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The "new dispersed systems formalism" (NDSF): a renovated description of the dispersed systems for ranking food systems by order of complexity

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Abstract
The "dispersed systems formalism", or DSF, was introduced for the description and study of dispersed systems, but the formulas in this system do not follow the logical order of decreasing orders of magnitude for the size of the constituent structures. This hinders the learning and use of the DSF. A renovation of the formalism, based on the top-down analysis of physicochemical systems, is proposed, with some other improvements, such as taking surface energy and entropy into account for ranking the various objects of the formalism. This renovation allows the introduction of a coherent classification of systems by order of increasing complexity. It helps deciding rationally an order for the study of the chemical and physical properties of systems.

Keywords
complexity, CDS, DSF, food systems, formalism, formulation, phases, NDSF, operators

Introduction

Food systems, as well as products from formulation industries (cosmetics, drugs, paintings and varnishes, etc.) are often colloidal systems (Umbach, 1998). Aerosols, emulsions, foams, gels, and suspensions are the simplest colloids, with two phases (Everett, 1988), but often, more than one phase is dispersed in a continuous phase. For example, a bearnaise sauce is a suspension of

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aggregates of coagulated proteins from egg yolks in an aqueous solution, with droplets of melted butter also dispersed in the solution (This, 2012). Dumplings are another example (Menon, 1749): they are gels, with a continuous network formed by the coagulation of proteins extracted from ground animal tissue (IUPAC, 2025); in this network, the aqueous solution simultaneously extracted from these tissues is trapped, along with dispersed gas bubbles (through the addition of whipped cream or whipped egg whites), and fat droplets (from cream), which are partly liquid and partly solid at the consumption temperatures (Lopez *et al.*, 2006).

In order to study the chemical and physical properties of such soft matter systems, it is wise to analyze them from the simplest to the more complex, which requires a quantification of complexity that can be based on the physical structure of systems (Pincus, 1991; Adami and Cerf, 2000).

Regarding a description of the physical structure, a "dispersed systems formalism" (DSF) was proposed (This, 2007) as an improvement of more simple formalisms for describing complex dispersed systems (CDS), introduced in 2002 (This, 2002) and published in 2005 (This, 2005).

In different works using the DSF, gels and suspensions had to be listed, and different orderings ("classes") were used, with not enough coherence (This, 2017; This vo Kientza, 2022). Also it was observed that the foundation of the DSF, although grounded in the definitions of the International Union of Pure and Applied Chemistry (IUPAC), was not following the sound rule of considering first the most important structures, before the second order ones.

This explains why a "new dispersed systems formalism" (NDSF) was proposed as an improvement of the DSF during the 14th International Workshop on Molecular and Physical Gastronomy (This, 2007). The NDSF takes into account the top-down analysis method proposed for molecular and physical gastronomy studies (This vo Kientza, 2025). It intends to make the description of physical systems more natural and easy, and it can be a sounder basis for the definition of groups of systems of increasing complexity.

1. Describing dispersed systems formally

In November 2001, at the European Conference for Interface Science, a first formalism for describing colloidal systems was introduced under the name of "complex dispersed systems formalism", or CDS (This, 2005), as a generalisation of formulas which were already used with no theoretical frame in the 1950's (Jellinek and Gordon, 1950; IUPAC, 2025). For example, IUPAC documents consider oil-in-water emulsions as O / W, where the letter O designates a dispersed liquid lipid phase, and the letter W an aqueous solution, the symbol / designating a random dispersion of oils droplets in the aqueous solution.

The first proposal included in the CDS formalism was to generalize this writing to more than the two O and W phases (with G, for gas, and S for solids), and to other colloidal systems such as aerosols (liquid, solid), foams, gels, suspensions (liquid, solid). This needed in particular the introduction of a second operator, "x", in order to describe the intermeshing of two continuous phases, as in some gels: for example, gelatine gels are made of two continuous networks, respectively liquid W and solid S (Djabourov, 1988).

