Cooking With Computers: The Vision of Digital Gastronomy

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The Food and Agriculture Organization (FAO) of the United Nations lists the main challenges in feeding 10 billion people in 2050 [8]. Many aspects of our food systems need to be improved, as today we waste around one-third of the food we produce. One way to minimize food waste is to rely on dry substances in the form of powders, which have a longer shelf life than fresh products and are easier to store.

As the food industry evolved after World War II, new ingredients were developed, moving toward more control over the mass production of food items. Many of these ingredients are produced and stored as powders, are fully homogenous in their nutritional values and molecular structures, and serve a specific cooking purpose, such as special sugars and salts, proteins, vitamins, acids, gums, carrageenan, alginate, lecithin, agar, and traditional substances such as flours and spices.

These modern ingredients have a significant role in improving our management of food waste. New composed formulas of mixed powdered ingredients can be nutritionally tuned to satisfy nutritional objectives [15]. For example, nutrigenomics is a recent research trend that studies how personalization of nutritionally oriented diets can "unfold the role of nutrition on gene expression" [28]. The nutrigenomics vision is that everyone will consume exactly what they need nutritionally, based on their medical and genetic records.

Hence, the movement to improve the efficiency of food supply and storage systems, minimize waste, and satisfy personal nutritional needs presages a future gastronomical horizon relying on more processed food than today, increased usage of dried powders, and new cooking technologies in order to efficiently produce personalized food. Although many 3-D-printing technologies rely on powders [22, pp. 65–84], as do most 3-D food printing technologies [21], [23], computational technologies will likely play a growing role in tomorrow's kitchen, from applying 3-D printing (as well as other digital fabrication technologies) to cooking, to relying on optimization methods for better use of ingredients, and personalizing diets using data science.

In contemporary fine dining, chefs hybridize a wide spectrum of techniques, presenting a culinary experience that goes beyond eating *per se* and demonstrates how traditional cooking mixes with modern scientific methods to achieve new flavors

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and esthetics [37]. Digital tools can allow us to calculate the nutritional content of ingredients or accurately affect cooking-related chemical reactions, and thus fit dishes to personal preferences. Indeed, there have been a growing number of projects recently that bring digital technologies into the kitchen, in the form of food printers [5], [10], [17], [41], robotic cooks [4], [6], [13], [20], [32], [35], and theoretical research on the semantics and procedural relationships in recipes [16], [25], [34]. Yet, the potential of computers to enhance our culinary culture is still awaiting its bloom. The kitchen is more than a territory for digital augmentation seeking efficiency and control: it is a place where culture and meaning evolve [2], and creativity is celebrated [14], inviting a deeper observation of the connection between DF and cooking.

Recent digital gastronomy (DG) projects [26], [39], [40] center on the integration of digital fabrication technologies into the kitchen so that they can influence our cooking and dining experiences. These projects conceptualize future gastronomy that considers food from a wide perspective, with the means to enable personal creativity and control in the preparation of food. At the center of this gastronomical vision, DG proposes a human-centered cooking practice, where chefs lead future culinary trends in order to balance the art and culture of cooking with tomorrow food challenges and requirements [12], and develop a new design space envisioning ways for us to manipulate food digitally.

A kitchen that features traditional and modern cooking tools side-by-side with digitally controlled equipment is envisioned, all part of the creative palette of the cook, seeking integration between traditional cooking and digital tools. To bring this vision to practice, several engineering challenges are present. First, there is a need to seed computational cooking into a technological and theoretical ground for a coherent research vision. In addition, computational cooking necessitates a vast engineering effort to develop computational methods and interaction technologies to digitally produce food.

I. BACKGROUND

The AI and HCI communities have long shared a growing interest in studying how to integrate computers into tomorrow's kitchens[1] [1], [14]. The focus, here, is on research activities that focus on making food with computers and digital fabrication facilities, aiming to achieve local control over the flavor and esthetics of food, to put new creative capabilities into the hand of cooks.

A number of recent products using 2-D fabrication techniques have enabled digital applications of patterns to food elements, such as digitally printing pancakes [30] or digitally dyeing cappuccino foams [36]. The use of laser cutting machines with food has been explored as well [11], [18], preceding additional work on laser inductive heating for selective Maillard reactions [24]. Blutinger *et al.* [3] have used blue lasers coupled with an infrared laser to demonstrate heat penetration of dough products.

