

Molecular Gastronomy, a Scientific Look at Cooking

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CONSPECTUS

Food preparation is such a routine activity that we often do not question the process. For example, why do we cook as we do? Why do we eat certain foods and avoid other perfectly edible ingredients? To help answer these questions, it is extremely important to study the chemical changes that food undergoes during preparation; even simply cutting a vegetable can lead to enzymatic reactions.

For many years, these molecular transformations were neglected by the food science field. In 1988, the scientific discipline called “molecular gastronomy” was created, and the field is now developing in many countries. Its many applications fall into two categories. First, there are technology applications for restaurants, for homes, or even for the food industry. In particular, molecular gastronomy has led to “molecular cooking”, a way of food preparation that uses “new” tools, ingredients, and methods. According to a British culinary magazine, the three “top chefs” of the world employ elements of molecular cooking. Second, there are educational applications of molecular gastronomy: new insights into the culinary processes have led to new culinary curricula for chefs in many countries such as France, Canada, Italy, and Finland, as well as educational programs in schools.

In this Account, we focus on science, explain why molecular gastronomy had to be created, and consider its tools, concepts, and results. Within the field, conceptual tools have been developed in order to make the necessary studies. The emphasis is on two important parts of recipes: culinary definitions (describing the objective of recipes) and culinary “precisions” (information that includes old wives’ tales, methods, tips, and proverbs, for example). As for any science, the main objective of molecular gastronomy is, of course, the discovery of new phenomena and new mechanisms. This explains why culinary precisions are so important: cooks of the past could see, but not interpret, phenomena that awaited scientific studies. For French cuisine alone, more than 25 000 culinary precisions have been collected since 1980.

The study of the organization of dishes was improved by the introduction of a formalism called “complex disperse systems/nonperiodical organization of space” (CDS/NPOS). CDS describes the colloidal materials from which the parts of a dish are made; NPOS provides an overall description of a dish. This formalism has proven useful for the study of both scientific (examining phenomena to arrive at a mechanism) and technological (using the results of science to improve technique) applications. For example, it can be used to describe the physical structure of dishes (science) but also to examine the characteristics of classical French sauces (technology).

Many questions still remain in the field of molecular gastronomy. For example, one “Holy Grail” of the field is the prediction of physical, biological, chemical, and organoleptic properties of systems from their CDS/NPOS formula. Another issue to be worked out is the relationship between compound migration in food and chemical modifications of those migrating compounds. These questions will likely keep scientists busy in the near future.



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Introduction

Many chemical sciences are based on a scientific study of “chemical arts”,¹ and famous scientists frequently built scientific knowledge from the study of phenomena occurring during daily pro-

cesses: Antoine-Laurent de Lavoisier published in 1783 the result of his studies of meat stock,² Michael Faraday studied steel alloys with James Stoddart in 1830,³ and William Henry Perkin obtained mauvein in 1855 while trying to make

quinine from aniline. Frequently science was mixed with technology ("applying scientific results to the improvement of technique"),⁴ as can be seen easily in Lavoisier's article on meat stock: "In 1730, M. Geoffroy showed a work on the same topic, but... his aim was different from mine. This chemist wanted to know, through chemical analysis, the nature of the nutritious substances, from animal or from plants.... My aim, on the contrary, was to get purely practical knowledge and to determine... what [meat] can give to a determined quantity of water after some long boiling process."² Indeed Lavoisier was studying meat stock because he was asked by the king to determine how much meat was needed for Paris hospitals.

Since these early works, "food sciences" developed considerably, so it is legitimate to ask whether Molecular Gastronomy was needed. Here we shall explain why the discipline was created, and we shall consider tools, concepts, and results.

The Issue of Food Sciences

What is "food"? In his article on meat stock, Lavoisier wrote: "One cannot avoid being surprised, each time one considers the most familiar objects, the most simple things, to see how our ideas are often vague and uncertain, and how, in consequence, it is important to fix them by experiments and by facts."

Food is indeed one such "familiar object", for which we do not ask enough questions: Why do we cook as we do? Why do we eat certain food ingredients and avoid others, even if they are edible? Dictionaries define food as "any substance that can give to living beings the elements necessary for their growth or for their preservation."⁴ Accordingly, raw plant or animal tissues should be considered as food along with elaborated dishes, but this is confusing, because human beings very seldom eat nontransformed products; raw materials are transformed, so chemical and physical changes determine the final composition of all food as well as its bioactivity (sensory, nutritional, toxic, and other effects): plant or animal tissues are at least washed and cut, not to mention thermal processing. Generally "cooks" (even in the food industry, as the difference between home and factories is generally a question of scale) devote themselves to cleaning microbiologically the food ingredients and change their consistency and flavor. Even for a simple carrot salad, there is a big difference between the root in the field and what we eat, that is, grated carrots in a plate, because cutting the tissue causes enzymatic reactions or because compounds can be exchanged between the dressing and the plant tissue. Accordingly "reagents" and "products" of "culinary transformations" should not be called



FIGURE 1. This "fibré" has the structure of meat, with hollow cylinders (green beans that were pierced) full of a gel (here, based on a special colloidal system called foie gras Chantilly). Its formula in the NPOS formalism is $(D_1@D_1)/D_3$. Reproduced by permission of Hervé This.

indistinctly food: we should distinguish between "ingredients" and "dishes".

