; they are also essential for an array of physiological functions in plants and animals that we eat. In particular, proteins, carbohydrates, and lipids are major determinants of the physical and mechanical properties of cells and nuclei. For example, the gluten protein network imparts a remarkable stretchiness to strudel dough; the carbohydrates that constitute plant cell walls are important for vegetable texture. Understanding the physical and molecular origins of the texture of cells, tissues, and biological materials is a major focus of research in our laboratory. Naturally, the major themes of our research share many commonalities with food; our findings may thus also provide unique perspective into the foods that we eat.

Using food as a medium for teaching, we have been developing methods to captivate people in science. Engaging students in science education through food and cooking has been successful in many contexts around the world [1-6]. Food can incite curiosity about everyday foods that we eat and is also an excellent, inexpensive tool for experimentation. Here we highlight some central concepts of our interactive approach to communicating science for a general audience.[a]

Correspondence: rowat@ucla.edu
Department of Integrative Biology & Physiology, University of California, Los Angeles, CA 90095, USA

Science in the molecules we eat

Taste tests for teaching quantitative science and scientific inquiry

Scientific lectures are an important component of teaching science. We also provide interactive demonstrations and activities to more fully engage participants in scientific concepts. For example, taste tests are an enticing way to further draw people in to learning scientific concepts. To demonstrate phase transitions and the effect of molecular composition on phase behavior, a popular taste test involves comparing milk and dark chocolates. Such a gustatory method also requires that individual audience members become scientists as they make observations of chocolate texture and flavor, while learning of the underlying scientific basis of these physical properties [7]. In a lecture on diffusion, taste tests of tofu marinated in soya sauce for 2 *versus* 24 hour intervals provide unforgettable experiences of the time and length scales of diffusion.

To ground the sensory observations of the taste experiments in the framework of quantitative science, simple analyses can yield interesting insights into the physical basis of phenomena in food and cooking. For example, diffusion underlies a multitude of processes in food and cooking ranging from irrigation to heat transfer to flavor infusion by marinating. The time and length scales of diffusion can be quantitatively understood in terms of the diffusion coefficient, as well as Fick's First Law: the flux of molecules (mass transport) is proportional to the concentration gradient, as described by $J_x - -D\frac{dc}{dx}$, where J_x is the solute flux, D is the diffusion coefficient, dc denotes the solute concentration difference, and dx is the relevant length scale. To illustrate the beauty and utility of Fick's First Law, we recently developed a simple hands-on experiment that requires students to perform an experiment, collect and analyze data, and interpret the results: by determining the mass of mushrooms over time during osmotic shrinkage (salting), together with simple geometric considerations and calculations, one can determine the diffusion coefficient of water, which turns out to be approximately $10^{-5} m^2/s$; this value is about 10,000× greater than the expected diffusion coefficient of water. Yet one can make sense of these results by careful observations and logical reasoning: mushrooms typically float in water, as they largely consist of air; the diffusion coefficient of water in air is approximately 10,000× faster than in water. An added bonus of food experiments is that students can eat their lab exercises: after calculating the diffusion coefficient, the salt-pickled mushrooms can be used in 'Marinated tofu wraps with salt-pickled mushrooms' (L. Zhou and A.C. Rowat, unpublished). Indeed, recipes provided throughout the class ranging from horchata to slow-roasted pork shoulder are popular among the students, and incite greater awareness of preparing and eating good food.

Guest lecturers provide complementary perspective on the molecules we eat

To bring culinary perspective to complement the scientific perspective of food, we incorporate chefs, farmers, and other food artisans into the classroom; this challenges students to integrate their newfound knowledge of science with cuisine and gastronomy. For example, *noma* chefs René Redzepi and Lars Williams are renowned for foraging the Danish wilds to discover novel foods and flavors. For a recent lecture in an undergraduate class at University of California, Los Angeles, they discussed their recent foray into the world of insects. Using insects, the duo is generating innovative flavors, however, eating these critters can challenge the common Western aversion to eating bugs. Yet inspecting the molecular composition of crickets reveals they have similar molecular composition to many foods that we eat [8,9]. Moreover, performing a simple calculation based on the average energetic content of carbohydrates, proteins, and fats, 4, 4, and 9 Cal/g, respectively, reveals that crickets have a relatively high protein and low fat content: a 100 g serving contains 5.1 g carbohydrates, 12.9 g protein, and 5.5 g fat [8,9]. Eating a single serving of crickets is thus nutritionally beneficial: it contains only 122 Calories, with 26% of the recommended daily intake of proteins.[b]