Beyond 2-D techniques, 3-D food printers can "manufacture food products with customization in shape, color, flavor, texture, and even nutrition" [33]. From NASA research on additive food manufacturing in space [27] to the 3-D Food Printing Conference [41], research and development of 3-D food printing is on the rise [5], [10], [23], [42]. One of the promising trends relates to printed meat supplements from nonliving sources, as proposed by companies such as Jet-Eat [19]. A different direction by Wang *et al.* [38] demonstrates shape-changing noodles that transform from 2-D sheets to 3-D shapes when they interact with water during the cooking process. Sushi Singularity[2] is a restaurant initiative by Japanese conceptual design studio Open Meals, which promise to customize novel structures of 3-D printed sushi, based on dinners' genetic information and dedicated computer-aided design (CAD) tools. Prior HCI works [26], [40] infuse computational tools into the cooking process via an interactive scheme. In addition to 3-D printing, the first robots have already been integrated into operational restaurants [6], [13], such as the AIC-AI cooking robot that cooks preprogrammed Chinese food [35], and a fully autonomous robot ramen restaurant in Nagoya, Japan [20].

A special lab-kitchen features standard digital fabrication devices, such as a 3-D paste printer, laser cutters, milling machines, and 3-D scanners, together with custom parametric design procedures. These projects center on a practice in which the cook leaves some of the elements (parameters) of the dish unfixed. When diners order their meals, they can fix these elements based on their personal nutrition and taste preferences. This results in hybrid recipes that combine the advantages of manual and digital cooking; merge parametric design tools, digital fabrication techniques, and traditional cooking; and introduce digital practices to chefs by integrating new capabilities into the kitchen.

II. COOKING WITH COMPUTERS: TECHNICAL CHALLENGES

Potentially, computers can contribute to cooking in several ways. Computers can allow the chef to digitally control the flavor, structure, and esthetics (FSA) of each dish by providing local control over the composition

[1]For examples see the "Cooking with Computers" workshop at IJCAI 2013, the "Multimedia for Cooking and Eating Activities and Multimedia Assisted Dietary Management" workshop at IJCAI 2018, and the "Crafting and Tasting Issues in Everyday Human-Food Interaction" DIS/C&C 2019.

[2]Scheduled to open in 2020, http://www.open-meals.com/sushisingularity/index_e.html

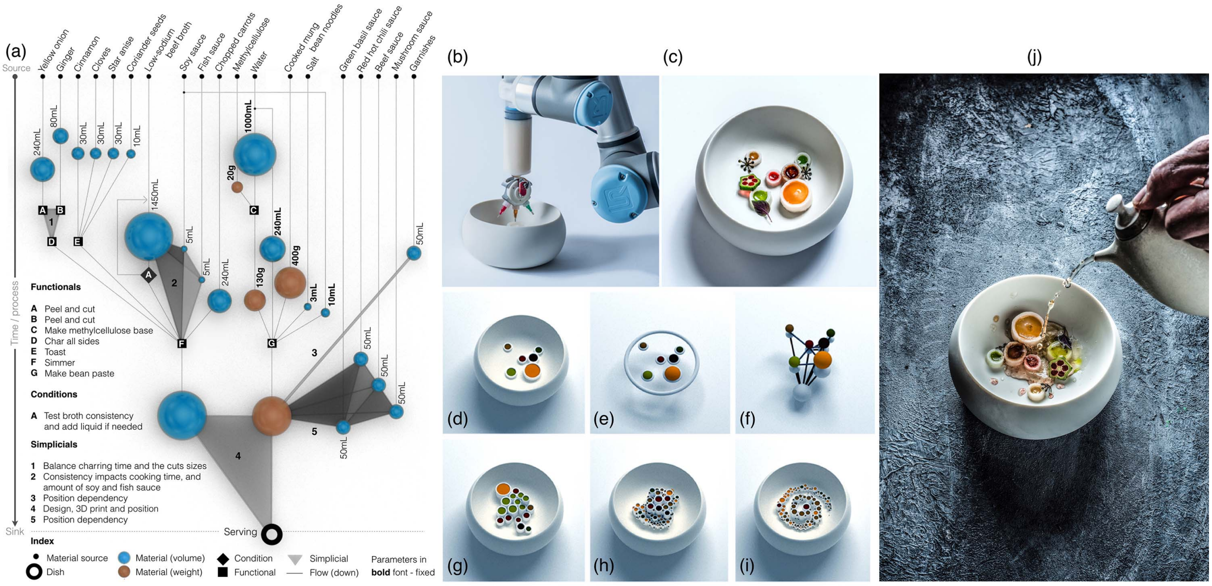

Fig. 1. ***(a) SF model for a segregated pho soup featuring a variations DG principle. (b) Photograph of a robot arm printing noodle pools using bean paste. (c) Photograph of printed pools with flavor liquids. (d)–(f) Various abstraction levels of the design model. (g)–(i) Potential pool designs demonstrating patterns and varying resolutions. (j) Photograph of a final dish being prepared.***