When we consider Molecular Gastronomy, it is also useful to distinguish science on one hand and technology on the other, because they "do not meet". In particular, Louis Pasteur, who did both science and technology,⁵ explained that "applied sciences" cannot exist (contrary to applications of science), because science is looking for mechanisms of phenomena using the experimental (also called hypothetico-deductive) method: if applications are the focus, then the activity is no longer science, and if the activity is science, applications are not considered, because mechanisms are the sole concern.

Let us say it differently: technology uses results from science to improve technique or craft, whereas science starts from phenomena to arrive at mechanisms. This led us to consider that there is a difference between the science of culinary transformations and the technology of food transformations. The technology of food (or culinary) transformations is not the scientific study of phenomena occurring during culinary transformations, what we named "Molecular Gastronomy" in 1988.

Molecular Gastronomy Is 20 Years Old

As considered before, many phenomena occurring during culinary transformations were studied before the paradigm of Molecular Gastronomy was introduced. However it is a fact that in the 1980s, food science neglected culinary processes. Textbooks such as the classic *Food Chemistry*⁶ contained almost nothing on culinary transformation; for example, even in the 1999 edition, most of the chapter on meat described



FIGURE 2. The two founders of Molecular Gastronomy celebrating the first Ph.D. of the discipline in 1996. Photograph courtesy of P. This.

either meat composition and structure or industrial products (sausages, meat extracts, etc.), but less than 0.5% was describing “culinary phenomena” (meat shrinkage during heating because of collagen denaturation); in the same textbook, the chapter on wine contains nothing about the chemistry of cooking wine!

Probably because culinary transformations are complex and because the food industry had first to produce enough to feed populations, food science had drifted toward the science of ingredients on one hand and toward technological questions on the other hand, neglecting phenomena that occur when cooking cassoulet, goulash, hollandaise sauce, etc. This is why the late Nicholas Kurti (1908–1998) and I⁷ decided in March 1988 that a “new discipline” had to be created.

The situation at that time was about the same as that for molecular biology some decades before. “The term “Molecular Biology” was first used by Warren Weaver in 1938 to describe certain programs funded by the Rockefeller Foundation, where it simply meant the application of techniques developed in the physical sciences to investigate life processes.”⁸ This is why the name “Molecular and Physical Gastronomy” was chosen. The choice of “Gastronomy” was obvious because it means indeed “intelligent knowledge of whatever concerns man’s nourishment.”⁹ The full name “Molecular and Physical Gastronomy” was used for the first international workshops that we organized, and even for a Ph.D. that I was asked to defend in 1996 (Figure 2), but it was later shortened.¹⁰

The interest of this new field was and remains scientifically clear: if one wants to discover new phenomena, the exploration of a new field is perhaps a good choice. Of course, as always when new knowledge is produced, there is the possibility to make important technological applications, and indeed since 2000, one application of knowledge obtained by Molecular Gastronomy or food science is proposed every

month (frequently, names of famous chemists of the past are given to new “dishes”) (Figure 4).¹¹

However, the initial program of the discipline was mistakenly mixing science and technology.¹² It was soon analyzed that recipes have three main parts. First a “definition”, defining the “objective”, is often mixed with “culinary precisions”, that is, useful technical information added to the definition but that is nonetheless not absolutely needed to make the dish; culinary precisions include old wives tales, proverbs, tips, methods, etc. A third part contains nontechnical information; its analysis could give useful sociological and anthropological information. But “cooking” also involves an artistic activity: a cheese soufflé is not cooking if the flavor is such that it is not eaten, but flavor is a question of art, not of technique. And finally a “social link” component is also very important: a “good” soufflé is not good if it is thrown at the face of the guests. All this led to the proposal of a new program for Molecular Gastronomy: (1) model “culinary definitions”; (2) collect and test “culinary precisions”; (3) explore (scientifically) the art component of cooking; (4) explore (scientifically) the “social link” of cooking.

With this clearer program, what is the most rational way of exploring the field of culinary phenomena? Because culinary transformations are dynamic processes involving systems with structure,¹³ it is natural to make complementary and time course descriptions of the physical state on one hand and of the chemical state on the other. The “bioactivity” of such systems is later considered, as the result of the two.

