

# Biophysics of Molecular Gastronomy

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**Chefs and scientists exploring biophysical processes have given rise to molecular gastronomy. In this Commentary, we describe how a scientific understanding of recipes and techniques facilitates the development of new textures and expands the flavor palette. The new dishes that result engage our senses in unexpected ways.**

Molecular gastronomy's beginnings can be traced to the 1970s and an emerging curiosity about the scientific aspects of the foods we eat. As Nicolas Kurti, Professor of Physics at Oxford, famously stated, "It is a sad reflection on our civilization that while we can and do measure the temperature in the atmosphere of Venus, we do not know what goes on inside our soufflés" (McGee, 1984). Acting upon this sentiment and in collaboration with the physical chemist Hervé This, Kurti began to convene regular gatherings in Erice, Italy, bringing together professional chefs and scientists—among them, Pierre Gilles de Gennes, the Nobel prize winning physicist who popularized the study of physics of soft materials, as well as Harold McGee, who wrote the remarkable treatise "On Food and Cooking" (McGee, 1984).

This questioning of the biophysical basis of foods coincided with a burgeoning movement in the culinary world, spurred largely by the chef Ferran Adrià, who aimed to use emerging knowledge about the science behind recipes to rethink and reengineer foods and create new textures and tastes. Part of his program involved developing more precise methods for controlling cooking protocols, such as immersion heaters, rotovaps, and centrifuges. When these are applied to foods, a panoply of rich transitions are uncovered, leading to new textures and tastes.

The simplest example of creating new textures is the common task of cooking an egg. Chefs routinely cook eggs in boiling water, but an immersion heater allows cooking them at any desired temperature and observing sensitive changes in the texture that have been otherwise impossible to note. Which chef was the

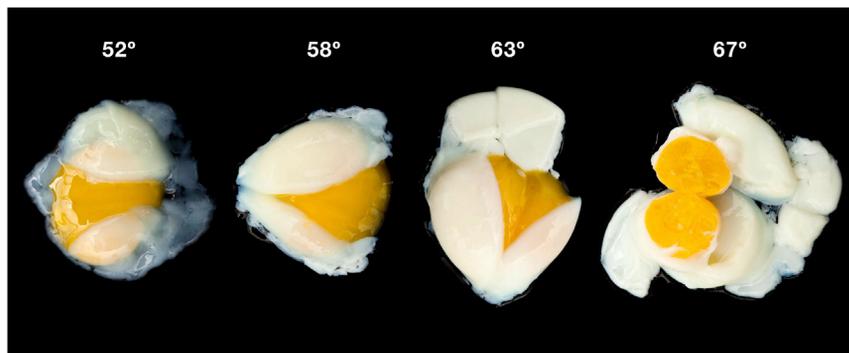
first to carry out precise temperature-controlled cooking on an egg is unclear, but a remarkable process was discovered: between 60°C and 70°C, critical biophysical transitions occur in chicken eggs; this is the range in which the different proteins within the yolk and white unfold. Strikingly, differences of less than 1°C lead to significant textural and structural changes. Indeed, a well-trained chef can predict the temperature of the water bath within a half a degree based on the texture of the egg, and eggs cooked even just a couple degrees apart have very different culinary applications (Figure 1).

At its core, the biophysical transitions that happen when cooking an egg are the same ones that biology regulates against: the unfolding and subsequent aggregation of proteins. Textures arise because denaturing proteins gradually expose previously buried fragments, enabling crosslinks to form between different proteins so that the protein mixture becomes a gel. As the temperature increases, more of the proteins are exposed, and the crosslinks become stronger and more numerous. This is due to both the continued unfolding of individual proteins and the ensuing unfolding of more stable ones. Microscopically, the unfolded proteins bond in complex patterns, and the resulting macroscopic texture arises from the nature of these arrangements. Thus, manipulating the crosslinked matrix by precisely adjusting the cooking temperature allows the control of macroscopic texture.

