Molecular Gastronomy

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1. Culinary Proverbs and Know-How

Molecular Gastronomy? This name seems unnecessarily pompous. If the discipline is only the chemical and physical exploration of culinary processes, why did we give a new name to what seems only food science? A look at the history of science below will show it.

Our discipline is born from observations that we made in the 1980s with the physicist Nicholas Kurti (1908–1998, former professor of physics in Oxford, FRS):[1] at home or in the restaurants of industrialized or developing countries, culinary activity is based on empirical traditions and not on the rational understanding of the phenomena involved in the culinary processes. This is the reason why culinary books (even modern ones) are a strange mixture of remarkable (sometimes very precise) observations and dubious, or false advice.

It is written, for example, that suckling pigs must have the head cut as soon as they are outside the oven, otherwise the crackling of the skin is lost; is it true?[2] It is said (in France) that women should not make mayonnaise[3] on "certain days of the month" (i.e. when they have their periods), otherwise the sauce fails; is it true? Anyway this idea does not hold in England; there, instead, it is said that women should not rub meat with salt on these particular days.[4] It is written that the potato slices in a potato salad are more tender if the slices are put in the dressing when they are still hot; is it true?[5] The cooks—and even certain chemists—write that, when preparing a stock, the meat should be put into cold water, otherwise "albumin coagulation" makes a crust at the surface of the meat and prevents juice losses into the water; the stock would have less taste. Is this true, as stock preparation takes as long as six hours?[6]

Up to now, we have collected more than one thousand open questions of this kind.[7] Their rational study obviously needs a multidisciplinary approach: culinary tests should be followed by interpretations of observed phenomena based on chemistry, and also physics, biology, history, and sociology. The exploration of what we call culinary proverbs, know-how, or old-wives tales is the core of molecular gastronomy.

This discipline is clearly part of food science, which has been providing food to populations for centuries. But it is a specific part, as it focuses primarily on domestic or restaurant cooking, and not on food in general. We decided to make molecular gastronomy a particular discipline, because we realized that there was a growing gap between food science and home cooking.

In the 17th or 18th centuries, this distinction could not have been made because the pioneers of food science were indeed interested in cooking: Antoine Laurent de Lavoisier (1743–1794) wanted to explore culinary processes when he measured the density of stocks,[8] Antoine Augustin Parmentier (1737–1813) proposed culinary processes as he tried to introduce potatoes in home cooking,[9] Justus von Liebig (1803–1873) and others wanted to rationalize stock preparation,[6] Eugène Chevreul (1786–1889) obtained major results in chemistry when he explored the chemical properties of fats.

"Classical" food science was (and still is, of course) very useful as, thanks to close collaboration with the food industry, it succeeded in giving enough to eat to western populations. But it slowly became more concerned with food and industrial food transformations than in domestic cooking. And as home economy is no longer taught in the schools of many countries, daily food preparation by millions of individuals is based only on recipes published in culinary books. These books, written by amateurs or professionals, but generally not by scientists, contain a lot of truths but also a lot of mistakes.

For example, it is true that a steak cooked in a pan turns brown. However, it is not true that, as said by many cooks, this browning is due to caramelization; chemists know that the browning is due to Maillard reaction, between amino acids and carbohydrates (see Figure 1),[10] and to many other reactions: just think of all the reactive groups in food molecules, and all the reaction possibilities!

It is also true that a thick sauce is formed when oil is slowly added to egg yolk while whisking. However, it is not true, as some cooks think, that the oil and the yolk mix perfectly; chemists know that the oil is divided into droplets (diameter between 0.01 to 0.1 mm), surrounded by denatured proteins and phospholipids (present in the yolk), that are packed into the small quantity of water that comes from the yolk (about 50% of the yolk).[11]

Clearly culinary activity would improve greatly if we dropped the bad and kept the good. The development of

