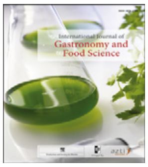

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The engineering inside our dishes

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Abstract

For an engineer the real value of a product is not in its molecular composition but in the intrinsic properties derived from the structure that is formed. Nobody cares about the molecules in a cellular phone except that they have to be arranged to receive and emit calls in reliable form. In the case of foods this brings the focus to the "engineering inside the product" rather than on the process engineering of mixing, drying, heating, freezing and so on, which has been the traditional realm of food engineering.

The objective of this article is to introduce food scientists, chefs and amateur cooks to basic concepts and terminology used in food materials science, and to give examples of the engineering inside what we eat.

Keywords: Cooking; Engineering; Taste; Microstructure

Introduction

The structures we eat as foods are derived directly from nature, transformed by processing or developed in the kitchen as recognizable meals and dishes. In fact, our senses are adapted to perceive and identify the unique properties of such structures in the form of appearance, texture, juiciness, sound, etc. Although the scientific study of cooking has traditionally concentrated on chemical and physico-chemical aspects, in the last decades much interest has arisen in understanding the formation and stability of food structures from the materials science viewpoint (Donald, 2004). Advances in this direction have been favored by the availability of powerful microscopes and analytical techniques that probe into the molecular mobility and localized mechanical and rheological properties.

By food microstructure we understand the spatial arrangement and interactions of identifiable elements in a food, whose sizes are $<100\ \mu m$ (Aguilera and Stanley, 1999). Fig. 1 shows several important structural elements related to foods, their approximate sizes as well as the sciences behind the phenomena at each length scale. The dimensions from molecules to products span almost eight decades. It is unfortunate that most of the structural engineering inside our foods occurs at sizes below 100 μm, being invisible to the naked eye.

For a physicist the range between the molecular size and the macroscopic scale is typical of soft condensed matter, or matter in a state between a liquid and a crystalline solid. At these dimensions molecules may participate in the formation of emulsions, viscous polymer solutions, gels and glasses. Thus, foods can be classed as soft matter but their multi-component nature and complexity set them apart from other forms of soft matter present in our daily life (Mezzenga et al., 2005). One important characteristic of soft matter is that some molecules tend to self-assemble, a first step in the formation of food structures. Thus, some ingredients such as surfactants and globular proteins may spontaneously associate into micelles or gels, respectively, given the right conditions.

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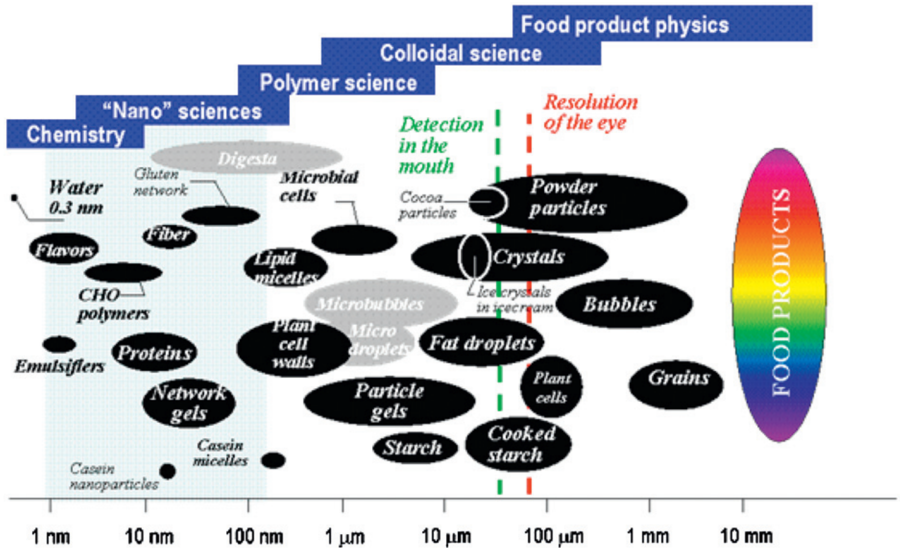

Fig. 1. Important structural elements related to foods and their approximate sizes. Dotted lines show the upper limit for particles to go undetected in the mouth and the minimum size that can be resolved by the naked eye. Gray area is the size range of nanosciences.

derived from the structure that is formed. Nobody cares about the molecules in a cellular phone except that they have to be arranged to receive and emit calls in reliable form. In the case of foods this brings the focus to the "engineering inside the product" rather than on the process engineering of mixing, drying, heating, freezing and so on, which has been the traditional realm of food engineering. One example illustrating this point are liquid dairy cream and whipped cream. Although the initial composition is the same, whipped cream being a foam and having air (which is not considered as an ingredient) dispersed as bubbles is a product with a higher value when it comes to decorating cakes and desserts. There are many other examples where the composition of foods is not a good predictor of their properties, but only a source of molecules to be exploited in making delicious structures.