Questions of Physical Changes

Let us focus first on the question of structure. A CDS (complex disperse system) formalism was introduced in 2002 for the description of the “material” from which the parts of dishes are made. Later, in 2003, another formalism called NPOS (nonperiodical organization of space) was proposed for the overall description of dishes; recently it was recognized that these two formalisms could be mixed into a more comprehensive description called CDS/NPOS, which could even describe dynamic phenomena.

As with other formulated products such as paints, cosmetics, or drugs, dishes often include colloids,¹⁴ that is, material systems that contain molecules or molecular associations in which one dimension is on the order of 1 nm to 1 μm or systems that include discontinuities with distances of this order of magnitude. Such systems are frequent in food, in particular because plant and animal tissues are formally gels, because they are made of cells whose smallest dimension is on the order of 1 μm ; most sauces are also colloids.

When complex systems are considered (for example, multiple emulsions), physics generally focused on the interface, that is, local descriptions of macroscopic systems, or on some thermodynamic properties.¹⁵ However this has two main disadvantages. First the global description of the systems is lost. Then, in more complex but familiar systems, the denominations are rather complex. For example, potatoes are mainly “suspensions dispersed in gels”, since amyloplasts (solid starch granules of less than 20 μm)¹⁶ are dispersed in the cytoplasm of cells (water or gel, depending on the description level), this phase being itself dispersed in the network of cell walls responsible for the “solid” behavior of the whole potato.

This is why the same idea as that proposed by Lavoisier for chemistry¹⁷ was introduced. Lavoisier wanted to facilitate the description of molecules and chemical processes: “In order... give directly, in one sight, the result of what goes on in metal dissolutions, I have constructed a special kind of formulas that look like algebra but that does not have the same purpose;... I invite you to consider that these formulae are notations whose object is to ease the operations of the mind.”

The same usefulness applies to the CDS formalism,¹⁸ but the physical nature rather than the chemical composition is considered. For food, symbols G, O, W, and S, respectively, stand for “gas”, “oil”, “water”, and “solid”. The distribution of the various phases can be described by operators. As recommended by the IUPAC, the “@” symbol describes inclusion: for example, O@W applies to some oil phase included into a water phase. Physical chemistry also uses traditionally the symbol “/” to describe the random dispersion of a large number of structures of one phase into another phase, such as in W/O (emulsion). And because many phases can be dispersed into another, the “+” symbol is needed, such as in (G+O)/W for describing aerated emulsions, with gas, G, and oil, O, dispersed in the continuous water phase, W. For operators as for phases, other symbols could be added if necessary to fully describe complex disperse systems, but up to now, no addition was really needed.

Some rules give more coherence to the formalism.

- Some simplifications have to be done. For example, W/W sometimes reduces to W.
- The various components of a sum (+ symbol) must be written in alphabetical order. For example, custard (it is not an emulsion O/W, contrary to what was published in culinary textbooks) is a dispersion in water of oil droplets, O (from milk), air bubbles, G (introduced by whipping), and small solid particles, S (due to egg coagulation); it should be described as (G+O+S)/W (Figure 3).

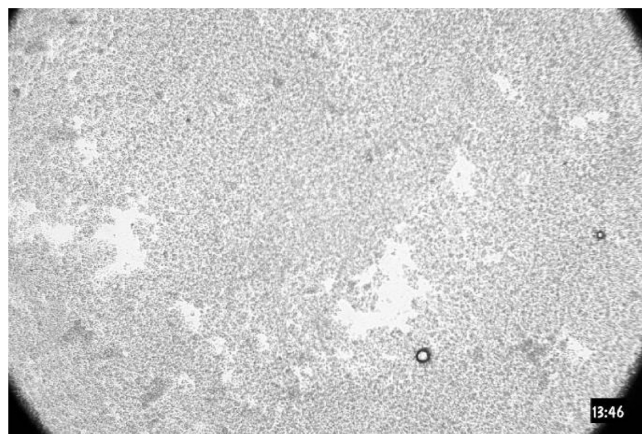
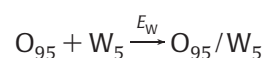


FIGURE 3. The CDS formula of custard is (G+O+S)/W, as it is indeed a foamed colloid whose consistency is mainly due to egg protein coagulation. Reproduced by permission of Hervé This.

- Repetitions can be described by exponents. For example, egg yolks are made of concentric layers called light and deep yolk, deposited, respectively, during the day and the night; their number is about 9.¹⁹ As Because each layer is composed of granules (S) dispersed into a plasma (W), the full yolk could be described as (S/W)^{@9}.

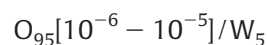
The basic formalism can be increased to give more precise descriptions of systems.