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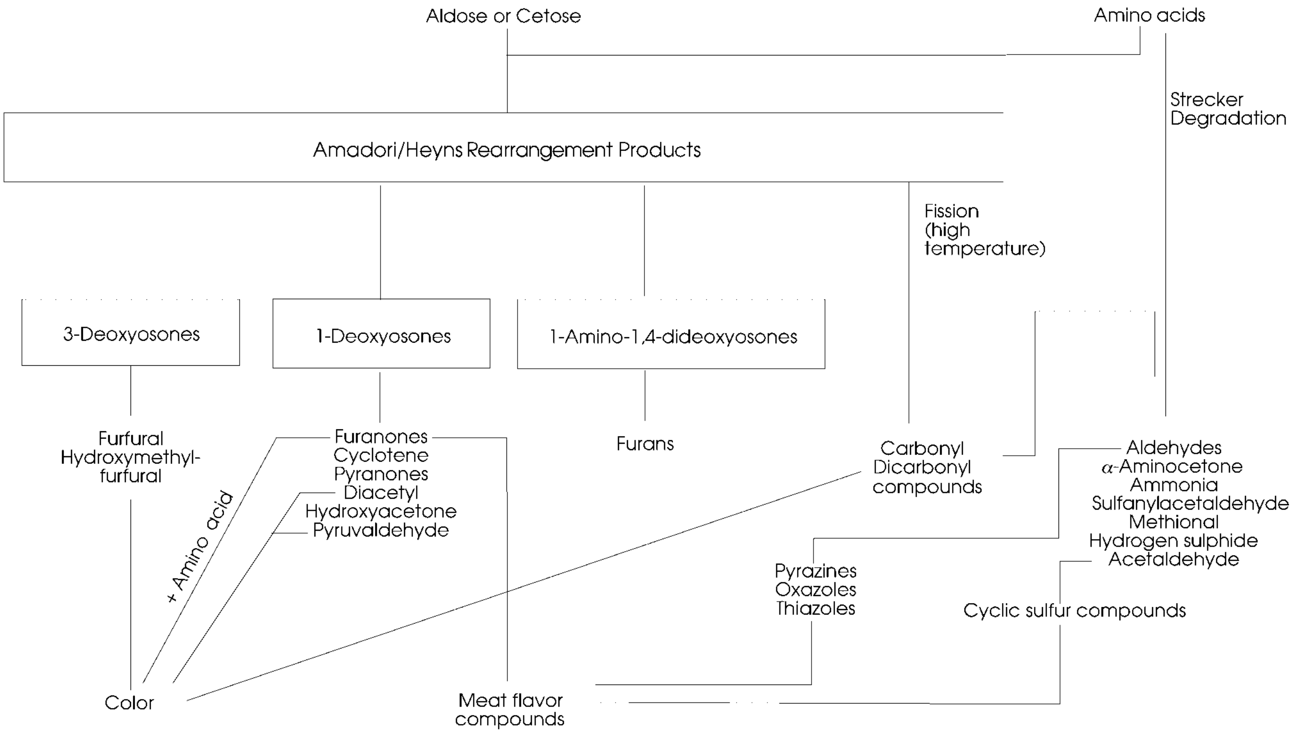

Figure 1. Pathways of formation of key flavor intermediates and products in the Maillard reaction. Osone is the former name of the 2-aldoketoses that could be prepared by the hydrolysis of osazones. Cyclotene = 2-hydroxy-3-methyl-2-cyclopenten-1-one.

culinary arts depends on this supporting work of molecular gastronomy.

A result of such explorations? There are many. For example, it has been written, with no explanation, by the French cook Auguste Escoffier (1846–1935) that red berries should not be put into copper pans or vessels coated with tin.[12] But if you just put raspberries in a pan with a tin coating, no visible change occurs. Would copper have an influence? Adding metallic copper to the fruits makes again no visible change. Of course there is a possibility that Escoffier repeated a previous false culinary indication, but molecular gastronomists have to be conscious that some cooks are very good observers. And it is known from chemistry textbooks that anthocyanidins can bind to metal ions, which results in a shift of the absorption towards the blue region of the spectrum.[13] Could metal ions inside pans be responsible for a change? The experiment of adding various metal ions to raspberries (about 0.01 g of metal salt per gram of fruit) shows that with Sn^{2+} ions raspberries turn such a dark purple color that the fruits seem spoiled or toxic![14] The conclusion is that over half a century ago the vessels were probably, by todays standards, very dirty: Escoffier's advice was probably right at Escoffier's time, but today the advice should be modified and made more precise: never put red berries in a dirty tin-coated vessel otherwise the berries turn purple.

