In order to describe existing or possible food systems, as well as physical changes of food ingredients during “culinary” processes, a preliminary version of the “disperse system formalism” (DSF) was first introduced under the name “complex disperse system” (CDS) formalism, later improved with the addition of the “non-periodical organization of space” (NPOS) formalism. The final, comprehensive DSF can give a description of the physical state of dispersion at any scale. It was shown to be important for the study of food, as well as for food innovation, which will be particularly useful for the preparation of “note by note” dishes (indeed synthetic food; see the corresponding chapter in this book), in which pure compounds are used instead of plant and animal tissues as food ingredients.

Dishes are indeed physico-chemical systems, with chemical composition and physical structure. Indeed, “cooking” was once said to be a “chemical art” because new compounds are produced during thermal processing (Cuvier, 1810; This, 2009). However, in this description, it was overlooked that physical transformations occur as well. How should we describe these?

Food ingredients and dishes are frequently made of various colloidal subsystems (Everett, 1988; Lyklema, 1991; Hiemnez, 1986; De Gennes, 1997; Jones, 2002), colloids being defined by the International Union for Pure and Applied Chemistry (IUPAC) as follows:

> a state of subdivision, implying that the molecules or polymolecular particles dispersed in a medium have at least in one direction a dimension roughly between 1 nm and 1 µm, or that in a system discontinuities are found at distances of that order. It is not necessary for all three dimensions to be in the colloidal range: fibers in which only two dimensions are in this range, and thin films, in which one dimension is in this range, may also be classified as colloidal. Nor is it necessary for the units of a colloidal system to be discrete: continuous network structures, the basic units of which are of colloidal dimensions also fall in this class (e.g. porous solids, gels and foams).

(IUPAC, 2001)

For instance, emulsions have been known under this name since 1560, when the French surgeon Ambroise Paré (1509–1590) understood that white thick liquids like milk or cream were often composed of water and fat (Paré, 1560). However, food colloids are generally more complex than such biphasic systems. Potatoes, for example, are suspensions of solid starch granules dispersed in the liquid inside cells, with cells themselves organized into a solid. Ice cream includes gas bubbles, protein aggregates, fat crystals and water crystals dispersed in a liquid concentrated solution (Israelachvili, 1992; Dickinson, 1994). For systems such as butter at room temperature (20 °C, for example), the physical microstructure remains poorly known (Lopez and Ollivon, 2009), but at least three phases coexist: solid fat, liquid water and liquid fat.

In order to describe the microstructure of colloidal systems, and of food systems in particular, the CDS formalism was introduced at the European Congress on Interface Science (ECIS) in 2002 (This, 2007). Later, in 2003, another formalism called NPOS was added for the overall description of dishes and the relative distribution of materials described by the CDS formalism. Finally, it was recognized that these two formalisms could be mixed into a more comprehensive description (DSF), which can be applied for the description of formulated products as well as for innovation (This, 2009).

Here, in order to present this description, we begin by describing an egg, before moving to the general formalism that we shall use for innovation.

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**A Simple Case for Training: How to Describe a Raw Egg**

The main issue of descriptions is that, like definitions, they can be a never-ending enterprise, but, at the same time, the idea of going into more precision by orders of magnitude can be useful (Raiman, 1991; Mavrovouniotis and Stephanopoulos, 1988). This idea has to be used in DSF: a choice of the pertinent descriptions to make is needed. In the following example of the description of a chicken (*Gallus gallus*) egg, of which the physical structure is, of course, known, we shall see how the various characteristics of DSF are needed.

Let’s begin by observing simply that an egg is made of a shell including the egg white, in the inside of which the yolk lies (Belitz *et al*., 2009). In order to make a shorter and faster description...
of this structure, we can use the “@” symbol, also used internationally in chemistry for describing inclusion in interstitial compounds. Here, using the letters S for shell, W for white, Y for yolk, the egg could be described as:

\[ Y@W@S \]

For colloidal systems, and for physical objects made of colloidal parts, it can be interesting to indicate the physical phases of the various parts: solid (S), or liquid (L), or gaseous (G). Focusing now on phases, the egg formula could be:

\[ (L_1@L_2)@S \]

However, the shell does not have the same “importance” as the white and the yolk; it is a thin layer, whereas the two other parts are bulky. This is why the “physical dimension” (number of dimensions, not size) is usefully taken into account in the formal description of DSF. Of course, the number of dimensions of physical objects is not exactly the number of dimensions of mathematical objects, but a formal definition can be given considering the diameters in the three directions of space, compared to a reference size, for example, the size of the plate in which a dish is served (Mandelbrot, 1982). In this regard, an object whose size in the three directions of space is smaller than the reference size by more than one order of magnitude should be considered to be of zero dimension (e.g., a rice seed on a plate). An object for which two directions are smaller than the reference size by more than one order of magnitude is of dimension one (a piece of spaghetti on a plate), and an object for which one direction is smaller than the reference size by more than one order of magnitude is of dimension two (a salad leaf on a plate). The other objects are three-dimensional.