- For example, the quantity of each phase can be added as a subscript. For example, O₉₅/W₅ would describe oil into water emulsion at the limit of failure, with 95 g of oil dispersed in 5 g of water. Using such subscripts, conservation laws can be used. For example, the overall making of a mayonnaise could be written as



where E_W stands for mechanical energy.

- Because the size of structures is important, it can be given inside brackets, such as in the emulsion formula



where the powers of ten indicate the minimum and maximum radii of dispersed oil droplets (international units).

- At the end of formulas, the size of the smallest structures considered can be given inside brackets as a “size cut-off”: in a mayonnaise formula such as O[10^{-5} , 10^{-4}]/W[$>10^{-5}$], the last brackets shows that the structures considered are larger than 10^{-5} m; that is, granules of egg yolk are not taken into account because their size is between 0.3 and 2 μm .

Until now, all food systems considered could be described using this formalism.²⁰ But do all formulas correspond to pos-

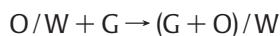
sible systems? This question is difficult because many disperse systems are only metastable. In emulsions or in suspensions, for example, creaming and sedimentation rates depend on the size of structures or on the nature of surfactants, but these systems are not stable. It is therefore a question of smartness to make these systems, or of kinetics, not of thermodynamics.

Describing objects is only a first step; the main point is studying the mechanisms of transformations. For example, for mayonnaise sauce with regular addition of oil starting from one egg yolk and one tablespoon of vinegar:

$$O_{(6+374t),t=0\dots 1}W_{20}$$

Here, t is used as a dynamic parameter (it could be time or energy), and the constants in indexes are chosen so that when the process is finished, the limit of emulsion stability (oil/water, 95/5, w/w) is reached.

Another example would be the foaming of an emulsion, which can be described as



Again kinetic parameters can be used to describe the evolution of the system. With a parameter t (it can be time, in seconds), the equation can be reduced to only one formula (here the gas would be introduced at regular pace; indexes give volume instead of mass):

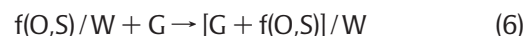
$$(G_{t=0\dots 50} + O_{30(100-t)/100})/W_{70(100-t)/100} \quad (5)$$

Applications

This CDS formalism was shown to be important both for scientific and for technological applications. For example, it was applied to the description of classical French sauces as compiled from classical or official culinary books. After observations by optical microscopy (size cutoff $d > 10^{-7}$), 23 categories were found. Surprisingly some simple types are missing, such as “foamed veloutés” ($(G + (W/S))/W$). Such systems are not difficult to produce practically, and their absence in the traditional repertoire leads to the question of why such sauces were not “invented” by cooks in the past. This led to a separate study on the number of different kinds of sauces as a function of time, using some traditional French culinary books. The increasing number of types of sauces with time shows that culinary empiricism has probably not had enough time yet to develop all possible kinds of sauces.

Let us consider now technological applications. In 1995, a new dish named “Chantilly chocolate” was based on a generalization of whipped cream. Milk cream is primarily made of fat droplets dispersed in a water phase (with an appropriate

size cutoff; micelles of caseins are not taken into account in this description). It is sometimes described as “oil-in-water emulsion resulting from the concentration of milk”, but this is wrong, because part of the fat is solid at room temperature;²¹ hence a formula such as $f(O,S)/W$ should be preferred to O/W , the expression $f(O,S)$ being as yet unknown, because it is not established whether $f(O,S)$ is equal to $S@O$ or to O/S . Anyway, the making of whipped cream can be described by the equation



Looking for formulas is an invitation to changes. O , it was said, can be any liquid fat, W any aqueous solution, and G any gas. This is why “Chantilly chocolate” is obtained when, starting from a chocolate emulsion, whipping is performed while cooling below 34 °C. Alternatively Chantilly foie gras, Chantilly cheese, or even “Chantilly olive oil” can be made when cooling is sufficient to make oil crystallize around air bubbles. In practice, making such products is easy. For example, with chocolate: first make a chocolate emulsion, O/W , by heating chocolate into a water phase (the proportion of chocolate and water has to be chosen so that the final fat/water ratio is about the same as the fat/water ratio in ordinary cream). Then whip ($+G$) at room temperature while the emulsion is cooled: after some time (some minutes, depending of the efficiency of the cooling), a “chocolate mousse” $[G + f(O,S)]/W$ is obtained. This mousse needs no eggs, contrary to traditional chocolate mousse, and the texture can be the same as in whipped cream. As whipped cream is called “Chantilly cream” when sugar is present, the name “Chantilly chocolate” was given to the new dish.

The number of possibilities is innumerable. It can be easily calculated that, using four phases and four operators, the number of formulas is 114 688, and more than 10^6 with six phases: there is plenty of room for innovation!