There are many other examples of the usefulness of chemistry in the kitchen. As for culinary advice, all possibilities occur: some advice seems trustworthy, and is correct, some seems trustworthy and is wrong, some seems wrong and is correct, and some seems wrong and is wrong (e.g. the mayonnaise and the periods of women: even this has been tested!).

2. Understanding Culinary Processes and Recipes

Investigations of culinary processes or know-how lead naturally to explorations of recipes, and in some cases to proposals for rationalization and "improvements"; this is the second aim of molecular gastronomy.

Let us examine one example: cheese soufflés. The basic ingredients are a viscous preparation, such as a béchamel sauce (made from melted butter, flour, and milk) to which, when at room temperature (or higher, but below 68 °C), grated cheese, egg yolks, and whisked egg whites are added.[15] The swelling of soufflés during cooking has been attributed to thermal dilatation of air bubbles from the whipped egg whites[16] but this model is clearly defective: using the data from measurements of the temperature and the pressure inside a soufflé (see Figures 2a and b), the ideal gas law predicts a maximum swelling of 20%, however, the volume of soufflés can double or more! Indeed the main effect is water evaporation: in contact with the ramekin walls (the walls of the container), the water (mainly from the milk, which is about 88% water w/w, and from the yolks)[17] inside the soufflé base is heated to a temperature equal to the inside temperature of the oven, that is, 180 °C.[18] The vapor formed at the top of the soufflé is lost to the oven, but the vapor formed on the bottom of the ramekin pushes the other layers upward. This model thus suggests that soufflés should be heated preferably on the bottom.

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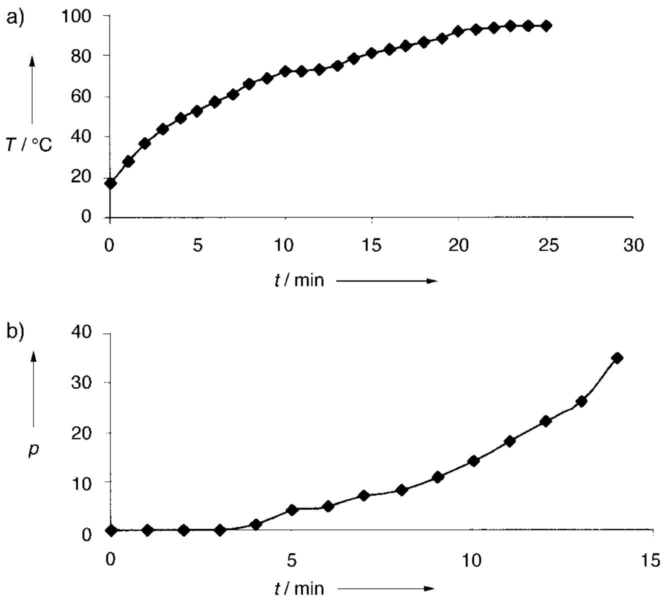

Figure 2. a) The temperature inside a soufflé was measured for 25 min with a thermocouple anchored to the soufflé dish (20 cm diameter and 10 cm deep) with its tip 2 cm from the surface of the mixture at the start. The dish was placed in the preheated oven (180 °C), and the soufflé was found to be perfectly cooked when removed from the oven a few minutes after the temperature T rose to about 65 – 70 °C. Of course, the temperature is always lower than 100 °C (otherwise, the soufflé would have been transformed into a crackling pancake). b) The pressure P [mm oil] inside a soufflé measured during the time t the soufflé was cooked. The pressure was measured using a manometer put at the center of a ramekin.

Figure 3. These two cheese soufflés have the same composition, but in the one on the right, the egg whites were much firmer, hence the difference in final volume.