The formulas of the simplest colloidal systems are listed in Table 1. For all studies, the definitions of the International Union of Pure and Applied Chemistry (2025) are used, and in Table 2 the definitions of the main dispersed systems are given, obviously starting with the general definition of colloidal systems.

In these descriptions, it is wise to take into account the structures by limiting oneself to the first order of size, because it is rare that what can be called a two-phase system - for example - is exactly reduced to two phases (it is to be added that order of magnitudes in size, or quantities, are formalised in This, 2013).

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For example, in food emulsions such as mayonnaise sauce (Carême, 1828), droplets of oil O dispersed in an aqueous solution W makes up the majority of the systems in terms of mass, but there may also be microscopic solids S, or gas bubbles G, for example (Figure 1). Without falling into an unnecessarily complex description, the CDS description therefore considered only what is of first order in size and quantities.

Colloidal systems are not limited to two phases. For example, chocolate is made (first order of quantities) of sugar (mainly sucrose crystals), fat and solid plant particles. Sometimes it is described as a solid suspension (Eur-lex, 2013; Konar *et al.*, 2024), but the physical nature of lipids in chocolate depends on temperature (Ziegleder *et al.*, 1994):

(1) At temperatures below - 10 °C, all the fat in chocolate is solid, and chocolate is a solid suspension (IUPAC, 2025), with two kinds of solids (sucrose crystals, plant particles) dispersed in the solid fat matrix. Here, the CDS formalism called for another operator, "+", so that the CDS formula can be $(S_1 + S_2) / S_3$, where S_1 stands for the sucrose crystals, S_2 for the plant particles, and S_3 for the solid fat matrix.

(2) At temperatures above 40 °C, all the fat is in liquid phase O, so the chocolate is instead a liquid suspension of sucrose crystals and plant particles dispersed in the melted fat, with the CDS formula $(S_1 + S_2) / O$.

(3) At intermediate temperatures, some of the fat is liquid (O) and some is solid (S_3), so chocolate becomes quadriphasic (alphabetic order O, S_1, S_2, S_3), with structures that can depend on the proportion of liquid fat O and of solid fat S_3:

- it is possible that liquid fat O makes a continuous phase in which sucrose crystals S_1, plant particles S_2 and particles of solid fat S_3 are dispersed: this corresponds to a suspension, and the formula is $(S_1 + S_2 + S_3) / O$;
- or liquid fat O and solid fat S_3 can make two intermeshed continuous phases $O \times S_3$, with a dispersion of the sucrose crystals S_1 and the solid plant particles S_2 in the structure either in the liquid fat phase O (formula $[(S_1 + S_2) / O] \times S_3$), or in the solid fat S_3 (formula $O \times [(S_1 + S_2) / S_3]$), or in both (in this case, the formula depends on which solids is in which continuous phase, with the following possibilities: S_1 and S_2 both in O and in S_3, or S_1 in O and S_2 in S_3, or S_1 in S_3 and S_2 in O). For all these possibilities, the systems are complex gels (IUPAC, 2025).

Table 1. The simplest colloidal systems. The phase given on the top is dispersed in the phase given on the left (Monnerie, 1978).

	Gas	**Liquid**	**Solid**
Gas	Gas	Liquid arosol	Solid aerosol
Liquid	Foam	Emulsion	Suspension
Solid	Solid foam	Gel	Solid suspension

As said, the description of systems calls for a simplification in terms of proportions (taking into account only the main phases), but another simplification must be in terms of size of structures, because the full description would need to consider structures of any dimension. Consequently the CDS was based on the description to objects of three successive orders of magnitude only. For example, for a mayonnaise sauce that is observed in a microscope, with a field of 10^{-3} m, the water phase is seen to include oil droplets of sizes between 10^{-5} and 10^{-4} m, corresponding to the formula O / W.