Farmers also provide unique insight that complements the scientific perspective of food. A major focus of some Californian farmers including Barbara Spencer, Windrose Farms, and Cynthia Sandberg, Love Apple Farms, is the importance of temperature for the flavor of fruits and vegetables. Understanding how temperature impacts the sugar content of winter vegetables, such as the sweetness of winter carrots, frames the concept of freezing point depression in a novel way that captivates student interest. For instance, the sweetness of winter carrots is a fine example of freezing point depression. There are many other excellent physiological examples of altered molecular compositions in organisms for temperature and pressure adaptation, such as freezing resistance in some Antarctic fishes [10]. From a scientific perspective, freezing point depression and boiling point elevation can be quantitatively described by $\Delta T_{b\ or\ f} = b \cdot K_{b\ or\ f}$. where ΔT is the magnitude of change in temperature, b is the molality of the solute, and $K_{b\ or\ f}$ is a constant; for water,

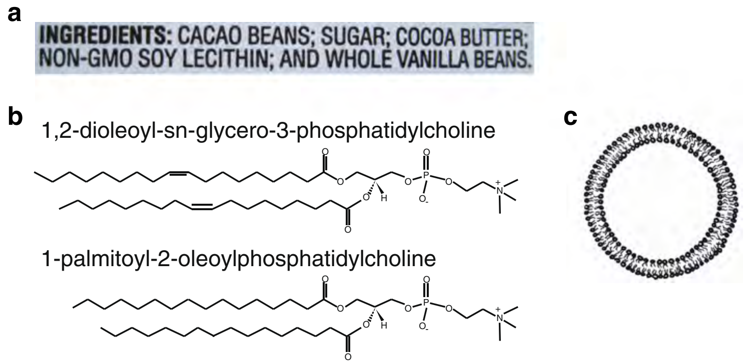

Figure 1 The molecules we eat. (**a**) Lecithin is essential in common foods, such as chocolate. (**b**) Lecithin consists of lipid molecules, such 1-palmitoyl-2-oleoylphosphatidylcholine and 1,2-dioleoyl-sn-glycero-3-phosphatidylcholine. (**c**) Lipid molecules spontaneously assemble into lipid bilayers, as shown in this schematic illustration. Lipid bilayers are the foundation of biological membranes that delineate cells and intracellular organelles.

$K_f = 1.86$ K kg/mol. This simple equation can be applied to calculate the effects of physiological concentrations of solute on freezing points. Informal student feedback suggests that learning of the origins of the molecules that we eat can also bring new appreciation and awareness of food; this is particularly important in an era where knowledge of the origins of basic foods is lacking [11-13].

Molecules in the media: communicating science to a general audience

Many of the concepts in the program Science & Food provide powerful material to enthrall a general audience in deepening their knowledge of science. Promoting the public understanding of science is essential, especially in light of misinformation that can be propagated through the media and generates fear of molecules. For example, in a recent book by Michael Pollan, he describes *Rules to Eat* [14]: 'Avoid food products containing ingredients that a third-grader cannot pronounce.' 'Avoid food products that contain more than five ingredients.' 'Avoid food products containing ingredients that no ordinary human would keep in the pantry. . . .Cellulose? Xanthan gum?. . . Whether or not any of these additives pose a proven hazard to your health, many of them haven't been eaten by humans for very long, so they are best avoided.' Such misinformation highlights the need to promote scientific literacy: cellulose is an essential molecule of plants. Many multisyllabic molecules may indeed pose a challenge for a third grader to pronounce, such as 1-palmitoyl-2-oleoylphosphatidylcholine and 1,2-dioleoyl-sn-glycero-3-phosphatidylcholine (Figure 1). Yet these lipid molecules are essential components of the lipid membranes that provide an essential barrier for individual cells. Phospholipids naturally occur in many other foods such as cacao beans [15], as well as egg yolk. Lecithin is also an effective emulsifier that is commonly added to chocolate (Figure 1), as well as other foods. Starting with the simple task of deciphering ingredient labels [7,16], scientists can play an important role in promoting scientific literacy and dispelling fear of molecules.

