Chemistry and Physics in the Kitchen

Bon appétit! *Scientists are beginning to understand how chefs accomplish their culinary masterpieces—and are making modest recipe suggestions of their own*

by Nicholas Kurti and Hervé This-Benckhard

Interest in the application of science to the art of cookery is growing. Cooks once regarded the introduction of scientific reasoning, let alone laboratory techniques, into their kitchens with suspicion, even with hostility. That time seems to be past. Nevertheless, both in restaurants and in domestic kitchens, many cooks tend to remain faithful to the grand culinary traditions and practices they were taught, without knowing why (or really even whether) those practices guarantee the best results. Thus, cooks add pinches of flour when heating custards to prevent them from curdling; they rigidly follow certain protocols in making soufflés; they generally do not vary the proportions of ingredients in their recipes, and so on. Perhaps for that reason, culinary superstitions and old wives' tales continue to flourish.

The mistrust of scientific explanations for culinary mysteries is all the more surprising given that music, painting, sculpture and the performing arts have prospered with experimental scrutiny and discovery. Science has improved the technologies for preserving, reproducing and disseminating works of art, which has led to a greater appreciation of those works by a wider audience. There is no proof that science and technology have compromised creativity in any way; they may even have helped it.

We believe it is the duty of scientists to acquaint culinary artists with principles and techniques that may stimulate their imagination, just as they have previously done for painters, composers and musicians. The time seems ripe for such an approach. Physics is beginning to explore the state of emulsions, suspensions, solid dispersions and foams—"soft matter," as physics Nobelist Pierre-Gilles de Gennes has called them—that often occur in cooking. Advanced structural chemistry can now elucidate the behavior of large molecules such as complex carbohydrates and proteins. New chromatographic methods make it possible to isolate the components of foods that give rise to tastes and smells. Scientific explanations are already appearing for many old and seemingly obscure culinary tricks.

In effect, a new discipline is being born: molecular and physical gastronomy, the science of food and its enjoyment. We would like to offer a small feast of discoveries from this field—concerning appetizers, main courses, desserts and beverages—that may be of practical value and interest to cooks. Several of our examples are drawn from discussions at the First International Workshop on Molecular and Physical Gastronomy, which we organized in August 1992 in Erice, Sicily.

A popular first course, *oeuf dur mayonnaise* (hard-boiled egg with mayonnaise), gives us the opportunity to examine the molecular and physical properties of emulsions. Mayonnaise, cream, butter and béarnaise sauce are all emulsions, in which droplets of one liquid are suspended in another with which it is immiscible.

Mayonnaise consists of vegetable oil, vinegar or lemon juice, and egg yolk. Because half the yolk is water, mayonnaise is actually an emulsion of oil in water. Ordinarily, no matter how thoroughly you whisk a mixture of water and oil, the two components separate into distinct layers. Mayonnaise is stable because the egg yolk contains so-called surface-active molecules such as lecithins. The two ends of these rod-shaped molecules have different properties: one is hydrophilic (it has an affinity for water), and the other is hydrophobic (it shuns water). Each oil globule in the mayonnaise



INSTANT ICE CREAM, produced by the vaporization of liquid nitrogen, is one of the culinary delights being created by a hitherto unused technique. The joint efforts of scientists and cooks are explaining why certain cooking practices work and, in some cases, how they can be improved.

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suspension is coated by at least one layer of lecithin, which allows it to mix freely with the aqueous medium because the hydrophilic part contacts the water while the hydrophobic part faces the oil. The droplets do not readily coalesce, because the hydrophilic ends protruding from their surfaces usually acquire small electric charges and consequently repel one another.

Cooks generally accept that one egg yolk can emulsify only 150 to 250 milliliters of oil. Yet that ratio is a gross underestimate, as Harold J. McGee, a writer on science and cooking, has revealed. Knowing that a yolk contains about two grams of lecithin and assuming that the oil droplets in a mayonnaise are one hundredth of a millimeter in diameter, he calculated that one yolk could stabilize 3.5 liters of



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oil—about 20 times the recommended quantity. The trick is to keep adding enough water, wine, vinegar or other aqueous solutions to keep the oil droplets separate.

