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TRENDS IN FOOD SCIENCE & TECHNOLOGY

Viewpoint

Molecular gastronomy: a food fad or science supporting innovative cuisine?

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The concepts, history and approaches of molecular gastronomy are discussed with an emphasis on the relation to food science and technology. A distinction is made between molecular gastronomy and science-based cooking, where the first relates to the *scientific* understanding of the cooking and eating processes and the latter refers to the *application* of the principles and tools from science for the development of new dishes, particularly in the context of *haute cuisine*. We argue that science-based cooking is closely associated with significant technological developments, as the realization of novel dishes frequently requires the use of non-traditional ingredients or preparation techniques, which are often derived from those used in industrial food production. Several approaches towards the scientific understanding of foods are highlighted, including the complex disperse system (CDS) formalism of This and the systematic compilation and interpretation of scientific and non-scientific information relating to foods, their ingredients and preparation methods as shaped into its modern form by McGee. We discuss how chefs are dealing with the available systematic knowledge on food and cooking, and how molecular gastronomy can facilitate the cumbersome, but much needed discussions among food scientists and chefs. Finally, we discuss the implications of molecular gastronomy for society. This includes the way the general public is considering food, and how molecular gastronomy could inspire food technologists to increasingly emphasize aspects relating to food origin, quality, and creativity in their product development efforts.

> "In a word, cookery, whilst continuing to be art, will become scientific and will have to submit its formulas which very often are still too empirical, to a method which leaves nothing to chance."
>
> Escoffier (1907)

Introduction

The world of food has rapidly evolved over the last few decades. Among many other developments, new and parallel approaches to the way chefs cook and food scientists do research have emerged in several restaurants and laboratories around the globe. This evolution encompasses both the use of ingredients and devices usually found within the context of mass food production into the domain of *haute cuisine*, and the growing awareness of (food) scientists that the scientific investigation of the numerous phenomena occurring during the cooking and eating processes is an important challenge. This, according to Adrià, Blumenthal, Keller, and McGee (2006), "is a turning point in the history of cooking [and probably food itself] that has been widely misunderstood, both outside and inside our profession(s)". We are talking about the phenomenon widely known as *molecular gastronomy*. Molecular gastronomy, which is mistakenly seen as a cooking style, is a scientifically oriented approach towards understanding the basic mechanisms occurring during cooking, has received significant publicity and media coverage during the last few years. Notwithstanding the abundant attention, molecular gastronomy remains a field that is surprisingly poorly communicated. For this reason, it stirs deep and often antagonist reactions among cooks, scientists and the lay public alike.

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The origins of molecular gastronomy as we know it today can be traced back to the late physicist Nicholas Kurti. He promoted the intellectual and artistic exchange between physicists and chefs through a now-classic speech "The physicist in the kitchen" given at the Royal Institution of London (Kurti, 1969). This, in the end, led to the creation in 1992 of a series of workshops in, originally, "molecular and physical gastronomy" (This, 2004) and to more focused attention within the popular scientific literature (Kurti & This-Benckhard, 1994a, 1994b).

A milestone in the scientific understanding of cooking was reached in 1984 with the publication of the book "On Food and Cooking" by Harold McGee, who proposed that "science can make cooking more interesting by connecting it with the basic workings of the natural world". Because of its breadth, depth and practical relevance, this book provided a new stimulus to the application of food science in cooking, and it has incited many chefs to more systematically explore the way they cook.

However, the scientific understanding of cooking was initiated several centuries ago. In 1794, Sir Benjamín Thompson, Count Rumford, natural philosopher and inventor of the forerunner of the stove as we now know it, wrote: "The advantage that would result from an application of the late brilliant discoveries in philosophical chemistry and other branches of natural philosophy and mechanics to the improvement of the art of cookery are so evident that I cannot help flattering myself that we shall soon see some enlightened and liberal-minded person of the profession to take up the matter in earnest and give it a thoroughly scientific investigation" (cited by This, 2004).

Gastronomy was also seen as having strong links to science. According to Jean-Anthelme Brillat-Savarin (1825), gastronomy is "the reasoned knowledge of all that relates to man feeding himself. Its aim is to attend to the preservation of man by means of the best possible food. It relates to and manages, following certain principles, everybody who explores, supplies or prepares those things which may be converted into food".[3] In a condensed way, gastronomy may be defined as the practice or art of choosing, cooking, and eating good food and, furthermore, it relates to a large number of disciplines, including biology, chemistry and physics (Brillat-Savarin, 1825).

Together with Rumford, scientists such as Lavoisier (chemist; studies on *bouillon* – see This, Méric, & Cazor, 2006), Parmentier (nutritional chemist), Pasteur (microbiologist), Chevreul (lipid chemist), von Liebig (agricultural and biological chemist; instrumental in the development of the meat extract which is a precursor of the *bouillon* cube – see This & Bram, 1998) and Maillard (food chemist), came to shape the origins of what would become food science. In the 19th and 20th centuries, the scientific understanding of food developed at a fast pace and, under the influence of industrialization, it focused on the modification and preservation of foods and on the mass production of foodstuffs rather than on the needs of those who cooked at home and the issues relevant to the emerging restaurant industry (Fuller, 2001; Roudot, 2004). Similarly home cooking was virtually ignored by scientists as a topic deserving systematic attention and only a pioneer such as Edouard de Pomiane further developed the understanding of home cooking and stimulated its communication to the general public (see e.g. de Pomiane, 2001; This, 2006a).