The objective of this article is to introduce food scientists, chefs and amateur cooks to basic concepts and terminology used in food materials science, and to give examples of the engineering inside what we eat [a glossary of gastronomy and engineering terms may be found in Alicia and elBullitaller (2006)]. The reader who wants to get serious on the subject of food materials science, its principles and applications, is referred to the book edited by Aguilera and Lillford (2008).

The engineering that cannot be seen but can be tasted

Interestingly, in reviewing the classic text on food and cooking by McGee (2004), the term structure is profusely used to describe the anatomical parts of organisms (that later will become foods) as well as the internal portions of processed foods as seen with an electron microscope. Engineering concepts such as stability of the structure of whipped cream (reinforced at the bubble interface by fat globules), the plasticity and elasticity of wheat dough, etc, are also referred to. This is a tacit recognition that a food "structure" is apparent to food scientists and cooks alike. People in referring to foods during mastication also use a terminology that is related to their structure: tough meat, grainy sauce, soft beans, etc.

In a first approach a food may be regarded as a building, a structure possessing many architectural elements made of different materials (e.g., glass windows, wooden doors, ceramic tiles, etc.) inserted within a continuous frame. Fresh plant foods derive most of their desirable properties from a structure formed by cells (around 100 μm in size) glued together by a complex pectin gel to make a tissue or organ. A thick wall, which is basically a polymer composite reinforced by cellulose fibers, surrounds each cell and provides resistance. Turgor, important in texture, is derived from the osmotic pressure exerted by the solutes in a solution that fills a vacuole inside the cell. Animal cells (e.g., muscle fibers), on the contrary, do not have walls and rely on an internal support system formed by proteins and encasing membranes to keep the cell's (in this case, fiber's) contents.

This construction analogy may be used to explain softening of tissues during cooking. Heating of grains and legumes swell the hydrated starch granules inside cells making them tender, but most of all, it solubilizes the cement binding cells together. Upon biting on a soft cooked bean individual cells slide one past the other, much in the same way as bricks stacked one on top of the other would fall in absence of mortar after being pushed. In a tough bean on the contrary, cells remain bound and mastication has to fracture the cell's content, which is equivalent to tearing down a wall made by bricks held by mortar. Meats also become tender by cooking when the collagen surrounding the fibers is solubilized.

Many processed foods may contain pores or air cells, crystalline and glassy phases, particles, oil droplets, etc, dispersed in a basic matrix (Fig. 2). The "architecture" in

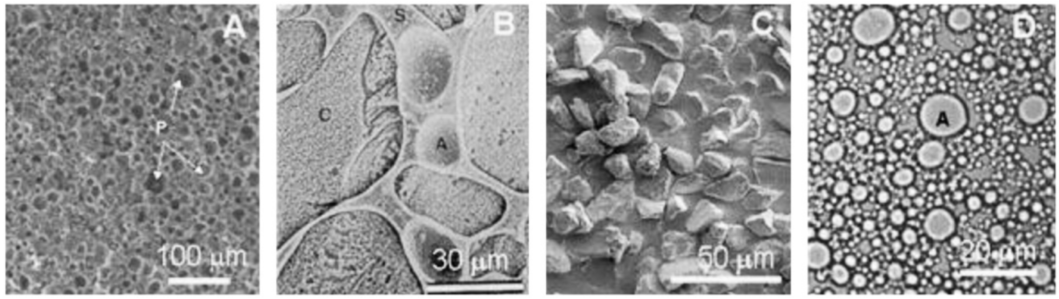

Fig. 2. Examples of the microstructures of some processed foods. (A) Freeze-dried instant coffee (P=pore); (B) ice cream (C=ice crystal, A=air, S=solution); (C) milk chocolate showing particles of cocoa, powder milk and sugar (courtesy of Dr. P. Braun, Buhler AG) and (D) mayonnaise (A=oil droplet).

foods is represented by the size, number, distribution and interactions between these elements that are critical to the identity and properties of each food. Let us take lyophilized instant coffee as an example. A glassy matrix of polysaccharides encapsulates and protects the valuable volatile aromas, while interconnected pores permit rapid rehydration of particles in contact with hot water, solubilization of the matrix and the release of aromatic molecules. The size of surface pores also affects the color of the product as larger pores reflect less light making the coffee particle to look darker. In the case of chocolate, particles have to be ground to less than 40 μm in size (around half the diameter of hair) otherwise they would be detected in the mouth as ''sandiness''. In turn, cocoa butter has to crystallize in the right form, (''tempered'') or the snap and gloss of a chocolate bar would be impaired.