All soufflé recipes emphasize that it is important to mix the whipped egg white thoroughly with the cheese béchamel so that no blobs of egg white remain; the folding in must be done gently so as to prevent the air bubbles from bursting or coalescing. But recipes do not agree about the firmness of the whisked egg white. After preliminary experiments, carried out in 1993,[19] we recently measured the effect that the firmness of egg whites has on soufflé preparation. We divided a cheese béchamel into two equal parts, and added to both parts foams of different firmness made from the same egg whites: in the first part, the whites were whisked until the first soft peaks were observed; in the second part the egg whites were so firm that an egg in its shell (62 g) could stand on top of them without sinking. The soufflés were placed in identical ramekins 15 cm diameter, 10 cm deep, filled up to 8 cm. They were cooked in the same oven (De Dietrich P5447), at the same time, and the volume of the two soufflés was compared (Figure 3).

There are two reasons for the differences. The first is a result of the difference in initial volume: differently whipped egg whites have different volumes. Second it is observed that when a soufflé with soft egg whites is cooked vapor bubbles go up, through the viscous soufflé preparation and burst at the upper surface of the soufflé; however, in the soufflé with firm egg whites, the firmness of the foam prevents (partially) the bubble from going through the soufflé preparation and the upper layers are pushed upwards.

Finally this model and a simple measurement shows that huge improvements in soufflé making are possible: a 345 g soufflé cooked in a traditional way looses about 10 g of water during cooking, which means that a volume of about 10 L could be obtained if the upper surface were made vapor proof!

This example shows how modeling leads to improvement of traditional recipes. Another example shows that modeling leads also to a rationalization of recipes. Many cooks begin their sauce preparation by "reducing dry" shallots with wine (in other words, complete evaporation of the wine).[20] Why do they boil and evaporate completely a costly liquid? Experiments with various wines show that different results are possible: because of composition differences of grapes and different wine-making methods, some wine have more non-evaporable compounds (glucose, fructose...) than others,[21] and boiling wines leads either to cooked shallots in an empty pan or in a thick brown syrup. There are many reasons for the formation of this viscous liquid. First, wine contains compounds that do not evaporate in the conditions of boiling: the ash content of wines is about 2 $g L^{-1}$.[22] Second, amino acids (about 200 – 800 $mg L^{-1}$) can react through Maillard reactions with reducing sugars (the carbohydrates (0.03 – 0.5 %) present in fully fermented wine are small amounts of the hexoses, glucose and fructose, and of nonfermentable pentoses, such as arabinose, rhamnose, xylose; incompletely fermented wines contain higher concentrations of both hexoses, but substantially more of the slower fermenting fructose). Third, carbohydrates, such as glucose and other sugars can make caramels,[23] as the temperature reached in white wine that is boiled until the volume is 1 % of the initial volume is as high as 130 °C.[24] Finally, a sensory comparison of shallots cooked under five sets of conditions (first done during the Second International Workshop on Molecular Gastronomy, Erice, Italy, may 1995) suggests that caramelization of glucose and fructose could give a better base for a good béarnaise than the product made by boiling an expensive wine (and evaporating most of its flavors); the conditions were: 1) with pure water, 2) with water and glucose, 3) with a poor dry wine, 4) with the same wine plus 10 $g L^{-1}$ of glucose or fructose, 5) with a good wine, such as a Noilly.

This result has culinary significance: a cook who wants to make a sauce and does not know in advance the composition of the wine he or she is using could cook some glucose or fructose with water and shallots,[25] thus making a caramel that will give a strong taste and flavor to the sauce.

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This idea was applied by the three-star cook Pierre Gagnaire (Restaurant Pierre Gagnaire, Paris, France) in one dish of the "Science and Cooking" menu that was served in March 2000 at the French Academy of Sciences, during a lecture on molecular gastronomy ("the proof is in the pudding, isn't it?"). Of course wine boiling should be investigated further to give new ideas of the chemistry that could be used as a start for other "chemically modified béarnaise".

3. New Products, New Tools, New Methods

There is room for much improvement in culinary practices. New products, new tools, and new methods could be usefully introduced into the kitchen.