Research inspired by the kitchen

An unexpected outcome of communicating science using food is that methods from the kitchen can impact research in our laboratory. In a recent undergraduate student project, students studied the mechanism of nitrous oxide to extract flavor from herbs. While nitrous oxide pressurization is commonly used for generating foams such as whipped cream, this method is also used to extract flavors from herbs [17,18]. The proposed mechanism for flavor extraction is mechanical disruption of cells upon pressure release, whereby the bubbles of nitrous oxide gas increase in size, and thereby disrupt cellular structures, such as lipid membranes [19]. Our preliminary results show that this method can also be used for subcellular fractionation and nuclear isolation protocols, where rupturing the plant cell wall is a prerequisite to liberating the internal contents of the cell. Using nitrous oxide pressurization can potentially provide a faster and easier way to disrupt plant cells: in contrast to other protocols, this method could sidestep the need for enzymatic treatment, which can be costly and time-consuming.

Summary

Based on preliminary student and audience feedback, communicating science using the tactile medium of food is an effective method to engage people in scientific inquiry. Food can also captivate people to understand more about the molecular and scientific basis of the foods, cells and nuclei that we eat. Given the increasing demand to promote knowledge of science and the origins of the foods that we eat, such dialogue on science and food is essential.

Endnotes

[a]More detailed information of topics and exercises is presented at scienceandfood.org.

[b]Percent daily values based on a 2,000 Calorie diet.

Competing interests
The author declares that she has no competing interests.

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OPINION Open Access

Integration of gastronomy and physics for innovation

Erik van der Linden

Abstract

Integration of physics with gastronomy can yield innovations in an efficient manner. An important element of this integration is the structure of food. The creation of food recipes often deals with designing new structures and a clear understanding of how food structure influences food properties is necessary. The physics that is required for this understanding can be demonstrated by considering the case of gelatin. A Master of Science (MSc) specialization is described, which addresses the integration of physics with gastronomy in an educational setting at Wageningen University, The Netherlands.

Introduction

At fast food counters, customers can choose between eating the meal at that place or to take it out. This food is 'ready to eat'. Although this food serves its purpose of providing nourishment, it does not usually create a high level of enjoyment. The latter is more a signature of what is currently recognized as 'gastronomy' and is practised in more sophisticated restaurants. Gastronomy is sometimes defined as 'the art of enjoyably eating and drinking'. This is usually achieved by stimulating different senses all at the same time, and/or stimulating one of the senses at different rates and levels.

Historically, the first phase of gastronomy evolution has been the creation of classical recipes over many previous centuries, which, at their beginning, may be referred to as innovations. The second phase has been the improvement of classical recipes. The third phase has been the formation of new and creative recipes by means of using ingredients and/or techniques that are novel, at least to the restaurant scene. It is these recipes that produce culinary innovation and trigger the overall sensory perception.

This overall sensory perception is composed of contributions from different senses. These contributions are interrelated, that is, changing one contribution can affect other contributions. In order to be efficient in achieving an overall positive sensory innovation, by means of using a new ingredient and/or technique, one needs an integrated approach regarding contributions from the different senses. Such integration should avoid that optimization if one contribution is detrimental to another. The integration is facilitated by physics, since most of the sensory contributions are physics-related: texture (relates to mechanics), fracture and breakdown during mastication (relates to sound), color (relates to optics), and smell (relates to volatile release and transport). The integration of physics with gastronomy can therefore yield innovations in an efficient manner.

The above provides an example of the general argument, originally presented by Donald Stokes [1], and suggests that the chance of innovation is highest when one integrates research that is curiosity-driven (in this case physics) with research that is application-driven (in this case gastronomy). It is important to note that curiosity-driven research also requires a continuous effort of development.

The importance of structure for integration

For food applications, from a physics point of view, one needs to understand how macroscopic physical food properties relate to molecular properties and interactions of the ingredients, as a function of the parameters of ingredient concentration, ingredient type, energy input, temperature and time. The values of these parameters are reflected by the food's microstructure. This structure allows an understanding of how macroscopic and molecular properties are related. Changing the preparation conditions will change the position of the

Correspondence: erik.vanderlinden@wur.nl
Laboratory of Physics and Physical Chemistry of Foods, Wageningen University, Wageningen, The Netherlands

diagram in Figure 1 and therefore the structure can change as well.

The design of new structures can allow the current physical theories to be tested and may yield new physical understanding. It may also yield new materials with new applications. This means that one can end up with different and even new structures when taking different trajectories through the diagram. In other words, taking novel paths through the diagram (such as novel ingredients and novel techniques or processes) can allow the design of new structures. The new structures allow the testing of existing physics and may even provide new physics. At the same time, designing new structures implies new material properties, functions and applications.