By introducing efficient and standardized manufacturing processes, the food industry has been highly successful, together with modern intensive agriculture, in improving the availability, choice and safety of food for the whole population, at least in the developed world (Fuller, 2001). These successes are even more impressive given the rapid population growth since the early 19th century. The negative side effects of the industrialization of farming and food manufacturing have, however, become increasingly clear over the last few decades (Pollan, 2006). These side effects include (a) a neglect of the sustainability of agriculture (Fuller, 2001); (b) an increased dependence on a very limited number of crops; (c) a loss of cooking skills and food traditions by the population in general and by the young, in particular (Larson, Perry, Story, & Neumark-Sztainer, 2006); (d) an excessive food consumption resulting in the obesity crisis of the developed world (Brownell & Horgen, 2004) and; last but not least, (e) a perceived decrease in the sensory qualities and the diversity of food.

Parallel to these developments, the interest of a minority group of critical consumers in high-quality origin-controlled foods has been rapidly growing. This has led, amongst others, to a rise in organic farming (Dimitri & Greene, 2002), to the creation of the slow-food movement (see www.slowfood.com), and it has also stimulated a new and highly creative branch of gastronomy where the emphasis is on the ultimate food experience.

Over a decade ago, a number of creative chefs started experimenting with the incorporation of ingredients and techniques normally used within the domain of 'food mass production' in order to arrive at hitherto unattainable culinary creations (see Fig. 1). It is almost ironic that pioneers of this new branch of cooking have been making extensive use of both scientific knowledge of food preparation and technological devices which were originally pursued and developed in the context of low-cost, industrial food manufacturing. This encompasses, on the one hand, knowledge of chemical reactions and physico-chemical phenomena in foods and, on the other hand, developments in cooking tools and techniques, as many of the novel dishes invented within the framework of the 'new cooking' cannot be prepared using standard kitchen utensils. These novel techniques, adapted from food technology, include, for example, high-speed homogenization and flash freezing.

[3] We thank an anonymous reviewer for pointing out the importance of consulting the original French text.