But the analogy between foods and buildings, or for that matter, any other product of our daily life (watches, computers, cars, clothes, etc.) fails short of being always valid. Industrial products are *designed* and built using technological knowledge so they deliver the expected benefits. Their parts or elements are constructed from an ample array of materials and assembled piece by piece according to a precise sequence of steps dictated by blueprints and a Gantt chart. To build a car more than five thousand different parts have to go in specific places and interact in precise ways: some have to slide, other to rotate, several provide rigidity, but all of them must last for many years. In contrast, ice cream was never designed, its ingredients are limited and critical elements, such as ice crystals, develop in different sizes and shapes during freezing of the whole mass. Ice crystals have a finite life in the freezer and the structure of ice cream has to fail in the mouth to provide a creamy and cooling sensation while releasing flavors and aromas. A ''designed'' ice cream would probably start by making small and equally-sized ice crystals and then adding them to the rest of the components.

It was only a few decades ago that food scientists started viewing food as structures and materials. This came about at realizing that food components – mainly water, proteins, carbohydrates and fats – by themselves could not explain the richness of textures and tastes of foods with similar composition. Although each component undergoes a series of changes during cooking (which are not different from those that they experiment in test tubes in the laboratory), it is in the interactions among them where most of the variability arises.

Nanotechnology and microtechnology of dairy products

It is remarkable that the wide assortment of dairy products is based principally on two building blocks: proteins (the casein micelles and globular whey proteins) and fat globules. In turn, casein micelles (ca. 300–400 nm in size) and fat globules (few μm in diameter) are a notable example of food nanotechnology as they are assembled inside the mammary cells of the cow's udder and released individually into the lumen where in conjunction with the globular whey proteins, lactose and minerals and other minor components form the milk. Thus, milk is as close to a ''designed food'' as we can think of: right nutrients in the form of versatile assemblies.

Emulsions (cream), foams (whipped cream), gels (yoghurt), a plastic solid (butter) and cheeses of many textures, among other dairy products, are the result of the interactions of these two types of elements (Fig. 3). Some interactions are driven by chemistry, as the gelling of casein micelles by the action of enzymes, while others are the result of surface phenomena (adsorption of whey proteins onto fat globules), or plain physics (grouping of fat globules denuded of membranes by mechanical action in butter formation).

Materials science in the kitchen

A most disregarded fact, but with important consequences, is that the foods we eat are rarely in equilibrium. A note before abandoning this section. Salt and table sugar are two ingredients in the crystalline (equilibrium) state and will remain like that for centuries if isolated from the environment. That foods are unstable is obvious for living tissues eaten raw, such as fruits and vegetables, which continue respiring after harvest and of meat and fish that suffer biochemical changes (not to mention microbiological decay). But approach to equilibrium is also apparent in foods that are served at temperatures above or below

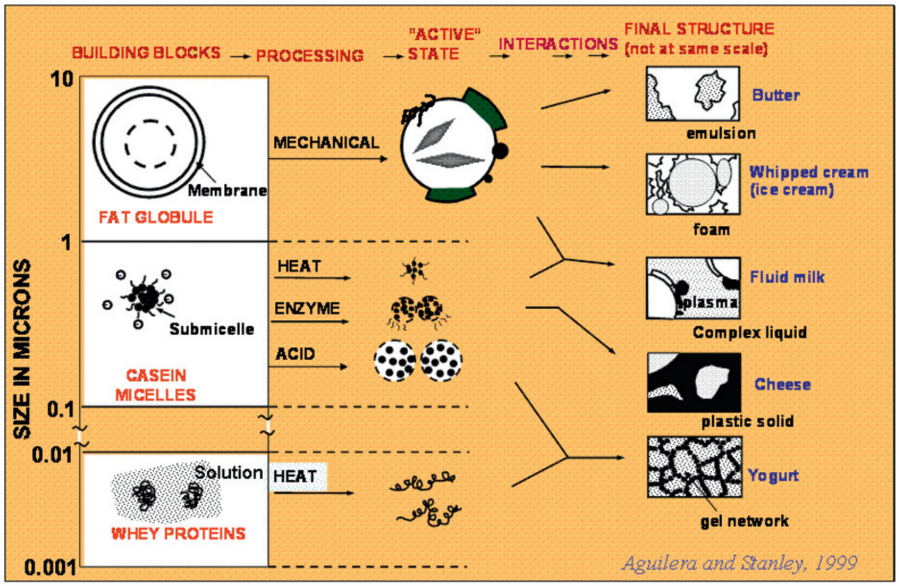

Fig. 3. The development of microstructures in dairy products. All is based on the interactions of 3 building units: casein micelles, whey proteins and fat globules.