McGee's work shows how science can extend the limits of a culinary process. We do not mean to suggest that one should abandon the traditional rule in favor of "one yolk per 3.5 liters," but the knowledge that it can be disregarded might sometimes prove useful. Suppose that a dinner guest desires an *oeuf dur mayonnaise,* but you can find only a single egg and no mayonnaise in the larder. With a hypodermic syringe, withdraw one milliliter of yolk from the egg, use that to make a tablespoon of mayonnaise and hard-boil the rest of the egg.

Some concerns have been raised, particularly in the U.S. and the U.K., about eating eggs contaminated by salmonella bacteria. In November 1988, for example, a junior minister at the British Department of Health made the exaggerated announcement that most eggs produced in Great Britain were infested with salmonella. Within a couple of weeks, egg consumption had dropped by one half, and several food writers were depicting a gloomy future devoid of soft-boiled eggs or fluffy omelettes.

One of us (Kurti), wondering whether scientific reasoning could avert this calamity, looked more closely at the problem of soft-boiled eggs. (We should note that the British soft-boiled egg has a soft but coagulated white and a creamy yolk, unlike the French three-minute *oeuf coque,* which is more liquid throughout.) He first ascertained that egg yolk coagulates between about 62 and 65 degrees Celsius and that salmonella organisms cannot survive more than a few minutes' exposure to 59 degrees C. A safe cooking method should therefore ensure that the temperature of the yolk never exceeds 62 degrees C but still remains between 59 and 61 degrees C for at least six minutes.

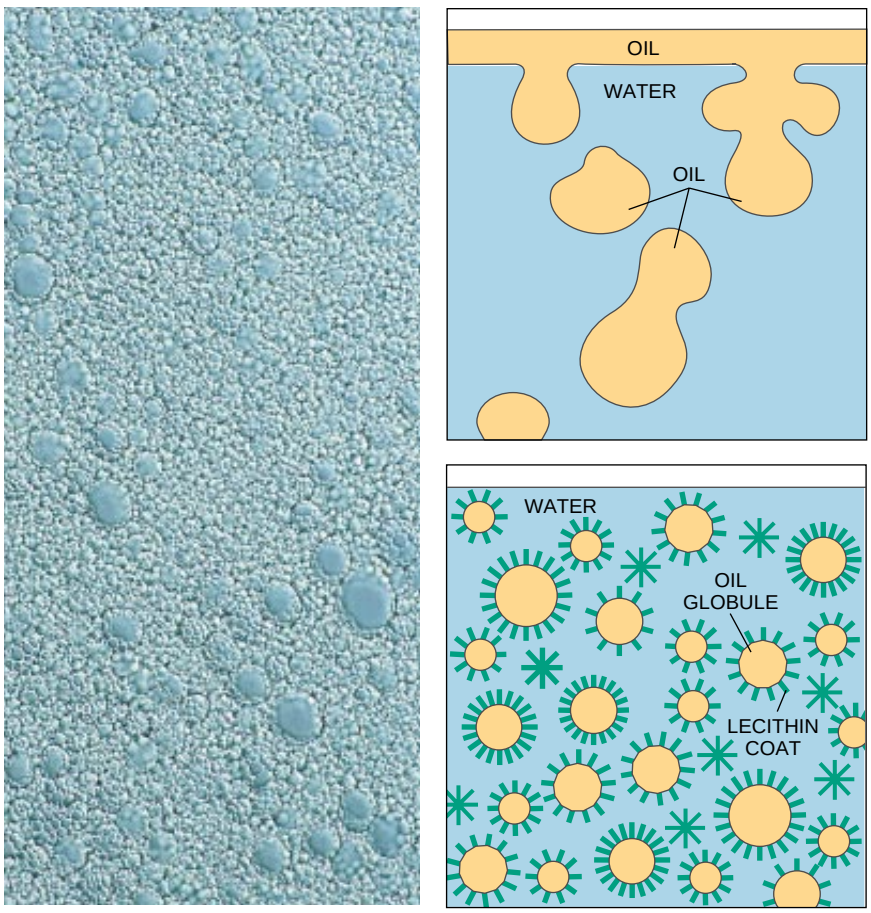
The temperature at the center of the yolk of an intact egg can be measured with a thermocouple, an electrical sensor whose output voltage varies with temperature. A fine thermocouple wire can be threaded through a hypodermic needle and anchored to its tip; the thermocouple can then be connected to a microvoltmeter calibrated in degrees C.