The above is an illustration of the overarching vision of the author's chair group of Physics and Physical Chemistry of Foods at Wageningen University, The Netherlands. According to this vision, an integration of physics with structure design and application-driven research (in this case gastronomy) yields innovations in an efficient manner [2]. Similarly, according to this same vision, an educational effort integrating science and application (in the current case of physics and gastronomy) may form the basis of an innovation competency for our graduates. A recently established Master of Science (MSc) specialization at Wageningen University, with interactions with the Rijn IJssel school for chefs in Wageningen, has been developed along these lines [3].

An example of physics relevant to gelatin

Gelatin elasticity, in terms of the characteristics of the gelatin microstructure, will be described in order to appreciate the depth of the physics required. Certain aspects of the physics have been developed only ten years ago. The account in this section has been addressed earlier [4,5] and will be briefly summarized.

A gelatin gel consists of triple helices connected by coil-like structures. Professor Djabourov and her group [6] proved that the type of gelatin does not matter for the elasticity, only the concentration of helices. They also demonstrate that the elasticity at low concentrations follows a scaling with an exponent of scalar percolation and with a critical concentration. The critical concentration is related to the persistence length, L_p, and hence stiffness of the helices [4]. A percolating (network) structure arises when there are about three contacts per length L_p. The stiffness of the helix also determines the initial elasticity of the gel [5]. At higher concentrations, a deflection length, L_d, needs to be introduced, which is the length over which the helix is stiff when confined within a tube of thickness D. This second characteristic length scale, L_d, in the system was introduced by Odijk [7]. The confinement of the helix by means of D is determined by the concentration of helices. The higher the concentration, the smaller D and the smaller L_d. The exact dependency of L_d on the concentration of helices is known [7]. The contribution to the elastic component of the shear modulus, G', due to the deflection length at high concentration, is given by:

$$G' = n * k_B T * (L/L_d)$$

where n denotes the number of helices per volume, $k_B T$ the thermal energy and L the contour length of the helices. Substituting the dependency of L_d on concentration allows deducing the elasticity contribution at high concentrations. There is one parameter that needs to be fitted using the high concentration data and that is the pre-factor (of order unity) in the scaling relation for high concentration. Finally, the total elasticity can be viewed as the sum contribution of two networks in series. The overall G' fits the elasticity of the gelatin perfectly [4].

The analysis shows that the deflection length is a characteristic length scale arising from the helix confinement at higher helix concentrations. In the end, only the temperature and the persistence length of the helices are

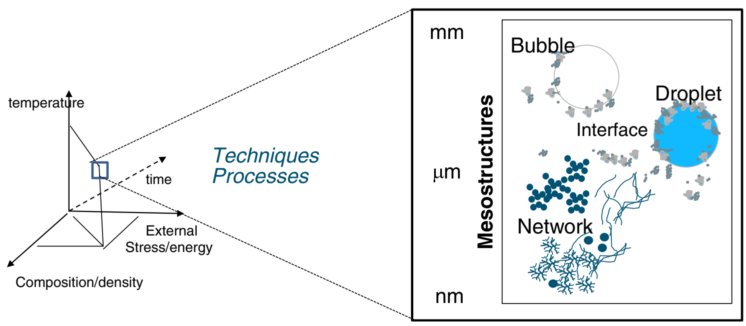

Figure 1 A trajectory through the parameter space, as initiated by techniques and processes, can change the according food structure.

the sole first parameters for the elasticity of the gelatin gel. This insight is beautiful by its simplicity, while the physics behind it remains complex, including the adaptation of helix dynamics to helix concentration. The simplification can help in efficient structure design.

Integration for innovation for educational purposes

In a recently established MSc specialization at Wageningen University, two course modules are based on integrating physics (and chemistry) with gastronomy. Both modules address physics and chemistry knowledge, and practical assignments challenge the creativity of the students and their knowledge of physics and chemistry with relevance to gastronomy. The practical assignments are performed at the Rijn IJssel school for chefs in Wageningen, which provides the necessary infrastructure. It also involves teachers from that school to cover the technical skills and knowledge from a chef's perspective. It exposes the students to real food systems instead of only model systems. Innovative recipes are developed and the best ones are to be incorporated into a book, which will also address recipe innovation as well as its scientific background. These results may also benefit other food professionals.

Conclusions and outlook

The opinion that the integration of physics and gastronomy can lead to innovations in an efficient manner is based on the general argument presented by Stokes [1]. Food structure and its design provide an important element in this integration. Physics is sometimes able to simplify matters considerably, as demonstrated in the case of gelatin, where the persistence length of the helices and the temperature are the only structure parameters necessary to explain the elasticity of a gelatin gel. The integration of physics and gastronomy has been incorporated in an MSc specialization and it is expected that this will help MSc graduates to apply the integration in their future careers of innovation.