of ingredients in a dish. Computers can ascertain the best way to design food that is constrained by the quantity of its ingredients and determine the best way to distribute these ingredients, considering the FSA as defined by the chef to satisfy diners' preferences.

A parametric model for a dish will enable numerous interpretations of a single metarecipe with high degrees of freedom (DOF). Such a model needs to solve the problem of balancing two-dependent criteria while cooking: 1) determining the quantity of ingredients in the dish and 2) determining the distribution of these ingredients and how it impacts the FSA of the food. Hence, to enjoy the potential of computational cooking, five main areas of investigation are identified: 1) developing food- and recipe-representation models; 2) developing and integrating new digital cooking agents; 3) developing dedicated interactive software; 4) deploying and evaluating computational cooking in real restaurant settings and kitchens; and 5) developing a hybrid (digital–traditional) culinary experience, including a complete interactive scheme, recipes, and dishes. Let us focus on the first three points as they hold the main engineering challenges of computational cooking.

A. Theoretical Framework

A recipe is a set of instructions for preparing a particular dish, including a list of the ingredients required [26], [29]. Usually, this list of ingredients is a fixed set of materials and quantities. However, dishes hold the potential to express many variations on the final flavors and esthetics and to satisfy different requirements from different chefs, cooks, and diners. To explore the full potential of computational cooking in the construction of dishes and recipes, there is a need to formally (digitally) represent both cooking procedures (recipes) and final results (dishes). A unified model for digital representation will allow a coherent research paradigm to organize research in the field, and an easy interface for collaboration between engineers and chefs.

1) Three-Dimensional Dish Design Problem: Generally, the representation of a final dish, or the arrangement of ingredients in a given space, resembles 3-D graphic models, with several differences. In addition to esthetic (visual) qualities that can be described by a given color system, food elements contain flavor, which is composed of taste, mouth-feel, and aroma [7]. Let us define a *flavor_voxel* as an element in 3-D space representing a value on a regular grid, such that flavor_voxel = *function*(color, taste, mouth-feel, and aroma), while mouth-feel is a function of mainly texture and temperature. The size and shape of a flavor_voxel depend on the specific cooking method, i.e., the regular grid is a function of the fabrication technology.

A *flavor_structure* is a spatial arrangement of edible material with unique flavor characteristics in the dish. In a dish having two or more flavor_structures, a chef can assemble *flavor_patterns*—i.e., control how flavor structures contribute to a dish, thus introducing the ability to control changes in the flavor while dining. To manage the digital design of a dish with complex flavor_patterns, numerous flavor_structures, and flavor_voxels, a parametric design procedure is needed.

Fig. 2. *Photograph of a final segregated flavors soup dish with 3-D printed noodle pools.*

2) Unified Dish-Recipe Model: One can explain recipes procedurally using flowcharts (see [4] and [25]), which allow the use of the same framework for all recipes, and can be easily used to describe and control cooking procedure, including hybrid procedures merging manual functionalities with digital and automatic ones. A simple cooking flowchart may include ingredient elements (in either volume or weight), functionals (manipulations on the ingredients), condition elements (checking whether the results of the previous step meet required culinary states), and spatial dishes or tool elements with a specific geometric model (that condition the special arrangement of ingredients). The relationship between food (or ingredients) and the dish can be described using a parametric design model, satisfying esthetic and dining requirements set by the cook.

Traditional recipes describe a set of ingredients with constant quantities, and a dish can be described as a point in the ingredients' space. However, from a culinary perspective, one can define dependence functions between ingredients to allow DOF in recipes: for example, flour, yeast, water, sugar, and salt have a complex interaction with the gluten connections in a dough, so that changing one element will affect the rest of them and the product. One can easily imagine a recipe being described as a function of ingredients with DOF rather than set quantities. Although static recipes cannot represent such complexity, a computer program can easily do so, envisioning a reality where a chef, together with a computer scientist, builds recipes based on kitchen experiments and constructs a high DOF function.