room temperature (e.g., hot plates and ice cream) that continuously exchange heat with the surroundings, thus, changing not only their temperature but the sensorial properties as well. Similarly, dry crunchy foods such as potato chips turn soggy and bread becomes dry by gaining and losing moisture to the neighboring atmosphere, respectively. More subtle are the cases of baked products becoming stale, food foams collapsing and emulsions separating into two phases upon storage. Notice that there is not major chemistry involved in the last examples, just a physical rearrangement of the components into a state of lower energy.

Prolonging the stability of foods requires introducing a "barrier" opposing to the inevitable change. Process engineering makes use of external barriers such as a plastic foam package to isolate a warm food, or an impermeable plastic film to keep moisture out. Edible films have been suggested to separate wet and dry portions of a food (e.g., in sandwiches) thus retarding moisture migration. Of course, instability related to chemical kinetics can be controlled to a certain extent by lowering the temperature or modifying the atmosphere around the product.

But in the kitchen the physical stability may be extended by introducing the barrier opposing change "inside the product". In emulsions oil droplets with clean interfaces are subject to coalescence but large molecules or particles if positioned at their interfaces preclude their coming close together. Another alternative is to reduce the mobility of the system by increasing the viscosity of the continuous phase (e.g., adding a thickener). This and other cases require a good understanding of the role of thickeners, surfactants and other additives at the molecular and colloidal levels. For example, stabilizing an O/W emulsion requires a different type of surfactant than a W/O emulsion and in either case the amphiphilic molecule must migrate fast to the interface. Similar knowledge of the specific action of additives is required for the case of controlling fat blooming in chocolate, delaying staling of baked products, or avoiding caking of powders, among many other cases. Physics also dictates that a foam with uniform size bubbles (e.g., a monodispersed size distribution) is more stable than one having a mixed population of sizes. Frozen foods may appear to be stable in the domestic freezer (-18 °C) within the usual storage period between purchase and consumption, but they are not. Although separating water as ice reduces the reactivity of the system, the maximal stability is only attained when the remaining concentrated solution becomes vitrified (which in the case of fruits and vegetables occurs at around -40 °C).

Thus, producing metastable or unstable structures is inherent to cooking. The extreme case may be the soufflé, whose short life after removal from the oven is explained by the law of gases: as temperature is reduced, the pressure of air decreases and water vapor condenses, thus, the volume starts to diminish. On the contrary, hard candies made of amorphous sugar may be stable for years without becoming crystalline (the equilibrium state), if protected from humidity.

It is characteristic of foods that several structure-building phenomena, from the molecular (e.g., protein denaturation) to the macrostructural level (formation of air cells), occur more or less simultaneously. Thus, it is the relative kinetics of many events that drives structure formation in foods. Fig. 4 shows how temperature influences some of the transformations that major food components may undergo. As can be imagined, in a mixture of ingredients held at a certain temperature several phenomena may take place simultaneously. For instance, in the oven the proteins in a dough may become denatured, while starches undergo gelatinization and the water vapor

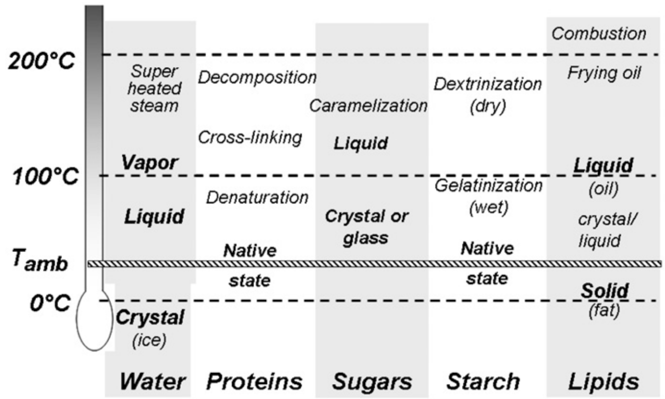

Fig. 4. Effect of temperature on phase changes, state transitions and some reactions of major components in foods. T_{amb}=ambient temperature.

released from the mass can be entrapped as air cells. Moreover, external transfer of heat originates temperature gradients within the product, thus, the rates of change will vary according to the position. At a certain point in time a structure sets in immobilizing the whole system. Besides temperature other variables may affect the kinetics of structure formation, among them, pH, ionic strength and the presence of certain ions. The microstructure of gels made of globular proteins varies depending on pH and ionic strength, hence, their properties: weak or strong, opaque or transparent, etc. A case in point is that of solutions of casein and whey proteins that may yield soft creamy gels or firm gels depending on the concentration of calcium.