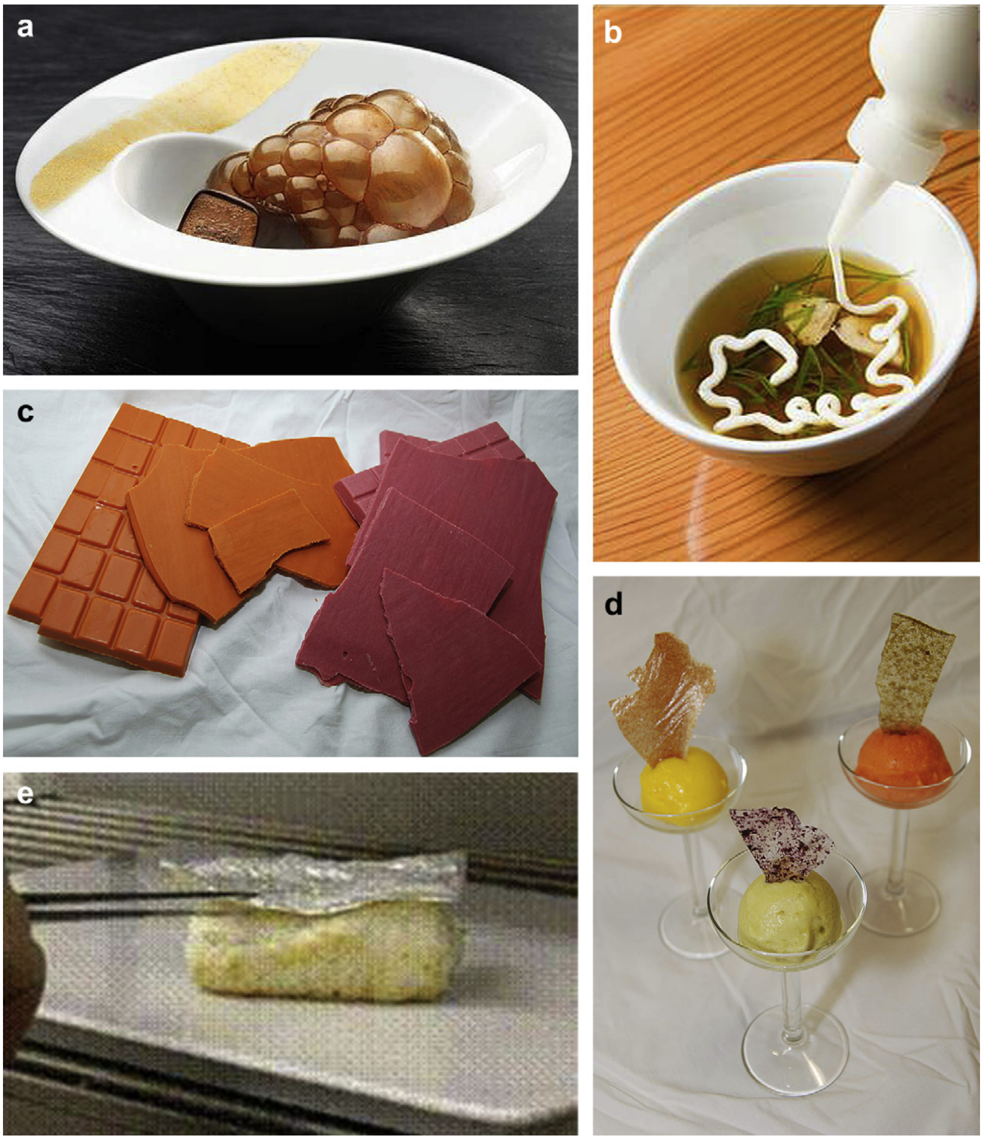


Fig. 1. Representative dishes developed with an in-depth use of food science and technology. a. Vanity: mouth watering chocolate cake, garnished with chilled cream, traces of gold, and smoky bubbles of cocoa (Mugaritz, Spain – picture by José Luis López Zubiria). An understanding of interfacial visco-elasticity using techniques such as pendant drop and surface dilational rheology allowed the formation of stable bubbles over extended periods of time (enabling plating of the dish ahead of time). A 10 mg/mL solution of spray-dried egg white was used to promote bubble formation. Xanthan gum (1 mg/mL) stabilized the interface against coalescence. Neutral pH favored the formation of large, stable bubbles, whereas as acidic pH (4.6) stabilized small bubbles (for further details see Arboleya *et al.*, 2007). b. Instant sesame "noodles" (WD50, USA – picture by Takahiko Marumoto). Pouring fluid sesame seed-flavored tofu, added with a modified cellulose, into hot miso soup creates an instant noodle. This is possible given the thermo-gelling properties of modified celluloses. c. Sweet or non-sweet "chocolate" with tomato- and blueberry powder replacing the cocoa. The powders replacing the cocoa powder were obtained by freeze drying fresh fruit pulp; the freeze-dried powders were finely milled before they were added to the "chocolate" base (picture by D. Curti). d. Piperade sorbet of sweet peppers in three colors decorated with glassy maltodextrin "windows" containing flakes of spices supplementing the taste of the various piperades. The sorbets were prepared by high-speed mixing and pureeing of frozen concoctions. The "windows" in the amorphous, glassy state were prepared by solvent-casting and drying under reduced pressure of 65 wt % maltodextrin DE21 solutions to which freeze-dried flakes of various spices were added (picture by D. Curti). e. Roast monkfish loin "with skin" (Mugaritz, Spain – picture by José Luis López Zubiria). Cod skins were heated at 80 °C for 2 h in order to extract the gelatin. This broth was used to replace butter and, after reducing its original volume to half, for the casting of edible films. The film was the cut, hand-painted and placed on top of a piece of monkfish as to mimic its skin. As the film gets warm, it acquires the shape of the piece of fish it is placed on. Figs. 1a and 1e are reproduced with permission of J.C. Arboleya; the images are part of a manuscript submitted to *Food Biophysics*. Fig. 1b is reproduced with permission of W. Dufresne. Figs. 1c and 1d are reproduced with permission of F. Beaud, D. Curti, L. Donato, O. Roger and J. Ubbink.

In this paper, we discuss the concepts, approaches and achievements of science-based cooking and molecular gastronomy with an emphasis on their relation to the fields of food science and technology. We present an overview of the scientific and technological developments of importance to science-driven cooking. Finally, we discuss the importance of stimulating the communication between scientists and cooks and the potential impact of molecular gastronomy and science-based cooking on society and on the food industry. First, however, we need to scrutinize the sometimes confusing terminology pertaining our discussion.

Definitions

It is important to distinguish between a number of different terms that relate to the application of scientific knowledge and techniques from the realms of food science and technology into home and restaurant cooking. The main term, which has been widely misunderstood, and hence abused, is 'molecular gastronomy'. During the round-table discussion on Molecular Gastronomy during the '2nd International Symposium on Delivery of Functionality in Complex Food Systems' held at the University of Massachusetts at Amherst from October 7–9, 2007, a heated discussion arose around this term. 'Molecular gastronomy' seemed to be interpreted quite differently by almost every participant and, furthermore, was almost universally disliked. To some, 'molecular gastronomy' is just a fancy term for food science; to others, a marketing strategy aimed to frame those chefs using (with or without true knowledge) stabilizers, emulsifiers or semi-industrial equipment in their kitchens. We believe that part of the confusion and the dislike is rooted in the (mis) use of and lack of communication on the original definition of 'molecular gastronomy' among (food) scientists, cooks, the media and the general public.

Molecular gastronomy according to one of its cofounders, Herve This, is defined as ''a branch of *science* that studies the physico-chemical transformations of *edible materials* during *cooking* and the sensory phenomena associated with their consumption'' (This, 2004). Given the closeness of this definition to that of food science, it is still debatable whether or not molecular gastronomy is a 'science' in its own right (Pedersen, 2007). That said, it is also important to emphasize that molecular gastronomy is *not* a type or style of cooking. Similarly, those who practice molecular gastronomy are mainly scientists with strong backgrounds in physics, colloidal and material science (Enserink, 2006).

A term that we would like to introduce and that relates to molecular gastronomy is 'science-based cooking'. This concept refers to the conscious application of the principles and tools from food science and other disciplines for the development of new dishes, particularly in the context of *haute cuisine*. A similar concept, 'molecular cooking', has been used interchangeably, but because it uses the rather confusing term 'molecular', we preferred to employ 'science-based cooking' throughout this paper.

Given the associated cost to access devices such as homogenizers, Pacojets, vacuum chambers, freeze-driers and the like, this type of cooking is practiced almost exclusively in the best restaurants in the world (*The S. Pellegrino World's 50 Best Restaurants, 2007*). The chefs of these restaurants also have their own view towards molecular gastronomy/science-based cooking. They state that ''the use of industrial thickeners, sugar substitutes, enzymes, liquid nitrogen, *sous-vide*, dehydration, and other non-traditional means'' do not define their cooking as they are seen only as available tools to make delicious and stimulating dishes. Furthermore, they address molecular gastronomy by saying that it is a ''quasi-academic name for food science that may be useful in fine cooking. It is not a style of cooking'' (Adrià *et al.*, 2006).

A third term, created by the Research Chefs Association (RCA) is 'culinology', which has been defined as ''the blending of culinary arts and the science of food'' (*Culinology*, 2007). Through colleges and universities, the RCA offers degrees that are focused on the science of mass food production and preservation of restaurant-like dishes based on culinary artistry (Cornwell, 2005). Notwithstanding its own merits, 'culinology' remains somewhat removed from an in-depth scientific understanding of the cooking process (the principal aim of molecular gastronomy) and from the level of culinary creations found in science-based kitchens and will, therefore, not be further discussed within the context of this paper (for more information, visit www.culinology.com).