Several scientific concepts describe the macroscopic aspects of texture and how they relate to the underlying microscopic arrangement. One is quantified by the elastic modulus, which mea-

sures the resistance of the material to deformation. Roughly speaking, the elastic modulus  $E = U_{\text{interaction}} / \ell^3$ , where  $U_{\text{interaction}}$  is the binding energy between the crosslinks, and  $\ell$  is the typical distance between the crosslinks. The material thus becomes harder to deform when the binding energy or density of the crosslinks increases. Another aspect of texture is plasticity, which occurs when crosslinks easily remodel; a material with high plasticity will not recover its original shape when deformed. Yet another concept is the yield stress, which is the minimal stress that can be applied to the material for the crosslinks to break and the material to fracture. Soft condensed matter science has given a qualitative understanding of how these macroscopic properties are related to the microstructure of materials. But how they apply in detail to the intricate suite of textural transitions in an egg is not well understood; we do not know how the microscopic structure of the egg's crosslinked interior changes as a function of temperature nor how the different parts of egg proteins contribute to the final texture. Importantly, we also don't know which physical properties correspond to the mouthfeel of a food.

These questions are not just academic: for example, if the biophysics of the transitions in an egg were better understood, it might be possible to redesign the egg to have different properties as it is heated. One could imagine mixing different concentrations of the protein constituting egg whites to manipulate the textural transitions, or mixing egg proteins taken from different organisms with distinct denaturation and aggregation properties. Moreover, tuning individual proteins to prescribed macroscopic



**Figure 1. Eggs Cooked at Different Temperatures in a Temperature-Controlled Water Bath** Even small differences in temperature result in significantly different textures. Image courtesy of *Modernist Cuisine*.

properties could have utility well beyond cooking.

Another aspect of Adrià's culinary revolution involved introducing new ingredients. One such set of ingredients are molecules called hydrocolloids, which can be used to create new textures in the form of different types of emulsions, foams, and gels, all hallmark components of the modernist kitchen. A particular explosion occurred with gelling agents, a subgroup within this category, which mostly consists of carbohydrates. Whereas a century ago, the major gelling agent in Western-style kitchens was gelatin derived from animal collagen, today's chefs routinely use gelling agents derived from a diverse range of organisms that allow control of texture and properties in new regimes. These ingredients include methylcellulose, xanthan gum, agar, and gellan, each having distinct biophysical properties that differ from the standard gelling agents. For example, whereas gelatin gels between 4°C and 35°C, methylcellulose gels between 50°C and 90°C. This property, allowing creation of a hot gel, led to Adrià's invention of hot ice cream, which has the same texture and rheology as ordinary ice cream but only when served at high enough temperatures. Similarly, spherification, one of Adrià's signature dishes and characteristic of molecular gastronomy, also makes use of a gelling agent: alginate, a polymer found in sea weed, which forms crosslinks with calcium ions, resulting in a thin gel that encapsulates a sphere of liquid flavor (Figure 2A). Another example is gellan, derived from the bacterium *Pseudomonas elodea*, which has both a high

melting temperature and also a low yield stress. This material enabled Heston Blumenthal to create a famous dish, hot and cold tea (Blumenthal, 2009), in which a glass of tea is divided into two halves: the left half is served cold, whereas the right half is served hot. Gellan strengthens the gel sufficiently to separate the two halves of the tea cup but breaks up immediately upon pouring. The textures of the two teas are identical, allowing the consumer to simultaneously taste hot and cold tea on different sides of the tongue.

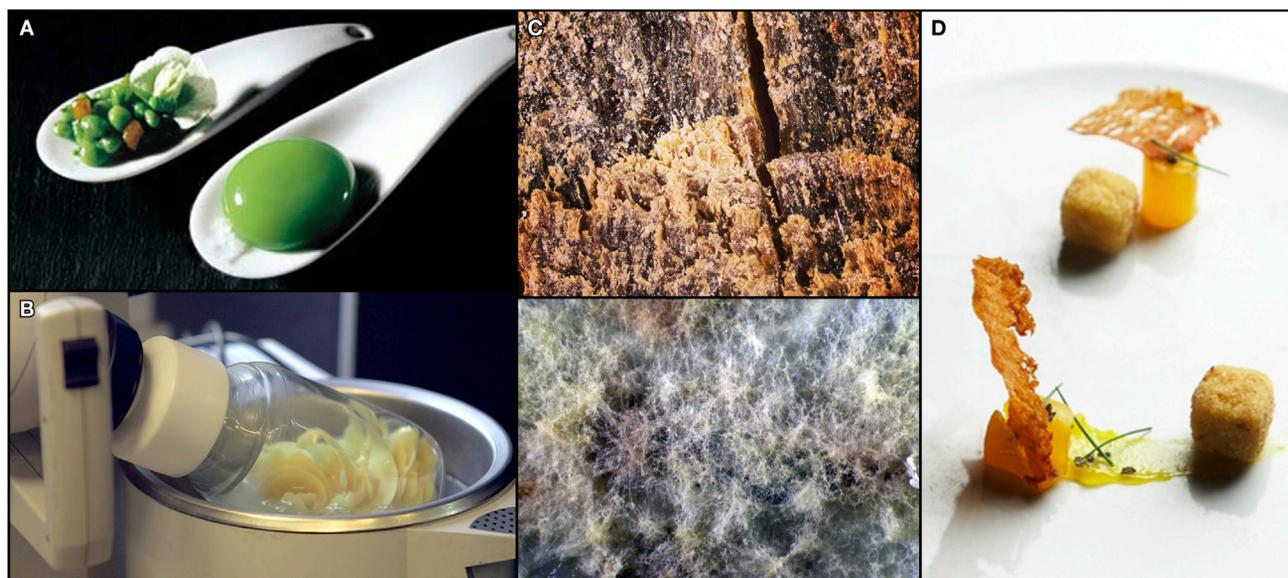
To date, chefs have capitalized on the tremendous diversity of gelling agents produced by organisms in the natural world to create a wide range of foods in new parameter regimes. There is much room for further creativity, with increased understanding of why the different gelling agents work as they do. For example, one could imagine engineering organisms to produce gelling agents with distinct properties.