That instrument has made it possible to develop a recipe for turning a contaminated egg into a safe soft-boiled egg. First, place a 60-gram egg into boiling water for 3.5 minutes. As Richard Gardner and Rosa Beddington of the University of Oxford have shown, that immersion will cook the egg white to the proper consistency but will raise the yolk temperature to only about 30 degrees C. Second, immediately transfer the egg into a water bath at 60 degrees C. The yolk temperature will then gradually rise to 59 degrees C in another 7.5 minutes. Thomas J. Humphrey of the Exeter Public Health Laboratory has shown that eggs inoculated with one million *Salmonella enteritidis* organisms were rendered safe by this treatment after a total of 18 minutes of cooking.

Can any treatment make raw eggs safe for use in mayonnaise and other dishes? Yes, because the temperature that kills the salmonella is below that of yolk coagulation. Put the yolks in a bowl, then set the bowl in a water bath at 62 degrees C for about 15 minutes, giving the yolks an occasional stir. Alternatively, mayonnaise can also be made from hard-boiled egg yolks diluted with some vinegar (the coagulation of the egg does not destroy the lecithins). In fact, most French cookbooks recommend hard-boiled egg yolks for preparing *mayonnaise tartare,* which contains onion, capers and herbs in addition to the usual flavorings of vinegar, mustard, salt and pepper.

Despite such advances, some mysteries about cooking with eggs remain. For example, in the preparation of many foods—custard, zabaglione (egg punch) and various savory sauces thickened with egg yolks—the yolks must be heated in the presence of another liquid. Very commonly, however, these mixtures will curdle over the heat. As chefs have long known, a pinch of flour can prevent this problem. In Erice, researchers discussed the mechanism of the chefs' solution.

The curdling occurs because, in a watery solution, long protein molecules from the egg yolk are freed from some of the weak bonding forces (such as hydrogen bonds and sulfur bridges) that

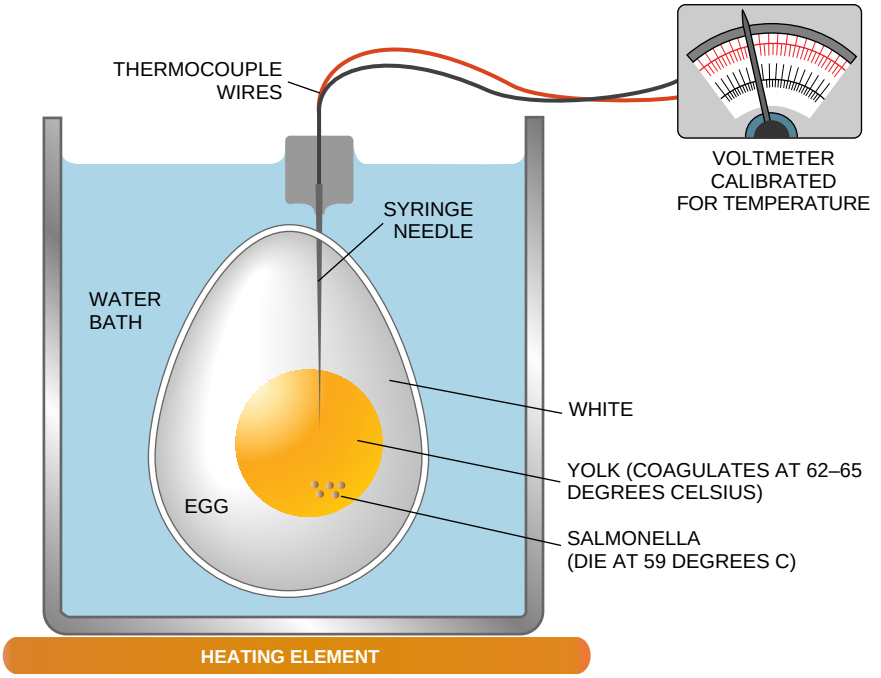


MAYONNAISE (*left, magnified 100 times*) is fundamentally a suspension of oil in water. Ordinarily, mixtures of oil and water separate into distinct layers (*top right*). Mayonnaise is more stable, however, because of lecithin in the added egg yolk. Because lecithins have one hydrophilic end and one hydrophobic end, coatings of lecithin can surround the oil globules and allow them to disperse in the aqueous solution (*bottom right*). The average size and size distribution of the oil drops depend on the proportion of the oil and the amount of whipping energy: as the amount of oil and whipping increases, the size decreases, and the range of diameters narrows.