Competing interests

The author declares that he has no competing interests.

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OPINION Open Access

Texture, taste and aroma: multi-scale materials and the gastrophysics of food

Thomas A Vilgis

Abstract

The common feature of the large variety of raw and cooked foods is that they are multi-component materials that consist at least of proteins, carbohydrates, fat and water. These basic classes of molecules define most of the structural and textural properties of the foods cooked and processed in the kitchen. Given the different solubility of these components in the basic solvents, water and fat, it becomes clear that many physical properties, such as structure and texture are determined by a large number of competing interactions between these different components.

Introduction

Cooking and eating are definitely pleasures. Cooking and eating are definitely materials research fields. Cooking and eating are definitely complicated forms of physical, chemical and biological processes with only one aim: pleasure, satisfaction, and satiation. Natural materials as grown in fields, on trees or in water change their state, structure, colour, taste, and smell. Consequently cooking involves simultaneous and non-separable physical, chemical and biological processes in a highly coupled manner, unlike in classical physics, chemistry and biology. Cooking and eating define a new class of multidisciplinary scientific problems on many length and time scales. However, cooking and eating remain culture [1].

The conformation and dynamics of water-soluble long carbohydrates and partially water-soluble native or denatured proteins define, together with the water content, the textural properties of foods. In addition, local short-range interactions of these macromolecules with comparatively small ions (salts), polar molecules (water, low molecular weight sugars) and amphiphilic molecules (emulsifiers) have a strong influence on macroscopic properties, for example, the mouthfeel as it is demonstrated with simple model systems such as tasty multi-component gels.

These pure 'materials properties' are typical in the field of soft condensed matter physics but all foods live from their sensory properties, taste complexity and specific aroma release. Here again, the water–oil/fat solubility of taste and aroma compounds plays a significant role. Water dissolves most of the taste-relevant hydrophilic units (ions, protons, sugars, glutamine acid), whereas oils and fats act as 'good solvents' for the lipophilic aroma compounds. Consequently, the interplay between aroma release and odour activity with structure and texture properties follows certain fundamental physical principles. Some of these 'universal' features define a relation between structure, processing, solubility and aroma release and close the circle from materials to cultural sciences via the 'culinary triangle' developed by the anthropologist Claude Lévy-Strauss. The large variety of texture, taste and aroma can already be viewed in the 'raw, cooked and fermented' state of corresponding foods.

Gastrophysics: multi-scales in foods and sensory sciences

From a purely physical point of view, foods need to be treated as multi-scale systems [2]. This becomes obvious from the sensory qualities of the food felt while eating [3]. By biting, chewing, and swallowing, foods are destroyed by the teeth, aroma gets released, taste becomes released, broken food pieces are wetted by the salvia and are transformed to a partially liquid bolus that can be swallowed with pleasure [4]. By translating these elementary processes into naïve physical ideas the relations to materials sciences become visible. The texture of the food is defined via its physical structure including the swelling and lubrication agents, water and oil. The

Correspondence: vilgis@mpip-mainz.mpg.de
Max Planck Institute for Polymer Research, Ackermannweg 10, 55128, Mainz, Germany

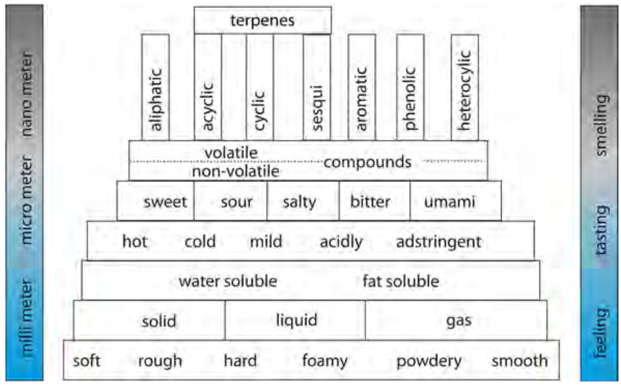

Figure 1 A simple view of the hierarchy in length scales and of the different sensory sensations.

rupture and breakdown of the structure determine, together with the water content and oil concentration, the aroma and taste release. The temperature of the food yields the perception intensity of the culinary sensation. Finally, size, surface states, wettability, and composition of the damaged food in the mouth determine volume and viscosity of the bolus, as well as the satiation.