Let us consider first the question of ingredients. Cooks are trained at using spices and herbs in their kitchen; in the laboratory, chemists also use, on a daily basis, fragrant products such as hexanal, *trans*-hexenal, 1-hexanol, 1-octen-3-ol, or benzyl *trans*-2-methylbutenoate. Could we use these chemicals in the kitchen? Very easily. If you cannot afford a very good olive oil, try hexanal in poor oil! If you do not have wild mushrooms, put some 1-octen-3-ol or benzyl *trans*-2-methylbutenoate in your dishes (these two compounds have, at the appropriate doses, a wonderful mushroom or forest taste). If you want to make some pastry with a violet flavor, use beta-ionone. If you cannot afford the price of a very good whisky, try adding some drops of vanillin solution[26] to a cheap whisky and you will see how the whisky becomes "round": the idea is only to replace the slow reactions that take place in the barrels, where ethanol extracts some lignin from the wood and reacts with it, forming various aldehydes (sinapic (4-hydroxy-3,5-dimethoxycinaldehyde), vanillic (4-hydroxy-3-methoxybenzaldehyde), syringic (4-hydroxy-3,5-dimethoxybenzaldehyde).[27] There are lots of chemicals that could be used to modify the taste of the dishes, and some others could be useful in managing texture.

Hence a question: how is it that domestic cooks generally fear the additives that are used by the food industry? Probably they fear what they do not know: if chemists have the feeling that these products are safe and useful they should ask that these compounds should be presented to the public, as well as their effects. And it would be probably a good idea to sell these products to the domestic cooks, so that they could be used to them: instead of using a whole lemon to prevent apple slices browning as a result of polyphenoloxidase enzymes, some drops of a ascorbic acid solution of the same concentration as lemon juice is as efficient and cheaper.

Cooks could also use new tools. Chemistry laboratories are full of well-designed hardware that could improve culinary preparations. If you filter with a Büchner funnel, for example, you will get a much clearer stock than if you use a culinary sieve. A glass column over a fritted glass makes easy foams, by injection of air under the fritted glass. Ultrasound boxes can make emulsions in seconds. Separating funnels can be used to separate aromatic (fragrant) molecules: if oil, water, and a tasty ingredient (mushroom, spice) are put in a bulb, the molecules responsible for flavor will be separated according to their different solubility in the two liquids, so that the cook will get two tastes from one. A reflux column, also, could retain the flavors over the pans better than lids.[28]

Eventually cooks will have to use new methods if they use new tools and new ingredients. But we have time as change will probably be very slow: in 1894, during a discourse at a banquet of the chemical industry, the French chemist Marcelin Berthelot envisioned a future where agriculture and cooking have disappeared, because of progress in chemistry; pills, he proposed, would have replaced dishes.[29] One century later, we still cook choucroute, soufflés, béarnaise, foie gras, and grilled lobsters. However, in our times, important questions of interactions of health and food arise. To deal with these complicated issues, one cannot only analyze foods from the toxicological or nutritional point of view: a detailed analysis of practices is important to know which compounds can be found in the real diet of the public.

For example, the public is seldom able to cook meat safely with a fire: nowadays in barbecues, the meat is most frequently placed directly over the fire, at a distance such that the amount of benzo[α]pyrenes—a carcinogenic compound the concentration of which should not exceed 1 $\mu g\,kg^{-1}$ end product[30]—is as high as 10 $\mu g\,kg^{-1}$![31] But if the meat is placed 5 cm higher, the benzo[α]pyrene content is reduced to about 0.7 $\mu g\,kg^{-1}$, and if the meat is placed before the fire instead of above, as was recommended by most old culinary books, the quantity of these compounds is reduced to 0.1 $\mu g\,kg^{-1}$, which is the natural content of the product.

4. Inventing New Dishes

All the studies in molecular gastronomy easily lead to new dishes. How successful will they be? One way to have them used would be to prepare them with the aid of only tools or ingredients already present in the kitchens. For example, the separating funnel used to separate flavors can be replaced by a simple jam pot with a lid (but what a pity!).