Thus far we have discussed culinary manipulations of food texture; the second major aspect of cooking affected by the culinary revolution is flavor. Flavor arises from the combination of several sensory experiences—most notably, the thousands of taste receptors on our tongues and the olfactory receptors in the upper nasal passages. While the number of tastes that can be experienced by humans are limited to the well-known five—sweet, salty, sour, bitter, and umami—we can sense orders of magnitudes more smells. Flavor compounds tend to be small molecules, and in the case of olfaction they are also volatile, which allows them to be transported

from the food to the nasal passage. While many flavor molecules exist as preformed compounds in the cooking ingredient and are released when the tissues of foods are damaged, as is the case with the pungent molecules in mustard seeds, others are formed during the cooking process through the application of heat, mechanical force, or other procedures. This is the case for many fruity aromas, which are created when tissue damage releases enzymes that react with molecules in fruit cells to produce esters.

There are three noteworthy methods for producing small flavor molecules in modern haute cuisine. The first is to capture and concentrate them. Modernist chefs use a variety of techniques to extract, isolate, and concentrate flavor and aroma molecules, many of which draw on methods and equipment from biology and chemistry laboratories. These range from filtering to centrifugation to vacuum infusions. For example, Nathan Myhrvold uses centrifugation as a way to isolate flavorful carotene butter from carrot juice and laboratory sieves and agar filtering to concentrate purees and soups (Myhrvold et al., 2011). One of the most popular pieces of equipment for isolating and concentrating flavor is the rotovap. Long a stalwart of chemistry laboratories but introduced in the last decade into high-end cooking, rotovaps allow gentle, low-heat separation of certain molecules based on their volatility. Thus, compounds that would easily boil off or decompose at standard boiling temperature can be captured and served as part of a dish. For example, Joan Roca, of the restaurant Can Roca in Spain, uses a rotovap to capture the flavor molecules of eucalyptus leaves and citrus peel, both consisting of molecules that easily vaporize and disappear; the distillates are then used as a base for sorbets and other cold desserts (Figure 2B). Roca also uses the same technique to make a gel from distilled forest soil, which he then serves with an oyster, creating a completely novel flavor combination that would be impossible to achieve without the rotovap.

A second method for producing flavor is creating small flavor molecules through chemical reactions. Aspects of this practice have clearly been a part of cooking long before the advent of molecular



**Figure 2. Examples of Dishes from Modernist Cuisine**

(A) Ferran Adrià's spherified pea ravioli. Image courtesy of Ferran Adrià.

(B) Joan Roca's rotovapped citrus peel. Image courtesy of Blua Producers.

(C) Close-ups of David Chang's pork bushi, a novel take on the Japanese fermented fish known as katsuobushi. Image courtesy of Momofuku.