Another example is the matter making up potato (*Solanum tuberosum* L.) tubers, that are solid (S_1) at macroscopic level. Optical microscopy with a 50 µm field shows primarily a continuous network (from the cell walls), with solid starch granules (S_2) dispersed in the protoplasm (Banks and Greenwood, 1975; Bowes, 1998). Assuming that the protoplasm is an aqueous solution W, the CDS formula for describing what appears on

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the microscopic picture would be (S_2 / W) / S_1; but if it were preferred to describe the protoplasm as the gel it is, with a liquid phase intermeshed with a solid S_3 (Shamipour *et al.*, 2020), the formula is [S_2 / (S_3 x W] / S_1, S_3 representing the solid network of the protoplasm (cytoskeleton, endomembrane network).

These two examples show how important it is to define a reference size for formal descriptions: each reference size leads to a particular formula, for a system. And once the reference size is chosen, only structures of this order of magnitude in size, as well as structures of the two next smaller orders of magnitude in size are taken into account in the description. For example, in Figure 1, showing a microscopic view of a mayonnaise sauce with a field of 0.1 mm (which is the reference size), droplets one or two orders of magnitude smaller (as small as 0.001 mm) can be seen.

The dispersed system formalism (DSF) was an improvement of the CDS description that included the mathematical "dimension" of objects: dimension 0 when the size of an object is smaller at least by one order of magnitude than the reference size (for example, a rice seed compared to a plate), dimension 1 when two dimensions of an object are smaller by at least one order of magnitude than the reference size (a spaghetti, compared to a plate), dimension 2 when one dimension is smaller than the reference size (sheet) and dimension 3 for objects whose 3 dimensions are of the same order of magnitude as the reference size.

Finally, the DSF was based on:

- phases : gas (G), liquid lipid phase (O), aqueous solutions (W), solids (S);
- topological operators: random dispersion /, inclusion @, intermeshing of phases x, stacking σ,
- the + operator to describe the coexistence of two (or more) phases in the same third phase.

For example, with a reference size chosen as 0.1 mm, the mayonnaise sauce shown in Figure 1 has the DSF formula D_0(O) / D_3(W), as oil (O) droplets (D_0) are randomly dispersed (/) in a continuous (D_3) water phase (W), coming from vinegar (aqueous solution of acetic acid and other minor compounds) and from egg yolk (50 % water) (Anses, 2025).

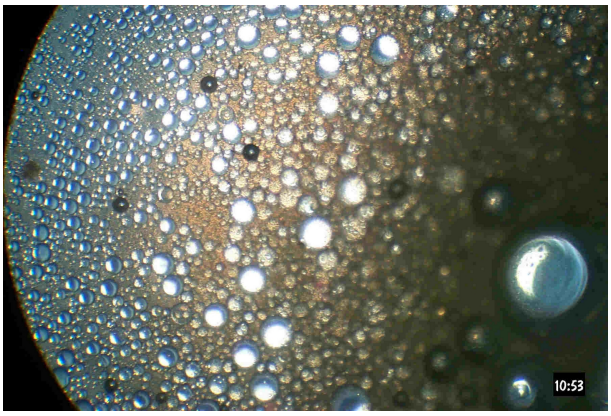

Figure 1. To observe the emulsion structure of a mayonnaise sauce, a field of view of 0.1 mm is required. Oil droplets as small as 0.001 mm are visible. The spheres with black edges are air bubbles (artifacts).

2. NDSF: an improvement of the DSF

The introduction of the top-down approach to the analysis of physicochemical systems, in 2025, has made it clear that the DSF formalism, particularly for teaching purposes, could be improved if the substructures of a system were considered in decreasing order of size (This vo Kientza, 2025).

In particular, there was a certain illogicality (albeit based on IUPAC rules relating to the definition of emulsions) in first considering the dispersed oil droplets in an emulsion before recognizing the system as a first-order aqueous phase on a macroscopic scale, and years of teaching DSF to international master's students (FIPDES, IPP AgroParisTech) have shown that this was the source of the difficulties they encountered when performing the exercises applying the course on the DSF.

Indeed, as seen before, the DSF formula of an oil-in-water emulsion is D_0(O) / D_3(W), when the

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reference size is about 0.1 mm: the oil (O) droplets, of dimension 0 (D_0), come first, whereas the continuous water phase W, which is three-dimensional (D_3) on the scale of the sauce (and at the level defined by the reference size) is at the end of the formula..