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held them in specific coiled conformations. Sufficient heating makes the proteins denature, or uncoil, and then form new weak bonds with other molecules. When the proteins meet and aggregate into clumps, they form curds.

Flour can stop this clumping because its particles consist mainly of two types of starch: amylose, a linear polymer of the sugar glucose, and amylopectin, a highly branched polymer of the same sugar. At high temperatures, these starches fall away from the flour granule and dissolve. The long starch molecules seem to inhibit curdling by limiting the movements of the proteins and stopping them from aggregating. Experimental studies should confirm or refute this explanation. They should also help quantify how much flour is needed to prevent curdling and what kind of starch works best. The number of experiments that just this one phenomenon suggests underscores the huge amount of work needed to understand fully even simple cooking facts.



TEMPERATURE INSIDE an egg being cooked can be measured using an electrical sensor called a thermocouple and a properly calibrated microvoltmeter. Experiments using this equipment have made it possible to devise a recipe for soft-boiling an egg in such a way that any salmonella bacteria would be killed.

Let us now consider some more complicated cooking: the soufflé. This dish is a pleasure to eat, but its preparation can be like a walk on a tightrope. The ideal soufflé expands greatly during cooking and has a crisp outside encasing a fluffy, slightly creamy interior. The basic ingredients are beaten egg whites, a viscous preparation such as béchamel sauce (a cooked mixture of butter, flour and milk) and—often—egg yolks. Fish, cheese, chocolate and fruit purée are also sometimes added and become important parts of the soufflé structure; vanilla, liqueurs and other ingredients can be used purely as flavorings. Recipes vary greatly in the proportions of all these ingredients. But all cookbooks agree on the importance of mixing the viscous preparation and the beaten egg whites uniformly; they also emphasize that when cooks are dispersing the foam in the béchamel, they must take care not to break the myriad air bubbles.

Some chefs believe that after the soufflé mixture is ladled into a soufflé dish, it should go immediately into a preheated oven. Others say the mixture can be safely kept for an hour or so at kitchen temperature or in a water bath of 40 degrees C for up to 30 minutes. According to some reports, small, individual soufflés may be deep-frozen and defrosted before cooking. We recently experimented with all four of those techniques, using small, individual soufflés [see "The Kitchen as a Lab," "Amateur Scientist," page 120]. All of them gave acceptable results, but the soufflé placed in the oven right after the whisked egg whites were folded in came out best. We presume that the other methods allowed bubbles in the mixture to coalesce and to escape from the mixture.

Whatever its method of preparation, a soufflé must be served immediately because, if it has risen noticeably, it will begin to collapse within seconds or minutes after it leaves the oven. Although some details of a soufflé's rise and fall are shrouded in mystery, the general explanation is relatively simple. Some observers have suggested that when the viscous mass of flour and egg yolks is heated, the air bubbles expand and raise the soufflé. The coagulation of the eggs then makes the material between the bubbles rigid enough to prevent the soufflé's collapse—at least until the temperature drops. Yet the heat-driven expansion of the air could account for only about a 20 percent increase in volume, whereas a soufflé can rise to more than three times its original size. It is actually water vapor that inflates the soufflé, as can be readily demonstrated: cut open a cooked soufflé, and water vapor escapes.