(D) Wylie Dufresne's deconstructed dish, eggs benedict. Image courtesy of Takahiko Marumoto.

gastronomy—simply heating or cutting into foods can initiate chemical reactions—but recent developments in techniques and equipment have not only brought advances in this field, but have also suggested further potential for discovery. One example is the diversity of flavors produced by caramelization and Maillard reactions. Caramelization denotes the decomposition of sugars at high heat, whereas Maillard reactions result from complex reactions initiated by amino acids reacting with sugars. Both reactions are highly temperature and pH sensitive and must be carefully controlled not to result in strong and bitter flavors. However, if correctly manipulated, these reactions contribute to the complex flavors of diverse foods ranging from steak to maple syrup to champagne. Modernist chefs found ways to enhance these effects using pressure cookers, which not only speed up flavor production, but also produce more intense flavors. Though Maillard and caramelization reactions create marvelous results even with a relatively modest knowledge of the underlying chemistry, both could potentially be deconstructed and controlled even more carefully, with the opportunity of isolating novel flavors

from the plethora of flavor molecules resulting from these reactions.

A third method of producing new flavors in foods is fermentation, which relies on microbes breaking down large molecules in vegetable and animal products, such as proteins, carbohydrates, and fats, into an array of much smaller molecules. Fermentation is an age-old method of producing intense, complex, and incredibly diverse flavors: coffee, soy sauce, cheese, chocolate, wine, and vinegar—the contemplation of almost any list of fermented foods is a telling illustration of the powerful relationship between fermentation and flavor. In many cases, flavor production is the primary purpose of the fermentation reaction, such as in soy sauce and traditional fermented fish sauces. But in other cases, the flavor molecules are delicious byproducts of what might be taken to be the primary goal of the process. For instance, in wine production, where the preserving and intoxicating properties of ethanol from glucose drive the fermentation, it is the myriad enzymatic byproducts that create the complex and nuanced flavors of wine.

A relatively recent trend in haute cuisine is the experimentation with fermentation reactions to create new foods. David

Chang, for example, works with unconventional combinations of foods and microbes to create new recipes, such as pomegranate seeds with lactic acid bacteria, commonly used in dairy fermentations, or locally grown farro with *Aspergillus oryzae*, a mold traditionally used in Asian cuisines for miso and sake production (Figure 2C). The design and characterization of such novel fermentation processes are still in their infancy but hold much potential as a field for further discovery.

We hope that we've succeeded in bringing across the message that the biophysical properties of molecules underlying cooking provide much interesting fodder for scientific inquiry. The culinary revolution has, however, pushed this notion further, and the design of new dishes has itself become a highly experimental enterprise. In the process of optimizing the incorporation of new ingredients and equipment into the kitchen, chefs experiment in ways similar to scientists. Failure of a given idea gives rise to new ones, eventually leading to creations that might not even be related to the original idea. Heston Blumenthal described this process in the context of creating the recipe for hot and cold tea as involving “endless trials” and

“infinitesimal precision” (Blumenthal, 2009). This is an attitude to cooking that sticks to this day and is apparent in many aspects of molecular gastronomy. For example, a common theme in modernist kitchens is the frequent and complete overturn of the menu preceded by intense periods of research and experimentation. Ferran Adrià initiated this trend at his famed restaurant elBulli, which closed for 6 months of the year while his team withdrew to a workshop in order to exclusively focus on the creation of next year’s menu. Interestingly, the emphasis on culinary experimentation not only expanded cooking into the realm of science, but it also allowed it to take on characteristics from the arts. With the realization that new ingredients and equipment do more than simply offer an opportunity to tweak traditional recipes, chefs began exploring the creation of uniquely novel dishes. These creations

play on the faculties of all senses, including notions of emotions and memories evoked by tastes and aromas, our expectations of food, and the element of surprise as a dish turns out to be something different from what it appears to be. As an example, a common theme in the modernist kitchen is the deconstructed dish, which separates the components of a familiar recipe into individual pieces with novel and imaginative textures. Wylie Dufresne’s take on eggs benedict, which consists of deep-fried hollandaise sauce served with concentrated egg yolk shaped into columns, is an example of this approach (Figure 2D). Another common theme is playing with the diner’s expectations by presenting foods that look different from what they are. Accordingly, Joan Roca famously serves an ice cream dish that is indistinguishable in shape from that of a cigar, and José Andrés of the restaurants Jaleo

and minibar uses spherification to make eggs in which the white has been replaced by a rich solution of parmesan cream.

In summary, the past two decades have seen an emergence of striking complementarity between the methods, ideas, and culture of the culinary world and basic science. The chef’s goal of transforming the properties of cells and proteins into another form is complementary to scientist’s efforts to understand them. There is much left to be learned at this intersection.

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