Using \( D_0 \), \( D_1 \), \( D_2 \) and \( D_3 \) to describing objects of dimension 0, 1, 2 and 3, respectively, one can improve the previous description of eggs: if the reference size is the length of the long axis of the egg, this one could be described as:

\[ [D_3(L_1)@D_3(L_2)]@D_2(S) \]

The example of eggs is interesting, because the yolk is made of concentric layers called light and deep yolk (Anton, 1998), deposited during the day and the night, respectively; the number of these is about nine, as shown from ultrasound scan pictures (Figure 30.1) (This, 2003; This, 2006). As each layer is composed of solid granules (S) dispersed in a plasma (aqueous solution of proteins and other compounds W), the full yolk could be also described as:

\[ (D_0(S)/D_2(W))@9 \]

However, the question is whether this second formula should be grouped with the first, as in:

\[ D_3((D_0(S)/D_2(W))@9)@D_3(L_2)@D_2(S) \]

Is it useful? The same question could be asked about the egg white, because it is not a simple solution of proteins but has a colloidal sub-structure, as demonstrated by the fact that it makes different thicknesses around the yolk when the egg is poured on a flat surface. The shell, as well, could be described in more and more detail. The answer to this question of the precision of the formal description is to be based on the goal of the description using DSF, keeping in mind that it is often not appropriate to mix two different scales. For sure, the egg yolk used for making an emulsion is made of granules (Figure 30.2), but they are unimportant when only the emulsion is concerned. Indeed, granules would not appear in a microscopic picture of a mayonnaise at a magnification that would visualize the oil droplets dispersed in the liquid. At the end of the next paragraph, we discuss this question more formally.

The Objects for the Formal Description

Starting from this example of an egg, one can now present the DSF system more generally. For the formal description of the
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physical structure of systems, the DSF describes three kinds of aspects: the nature of the material, the organization of the dispersions, and the dimensions of colloidal parts.

Let us observe that the DSF is a generalization of the old O/W description used in colloid science.

Indeed, for phases, the letters G, O, W and S are proposed to stand for “gas”, “oil” (any hydrophobic liquid phase), “water” (any aqueous solution) and “solid”. If needed, indexes can be added (for example, when two different solids are present), and other symbols could be used when needed (such as E for “ethanol”).

Operators are used, between the letters representing phases, to make formulas. As said before, the IUPAC symbol “@” describes an inclusion, and the symbol “/” has been used in physical chemistry to describe a random dispersion, such as in emulsions and foams. The symbol “+” is used to describe a mixture of phases that can be dispersed into another one, such as (G+O)/W for an aerated emulsion: a water solution is the continuous phase, and gas bubbles and oil droplets are randomly dispersed into this solution. The symbol “σ” indicates a superposition.

If needed, geometrical connectors such as σx, σy and σz can be used instead to represent superposition in the direction x, y and z, respectively. Any particular direction can be given by the Cartesian coordinate of the vector, such as in (u, v, w), or other coordinate systems such as {r, θ, φ} for a spherical organization. Finally, the “x” symbol is used to describe the mixing of two continuous phases, such as in gelatin gels (SxW). Up to now, these connectors have been enough to describe all food systems that have been considered, but, again, more operators could be introduced if needed.

Now, for describing the non-periodical organization of all the phases in space, the elementary objects are described according to their “physical dimension”: D₀, D₁, D₂ and D₃. D₀ stands for zero-dimensional objects (“dots”), i.e., objects whose size in the three directions of space is more than one order of magnitude lower than a “reference size” that was chosen initially (the scale where the full object is considered). D₁ stands for lines, i.e., objects with only one macroscopic dimension. D₂ stands for surfaces, i.e., objects with one dimension lower than the two others by more than one order of magnitude. D₃ stands for volumes. If necessary, Dₜ objects could be considered, “k” being non-integer, and these objects then being fractals (Mandelbrot, 1982).