The first measurements of the changing temperature inside a soufflé being cooked were made 25 years ago. A thermocouple enclosed in a hypodermic needle was anchored to the dish, its tip 20 millimeters below the surface of the soufflé at the beginning of the experiment. That work showed that during the first 10 minutes, the temperature inside a soufflé reaches about 45 degrees C. It then sometimes levels out (perhaps because of protein coagulation) and may even dip as the thermocouple touches cooler, uncooked parts of the mixture. After a further 25 minutes or so (the time depends on the size of the soufflé), the temperature again rises rapidly as the water quickly evaporates from the top. The rapid rise indicates that the soufflé is done. Amateur cooks who are not averse to the introduction of thermocouples into the kitchen may find the remote sensing of the soufflé's progress a convenient aid.

So far in our discussion we have mainly considered ways to understand various cooking processes rather than to improve their results. But there are cases in which even small modifications of traditional methods might produce changes in flavors. The concentration of a bouillon for the preparation of a *fond* is a good example.

A bouillon is made by boiling meat and vegetables in water. Aside from their value as foods themselves, bouillons also form the *fond,* or base, of many sauces. For that use, bouillons are boiled to reduce, or concentrate, them to one tenth or one twentieth of their original volume. But when you boil a mixture of chemical compounds, the composition of the vapor usually differs somewhat from that of the liquid. For instance, when you boil wine, a mixture

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of alcohol and water, more of the alcohol evaporates first. The difference between the vapor and the liquid depends on the heating temperature. Would a *fond* prepared by reducing a bouillon at 100 degrees C be different from one prepared at 80 or 60 degrees C?

At the Erice workshop, participants were shown a makeshift apparatus that demonstrated how a bouillon could be reduced at a lower temperature by lowering the air pressure. A glass jar containing bouillon was connected to a filter pump, and its internal pressure was lowered to half an atmosphere (or about seven pounds per square inch). At that pressure, the bouillon boiled away at a temperature of only 80 degrees C. A better apparatus is now being assembled to establish whether low-pressure cooking could have gastronomic advantages.

Before we proceed to our main course—a cooked meat—we must say a few words about heating. Traditional cooking embraces two basic methods of bringing heat to foods. One is to expose the material to a hot liquid (as in boiling, stewing, frying and sautéing) or to a hot gas (as in oven roasting and baking). When the molecules of the heating medium strike the surface of the food, they transfer their kinetic energy to it. In the second method, represented by grilling, electromagnetic radiation strikes the food and is converted into heat. In both cases, the heat reaches the inside of the foodstuff only through convection and conduction. Because different parts of the food being cooked vary in their exposure to the heat, the taste and texture are not uniform. Our enjoyment of a rare steak, a crisp bread roll or a fluffy omelette is greatly influenced by such temperature gradients and discontinuities in texture and composition.