To allow a model to represent cooking procedures (flowchart) while permitting recipes DOF and describing a complex interaction between the diagram's elements (vertices), merging flowchart representation with an additional topological model, a simplicial complex is suggested.

Formally, a simplicial complex K in $\mathbb{R}^n$ is a collection of simplices in $\mathbb{R}^n$ such that 1) every face of a simplex of K is in K and 2) the intersection of any two simplices of K is a face of each of them [31]. In the data structure, a simplicial complex used to describe the interaction with elements in any dimension, comparing to a graph representation that describes only 2-D interactions with its arches [9]. Fig. 1(a) shows a high-level hybrid simplicial flowchart (SF) model, demonstrating a basic implementation of a metarecipe.

Let us now look in more detail at the implications of the new cooking principles: variations, progressions, and morphing, which together realize the deeper contribution of computers in rethinking dishes and recipes.

Theoretical Framework (Digital Gastronomy Principals): To highlight the creative potential of DG and the SF model, three digital cooking principles, each focusing on a different quality enabled by the new cooking territory, are considered.

First Principle (Variations): In a realm where a recipe is being extended to a wide opportunity space, a dish-domain presents numerous possible instantiations for the same metadish. When a chef can define the relationship and dependencies between cooking elements, each diner can have a personalized product based on personal preferences and needs. To visualize such a principle, Figs. 1 and 2 show a version of pho soup. The broth was segregated to basic liquids, which are reassembled into special 3-D-printed poollike beam noodles. Traditional pho contains several distinct flavors (mixing acidity introduced by lime, freshness introduced by green leaves, MSG and salt introduced by soy or fish sauces, and spiciness introduced by chili peppers). Hence, the basic pho flavors were segregated and reconstructed to achieve many varying instantiations of the same soup metarecipes.

Second Principle (Progression): A programmable modular mold can be used to achieve a variety of shape variations for a recipe, relying on several distinct flavors (sweet, sour, and bitter tastes) and colors, allowing the control of *flavor structures* in the dish by genetic algorithm (see Figs. 3 and 4). The mold not only overcomes the slow production time of 3-D food printing but it also allows for a high DOF in numerous shapes produced. This flexibility can potentially satisfy chefs' and diners' diverse requirements while demonstrating how flavor_structures can give chefs a powerful tool to control the diner's temporal experience by spatial progression on the flavor_patterns. The procedure exploits a new digital cooking concept of programmable flavor structures and patterns to enrich user interaction with a given recipe.

Third Principle (Morphing): Flavor transitions can be planned, controlled, and used to morph one dish into another to create a journey of taste transformation (see Fig. 5) through

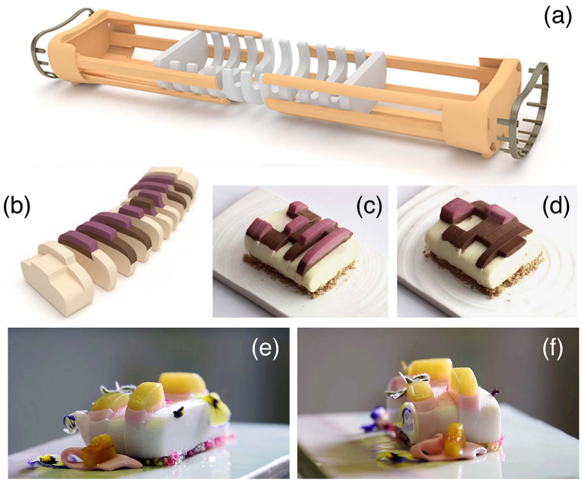

Fig. 3. *(a) Illustration of a modular casting mold. (b) Illustration of the flavor_pattern evolving in the dish. (c) and (d) Photographs of two different desserts featuring bitter, sweet, and acidic flavors constructing a flavor_pattern. (e) and (f) Additional desserts made using the same process with banana gelatin.*