Describing the Nonperiodical Organization of Space

Whereas the CDS formalism describes the matter of which food and formulated products are composed, these formulated products are frequently highly organized systems, made of many parts. Moreover, this organization is frequently very important for bioactivity. In order to get a full description of systems, another formalism seemed to be needed. The same idea as above (using “objects” and “operators”) was proposed. However in the NPOS formalism, it was found useful to describe parts as objects of particular dimension: D_0 , D_1 , D_2 , and D_3 . A “reference size” being chosen (see below), D_0 stands



FIGURE 4. This “liebig” made by chef Pierre Gagnaire, in his Paris restaurant is based on the equation $O/W \rightarrow (O/W)/S$: it is obtained by whipping oil in a hot gelatin solution; when the emulsion cools, the oil droplets are trapped in a gel. If a chemical gel is made instead, the dish is called a “gibbs”: this can be achieved, for example, by whipping oil in an egg white, and heating the obtained emulsion in a microwave oven. Reproduced by permission of Hervé This.

for objects of zero physical dimension (“dots”), that is, objects whose size in the three directions of space is more than 1 order of magnitude lower than the “reference size”. D_1 stands for “lines” (with only one dimension of the same order of magnitude as the reference size), D_2 for surfaces (with two dimensions of the same order of magnitude as the reference size), and D_3 for volumes. If necessary, D_x objects could be considered, x being noninteger and these objects then being fractals.

Reference size is an arbitrary size that one chooses in order to make the needed description. For example, for food systems, it can be the size of the plate or of teeth, but more generally, reference size, being the scale where the full object is considered, can be added in brackets. For example, $D_1[10^{-5}]$ would indicate a linear structure whose length is of the order of magnitude of 10^{-5} m (and, accordingly, whose radius is more than 1 order of magnitude lower). The direction of sheets and fibers is sometimes usefully added, using the Cartesian equation in the same bracket.

Again the various objects D_k are included in formulas using operators: the operator @ represents inclusion; geometrical operators such as σ_x , σ_y , and σ_z represent, respectively, superposition in the directions x , y , and z (but any particular direction could be given by the coordinates of a vector). However in many systems, some disorder has to be described, and this is why new operators should be used instead. In particular, the “/” operator is again useful for the description of the random accumulation of objects in space. Other operators may be added as needed.

With this new formalism, the geometrical shape of formulated products is not described: a square has the same NPOS



FIGURE 5. This orange “conglomerate” is an artificial system mimicking a real *Citrus* fruit based on the formula D_0/D_3 . In this dish by Pierre Gagnaire, the seasoned orange juice was first trapped in pearls with a liquid core, obtained by jellification of sodium alginate using calcium ions; then the pearls were glued together with gelatin. Reproduced by permission of Hervé This.

formula as a disk. And because the two formalisms (CDS on one hand, NPOS on the other hand) use the same operators, they can be mixed easily in order to get a more precise description of formulated systems (the name “CDS/NPOS formalism” was proposed). For example, meat, being formed of aligned muscular fibers full of a jellified solution,²² could be described as $D_{1,x}(W/S_1)/D_3(S_2)$, if x represents one arbitrary direction (for short, the x direction could be omitted, so that the formula would simply be $D_1(W)/D_3(S)$). And an oil-in-water emulsion could be described by $D_0(O)/D_3(W)$ (the oil droplets are more than 1 order of magnitude smaller than the continuous, aqueous phase, so that they are described as having zero dimension).

One important remark about food: this CDS/NPOS formalism makes a difference between the various kinds of gels. This is important because, as we said, plant tissues and animal tissues are gels, as well as gelatin or pectin gels. However, gelatin gels ($D_3(W)/D_3(S)$) are very different from plant tissues, because their liquid phase is continuous, which is not the case for the liquid phase of plant tissues ($D_0(W)/D_3(S)$), where it is localized in the cells (except in the vascular tissues) (Figure 2); and plant tissues are very different from animal tissues in muscles, because muscle fibers are elongated cells of length up to 20 cm ($D_1(W)/D_3(S)$) (Figure 1).

Chemistry Is Needed

Concerning the chemical analyses of culinary transformations, much work was done by food science or even by organic chemistry, but the situation is strange, because while the Maillard reactions are the focus of regular international meetings and while odorant molecules formation are extensively stud-

ied, simple culinary questions remain unanswered. For example, when a carrot stock is prepared by heating slices of carrot (*Daucus carota* L.) roots in water at 100 °C, glucose, fructose, and sucrose are extracted. Sucrose is hydrolyzed in the stock, but is it also hydrolyzed in the plant tissue, where the environment is comparable (aqueous medium, same temperature after some minutes)?