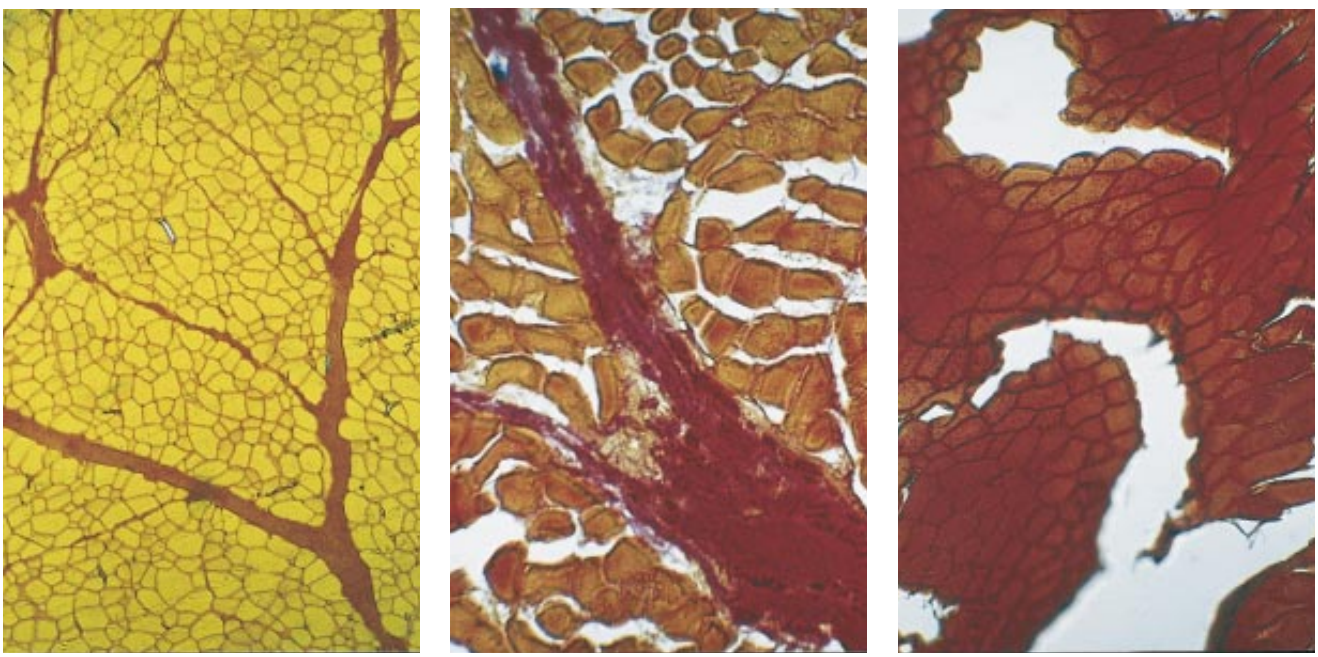
The possibility of heating the inside of a material without first heating the outside arose during World War II through a chance observation that microwaves of about a 10-centimeter wavelength could pass through considerable thicknesses of materials while giving up some energy as heat. The effect depends on the presence of polar molecules such as water, which are electrically neutral but carry asymmetrically arranged charges. Microwaves can make polar molecules rotate or oscillate; friction within the material converts that kinetic energy into heat. Ice does not absorb microwaves, because its water molecules are locked into crystals and unable to rotate. Thus, using microwaves, one can boil water inside an ice block or create an inverted Baked Alaska—the so-called Frozen Florida, which has a hot interior and a frozen shell.

When meat is prepared in a microwave oven, it uniformly warms to 100 degrees C and stays at that temperature for as long as it still contains water. This microwave method of cooking meat has two advantages: it is faster and more energy efficient. On the other hand, conventional boiling in a bouillon containing herbs and vegetables can lend additional flavors to meats.

Roasted meat is more flavorful than boiled meat because of browning reactions that intensify above 100 degrees C. Sugars and amino acids in the meat can then cross-link and create many kinds of compounds, some flavorful, some dark brown in color. These Maillard reactions, as they are known, produce the crackling on roasted meats. Some types of browning reactions—such as caramelizing sugar—are easy to induce during microwave cooking, but those are not Maillard reactions.

For the tastiest results, a chef may wish to combine traditional grilling and microwave cookery. A good example is roast duck Pravaz-Cointreau, named in part for the French physician Charles Gabriel Pravaz, one of the inventors of the hypodermic syringe. Pieces of a jointed duck are first grilled or fried to brown them, then injected with the orange liqueur Cointreau (a good absorber of microwaves because of its high water content). They are then placed in a microwave oven to cook their insides, which takes only a few minutes. By such a method, the meat is boiled from the inside in an orange medium; the dish looks like a modernized version of *canard à l'orange.*

No good dinner is complete without dessert. From the world of physics comes a recipe that not only eases the task of a chef but also produces a magnificent spectacle. This dessert, instant



COOKING OF MEAT produces a variety of physical and chemical changes in it. In its fresh, uncooked state (*left*), the meat fibers (*red*) are separated by collagen (*yellow*). After a short period of heating (*center*), the collagen begins to break down. Thoroughly cooked meat (*right*) is tender because almost all the collagen has dissociated into gelatin.

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ice cream, was devised by Peter Barham of the University of Bristol. As a suitable finish for a public lecture on ice cream, Barham developed a way to make enough of it in about two minutes to feed an entire audience. The same recipe can be adapted to a domestic scale.