The last term, to which most of us scientists were recently introduced to at the meeting in Amherst (see above), is 'experimental cuisine'. This term was derived from 'experimental cuisine collective' which was proposed by a group of academics, chefs, and scientists as a name for their organization that among other things, seeks to (a) contribute to a rigorous scientific understanding of the physical basis for cooking processes; (b) enhance understanding of the social contexts for cooking and the societal ramifications of new food technologies; and (c) accelerate the discovery of scientific and experiment-based approaches to innovative culinary practices, unorthodox flavors, and new dining traditions (*Experimental cuisine*, 2007). Given its recent creation, it will take some time to see if the 'experimental cuisine collective' can fulfill its objectives, which, in principle, we judge to have a good *raison d'être*.

The debate around these definitions will only increase as the interactions between cooks and scientists become more the rule than the exception. It is for this reason that we believe this manuscript, aimed to provide a deeper perspective into the repercussions of such interactions, is a timely contribution to the field of food science.

Principal approaches

There are various approaches towards the scientific understanding of foods and cooking. These not only concern the fundamental insights themselves, but also the communication to the public, including the chefs. One fundamental approach was taken by Harold McGee in his book ''On

Food and Cooking: The Science and Lore of the Kitchen''. In this now-classic book, basic knowledge on all important classes of food ingredients is summarized, as well as information on the chemical and physical transformations occurring during food preparation. Although superficially looking like a cookbook in format and layout, ''On Food and Cooking'' is in fact an unique compilation of fundamental, but practically relevant information on food and its methods of preparation. It is structured in such a way that it incites to cook based on an understanding of the main physical and chemical processes occurring during cooking.

Closely associated with the original concept of 'molecular gastronomy' is the work of Hervé This. In his opinion, one of the principal goals of molecular gastronomy is to rationally assess the impact and relevance of the numerous and often arbitrary steps which make up a traditional recipe. These steps will be referred to as *precisions,* as suggested by This (2004). Take, for example, the belief (i.e. a precision) that whipping egg whites in a copper bowl renders a stronger foam compared to those made in either a glass or stainless steel bowls. The validity of this precision has been tested scientifically (McGee, 2004; McGee, Long, & Briggs, 1984; Sagis, de Groot-Mostert, Prins, & van der Linden, 2001). This, however, is not the case with most of the precisions which are either listed in cookbooks or rooted into people's minds (even of food scientists). In fact, only a small fraction of the over 25,000 precisions collected by This (2004, 2005a) have been tested.

In order to be truly useful in cooking, these precisions should (a) have substance in themselves and (b) be meaningful in the context of a specific recipe or across recipes. Hence, by applying principles from food chemistry, food physics, and polymer and material science, precisions can be categorized into five main groups (This, 2004):

1. Some precisions seem wrong, and they are wrong;
2. some seem wrong and they are right;
3. some seem right and they are wrong;
4. some seem right and they are right; and
5. some depend on environmental conditions and on the time scale of observation.

Examples of each class include:

1. While cooking a *crème anglaise*, one should always stir in the same direction, otherwise the sauce will phase separate (A. Massafra, personal communication, 2006).
2. Leaving a piece of roast 'to rest' for half an hour before eating it will increase its juiciness (Fearnley-Whittingstall, 2004).
3. Putting meat in a hot frying pan (searing) seals in the juices (Von Liebig, 1847).
4. Adding lemon juice to freshly cut apple will delay the latter's enzymatic browning.
5. Meat is tenderized when it is marinated in pineapple juice (McGee, 2004).

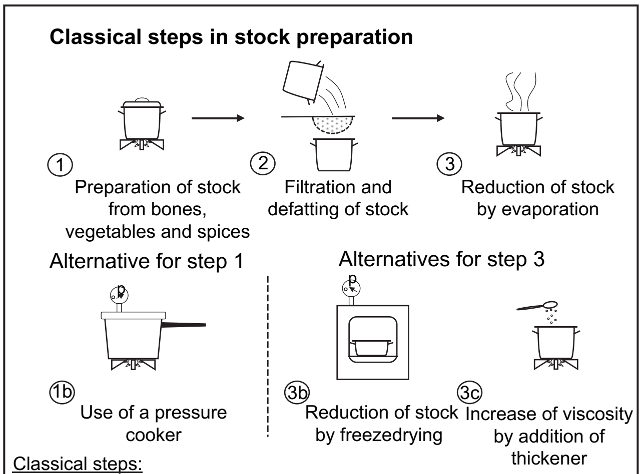
It is not surprising that most food scientists approach their hypotheses by use of model systems and this is justified by the intrinsic complexity of food. If we are to study the physico-chemical changes occurring during cooking, the theoretical 'modeling' of the dishes, which may be seen as complex dispersed systems, could facilitate their analysis. This (2004, 2005a, 2005b) proposed a symbolic language that, in principle, should enable the description of any dish (known or unknown) in the way of unambiguous formulae. This symbolic language, known as the 'complex disperse systems' formalism (CDS) and which we discuss in more detail below, may be used to describe food systems from simple oil-in-water emulsions to complex products such as puff pastry (This, 2005b).

As the 'new' science evolved, so did the problems it addressed. Today, molecular gastronomy uses a strongly interdisciplinary approach to study questions concerning the transformation pathways of food, from the field to the table. Some of the questions exemplifying the new approach were formulated by Barham (2004):

- How do production methods affect the eventual flavor and texture of food ingredients?
- How are these ingredients changed by different cooking methods?
- How do our brains actually interpret the signals from all our senses to tell us about the flavor of food?
- Can we devise new cooking methods that produce unusual and improved results of texture and flavor?