The unconscious way of eating involves more than is visible on a macroscopic scale. Of course, its macroscopic shapes and its surfaces determine the first impression when the food is taken into the mouth, but only a number of non-visible processes lead the overall pleasure and the flavour of the foods. Figure 1 illustrates the hierarchy involved during eating [5]. At the lowest level, the basis, some of the macroscopic properties are listed. They concern surface properties, such as roughness, properties like hardness or softness of the state of the food, for example foaminess or creaminess. The next level in Figure 1 shows another form of the complexity: most foods are composite and structured materials that contain more than one aggregate state of the matter. Gases inside bubbles form with liquids or solids inside the boundaries foams. 'Solid' chocolate consists of solid spherical crystals with liquid cores of fatty acids of higher unsaturation degree [6].

Both the water and fat content of the foods determine the solution properties of aroma and taste-relevant compounds and ions, exploit spreading on the tongue and stimulate taste buds and trigeminal channels. At the highest level and smallest scales in the scheme shown in Figure 1, aroma release takes place. Characteristically shaped volatile aroma compounds are detected by its receptors in the olfactory bulb.

'Eating with pleasure' involves thus the entire length scales ranging from macroscopic dimensions down to molecular scales almost simultaneously. Consequently, gastrophysics similarly involves many time scales, which are not independent and cannot be clearly separated from each other, since at the perception level all length and times matter - unlike in food processing where time and lengths scales can be selected to design certain properties of foods.

Molecular hierarchies

From the physicist's point of view, foods are hierarchical complex systems where structure and texture can be related to structural polymers, such as proteins and carbohydrates with different solvability. Figure 2 shows the basic building blocks of all foods. Every food consists of proteins, carbohydrates, oil, and water. Proteins and carbohydrates form the basic structure. The two contrary solvents water and fat (oil) determine their self-organization in the foods. Carbohydrates are mainly water soluble,

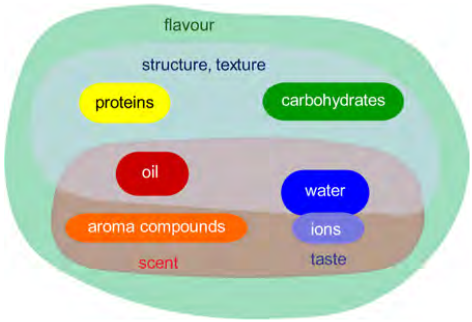

Figure 2 Classification of the food constituents. Proteins and carbohydrates basically define, together with the water and oil distribution/ratio, the structure/texture, whereas aroma compounds and ions determine the taste. The overall perception is usually described by the flavor.

proteins, which consist of hydrophilic and hydrophobic amino acids, accept partially water and oil as solvent, depending on their function and their primary structure, that is, the arrangement of the amino acids along the backbone of the protein chain contour.

The basic taste qualities [7], sweet, sour, salty, bitter and umami of the foods are governed a number of small molecular compounds, which are in most cases water soluble. All sugars and sweeteners are ions or dipolar molecules, salts dissociate in their ions. The acid taste is related to proton activity and umami to a number of water-soluble molecules, the most well-known glutamic acid [8]. Moreover, the ions and the overall ionic strength (salt content) in foods have some implication for the structure and texture of the foods. Monovalent ions contribute to the screening of electrostatic interactions [1]. Bivalent ions can, under certain circumstances, provoke liquid-to-solid phase transitions like calcium or magnesium ions in certain alginates [1,9].

Aroma compounds are, in contrast, mostly weakly water soluble but dissolve strongly in a fatty environment. Indeed, their odour activity is more or less determined by the volatility (a thermodynamic property defined by the corresponding vapour pressure) and the odour threshold (a physiological-chemical property). Both quantities can be easily measured in defined solvents at a certain temperature. Nevertheless, odour impressions turn out to be more complicated in real foods; many proteins in food have special (hydrophobic) binding sites for aroma compounds that define a 'local' vapour pressure [10]. Thus the same aroma compound will appear with different odour activity values in different foods.

Are model systems of help?

The study of simplified model systems is one of the basic approaches in all areas of physics. Model systems contain, despite a high degree of simplifications, most of the general features of the original system. In many cases, model systems define a class of universality valid for many systems. In gastrophysics (as in biophysics) the basic concept of universality does not lead to the most appropriate answer, since local interactions and their origin in a detailed chemical structure matters for the final result - in the 'laboratory mouth'.