The current proposal of the "novel dispersed system formalism" (NDSF) is to begin the formula of a system by the description of the structures at the level of the reference size, and then to indicate the other structures in descending order of magnitude for the size. For example, for a mayonnaise sauce at room temperature (water and oil are liquid), the NDSF formula is $D_3(W) \setminus d_0(o)$. In this proposal, the continuous phase comes first, and the DSF operator / is replaced by \, which preserves a certain familiarity with the IUPAC notation, the inclination being towards the continuous phase; the first order structures (same order of magnitude as the reference size) are designated by capitals, and lower case letters are used for the structures of second or third order of magnitude in size.

For potato tubers, if the reference size is chosen equal to the diameter of tubers, one has simply to recognize that it is a solid $D_3(S_1)$; then one would describe the protoplasms (assuming that they are liquid) as $d_0(w)$ and the starch granules dispersed in them as $d_0(s_2)$ (they are of the same order of magnitude as the cells), so that the formula is $D_3(S_1) \setminus (d_0(s_2) \supset d_0(w))$: the IUPAC symbol @ used for inclusion in the DSF is replaced by the inclusion symbol $\supset$.

3. Rankings in order of complexity

For many purposes, in scientific research and in technology, it is useful to classify the studied systems in order of increasing complexity, as it is logical to study the simplest before the most complicated (Descartes, 1637). Many measures of complexity have been proposed in the past (Wiesner and Ladyland, 2020), but quantitative measures of complexity can quantify only aspects of complexity rather than complexity as such.

In 2004, for example, a CDS ranking of French

Table 2. IUPAC definitions for simple dispersed systems (IUPAC, 2025). The official definition of emulsions does not give the meaning of O ("oil"), W ("water"), and "/" (dispersed into).

Colloid:
A short synonym for colloidal system.

Colloidal system:
The term refers to 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.

Emulsion:
A fluid colloidal system in which liquid droplets and/or liquid crystals are dispersed in a liquid. The droplets often exceed the usual limits for colloids in size. An emulsion is denoted by the symbol O/W if the continuous phase is an aqueous solution and by W/O if the continuous phase is an organic liquid (an 'oil'). More complicated emulsions such as O/W/O (i.e. oil droplets contained within aqueous droplets dispersed in a continuous oil phase) are also possible. Photographic emulsions, although colloidal systems, are not emulsions in the sense of this nomenclature.

Suspension:
A liquid in which solid particles are dispersed.

Gel:
Non-fluid colloidal network or polymer network that is expanded throughout its whole volume by a fluid.
Notes:
A gel has a finite, usually rather small, yield stress.
A gel can contain:
- a covalent polymer network, e.g., a network formed by crosslinking polymer chains or by non-linear polymerization;
- a polymer network formed through the physical aggregation of polymer chains, caused by hydrogen bonds, crystallization, helix formation, complexation, etc, that results in regions of local order acting as the network junction points. The resulting swollen network may be termed a thermoreversible gel if the regions of local order are thermally reversible;
- a polymer network formed through glassy junction points, e.g., one based on block copolymers. If the junction points are thermally reversible glassy domains, the resulting swollen network may also be termed a thermoreversible gel;
- lamellar structures including mesophases, e.g., soap gels, phospholipids and clays;
- particulate disordered structures, e.g., a flocculent precipitate usually consisting of particles with large geometrical anisotropy, such as in V2O5 gels and globular or fibrillar protein gels.

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classical sauces was proposed, after an optical microscopy study of the 451 sauces (This, 2004), and 23 CDS categories were found (Table 3). At that time, the formulas were listed in increasing length of their formula (number of symbols), without making differences between first and second order phases, without taking the nature of phases into account, and without taking the dimensions of structures into account.