Another example: the analysis of the preparation of Chantilly cream suggests a transposition of the process.[32] In its principle, the process is the foaming of an emulsion (cream is an emulsion, and whipped cream is an hybrid system, both an emulsion and a foam; Chantilly cream is whipped cream with sugar). How can we make the transposition? Let us remark first that, if we heat chocolate and water together, we get a chocolate emulsion that could be named "chocolate béarnaise", because the process is the same as a classical béarnaise preparation: water is substituted for vinegar, lecithin present in the chocolate for egg proteins, and cocoa butter for milk butter. Whipping this chocolate béarnaise (first put the pan on ice cubes for faster results) finally generates foam. This foam is brown, but of a lighter color than the original emulsion. Its texture is the same as whipped cream, if the proportions are correct, that is, about 225 g of chocolate for 200 mL of water (the exact proportions depends on the kind of chocolate used). We named this foam "Chantilly chocolate".

The same process can be applied to other products containing a large amount of lipids. For example, one can make "Reblochon Chantilly" with Reblochon cheese, "Roquefort Chantilly" with Roquefort cheese, "Munster Chan-

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tilly" with Munster cheese or even a foie gras chantilly with foie gras.

Another more recent example shows how pure science can lead to new dishes. Let us begin with the concept of emulsion. The most famous emulsion, in the kitchen, is the mayonnaise, a sauce traditionally made with some water (from the egg yolk, from the vinegar, and from the mustard if used), surfactants (egg yolk proteins, but also egg phospholipids), and oil.

Let us first note that a "mayonnaise without yolk" can be made with egg white: while whipping an egg white, add oil.[33] Another variation of this theme is the "mayonnaise without egg": heat some "water" (or any water solution; it can be a very good lobster "fond"), dissolve half a gelatine sheet and add some oil as you whip the mixture. A white emulsion is formed that slowly jellifies. Under the microscope, the oil droplets fuse locally, and finally an emulsion is trapped into a gel (see Figure 4). This gel is a result of gelatine molecules that form segments of triple helices.[34–36] Now consider the general phenomenon that took place: an emulsion was trapped into a physical gel. Could the same phenomenon be observed but with a chemical gel? The test is easy: take the mayonnaise with egg white, and put it in the microwave oven for one or two minutes; the heating generates a semi-solid mass, where the emulsion can still be seen under the microscope and characterized by small angle X-ray diffraction.