In order to ask the right “molecular gastronomy” chemical questions, one has to consider that most dishes are produced from plant and animal tissues. Indeed, we eat either such tissues after thermal processing or liquids prepared from them, including aqueous solutions obtained by thermal processing of plant or animal tissues in water (“stocks”, “sauces”, etc.). Accordingly, the chemical component of molecular gastronomy should focus on the chemical modifications observed during the processing of these “culinary reactants”, either directly inside the living tissues, at their surface, or in aqueous solutions.

Animal tissues are mostly muscular tissues, made of bundles of elongated cells containing mostly contractile proteins (primarily actin and myosin), enclosed in a tissue made itself of proteins (collagen); these tissues also contain some fat deposits.²² Plant tissues are primarily made of water enclosed in cells with phospholipid bilayers and a cell wall primarily made of carbohydrates (cellulose, hemicelluloses, pectins) and proteins; some tissues have a high content in lipids or in starch.

During culinary transformation (mainly thermal processing), the 100 °C limit is particularly important (as long as some water remains inside a dish, the 100 °C limit is not reached by more than some degrees). This is why in order to investigate the chemistry of phenomena occurring during culinary transformations one should divide the study between processes in water at temperatures between room temperature and 100 °C, on one hand, and pyrolysis, on the other. One has to add that some culinary processes can give unforeseen results, because they can be very long: some culinary processes such as pig trotters “à la Sainte Mennehoult” can be as long as 72 h.²³

Protein denaturation has been extensively studied (see transition temperatures for egg proteins in Table 1). This explains the important difference in consistency between an egg heated until thermal equilibrium (about 1 h) at 69 °C or at 70 °C (Figure 6): the second coagulation generates a very different result, because a second network is created inside the first, so that the hardness of the formed gel increases (it is possible that the two protein networks are independent, because the thiol groups from ovotransferrin should be all engaged in

TABLE 1.²⁴

proteins	denaturation temperatures (°C)	
	Egg White	
ovotransferrin		61
ovomuroid		70
lysozym		75
ovalbumin		84.5
globulin		92.5
	Yolk	
LDL		70
HDL		72
α -livetin		70
β -livetin		80
γ -livetin		62
phosvitin		>140

disulfide bridges when ovomuroid denatures, but it would be interesting to know whether the two networks link through rearrangement of these disulfide bridges when the chemical conditions are favorable).

For proteins, as well as for other polymers, hydrolysis can occur. For example, cooking plant tissues (and softening them) is associated with thermal degradation of pectin (mostly poly-

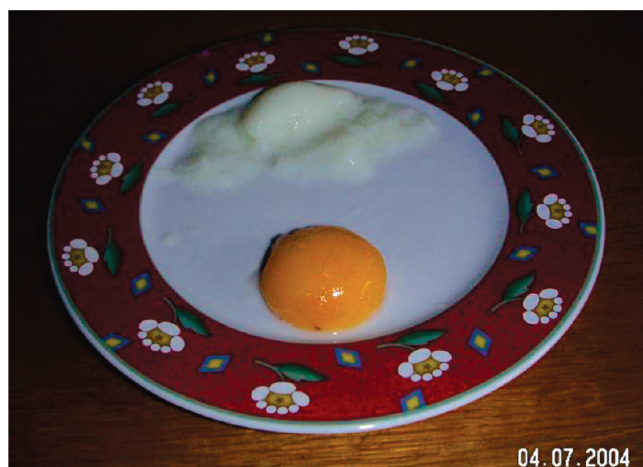


FIGURE 6. (Top) Egg cooked at 65 °C for many hours. Only one protein (ovotransferrin) coagulated in the white part. (Bottom) Egg cooked at 71 °C. The difference in the egg white is due to ovomuroid coagulation. Reproduced by permission of Hervé This.

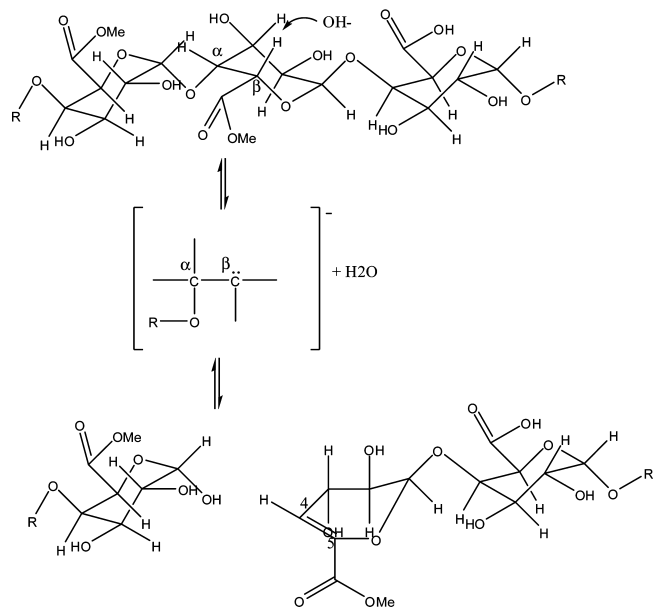


FIGURE 7

mers of galacturonic acid or (2*S*,3*R*,4*S*,5*R*)-2,3,4,5-tetrahydroxy-6-oxohexanoic acid), GalA through β -elimination,^{25,26} a hydrolysis process due to breaking chemical bonds between galacturonic residues according to the mechanism given in Figure 7.