Scientific basis

The scientific and technological merits of molecular gastronomy rely on the generation of knowledge and the applicability or functionality of such knowledge, respectively. To this end, understanding of the physical and chemical changes occurring during the preparation of food enables the cook, technologist or scientist to hypothesize on new pathways to achieve the same or improved end result. In Fig. 2, an example is given for the preparation of stock and sauces based on technological insights. In the same context, the cooking of meat, supported by knowledge on the physical chemistry of tissue, can be a rewarding experience: tough cuts of meat (lamb shanks or pork belly) are best cooked when braised at relatively low temperatures (60–65 °C) and often for long periods of time (4 h or more) (McGee, 2004). These conditions are optimal for tenderizing the meat as denaturation, dissolution and hydrolysis of connective tissue (collagen) into gelatine take place at these relatively low temperatures, while minimizing the loss of water (McGee, 2004). In principle, two alternative methods could be used: (a) the use of a pressure cooker as a *technological* tool, leading, at least initially, to the loss of juices from the meat, and a completely different texture at the end of the cooking process or (b) marinating the meat in fresh pineapple or papaya juice, which are rich in the proteolytic enzymes bromelain (EC 3.4.22.33)



<u>Classical steps:</u>

1. Extraction of flavors and thickeners (mainly gelatine), depends on quality of ingredients, pretreatment of bones (oven) and duration of extraction. Step 1 may be repeated several times on same stock.
2. Filtration and de-fatting.
3. During reduction, flavor compounds are lost by evaporation, but are generated by reactions. Body is formed by concentration of thickeners.

<u>Alternatives for step 1:</u>

1b. Use of a pressure cooker for a more rapid and efficient extraction.

<u>Alternatives for step 3:</u>

3b. Original flavor notes are retained during freezedrying, but flavor profile is not necessarily better because flavor-generating reactions do not occur.

3c. Thickeners may be added to give body to fond at lower levelsof stock reduction, and thereby impact flavor loss, generation and release.

Fig. 2. Schematic diagram for the preparation of a stock for a sauce fond. The process is critically dependent on 1. The preparation of the stock, whereby aroma compounds are extracted and collagen is hydrolyzed and extracted from the bones in the form of gelatin; 2. The filtration and defatting of the stock and 3. The way the stock is reduced. Only few aspects of this classical process are quantitatively understood (McGee, 1999), leaving the overall process open to considerable and often arbitrary interpretations. For instance, fairly little is know of about the kinetics of extraction of gelatin under the fairly gently conditions during the brewing/infusion of the stock (Step 1) and almost nothing is known about the chemistry of aroma generation and degradation occurring during the reduction step (Step 3), which, as its name implies, is first and foremost considered to be a concentration step. If aroma concentration (but not generation) is occurring during reduction, a favorable alternative process would be freeze-drying (Step 3b). If the main objective of the reduction is viscosity enhancement, the use of added thickening agents could be considered (Step 3c).

and papain (EC 3.4.22.2), respectively. Marinating the meat, a biochemically assisted step, could then precede a short(er) braising step. In essence, braising is a cooking method aimed to develop an agreeable texture to an otherwise unpalatable piece of meat, which when based on physico-chemical insights on protein denaturation and solubilization, a process that a food scientist could explain as mere texture control and design.

The development of the CDS formalism (This, 2004, 2005a, 2005b) has to some degree bridged the divide between gastronomy and colloid science by extending the simple formalism used in colloids/materials science to describe the generally more complex food systems. If we acknowledge that food is composed of one or more co-existing phases: solid, liquid or gaseous, we can assign letters to each of these phases: G for gases; O for oils; W for water; and S for solid(s). These phases then interact at different levels, which can be described by the use of operators such as:/, dispersed in; +, mixed with; −, removed from; @, included into; and σ, superposed. To this end, a simple oil-in-water emulsion is described as O/W, which seems rather familiar. Nonetheless, when the symbolic language (CDS) is applied to more complex foods, one comes to realize its true potential, as elegantly exemplified by the modeling of puff pastry (This, 2005a, 2005b).

To illustrate the use of the CDS as originally proposed by This (2004), the formula for whipped cream is:

$$\mathrm{O/W + G \rightarrow (G + O)/W}$$

This describes the addition of a gas (air) into an oil-in-water emulsion, which results into the dispersion of gas and oil-in-water. This formula is an oversimplification of a not so simple colloidal system as it doesn't specify (a) the volume fraction (ϕ) of oil, (b) the phase/state of such an oil, (c) the volume fraction of air to be whipped in, and (d) any other particular conditions that should be met in order to obtain the final product. Hence, by including all these, we would have:

$$\left[\left((\mathrm{O_{cr}/O})_{\phi>0.25}\right)\right]\Big/\mathrm{W} + \mathrm{G} \overset{\mathrm{mdg},\ T<10^{\circ}C}{\rightarrow} (\mathrm{G}_{\phi=0.5}@\mathrm{O_{cr}})/\mathrm{W}$$

It is known that to effectively whip cream, the volume fraction of emulsified milk fat should be at least 0.25 (Van Aken, 2001). That whipping should be performed at temperatures below 10 °C to favor the formation of crystalline fat dispersed into discrete liquid fat droplets ($\mathrm{O_{cr}/O}$). Similarly, the presence of low molecular weight emulsifiers, such as mono- and diglycerides (mdg) enhances the phenomenon of partial coalescence which provides stability against drainage and loss of volume to the finished product (Lopez *et al*., 2002; Smith, Goff, & Kakuda, 2000).

More complex food systems, such as ice cream [50% overrun, 10% fat ≈ 24% w/w disaccharides (sucrose and lactose) at −20 °C], have also been described by use of the CDS formalism (Vega & Ubbink, 2007):

$$\left[\left(\mathrm{G_{0.33}@O_{cr(0.10)}}\right) + \mathrm{W_{ice(0.3)}}\right]\Big/\left[(\mathrm{S_1 + S_2 + S_3 + S_4})/\mathrm{W}\right]_{0.27}$$

The formula specifies that the final volume fraction of air is 0.33 ($\mathrm{G_{0.33}}$), that such air is included into a crystalline network of fat ($@\mathrm{O_{cr(0.10)}}$) that co-exists with a volume fraction of ice of approx. 0.30 ($\mathrm{W_{ice(0.3)}}$) − calculated from the equilibrium freezing curve for a 24% w/w sucrose solution (Whelan, Regand, Vega, Kerry, & Goff, 2008). These two phases are dispersed into (/) a freeze-concentrated unfrozen phase (0.27) where sugars, proteins, stabilizers and emulsifiers (S_1, S_2, S_3, and S_4, respectively) are also dispersed or dissolved.