Good ice cream contains abundant air bubbles (to keep it light) and only very small ice crystals (so that the texture is smooth). Traditionally, ice cream makers have churned the mixture of milk, eggs, sugar and flavorings as it slowly chilled: the churning folded air into the material while also continuously breaking up large ice crystals. A simpler and more efficient way is to pour liquid nitrogen directly into the ingredients. At a temperature of –196 degrees C, liquid nitrogen can freeze the ice cream mixture so fast that only small ice crystals have time to grow. As it furiously boils, the liquid nitrogen also creates plenty of small gas bubbles. And as a further delight, the cold produces a cloud of dense fog, thus adding a crowd-pleasing, highly dramatic touch.

You will need about equal volumes of liquid nitrogen and a mixture for ice cream or sorbet. After preparing the mixture in the usual way, place it in a large metal bowl. (Do not use a glass or plastic bowl, which might break from thermal shock.) While observing the proper safety precautions (as set out below), pour in about half the liquid nitrogen, stirring gently with a wooden spoon. Continue to stir while adding more of the coolant until the ice cream is nice and stiff. Make sure the ice cream has stopped giving off fog—which signals that all the nitrogen has evaporated—before serving.

Two important safety points need to be made. First, always wear gloves and safety glasses when handling the liquid gas or any objects that have been exposed to its extreme cold. Second, if you are making the ice cream in front of guests, be sure they are out of range of any splashes. You should be able to obtain liquid nitrogen (or directions to a commercial source for it) from your local university's physics or chemistry department or from a hospital. The best way to transport liquid nitrogen is with a vacuum flask; inside a well-made one, it will last for up to a day.

Would you like a postprandial drink? Much research has been done in the past decade on the chemistry and biochemistry of wine and spirit production. Oenological research institutes have studied the composition of some of the great wines and counted in some cases more than 500 compounds that may contribute to a wine's character.



ROAST DUCK PRAVAZ-COINTREAU is prepared using both a conventional and a microwave oven. The conventional oven induces tasty browning reactions in the skin. Microwaves acting on liqueur injected into the duck then quickly cook the interior in an orange-flavored medium.

Vintners routinely age many spirits and some wines in oak barrels because chemical reactions with the wood improve the liquors' flavor. Wood contains many complex chemical compounds, among them cellulose, hemicellulose, lignin, tannins (chemicals that are often astringent) and resinous molecules. Oak is the preferred material for those barrels because it is strong and waterproof and contains none of the resins that give retsina wines their flavor.

In the late 1970s and 1980s Jean-Louis Puech of the National Agronomic Research Institute in Montpellier demonstrated how the ethyl alcohol in a spirit extracts tannins and lignin from its wooden container. Through the simple but lengthy experiment of putting alcohol in an oak barrel for more than 10 years, and also by macerating pieces of wood in alcohol, he studied how both the liquid and the wood changed over time. The concentration of tannins in the wood decreased by 75 percent. Moreover, the extracted tannins had been oxidized into a variety of flavorful compounds. The concentration of lignin on the inside of the barrel was 5 percent lower than on the outside. The cellulose content was almost unchanged, but the hemicellulose had been modified: it had dissociated into sugars, such as fructose, xylose, arabinose and glucose.

For the molecular gastronome, perhaps the most significant discovery was that vanillin, the major aromatic molecule of vanilla, was a final product of lignin degradation during aging. Indeed, the vanilla flavor can be detected in old cognacs, rums and whiskeys. The manufacturers of wines and spirits are typically forbidden by law to improve the taste of their products by adding sugar or other chemicals. Nevertheless, if the consumer wants to use the results of chemical research to enhance the qualities of inferior wines or spirits, should he or she not be encouraged to do so? A few drops of vanilla extract may wonderfully enrich the flavor of a bottle of cheap whiskey.

This kind of experiment can be extended to a large number of beverages and dishes. Perhaps in the cookbooks of the future, recipes will include such directions as "add to your bouillon two drops of a 0.001 percent solution of benzylmercaptan in pure alcohol."

Science can explain, analyze and help in the creation of new dishes. But even though we are convinced that science has an important role in gastronomy, we also firmly believe the scientist will never dethrone the chef. The great culinary creations will be, as they have always been, the result of artistic imagination seasoned with a blend of empiricism and tradition and only a soupçon of science. These sentiments lead us to hope that Comus, the patron spirit of the culinary artists, will join the Muses in accepting science as an ally in the practice of the arts.

FURTHER READING

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