Whereas cellulose is highly heat resistant, starch (amylose and amylopectine) or proteins dissociate slowly with time, particularly when the environment is acidic, such as in meat or in most dishes. These processes generate, respectively, saccharides or amino acids, which can then react by processes such as dehydration of hexoses (generating 5-(hydroxymethyl)-2-furaldehyde, for example) or Strecker degradation.^{25,26}

The chemical study of food processes is interesting in many respects and in particular because these processes seem “green”: reactants are part of food products, and the processes (100 °C, many hours, being “culinary” conditions) are considered (perhaps mistakenly) safe. Moreover, as said above, many culinary phenomena remain unexplained. For example, the formation of hydrogen sulfide during egg processing has been studied,²⁷ but no publication explains why this process does not occur when eggs are thermally processed for more than 12 h at 65 °C.

Of course, model systems can be used to investigate all these processes, but in order to understand the chemistry of culinary processes, one needs to consider whole food systems, with many interactions. For example, when plant or animal tissues are heated in water, the aqueous solution can dissolve “raw” or “transformed” compounds. By “raw” compounds, we mean compounds that are present in tissues and that have the possibility to migrate toward the aqueous envi-

ronment, such as products from sap (in channels such as phloem and xylem, for plants) or from blood (in blood vessels for animal tissues). By “transformed” compounds, we mean, for example, hydrolysis products such as GalA or 4,5-unsaturated residues made from pectins. Which of the raw compounds are extracted, and which of the extracted compounds are modified? Do all compounds react the same way inside food (aqueous environment, but possible interactions with the “matrix”) or in an outside aqueous solution? For example, is meat stock the same when it is made from cut meat or intact muscular tissues? What is the importance to stock composition of changing the pH or the salt content? If light has an influence on the color of stock, probably because of GalA or 4,5-unsaturated residues made from pectins,²⁸ is there a first-order change of composition?

Questions of this kind arise for color in general. Reactions of chlorophylls, carotenoids, and phenolics have been extensively studied, but many of the studies were not done under culinary conditions, so if the bases for the interpretation of culinary phenomena now exist, the real work remains to be done,²⁹ with possible surprises because food is generally a mixture of compounds with possible interactions and not model systems.

Conclusion

This leads to the question of bioactivity, either for organoleptic perception or for nutrition or toxicology. Second-order phenomena in one of the three fields of interest (physical structure, chemical composition, and bioactivity) can be of first-order in another field. For example, whereas tea or wine are mostly made of water, the tiny quantity of phenolics or odorants is of primary importance for sensory appreciation. Here matrix effects can be very important; they are extensively studied in pharmaceutical studies, because they are the basics of galenic formulation.³⁰ This is not surprising because food, drugs, cosmetics, and other formulated products are generally complex chemical and physical systems, composed of many parts, each made of different phases (aqueous solution, gas, fats, etc.), and their organoleptic (for food) or bioactive (for drugs) properties are dependent on the spatial distribution of their molecules. Whereas the structure/activity question remains in pharmaceuticals after years of study in the field of drug design, one “Grail” of Molecular Gastronomy remains the prediction of the physical/biological/chemical/organoleptic properties of systems from their CDS/NPOS formula. Another issue is the relationship between compound migration in food and chemical modifications of the migrating compounds. The matrix effect is particularly interesting, because it is probably

acting through supramolecular associations. It makes a bridge between physics and chemistry.

BIOGRAPHICAL INFORMATION

Since 2006, **Hervé This** has been director of the INRA Molecular Gastronomy Team at AgroParisTech. He got his diploma from the Ecole Supérieure de Physique et de Chimie Industrielles de Paris in 1980 and worked then both at the French edition of *Scientific American* and in his own laboratory, until he was invited by Jean-Marie Lehn at the Laboratory of chemical interactions of the Collège de France in 1995. His Ph.D. was entitled "Molecular and Physical Gastronomy", obtained in 1996.