Later calculations limited to surface tension were used to rank the DSF operators (This, 2017; This vo Kientza, 2021) while alphabetical order was used for the phases. Using this ranking, gels and suspensions were determined, and grouped in "classes" of growing complexity (This vo Kientza, 2022). For example, gels with only one liquid phase in the solid phase (e.g. NDSF formula $D_3(S) \times D_3(W)$) were classified as class 1; gels with two liquid phases in the solid phase (e.g. NDSF formula $D_3(S) \times [D_3(W) \setminus d_0(o)]$ were classified as class 2. Introducing now the NDSF is an opportunity to set up a rational and unique way of ranking the systems in order of complexity.

Various quantitative parameters have been proposed in different sciences, for measuring the complexity of sequences of symbols, or chains, such as NDSF formulas (Shiner *et al.*, 1999; Adami and Cerf, 2000; Li and Vitanyi, 2008; Wiesner and Ladyman, 2020; Rebout *et al.*, 2021). A classic measure of complexity is the Kolmogorov-Chaitin complexity, which is based on the compressibility of chains (Kolmogorov, 1965; 1983; Chaitin, 1966; 1975). Chains are intermediate between perfectly regular chains and perfectly random, incompressible chains. A string is regular if the algorithm required to produce it on a universal Turing machine is shorter than the string itself. For example, the string 1010101010 can be reduced to the description "repeat the pattern 10 five times". More generally, Kolmogorov complexity for a string *s* is defined (within the limits of long strings) as the length, in bits, of the smallest programme *p* that produces the string *s* when implemented on a universal Turing machine T:

$$K(s) = min(|p|:s=C[T](p)) \quad [1]$$

where $|p|$ is the length (in bits) of the programme

Table 3. Physical formulas of classical French sauces (This, 2008), ordered by increasing length of CDS formulas. Here, as in the IUPAC definitions of colloids, O stands for "oil" (non-aqueous liquid), W for "water" (aqueous solution), / for "randomly dispersed into", S for "solid", G for gas.

W
O
O/W
W/O
S/W
(W/S) / W
(G + O) / W
(O + S) / W
(O + (W/S)) / W
(S + (W/S)) / W
(O + ((G+O)/W)) / W
(G + O + S) / W
(O + S + (W/S)) / W
(O + S + (G/W)) / W
(O + S + ((G + O) / W)) /W
…

and where *C[T](p)* is the result of the execution of the programme *p* on the Turing machine T. The Kolmogorov complexity is only defined if one takes into account the number of instructions that need to be added to the programme in order to simulate any other computer, but it is accurate within the limits of infinite chains.

A link between automata theory and information theory was quickly observed when the relationship between Kolmogorov complexity and entropy (in the sense of information theory, Shannon and Weaver, 1964) was discovered: for a source, which is a discrete random variable X with n symbols, each symbol x_i having a probability p_i of appearing, the entropy H_b of the source X is defined as:

$$H_b(X) = -E[\log_b(P(X))] = \sum_{i=1}^{n} (p_i \log_b(\frac{1}{p_i}))$$

$$= -\sum_{i=1}^{n} (p_i \log_b(p_i)) \quad [2]$$

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where E denotes the expected value, $\log_b$ the logarithm to the base b (with a base 2, the unit of entropy is the bit). In this case, $H_b(X)$ can be interpreted as the average number of yes/no questions that the receiver must ask the source, or the amount of information in bits that the source must provide to the receiver so that the latter can unambiguously determine the value of X. Adaptations of entropy have been proposed to take into account the particular environment of symbol strings (Adami and Cerf, 2000). In particular, it has been observed that random strings have zero complexity because they are devoid of information.

However, as with previous measures of complexity, these proposals do not take into account the physical and chemical relationships between phases: for sure the NDSF codes are chains of characters, but the systems corresponding to formulas have characteristics that must be taken into account when classifying them in order of increasing complexity.

In the discussion on measuring information using entropy, no energy is considered, even though it is crucial for creating dispersed systems such as emulsions, foams, gels, suspensions, etc. For determining a complexity parameter, the main phenomena to be considered are: (1) the energy of division, (2) the increase in surface energy, and (3) the increase in entropy. Some more observations have to be done:

1. The NDSF formula of a particular system can be found only after the choice of the reference size. But when the question is classifying systems, the reference size can be set arbitrarily; it needs only to remain the same for all formulas.