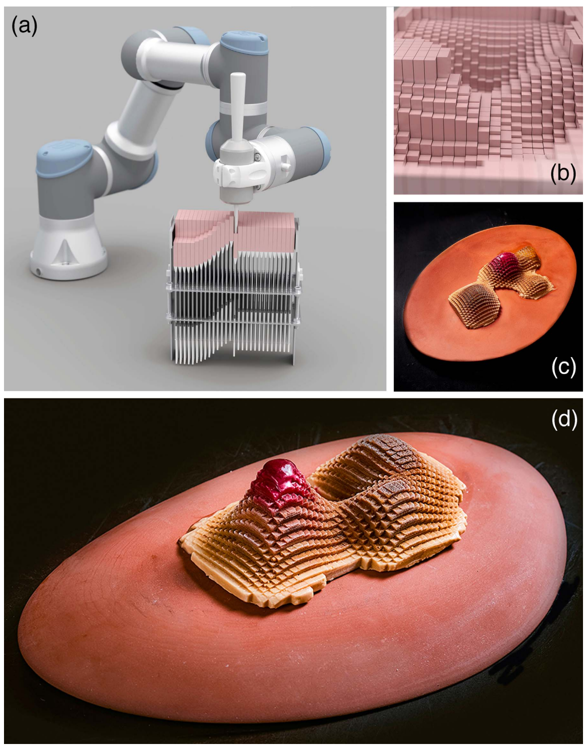

Fig. 4. *(a) Illustration of a robot arm modifying a programmable silicon mold. (b) Mold. (c) and (d) Two versions of a mousse dessert, exemplifying the potential of the modular mold.*

meticulously planned placement of (discrete) ingredients that provide a visual hint of the taste escalation taking place on the plate. Black and red quinoa, baked beetroots, purple onions, yellow and red bell peppers, chilies, and herbs are dressed with a cardamom espresso vinaigrette. This quinoa recipe contains various Latin American elements that progress and change throughout the dish. Although this example was hand-made, future research will integrate digital procedures into similar dish concepts, to fully deconstruct the traditional paradigm into a new gastronomical concept.

B. Hardware: Digital Cooking Machines

In the DG project, a single robotic arm is used as a multiresolution edible paste 3-D printer, developing inks for the printer in the form of edible pastes mainly made out of rice, mung beans, and methylcellulose. A major challenge encountered was the printing speed, which was addressed by developing a multiresolution print head that allows the user to change the printing resolution within the same print and adjust it to the currently printed part.

Unlike standard DF machines, a robotic arm is a multipurpose device and can be used for many different cooking tasks, which makes it a fundamental technology in the computational cooking vision [4], [6], [13], [20], [32], [35]. As the tool-path of the robotic arm is controlled, integrate several arms working together can be integrated on the same dish while restraining them from collisions (each arm is responsible to a different functional vertex in our SF model). This allows work in parallel: for example, while one arm 3-D prints a food element, an additional arm can position ready-made elements in the dish, and a third arm heats parts of the dish with a laser. Hence, a workstation of multiple arms that can work simultaneously is envisioned. To realize such a multicapable station, there is a need to develop software to control multiple cooking robots, to prevent collision, prioritize tasks, and allow parallel food production.

C. Chef–Diner–Computer Interaction

To practically apply computational cooking in kitchens, there is an interaction challenge with the aim of enabling dish manipulations: 1) to globally personalize nutritional values