Although the CDS formalism could become an important tool to logically visualize the main building blocks of any dish or processed food, it still offers significant room for improvement as it fails to address some important colloidal and thermodynamic phenomena:

- the phase transitions that a single or several components within a complex matrix need to undergo in order to become functional (e.g. starch gelatinization during the preparation of a custard);
- the existence of the glassy state. How would cotton candy or the brittle top of a *crème brûlée* be described?
- Enzymatic reactions that are key in the development of food-structure (chymosin in cheese manufacture) or characteristic flavor/aroma profiles (lypoxygenase in freshly cut tomatoes);
- biopolymer–biopolymer interactions and their well documented effects on texture and flavor delivery (Norton & Frith, 2001);
- symbolic operators such as – (removed from) and @ (included into) which emphasize an action rather than a state are difficult to logically incorporate into a formalism essentially based on thermodynamics;
- the length scale of emulsion droplets (micro- and nano-emulsions); and the textural properties of food (i.e. crispiness, creaminess, chewiness, etc.) were originally not explicitly taken into account. However, This (2005a, 2005b, 2007) has recently attempted to take length scales into account in a modified version of the formalism.

As is clear from the previous discussion, the current state of molecular gastronomy is very much based on learnings from food science and its related disciplines of colloid science and food chemistry. However, questions specifically arising from a culinary or gastronomic perspective are beginning to have an impact of how food science is developing – with interesting consequences for both our cooking and the future of food science.

Food technology in the restaurant kitchen

The growing awareness amongst chefs of the physical and chemical processes occurring during cooking and the increasing emphasis on eating as an innovative, intellectual, and sensorial experience, has led to the adoption in *haute cuisine* of ingredients and techniques originally developed for industrial food production. In addition, because of the small scale of both a kitchen and a laboratory and the basic similarity of a number of operations, there has been a transfer of tools and utensils from the laboratory to the kitchen. This is an interesting reverse of an old trend to use cooking utensils in the laboratory. This latter trend was widespread especially in the biological sciences, as it witnessed by, for instance, the famous "Waring blendor-experiment", where an ordinary kitchen blender of that make was used to determine the precise mechanism of transfer of genetic information between organisms (Judson, 1996).

A number of food ingredients developed for use in the food industry have slowly but steadily found their way into *haute cuisine* because of their special functional properties (Table 1). For instance, a wide range of thickeners and gelling agents is now used in the kitchen in order to develop special textures, with unusual dependence on environmental parameters such as temperature, pH and salt concentration. In addition, several specialty sugars are increasingly used in innovative dishes. For example, isomalt (1-*O*-α-D-glucopyranosyl-D-mannitol) is used, often in a mixture with glucose, to form glassy shells, flakes and other structures in dishes of which the moisture is too high to enable the use of amorphous sucrose.

In parallel, a wide range of tools known from food technology have found their way into the kitchen – generally in a miniaturized form (Table 2 – see also http://www.cookingconcepts.com/ENG/index.html). Some of these techniques, such as thermo-stated water baths have been introduced into the kitchen because scientific insights into the mechanism of cooking have emphasized the importance of maintaining a precisely controlled temperature during cooking.

Other tools have been introduced in the kitchen to enable the creation of novel textures which cannot be made using conventional kitchen utensils. For instance, by using liquid nitrogen or freeze-milling, ingredients which are soft and ductile under normal conditions can be turned into very fine, cold powders (e.g. soy sauce or foie gras snows) which are either directly served or used in the preparation of special dishes. High-speed homogenizers and blenders have also been used for this purpose, but these tools are also used to facilitate the production of more conventional dishes.

Many of the aforementioned techniques have been introduced into the kitchen through trial-and-error. For instance, *sous-vide* cooking, which is the low temperature cooking of food sealed in vacuum pouches in a laboratory-style water bath, was originally developed by trial-and-error for the preparation of *foie gras* (Haas, 2006). By cooking at low temperatures (typically 55–65 °C), meat develops a very soft, delicate texture unattainable otherwise (McGee, 2004), while losing significantly less weight during the preparation. However, also in this case, scientific insight in the mechanism is important to understand the texture development and to understand that the decrease of the loss of juices from the meat tissue[4] is not caused by the vacuum in the pouches keeping the juices in, but by the low temperatures that limit the shrinkage of the meat fibers. However, one should realize that scientific knowledge on the meat cooking process (see section above) was applied for the

[4] In case of preparation of *foie gras*, it is also the loss of fat which is reduced.

Table 1. Examples of the use of novel ingredients in haute cuisine

Ingredients	Dish	Functionality
Hydroxypropylmethyl-cellulose (2-hydroxypropyl methyl ether of cellulose, CA registry 9004-65-3)	Instant noodle soup[a]	Gels when heated
Maltodextrin (starch hydrolysates, CA registry 9050-36-6)	Lyophilized edible cocktails (i.e. gin & tonic)	Carriers of flavoring ingredients, structuring amorphous material
Lecithin (phosphatidylcholine, CA registry 8002-43-5)	Edible "airs"	Foaming agent
Sodium alginate (CA registry 9005-38-3)	Apple caviar, skinless ravioli	Thin film-mediated liquid encapsulation
Isomalt (6-*O*-α-D-glucopyranosyl -D-arabino-hexitol, CA registry 64519-82-0)	Desserts	Improved moisture-sensitivity of sugar-confectionary

[a] See Fig. 1.

sous-vide technique only after its technological conception. In addition, knowledge of microbiology turns out to be essential to guarantee a minimum level of food safety (Vijay & Snyder, 2007).