2. Physicochemical systems can comprise a very large number of different phases, but the description is limited to those whose quantity (mass or volume) is of the first or second order.

For example, mayonnaise sauces (e.g. 5 % aqueous phase, 95 % oil) may contain a few air bubbles, but these should not be considered first: the sauce is mainly composed (in descending order of composition) of oil and an aqueous solution. In other words, within the limits of negligible quantities, the proportions of ingredients will not be taken into account, otherwise there would be no point in a ‘topological” description of the systems.

3. Again for phases, the description is limited to those that are of the order of magnitude of the reference size, or of the first lower orders. For example, egg yolk consists of granules dispersed in a plasma (Anton, 2013), and these granules may remain in the final sauce, but they will not be taken into account in the NDSF formula for mayonnaise sauce with a reference size of 0.1 mm, which is limited to two scales: to describe the emulsified $D_3(W) \setminus d_0(o)$ structure, it is necessary to ‘see’ the oil droplets, whose diameter is in the order of 10^{-6} to 10^{-4} m; in other words, because the microscopic field that allows the emulsified structure to be seen is 10^{-4} m, the granules are too small to be visible, and therefore should not be described.

4. Complexity increases with the number of phases: a single-phase system is less complex than a two-phase system, and a two-phase system is less complex than a three-phase system, etc.

5. The nature of the phases only comes into play after their number, and in the order S, W, O, G, because there is more order (low entropy) in a solid than in a liquid, and even less in a gas. For ranking water and oil, it can be considered that water is more associated than oil. Therefore, the order will be S, W, O, G.

6. The degree of complexity does not depend on the quantities or sizes of the various phases. For example, a 90 % oil $D_3(W) \setminus d_0(o)$ emulsion has the same complexity that a 80 % one.

7. The change in phases is much more profound, in terms of free energy, than the change in forms (mathematical dimension). The dimension (D_3, D_2, D_1, D_0) therefore comes into play in complexity after the nature of the phases and after the description of the

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operators (last, therefore).
8. About these, it was calculated that superimposition σ corresponds to less complexity than inclusion ⊃, in part because of surface energy, but mainly because of the energy needed to dip a phase B into a phase A (in particular, buoyancy for liquids).
About intermeshing of two phases A and B (A x B) and random dispersion A \ b, a network calculation shows that the surface energy is of the same order of magnitude, but the random dispersion corresponds to only one phase at the first order of magnitude, while the intermeshing involves two phases at this order. This means that A \b systems have to be considered less complex than A x B systems.
As a conclusion, the number of phases is the main criteria for ranking. Then there are orders to be found for (1) phases (order S, W, O, G), (2) operators (σ, ⊃, \, x), (3) dimensions (D_3, D_2, D_1, D_0). For only one phase, the ranking is S, W, O, G. This phase can be D_3, D_2, D_1, but it would not make sense for it to be D_0.
As D_3 objects are more favourable in terms of energy and entropy (blocks have less surface / volume ratio than sheets and wires, not to mention dots), the final order is:
D_3(S), D_2(S), D_1(S)
D_3(W), D_2(W), D_1(W)
D_3(O), D_2(O), D_1(O)
D_3(G), D_2(G), D_1(G)
For 2 phases or more, the same principles for ranking are proposed.

Conclusion

The DSF has been taught for many years, at various university levels, because it is a tool for understanding physical dispersed systems and for innovation. Any formula can be made into a real physical system, with special physical and chemical properties, but also biological properties (sensory, nutritional, toxic, etc.) when the systems are interacting with living organisms.
No error was found in the DSF, but the new formalism, NDSF, should make the learning of the use of the formalism easier, because it offers a more systematic description, from the largest structures to the smallest. It should as well help the students to have the reflex of using the descending approach for the analysis of formulated systems such as food. Finally it can give a way of organizing systems in order of increasing complexity.

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