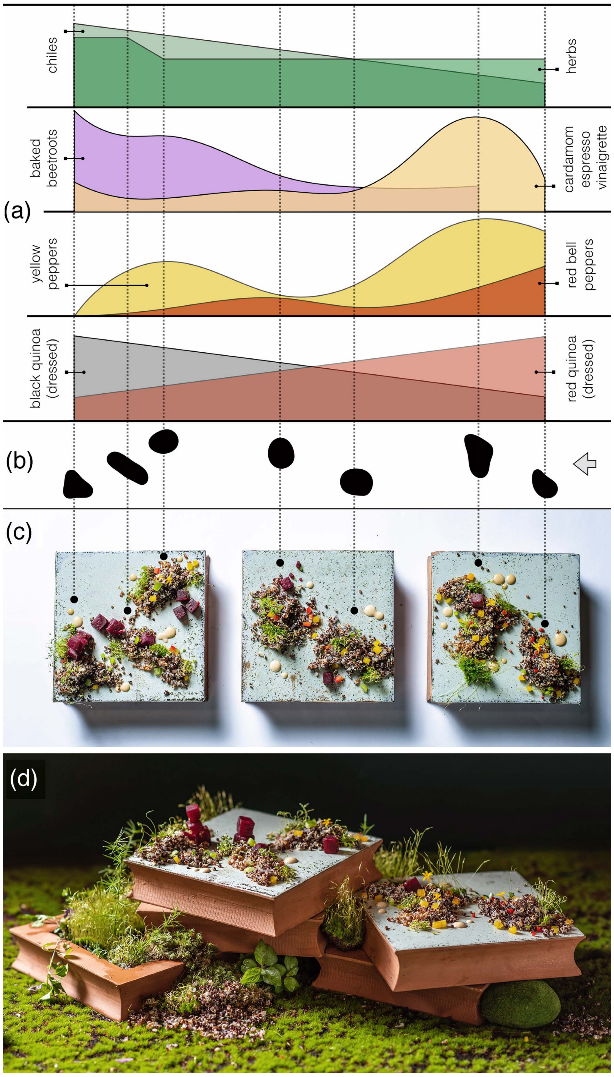

Fig. 5. ***(a) Deposition function of ingredients can be used to apply transitions between several flavor centers (b) by morphing one section into another to create taste transformation. (c) and (d) Final dish.***

and overall material quantities and 2) allow for the cook's creative modifications, which satisfies 1). Special consideration needs to be given to digital cooking technologies, as they will modify our definition of flavor_voxel and the overall quality of production.

Assuming a proper SF model is fully constructed, an applied interaction model between cooks (diners) and SF will be required. A simple model of interaction based on a reduced SF model that will allow real-time generation of numerous dishes from the metarecipe can be envisioned, to satisfy the cook's creative interpretation of a dish and satisfy the diners' personal preferences, nutritional needs, and quantity requirements. A real-time SW solution can modify and personalize the dish, while generating CAD and computer-aided manufacturing (CAM) output files and control instructions to computational cooking devices, as well as manual recipes integrated together in the hybrid cooking scheme.

There is, however, a special challenge in developing a parametric design representation for the dish that is integrated within the SF model, thus merging the interaction between recipe modification to the arrangement of a dish and its presentation. As one of the main contributions of computational cooking is the ability to control flavor_structures and flavor_patterns, an interactive SF model will need to take into account the dish's nutritional values, quantities, structure, and design. This is a challenging task, as the parametric design of a dish is set explicitly for that specific dish. Parametric design models, on the other hand, vary in their method of representation when defined geometrically [see Fig. 1(d)–(f)].

III. CLOSING NOTE

There is a high probability that computers will play a growing role in tomorrow's cooking practices, based on three observations: 1) there is an increasing trend by researchers and industry toward digitizing cooking using various technologies; 2) computers can help to optimize the use of ingredients and minimize waste; and 3) computers can help to tailor personal diets for users based on their health records and genomic data. Computers can help to minimize waste and personalize dishes by using ingredients with well-known nutritional values; relying on the long shelf life of dried ingredients; and giving chefs novel creative cooking tools to justify computational cooking from a culinary perspective.

In order for computers to enhance the traditional kitchen with new capabilities and expand the chef's creative palette, it requires not only rethinking recipes but also building them with a high DOF that relies on novel digital cooking principles, such as the use of dish variations, flavor pattern progressions, and gradual morphing of dishes. A parametrically generated dish-design model will determine the exact distribution of the ingredients to fulfill personal preferences as well as a distribution model, both mathematically determined by the chefs while they plan dishes and hybrid recipes. Hence, a chef and a computer scientist building recipes using SF models (or similar) can be envisioned, to later allow professional or domestic cooks to generate personalized dishes, meeting personal dining and health preferences. Moreover, using parametric design tools, we can achieve a variety of results from the same metarecipe and never repeat the serving exactly, even with the same constraints.

To guide computational cooking toward a human-centered creative practice that sustains traditional food culture side-by-side with new developments and opportunities, there are several cooking and engineering challenges. First, there is a need to continue and study how digital cooking machines and interactive design software can be integrated into hybrid kitchens to promote computational cooking. A theoretical framework is needed to allow the chef's new creative capabilities, controlling flavor patterns and structures, and featuring a new cooking language. Beyond the automation of cooking, the computational cooking vision focuses on the creative potential of computers for tomorrow's cooking; presenting new cooking principles, methods, theories, and interactive schemes; and developing a revolutionary yet grounded culinary practice and publicizing it to promote a human-centered, digital enhancement of culinary traditions. ■

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