A last development that we should note here is that, from food technology, not only tools or ingredients are transferred to the gastronomic domain, but increasingly also rational and optimized working processes. Once again, the leading restaurants in the world offer examples of how a systematic (science-based) approach towards the cooking and creative processes can lead to the creation of outstanding dishes. Both The Fat Duck and elBulli have research kitchens and staff dedicated almost entirely to the creation of new dishes and techniques. At The Fat Duck, they have developed an internal computer-based encyclopedia ('duckopedia') that serves as a virtual laboratory notebook where all the procedures, results and conclusions of their culinary 'experiments' are registered. At elBulli, in order to better understand the fast evolution of their innovative cuisine, they systematically catalogued all their creations by grouping them into families. The least traditional include (a) airs, (b) cold or hot preparations using gelling agents, (c) nitros, and (d) spherification. This huge effort (there are more than 1200 creations catalogued[5]), coordinated with the opening of their science department, was motivated by the conviction that the awareness of the scientific processes involved in cooking was the basis for evolution (*The story of elBulli, 2007*).

Whereas leading chefs excel at inventing creative new dishes, they usually have a lesser inclination to look at the organization of the cooking process in a rational way. As an example, consider the restaurant where, in order to maintain the delicate texture and flavor profiles of their 'ice creams', small batches of every flavor are prepared every single day, which is an unnecessary waste of resources. This practice is the result of an accelerated rate of ice crystal growth and coarsening of the ice cream due to the way the product is handled during service (a) every time a *quenelle* of ice cream is served, the whole container is taken out of the refrigerator, leading to a series of heat shocks; and (b) the spoons/scoops, more often than not, are wet. A solution obvious to any food technologist would be to prepare a larger amount of ice cream, split it into several smaller batches, which can then be individually stored until needed. Alternatively, modern food equipment such as the Pacojet is being used to prepare on the spot small portions of very smooth 'ice cream' from previously frozen mixes.

As a result, a group of creative chefs started experimenting with the incorporation of ingredients and techniques normally used within the domain of food mass production. The most outstanding of them currently include: Ferrán Adriá (elBulli, Spain), Heston Blumenthal (The Fat Duck, UK), Pierre Gagnaire (Pierre Gagnaire, France), Andoni Aduriz (Mugaritz, Spain), Alex Atala (DOM, Brazil), Davide Scabin (Combal Zero, Italy), Grant Achatz (Alinea, USA), Claudio Aprile (Colborne Lane, Canada) and Wylie Dufresne (WD-50, USA). These chefs have adopted a cooking style that incorporates a basic understanding of science and technology and have created dishes that defy our preconceptions of what food should be and make us pay more attention to what we eat.

Impact on society

Why people choose what, how and when they eat in restaurants or at home, responds to a variety of reasons. Nutritional aspects as well as culture, religion, economics, brand, experience and personality, are all part of the equation, just as factual knowledge of food is (Gustafsson, 2004; Meiselman, 2000; Shepherd, 2001).

What are then, the most important variables for customers visiting restaurants? How do chefs strive to make restaurant meals more appealing? As society evolves, so does its eating habits and preferences, which are manifested in the large assortment of ready-to-eat foods available in supermarkets today. Is it possible to get acceptance at restaurants whose menus are sprinkled with or even brined in science? Does this sacrifice or stimulate variety and taste of what is on offer? Furthermore, suspicion arises from the use of cooking methodologies that alter the taste, consistency and appearance of food through intentional changes in its chemistry and physics (Gustafsson, 2004). These are some of the challenges science-based restaurants are currently faced with.

The last important culinary revolution occurred in the 1970s and was known as *nouvelle cuisine*. Paul Bocuse

[5] See http://www.elbulli.com/catalogo/catalogo/index.php?lang=en.

Table 2. Adaptation of techniques from food technology for kitchen use

Unit operation	Typical equipment	Importance in haute cuisine
Homogenization	High-speed blenders and homogenizers	Preparation of very fine and smooth textures, including emulsions and foams.
Heating	Induction cooking plates equipped with temperature sensors	Optimized control over cooking times and temperatures; control of phase behavior of gels and emulsions.[a]
Dehydration	Freeze- and vacuum dryers	Concentration of flavor-providing ingredients without loss of key volatiles; creation of unusual textures.[b]
Rapid freezing	Liquid nitrogen; flash-freezing stations	Unusual textural and cooling sensations in the final dish.[b]
Freeze-milling and freeze-homogenization	Low temperature homogenizers and cutters	Milling of frozen concoctions into very fine powders (i.e. snow);preparation of very fine sorbets.
Sous-vide cooking	Vacuum sealer; thermo-stated water bath	Controlled slow cooking at very low temperatures, resulting in improved meat texture and flavor.
Extraction	Pressure cooker[c]	Rapid and effective extraction during stock infusion.[d]
Concentration	Rotavap	Concentration of volatile aroma fractions.

[a] Another benefit of induction heating is that it is more energy efficient than a traditional gas-fired stove. This reduces expenses and improves the working conditions for the cook (lower temperatures).
[b] See Fig. 1.
[c] Originally, a 17th century cooking utensil used in the common kitchen for at least a century, but here differently employed.
[d] See Fig. 2.

(Lyon, France) was the most exuberant exponent of that movement, the renaissance that transformed French cooking by making it lighter (more olive oil, less butter and cream), fresher (local and seasonal produce), broader (Asian influences), and prettier (more appealing plating) (Rao, Monin, & Durand, 2003). Interestingly, to the general public (including food scientists), *nouvelle cuisine* was reduced to merely ‘small portions and beautiful presentation’ (this idea prevails even today). We believe that this is a consequence of (a) a poor communication from part of the trade, and (b) a lack of interest from the final consumer in the real meaning of food.