FOOTNOTES

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REFERENCES

- Chaptal, J. A. *Essai sur le perfectionnement des arts chimiques en France*; Imprimerie nationale: Paris, 1800.
- This, H.; Méric, R.; Cazor, A. Lavoisier and meat stock. *C. R. Chim.* **2006**, *9*, 1510–1515.
- Coulston, Ch. In *Dictionary of Scientific Biography*; Gillispie, C. C., Ed., American Council of Learned Societies, Charles Scribner's Sons: New York, 1980; Vol. 10, pp 526–540.
- Trésor de la langue française, 2006; electronic version, <http://atilf.atilf.fr/tlf.htm>, accessed 01/10/2006.
- Pasteur, L. Note sur l'enseignement professionnel, adressée à Victor Duruy. In *Œuvres complètes*; Masson: Paris, 1924; Vol. 7, p 187.
- Belitz, H. D.; Grosch, W. *Food Chem.*; Springer: Heidelberg, 1999.
- This, H. Froid, magnétisme et cuisine: Nicholas Kurti (1908–1998, membre d'honneur de la SFP). *Bull. Soc. Fr. Phys.* **1999**, *119*(5), 24–25.
- Weaver, W. T. Molecular biology, origins of the term. *Science* **1970**, *170*, 591–592.
- Brillat-Savarin, J. A. In *Molecular Gastronomy*; This, H., Ed.; Columbia University Press: New York, 2006.
- This, H. La gastronomie moléculaire et physique, Ph.D. Thesis, Université Paris VI, Paris, 1996.
- <http://www.pierre-gagnaire.com>, see "Art et Science", accessed 22/08/2008.
- This, H. Molecular gastronomy. *Angew. Chem., Int. Ed.* **2002**, *41* (1), 83–88.
- Dickinson, E. Colloid science of mixed ingredients. *Soft Matter* **2006**, *2*, 642–652.
- http://old.iupac.org/reports/2001/colloid_2001/manual_of_s_and_t/node33.html, accessed 21/08/2008.
- Israelachvili J. *Intermolecular & Surface Forces*, 2nd ed.; Academic Press: London, 1992.
- Bowes, B. G. *Structure des plantes*; INRA Editions: Paris, 1988.
- Lavoisier, A. L. Considérations générales sur la dissolution des métaux dans les acides. *Mémoires de l'Académie des sciences* **1782**, 492 also in *Œuvres complètes*; Imprimerie Nationale: Paris, t. III.
- This, H. Formal descriptions for formulation. *Int. J. Pharm.* **2007**, *344* (1–2), 4–8.
- This, H. La gastronomie moléculaire. *Sci. Aliments* **2003**, *23* (2), 187–198.
- Van der Sman, R. G. M.; Van der Goot, A. J. The science of food structuring. *Soft Matter* **2009**, *5*, 501–510.
- Michalski, M. C.; Ollivon, M.; Briard, V.; Leconte, N.; Lopez, C. Native fat globules of different sizes selected from raw milk: Thermal and structural behavior. *Chem. Phys. Lipids* **2004**, *132* (2), 247–261.
- Kopp, J. Le rôle du collagène dans les phénomènes de restructuration des viands. In *La restructuration des viands*; Dumont, B. L., Ed.; Erti: Versailles, 1986; pp 55–77.
- Toussaint, J. M. *Les recettes vosgiennes*; PLI-Gérard Louis: Haroué, 2001.
- Li-Chan, E.; Nakai, S. Biochemical basis for the properties of egg white. *Crit. Rev. Poult. Biol.* **1989**, *2* (1), 21–58.
- Keijbets, M. J. H.; Pilnik, W. Beta-Elimination of pectin in the presence of anions and cations. *Carbohydr. Res.* **1974**, *33*, 359–362.
- Cazor, A.; This, H. Sucrose, glucose and fructose extraction in aqueous carrot root extracts prepared at different temperatures by means of direct NMR measurements. *J. Agric. Food Chem.* **2006**, *54*, 4681–4686.
- Germis, A. C. Hydrogen sulfide production in eggs and egg-products as a result of heating. *J. Sci. Food Agric.* **1973**, *24*, 7–16.
- This, H.; Cazor, A.; Trinh, D. Color evolution of aqueous solutions obtained by thermal processing of carrot (*Daucus carota* L.) roots: Influence of light. *J. Food Sci* **2008**, *73* (4), 176–182.
- Valverde, J.; This, H. ¹H NMR quantitative determination of photosynthetic pigments from green beans (*Phaseolus vulgaris* L.). *J. Agric. Food Chem.* **2008**, *56* (2), 314–320.
- Phan, V.-A.; Liao, Y.-C.; Antille, N.; Sagalowicz, L.; Robert, F.; Godinot, N. Delayed volatile compound release properties of self-assembly structures in emulsions. *J. Agric. Food Chem.* **2008**, *56* (3), 1072–1077.