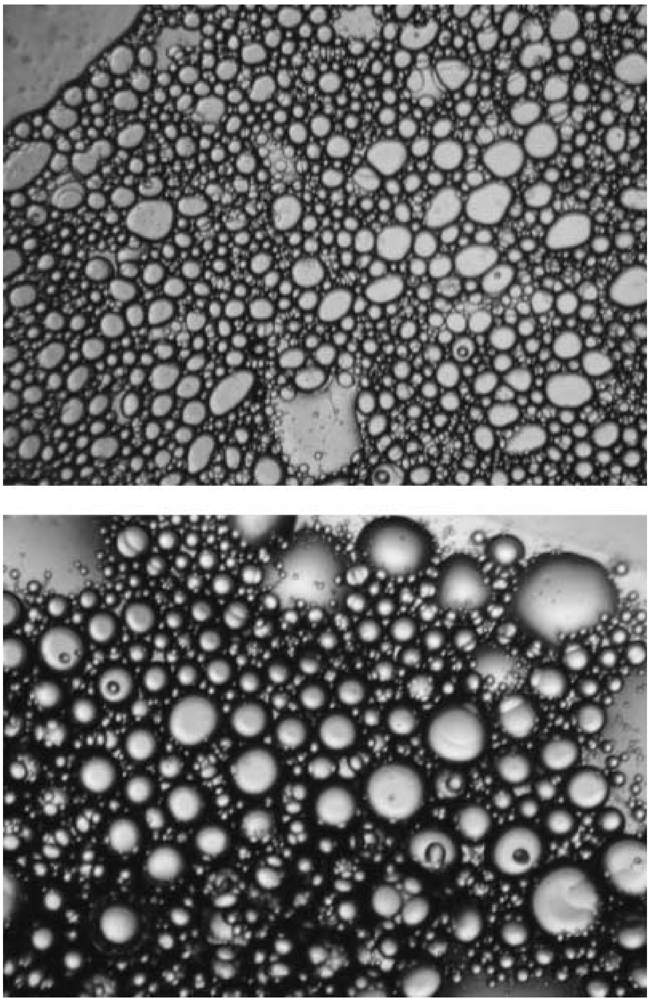

Figure 4. Top: The microscopic structure of an emulsion made from water, gelatine and oil, immediately after the preparation. Bottom: some minutes after preparation (depending on the process and environment) the emulsion gellifies. The result is an emulsion trapped into a physical gel.

You think that this oil dispersion is not very pleasant on your table? Replace the oil with melted chocolate, and you get a chocolate cake in one minute: of interest is the very tender texture, because the chocolate is melted, and the powerful aroma, because of the high temperature of the chocolate. I propose to name this dish a "chocolate dispersion" because chocolate is dispersed twice: once in the emulsion, and one in the chemical gel.[37]

5. *Science and the Citizen*

All the four first aims of molecular gastronomy are intended to benefit the lay person that cooks. He or she is gaining from the results of the explorations or innovations based on the molecular understanding of culinary processes. He or she is being presented with new methods, tools, or ingredients. He or she is being shown that sciences are wonderful intellectual tools to understand the world we live in. The final aim of molecular gastronomy is to end the bad public image that sciences have too often, mostly during food crises (epidemics of mad cow disease, affairs of dioxin-contaminated chickens).

If we can show that cooking is just chemistry and physics, the public will have to conclude that sciences are not bad, in fact will be able to make useful distinctions between science, the marvelous intellectual activity, and the applications of science, the responsibility of which rests with those who use it.

[1] H. This, *Bull. Soc. Fr. Phys.* **1999**, *5*, 119.
[2] H. This, *Manger magique*, Revue Autrement, Paris, **1996**.
[3] Auguste Escoffier (*Le guide culinaire*, Flammarion, Paris, **1921**, p. 48) describes the preparation of the mayonnaise sauce as follows: 1. Broyer au fouet six jaunes d'oeufs dont le germe doit être retiré; un litre d'huile, 10 grammes de sel, un gramme de poivre blanc; une cuillèrée et demie de vinaigre, ou l'equivalent de jus de citron si on veut l'obtenir très blanche. 2. Ajouter l'huile goutte à goutte pour commencer, et al laisser tomber ensuite en petit filet dans la sauce quand celle-ci commence à se lier. 3. Rompre le corps de la sauce de temps en temps par addition de vinaigre ou de jus de citron. 4. Additionner finalement la sauce de 3 cuillerees d'eau bouillante; ce qui a pour but d'en assurer la cohesion et de prevenir sa decomposition si elle doit etre tenue en reserve. English translation: with a whisk, "grind" six egg yolks whose germ has to be taken away, plus salt (10 grams), pepper (one gram), half a tea spoon of vinegar; add one liter of oil drop by drop in the beginning, and faster later, when the sauce has some firmness; add some vinegar or lemon juice from time to time, and finally add 3 spoons of boiling water that will increase the cohesion and prevent the decomposition of the sauce if it is to be kept for some time.
[4] Nicholas Kurti, personal communication.
[5] B. Loiseau, *Trucs, astuces et tours de main*, Hachette, Paris, **1990**, p. 183.
[6] H. This, G. Bram, *C. R. Acad. Sci. Ser. IIc* **1998**, *11*, 675–680.
[7] H. This, *Le programme de la Gastronomie moléculaire en 2000*, document présenté pour l'Habilitation à diriger des recherches, University Paris-Sud, Orsay, June 20, **2000**.
[8] The chapter describing the experiments of November 1783: "*Mémoire sur le degré de force que doit avoir le bouillon, sur sa pesanteur*

spécifique et sur la quantité de matière gélatineuse solide qu'il contient": "On the strength of stock, on its density and on the quantity of solid gelantinous matter it contains." A. L. de Lavoisier, *Oeuvres complètes, Vol. III*, Imprimerie Nationale, Paris, **1865**, pp. 563–575.