With this in mind, what are the chances for science-based cooking to permeate into, to be understood and hence, accepted, by our society? By applying principles pertaining, but not limited to, food chemistry and physics, architecture, interior design, psychology, industrial engineering, sensory science, and the performing arts, some chefs have been able to create dishes that make people reflect on what they eat. They re-awaken our senses by challenging (or even re-establishing) our eating paradigms – giving us people something to think and talk about.

For example, if you give people a spoonful of ‘ice cream’ and tell them that it is crab ice cream, they will react. On the other hand, if you tell them that it is frozen crab bisque, they will eat it without problem. That is because we associate the term ‘ice cream’ with desserts, and this alone creates the barrier (Blumenthal, 2003). Another elegant example was developed at elBulli: four almonds were peeled and blanched; each of them was then soaked into a different solution, which were salty, sweet, bitter and sour. The guests were asked to bite one by one (with palate cleansing with cold water in-between) in order to experience one well-known ingredient (almonds) in four of the basic tastes in their most primal state. As with many of the dishes at elBulli, reactions vary, from awe to disgust, but the essence is always the same, dining as an intellectual and sensual experience.

As stated in the Introduction, molecular gastronomy has not passed undetected by the media radar. As early as 2001, reports regarding elBulli as the Mecca, or ground zero, of culinary innovation were published in Time Magazine, Le Monde 2, The New York Times Magazine, and Toronto Life, among other publications. Media coverage can have its downfalls (Renton, 2007). Ignorant, sensationalist journalism has the power to hold back progress by fuelling public’s ‘irrational’ reaction to novel food processes or developments, such as genetically modified foods and the so-called ‘nano-foods’ (*Down on the Farm 2004*; Renton, 2007). Most critics lack the scientific background to understand the underpinning principles (notwithstanding the craftsmanship) used to develop a particular dish. Even worse, some of them have not actually eaten the dishes they are talking about. In addition, scientists draw attention with often exaggerated claims about food nanotechnology (Moraru *et al.*, 2003), and thus unduly arouse public concern (*Down on the Farm 2004*) while more important and more serious issues of food production, manufacturing and consumption (as mentioned in the Introduction) are largely left aside.

On the other hand, it also has to be acknowledged that, just like *nouvelle cuisine*, science-based cooking is at risk of generating an army of imitators who execute this type of cuisine without a real understanding of its context or rationale, which eventually could drag it into a parody (Chatto, 2006). In this context, the ‘elBulli effect’, referred to as the increasing number of restaurants adhering to the scientific-kitchen movement (Galvin, 2005) is blamed for the extensive use of technological gadgets in the kitchen which is creating a culinary atmosphere far away from what traditional cooking was meant to be. This misconception has engendered a sort of 'culinary neo-impressionism' where chefs, attempting to modernize classic recipes, have, in fact, 'de-constructed' food with not always edible outcomes (This, 2004). It is probably this thoughtless copying of a cooking style which has provoked the recent backlash of several well-known chefs and cooking researchers (Adrià *et al*., 2006) and which, as a food fad, is increasingly judged to soon disappear (Hüberli, 2007).

Parallel to the changes in the restaurant industry, society's eating habits have adjusted to a new living pace. The demand for both home cooked and restaurant quality foods made quick, delicious and convenient is now the standard sought after by an increasing number of consumers. Culinary awareness is also on the rise, and, in addition to the ever growing range of luxury cookbooks authored by famous chefs, an increasing number of books aimed at the lay public is appearing with an emphasis on the physics and chemistry of cooking (Barham, 2000; Mariën & Groenewold, 2007; This, 1993, 2006b; Vilgis, 2005).

The increase in consumer expectations leads, in the food industry, to an increase in the level of cooking skills of professionally trained chefs. Unfortunately, the necessary interface between chefs and food scientists is not straightforward principally because of the vastly different backgrounds. Combined, these two factors encourage chefs and food scientists to pursue further scientific and culinary training aiming to have better foundations for interactions. It is of interest to note that at several universities, the interaction between chefs and scientists is taken seriously and that seminars and courses in molecular gastronomy and science-driven cooking are organized.

Concluding remarks

Food science, food technology and food product development are all experiencing a radical change in focus from their traditional emphasis on model systems processes and unit operations, towards the design of products that deliver convenience, health and well-being (Aguilera, 2006). Attributes such as consumer engagement, understood as the active participation of the consumer on the structure-building process of the food prior to consumption, are also part of this development. Creative chefs have played an important role in this change of focus. As the language and the cooking utensils used by those within the *haute cuisine* and the more mundane food industry increasingly overlap, chances for cross-fertilization increase rapidly and part of the passion and creativity of chefs could indeed inspire food scientists and technologists to progressively look to food quality and perception as driving forces for their work, instead of purely rational grounds such as ingredient safety, ease of processing and cost.

As we argue throughout this paper, molecular gastronomy encompasses the understanding of fundamental processes occurring during food preparation, whereas science-based cooking is the application of this fundamental understanding (mainly through traditional food science) in *haute cuisine*. Apart from the fundamental knowledge, science-based cooking also relies on novel technology, which, as we have shown, often comprises the down-scaling of equipment from food mass production to the restaurant kitchen. The primary purpose of these novel or adapted kitchen utensils is to enable the practical realization of dishes based on the combination of an inspired idea and fundamental understanding. There is, however, not only an impact of food science on *haute cuisine*, but also *vice-versa*, as is visible in, for example, the just-published article on the localization of umami-taste in tomatoes (Oruna-Concha, Methven, Blumenthal, Young, & Mottram, 2007). The consciousness about food and its impact on human health and well-being is growing — and for us food scientists, learning from science-driven cooking (while transforming it into molecular gastronomy) could bolster our creativity. This, in turn, would be manifested in how we approach any particular food system and finally, in the way we develop foods and how we communicate knowledge on healthy and pleasurable eating to society at large.

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