It has been mentioned in the case of dairy products that the interaction between food components provides additional possibilities for structure development. Proteins and polysaccharides in solution may form association complexes through interactions of parts of the macromolecules having opposite charges. In addition, separation into a protein-rich phase and a polysaccharide-rich phase is not uncommon for concentrated solutions of this type of biopolymers. The disengagement of phases is generally slow, thus microstructures with different morphological characteristics may be "frozen" during the approach to equilibrium, for example, by gelation.

The state of "glass", taken from polymer physics, is the quintessential synonymous of a metastable condition for sugars, polysaccharides and some proteins in foods. Technically, a glass is formed when a pure liquid is cooled so rapidly that molecules are trapped as a solid occupying almost the same positions as in the liquid phase. Something similar occurs when water is removed from a sugar solution at a fast rate, as is the case of spray-dried products. Molecular mobility in the glassy state is significantly reduced, hence, food powders, crackers and pasta products exhibit excellent stability while they remain dry. Glassy foods have low moisture and are hard and brittle, emitting acoustic signals when fractured that are typical of crunchy foods. Unfortunately, glassy foods are avid for moisture and upon absorbing humidity from the atmosphere they become rubbery losing most of their desirable characteristics.

Salt and table sugar are two ingredients in the crystalline (equilibrium) state and will remain like that for centuries if isolated from the environment. But it is well known that some seeds remain viable (i.e., they can germinate) after being stored for long periods of time, meaning that they were "stable". Nature has engineered these seeds so that under low moisture conditions a glassy matrix made of sugars protects the genetic material and the enzymic machinery inside them.

What is ahead

In a sense, the processed food industry of the XX century was successful in providing low-cost, convenient products that continue to appeal to a large segment of the population. However, some of these foods (those so-called *junk food*) if consumed repeatedly may not be adequate for the present sedentary lifestyles and alternatives are urgently sought after to combat overweight and obesity. Here is an opportunity to design foods that are less calorie-dense than their highly demanded counterparts but equally tasty, since it is in human nature that what we eat has to be pleasant to our senses. Examples of improved products are most "light" versions of traditional foods. A second area where product design and engineering is likely to contribute is in the protection and target delivery of bioactive components and beneficial bacteria that have proven to be beneficial for our health.

At the other extreme are a growing minority of people around the world interested in eating well and experiencing novel sensations. They are open to new formats in cooking and enjoy the creativity and boldness of modern cooks. Some of the most reputed chefs are known to have their own laboratories or engage in associations with renowned scientists to bring innovation into their dishes. Edible films, cryogenic frozen desserts, foamed sauces, hot/cold gels, crunchy structures, artificial caviars, are just some of the proposals of the so-called *techno-emotive cuisine*. Again, there is a lot of engineering in these creations.

In academia, foods and gastronomy are becoming fashionable subjects that attract a multitude of students. An example of this trend is a new course at Harvard University bringing together famed chefs and eminent academics aiming to inspire students and advance kitchen science. In the words of David A. Weitz, Mallinckrodt Professor of Physics and of Applied Physics in the School of Engineering and Applied Sciences at Harvard "*much of what we do in the lab is what chefs like Ferran Adrià are now doing in their kitchens. Cooking provides an ideal framework to study a variety of complex phenomena—from basic chemistry to materials science to applied physics*".

As knowledge accumulates on the structure-forming capabilities of old and novel ingredients and how some of the complex microstructures of foods come into being, we will come closer to *designing* food structures for pleasure and health.

Conclusions

It is unfortunate that we cannot see the engineering inside our foods and dishes. It is like an architect being able to see only the outside of a house but not the layout of the rooms and the fine details of the decoration. In our mouths the engineering of foods is expressed in the breakdown of the food matrix, the release of flavors and juices and other multiple gratifying sensations. In our gut the structure of foods is likely to influence the bioavailability of many nutrients. For the first time in the history of foods and gastronomy a good body of scientific knowledge has accumulated that allows food technologists and chefs to design food structures for health and pleasure.

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