Nevertheless, a number of model systems, in most cases gels with different types of hydrocolloids have been developed that show significant differences in crack behaviour during chewing and mouthfeel, properties that are defined by length and time scales defined by the size of the molecules, respectively the mesh sizes of the gels. Their water binding as well as taste and aroma release are, however, determined by local scales and the rupture of individual chains forming the network. By adding different sugars (monosaccharides, disaccharides, sugar alcohols, and so on) it can be demonstrated how local properties such as hydrate shells have indeed a strong influence on the gelling properties and mouthfeel. These are indeed important questions especially for sweets, desserts and confectionaries. The interplay between hydrocolloids with different persistence length (stiffness) and polar and ionization (for example, agarose as a polar gelling agent, and xanthan as a rather stiff polyelectrolyte) and their different interactions with low molecular weight cosolutes, show ways how the strong effect of sugars on the elastic properties can be minimized [11-13]. Model systems in gastrophysics do then indeed have practical implications ranging from gastronomy to the food industry.

There exist many more examples how simple model systems show basic physical correlations between different food constituents. In addition, some of the dishes created by Ferran Adrià and others of that kitchen style can be viewed as physical model systems, for example when the same food is presented by different drying methods. Drying at moderate temperatures brings different textures and taste compared to freeze-drying or microwave drying. The differences are clear signs of the energy of water binding, the state diagram of the food and the corresponding thermodynamic pathways to the glassy state [14]. Even when the remaining water content of the freeze-dried and temperature-dried food is similar, taste and mouthfeel are different. Both methods define therefore different culinary functions. Here as well, different length scales play essential roles: local scales and interactions (polarity, charges) on molecular scales up to the resulting porosity due to the water dehydration.

Cooking is more than natural science: gastrophysics links to cultural sciences

Even when model systems show some physical qualification, in most cases they appear far away from natural

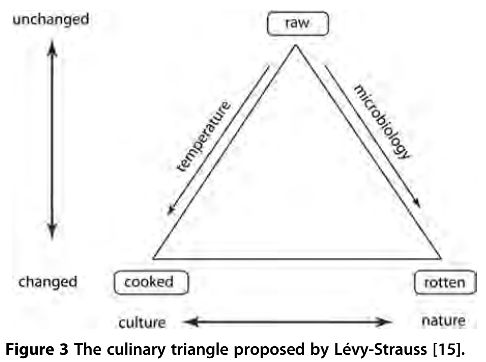

Figure 3 The culinary triangle proposed by Lévy-Strauss [15]. The transition from raw to cooked is temperature-driven, from raw to rotten by microorganisms.

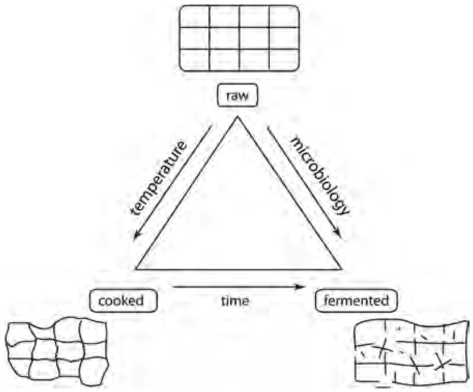

Figure 4 The physical interpretation of the culinary triangle. Temperature changes the structure (symbolically drawn as lattice) physically: polysaccharides and corresponding cell structures become softer, proteins denature. Microbiology changes the structure by destroying certain structural elements. Long cooking implies hydrolysis of certain structural polymers, too.

food and cultural background. Nevertheless, physical ideas appear useful even to cultural sciences and anthropology. One example is the idea of the 'culinary triangle' developed by Lévy-Strauss [15]. He proposed cooking, after the use of the fire in the early days of humankind, as the transition from 'nature' to 'culture'. To visualize the idea of such a 'universal structuralism' a triangle was proposed, whose sides join the edges of 'raw', 'cooked' and 'rotten, see Figure 3. Physically, this triangular construction also makes sense when the physical food structure to each of the three edges and the pathways for the transitions are assigned. 'Raw' then becomes the original structure of the foods as grown by nature. 'Cooked' then means the structural transitions induced by changing temperature. 'Rotten' can be translated into 'fermented', when the structure of the foods becomes transformed by microbiological processes by bacteria or enzymes. The latter stands, for example, for foods like yoghurts, ripe cheeses or fermented vegetables. With this definition, motivated from natural sciences, one long-debated dilemma of the culinary triangle can also be resolved: the 'cooked' is close to 'rotten/fermented', because long cooking times correspond always to a hydrolysis of proteins and carbohydrates, which define the structure of the foods, as schematically depicted in Figure 4. Moreover, modern cooking and its arrangements of plates as practised in avant-garde cuisine, New Nordic Cuisine, '*nova regio*' cuisine and other forms require a systematic extension of the culinary triangle according to the underlying physical and chemical processes. These ideas will be published elsewhere [16].