[9] A. Balland, *La chimie alimentaire dans l'oeuvre de Parmentier*, Baillère, Paris, **1902**.

[10] F. Ledl, E. Schleicher, *Angew. Chem.* **1990**, *102*, 597–626; *Angew. Chem. Int. Ed. Engl.* **1990**, *29*, 565–594.

[11] H. D. Belitz, W. Grosch, *Food Chemistry*, 2nd ed., Springer, Heidelberg, **1999**, p. 513–526.

[12] A. Escoffier, *Guide culinaire*, Flammarion, Paris, **1921**.

[13] H. D. Belitz, W. Grosch, *Food Chemistry*, 2nd ed., Springer, Heidelberg, **1999**, p. 772

[14] H. This, *Thèse de doctorat ès sciences*, University Paris VI, **1996**.

[15] In all our experiments, we used the same proportions: a "roux" was prepared with flour (75 g), butter (75 g); the mixture was heated up to 100 °C, and, when a homogeneous paste was obtained, milk (400 mL) was added; after this mixture thickened by slow cooking (the thickness is because of starch granules swelling when they absorb water), after the mixture had cooled to room temperature grated cheese (50 g) and four egg yolks were added. The four egg whites where whipped separately and thoroughly mixed into the cheese béchamel.

[16] *Larousse gastronomique*, Larousse, Paris, **1982**.

[17] J. C.Favier, J. Ireland-Ripert, C. Toque, M. Feinberg, *Répertoire général des aliments, tables de composition*, Technique et Documentation, Paris, **1995**.

[18] The time after which the temperature of the soufflé is equal to the temperature of the oven depends of course on the type of ramekin—metal, ceramic—and on its thickness.

[19] A. M. Blanchet, TF1 News 13.00, December 23, **1993**.

[20] A. Daguin, *Le nouveau cuisinier gascon*, Stock, Paris, **1981**.

[21] H. D. Belitz, W. Grosch, *Food Chemistry*, 2nd ed., Springer, Heidelberg, **1999**, pp. 843–866.

[22] L. Usseglio-Tomasset, *Chimica Enologica*, Edizione AEB, Milano, **1978**.

[23] J. Defaye, J. M. Garcia Fernandez, *Zuckerindustrie* **1995**, *120*, 1.

[24] For this measurement, we used a low price white wine, "Special Marée blanc de blancs" from Les Celliers de Haute Croix, Prabecq (France).

[25] For example fructose (10 g) in water (5 mL).

[26] In many lectures, we used "Extrait de vanille liquide", *Vahiné*, a product sold in every French supermarket, but any other similar product could be used instead; (you should not be able to smell the vanillin in this experiment; adjust your particular vanillin solution so that the concentration in vanillin is just lower than the smell perception threshold.

[27] J. L. Puech, M. Moutounet, *J. Assoc. Off. Anal. Chem.* **1988**, *71*, 512–514.

[28] H. This, *Actual. Chim.* **1995**, *6*, 42–46.

[29] M. Berthelot, *En l'an 2000*, discourse of the banquet for the Chambre syndicale des produits chimiques, April 5, **1894**.

[30] H. D. Belitz, W. Grosch, *Food Chemistry*, 2nd ed., Springer, Heidelberg, **1999** p. 461.

[31] http://www.arte-tv.com/hebdo/archimed/20000314/dtext/sujet3.html; in these experiments, J. Tulliez used Toulouse sausages.

[32] H. This, *Pour la Science* **1996**, *230*, 20.

[33] H. This, *Révélations gastronomiques*, Belin, Paris, **1995**.

[34] M. Djabourov, *Contemp. Phys.* **1988**, *29*, 273–297.

[35] M. Djabourov, J. Leblond, P. Papon, *J. Phys.* **1988**, *49*, 319–332.

[36] M. Djabourov, J. Leblond, P. Papon, *J. Phys.* **1988**, *49*, 333–343.

[37] H. This, *Pour la Science* **2001**, *280*, 8.

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