Added rules give coherence to this formalism. First, in order to avoid having more than one formula for a particular physical system, the components of a sum have to be written in alphabetical order, for example, (G+O+S)/W. Secondly, simplifications sometimes have to be made; for instance, G/G is equal to G. More importantly, an order also has to be respected for operators. In order to do this, the determination of a free energy can be used, assuming, for example, simply an interface energy γ_{AB} between the phases A and B (Figure 30.3).

FIGURE 30.3 The four distributions for which energy is calculated.
Considering two phases that do not mix at a temperature $T$, such as oil and water, the ratio of free energy (or more precisely, free enthalpy) between superposition and inclusion can be calculated simply. Let us assume two material substances, A and B (A being less dense than B), with respective volumes $V_A$ and $V_B$. The surface energy between A and air is neglected, and the two phases have a contact surface of area $c^2$ (where $c$ is the length of the edge of A, assuming it has a cubic shape). The free enthalpy is then equal to $\gamma_{AB} V_A^{2/3}$. For the inclusion of a phase into another, corresponding to the operator $\oplus$, it would be equal to $6 \cdot \gamma_{AB} V_A^{2/3}$, showing that the free enthalpy for inclusion is about one order of magnitude higher than for superposition.

To compare the free enthalpy for mixtures (intermixing operator $\times$) and dispersions (operator $\bigoplus$), the calculation was made on a network.

Let us assume that, for the system A x B, the phase A is around the edges of a cubic cell with $n$ elementary cells per side of the total volume. The free enthalpy would then be:

$$4 \sqrt[3]{3 \cdot \gamma_{AB} \cdot n \cdot V_A^{1/2} (V_A + V_B)^{1/6}}$$

For the dispersion, $n^3$ elementary cubes of A are considered dispersed in B, and the total free enthalpy is:

$$6 \gamma_{AB} \cdot n \cdot V_A^{2/3}$$

Numerical comparison (with $\gamma_{AB}$ chosen to be 80, $n = 100,000$, $T = 300$ K, $V_A = 1$, $V_B = 1$) shows that intermixing needs about 1.3 times more free energy than dispersion.

The formal description can be increased in many ways, if needed. For example, repetitions can be described by exponents, as could be seen for the example of the egg. Another possibility is to give the quantity of each phase by a subscript, as in $O_{95}/W_5$ to describe an emulsion of 95 g oil into 5 g water. The size of structures can be also given in brackets, such as in $O_{200\times10^{-6}-10^{-5}}/W_{5}$, where the powers of 10 indicate the minimum and maximum radii of dispersed oil droplets (SI units should be used). In order to be more precise about the size of structures, the size of the smallest structures considered can be given in brackets as a “reference size” at the end of the formula. For example, $O[10^{-5}-10^{-4}]/W_5$ indicates that the structures considered are larger than $10^{-4}$ m, so that smaller granules are not taken into account. Kinetic parameters such as time or energy can be added to describe the evolution of the system. The equation $O/W + G \rightarrow (G+O)/W$ can be replaced by the following formula:

$$(G_{t=10...50} + O_{300\times10^{-6}-10^{-5}})/W_{70\times10^{-6}-10^{-5}}$$

where the time $t$ is in seconds, the gas would be introduced at a regular rate and indices give volume instead of mass.

Up to now, no food system has resisted description by this formalism. However, do all formulae correspond to possible systems? Many dispersed systems are metastable and not thermodynamically stable. Indeed, they evolve, depending on the size of their structures or on the nature or quantity of stabilizing elements like surfactants in emulsions. This is also a question of kinetics, not of thermodynamics.

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**Mixing Orders of Magnitude for an Overall Description**

Let us finish this discussion by considering many orders of magnitude together. Using DSF, one can describe any physical structure at any scale. For example, let us consider a dish $P_1$ made of many macroscopic parts $P_{1,1}$, $P_{1,2}$, ..., $P_{1,n}$, each part being made itself of parts at a smaller scale, and so on. Using the DSF operators, this could be described as:

$$P_1 = P_{1,1} \oplus P_{1,2} \oplus P_{1,3} \cdots o_{1,\omega(1) - 1} P_{1,\omega(1)}$$

where the $o_{ij}$ are chosen among the DSF operators and where $P_{1,i}$ is itself made of parts, such as in the equation:

$$P_{1,i} = P_{2,i,1} \oplus P_{2,i,2} \oplus P_{2,i,3} \cdots o_{2,\omega(2,i) - 1} P_{2,\omega(2,i)}$$

and so on until molecular scale.