Conclusion

Gastrophysics joins many length and time scales. Apart from 'food physics' and physical-oriented chemistry, it also needs to take into account physical aspects of aroma chemistry and structural thermodynamic aspects of aroma compounds. It also ranges deep into the understanding of biophysical processes in cell physiology via the dynamics of receptors and psychophysics of perception. Even from a pure physicist's point of view, cooking-related problems are non-trivial: most of them are of highly non-equilibrium nature. The final states of cooked food depend strongly on the pathway, that is, the 'processing'. In contrast to many (classical physical) material properties, the resulting structure depends on the processes themselves and apart from a structure–property relationship, gastrophysics needs a clear structure-process-property-flavour relationship.

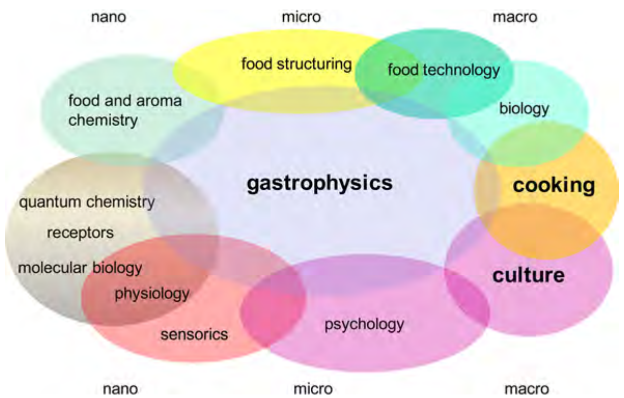

Figure 5 Gastrophysics and its overlap with different scientific disciplines as motivated by its multi-scale character.

The multi-scale character of gastrophysics implies a link to many other fields of sciences, as cartooned in Figure 5. Pure aroma chemistry, without the appropriate quantum and statistical physical properties of the aroma compounds and their coupling to appropriate receptor proteins, does not automatically provide a deeper understanding of the foods and the perception [17,18]. Sensory studies without the proper links between the behaviour of molecular scales, length scales that define food structures and macroscopic scales, remain empirical and phenomenological. So what about 'gastrophysics'? It starts indeed often in the kitchen where many questions pose themselves. It ends in laboratories, at desks and computers, where some of them are solved, and many others are reposed, but in any of these cases, gastrophysics helps to make dishes more exciting and taste better. Gastrophysical results show their consequences immediately.

Competing interests
The author declares that he has no competing interests.

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ABOUT THE EDITORS OF THE EMERGING SCIENCE OF GASTROPHYSICS

Ole G. Mouritsen PhD DSc is a professor of molecular biophysics at the University of Southern Denmark. His research concentrates on basic science and its practical applications to biotechnology, biomedicine, gastrophysics, and gastronomy. He is an elected fellow of the Royal Danish Academy of Sciences and Letters, The Danish Academy of Technical Sciences, and the Danish Gastronomical Academy. He is director of *MEMPHYS*-Center for Biomembrane Physics and *Taste for Life,* a national Danish center for taste. He is the president of the Danish Gastronomical Academy. He has received a number of prestigious science and science communication prizes. In his spare time, he cooks and furthers his knowledge of all aspects of food, often in collaboration with chefs. His books include *Life: As a Matter of Fat* (2005, 2015); *Sushi: Food for the Eye, the Body, and the Soul* (2009); *Seaweeds: Edible, Available, and Sustainable* (2013) and *Umami: Unlocking the Secrets of the Fifth Taste* (2014).

Jens Risbo PhD is an associate professor of food chemistry at the University of Copenhagen. The research of Jens Risbo concerns aspects of food materials science and the physical and colloidal chemistry of foods. He coordinates the EU project BIBAFOODS with the aim of developing colloidal food delivery systems for probiotics and enzymes. He is engaged in several industrial related projects, for example research directed towards developing new colloidal principles for making ice cream with reduced amounts of saturated fat. He has taken part in maturing and defining molecular gastronomy and gastrophysics as sciences and has supervised the first three PhD students of molecular gastronomy in Denmark.