All scales are not always useful. For example, if the first reference size is between $2 \times 10^{-4}$ and $2 \times 10^{-3}$ m, the second scale could be between $2 \times 10^{-5}$ and $2 \times 10^{-4}$ m, the third between $2 \times 10^{-6}$ and $2 \times 10^{-5}$ m, and so on until $2 \times 10^{-10}$ and $2 \times 10^{-9}$ m (molecular scale). It is perhaps not useful to describe the system at all scales (nine orders of magnitude), because some objects would not appear to be different on more than two orders of magnitude. For food, studies in our group show that it would often be enough to consider macroscopic sizes, between 10 cm and 1 mm (scale 1); microscopic, between 0.1 mm and 0.001 mm (scale 2); nanoscopic, between 1 μm and 0.01 μm; and molecular, between 10 nm and 0.1 nm (Hornyak, 2009).

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**Use of DSF for Scientific Explorations and for Innovation**

DSF was initially introduced for the analysis of the differences between different kinds of “gels”, but it is also useful for innovation. The importance of algebraic notation has been recognized for many centuries, and it was a major success of René Descartes, Wilhelm Gottfried von Leibniz and Isaac Newton to use it in mathematics and physics. In a treatise on logic published in 1918, the French logician Edmond Goblot discussed how notation can lead to discovery (Goblot, 1918):

For the algebra of logic, its inventors probably never thought that it was only a notation of concepts, relationships and elementary operations for logicians, and they had never had any doubt on the difference between discovery of a truth and the invention of a notation for expressing it when it is discovered. Notation can lead to discovery, as it occurred frequently in algebra. To general and abstract concepts, intractable without formula, cumbersome to use with words and common
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language, the algebra of logic, as ordinary algebra, substitutes concrete and regular symbols which can be organized in a wealth of combinations and reduce heavy mind operations to very simple written processes.

This idea to simplify operations through an algebraic formalism was already developed by Antoine Laurent de Lavoisier (1743–1794), and it was the basis of the introduction of modern chemical notation (Lavoisier, 1782):

In order to better show the state of the issue, and to present synthetically the result of what is going on during metal dissolutions, I build formulas, that could be confused with algebra, but do not derive from the same principles; we are very far from the time when the precision of mathematics can be introduced in chemistry, and I invite the reader to consider the formula that I shall give only as simple annotations, whose aim is to think easier.

Indeed, in 1995, a new dish named “Chocolate Chantilly” (see the chapter on Chantillys in this book) was based on the equation $O/W + G \rightarrow (G + O)/W$ (This, 1996). First, a chocolate dispersion $(O+S)/W$ is made by heating chocolate in water with the same final fat/water ratio as in ordinary cream: here O stands for the melted cocoa fat and S for the cocoa plant particles, the sugar crystals having dissolved in the aqueous phase. Then, this dispersion (mainly an emulsion) is whipped (+G) at room temperature while cooling. The very unstable hot $(G+O)/W$ system is slowly transformed into a more stable “chocolate mousse” $G/g(O, S, W)$, when part of the fat crystallizes and traps the dispersed oil and gas structures (here we use again a function g to indicate the unknown continuous structure made of liquid fat, solids – fat and plant pieces – and aqueous solution). This mousse contains no eggs, in contrast to a traditional chocolate mousse (Larousse Gastronomique, 1996), and its texture can be the same as that of whipped cream. Of course, chocolate can be replaced by other food products, such as as cheese, foie gras or even butter, leading to “cheese Chantilly”, “foie gras Chantilly” or “butter Chantilly”, respectively.

The use of DSF can lead to a wealth of other new systems with both scientific and culinary interests. For example, using four phases and four connectors, the number of formulae is 114,688, and more than 106 with six phases; there is plenty of room for innovation. Indeed, DSF will be a valuable tool for the creation of “note dishes” (This, 2016a, 2016b), i.e., dishes made from pure compounds, as the consistency will have to be built, and it is likely that the gels of class 1 will not be enough to achieve the target systems.

Conclusions and Perspectives

As we said, DSF can lead to innovation (technology), but it can also contribute to the scientific development of molecular and physical gastronomy, as for the study of flavour release. For example, considering the many possible gels of class 2, one can now ask whether they can be grouped into categories of flavour releasing systems. This is shown in the chapter about gels in this book.

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