

Physical properties of a perfect pasta sauce

Understanding how ingredients interact can help cooks consistently achieve delicious results.

By **Daniel Maria Busiello, Vincenzo Maria Schimmenti, and Ivan Di Terlizzi**

Cooking tasty food requires more than culinary intuition; it's a science. A principal actor in cooking is heat, which drives the transformation of ingredients and their molecular components into a delicious dish. In an Italian kitchen, the protagonists are often pasta and a sauce. To create a sauce that is smooth and clings well to the pasta, a cook must rely on a combination of factors, including texture, viscosity, and the wetting properties that govern how the sauce spreads and adheres to the pasta surface.

At heart, sauces are soft-matter dispersions: Many components coexist in a metastable state in which fat, water, proteins, and carbohydrates share space without separating. In the sauce for spaghetti aglio e olio, a dish made with generous amounts of garlic and olive oil, starch-enriched pasta water helps stabilize the oil-water dispersion by coating oil droplets and thickening the surrounding liquid, preventing large oil globules from forming. Tomato-based sauces benefit in a similar way: Without the viscosity-enhancing effects of both starch from the pasta and pectin from the tomatoes, the sauces would stay too fluid to remain on the pasta and drain away.

Stabilizing starches and other thickening ingredients appear in not only Italian food but many other cuisines as well, including Chinese cornstarch-based sauces, Indian gravies, and Mexican moles. Understanding the scientific process behind those beloved dishes can help cooks to both better appreciate them and learn science-backed techniques to make a sauce that is velvety and clings to pasta.

How sauces stay together

Whether a dispersion separates or becomes stable and uniform is set by the physics of the interfaces between the sauce's components, such as fat droplets and the surrounding water. The pressure difference between the interior and exterior of a curved droplet interface is proportional to the surface tension, which reflects

the tendency of the interface to minimize its area, and is inversely proportional to the droplet radius. Small droplets with high pressure differences are unstable and tend to merge into larger ones, which pushes the sauce's components to separate.

Two strategies can counter the component separation effect and stabilize the dispersion. The first is to introduce ingredients such as emulsifiers, which hinder droplet merging and adsorb at oil-water interfaces to lower surface tension. The second is to vigorously mix the sauce to maintain a small droplet radius. Starch, such as that released into water by boiled pasta, helps stabilize the dispersion through a complementary mechanism. Once heated above their gelatinization temperature, starch granules swell and release sugars, which form a loose network that slows the drainage of thin liquid films between droplets and reduces their likelihood of merging. Gelatinization takes place when dry pasta becomes soft after boiling.

Rheology is another factor that helps explain the texture and viscosity of sauces. When a sauce is stirred or poured, the key quantity is the effective viscosity, which is a measure of a fluid's resistance to deformation under shear. In many sauces, it is beneficial for viscosity to decrease as the shear rate increases. That behavior allows the sauce to spread easily during mixing, when shear rates are high, yet cling to the pasta at rest, when shear rates are low. In the kitchen, starch and pectin are practical ingredients that change a sauce's effective viscosity.

Many of the interfacial and rheological effects are strongly influenced by temperature. Heat drives nearly every transformation in a sauce: It reduces viscosity, promotes mixing, swells and gelatinizes starch, melts fats, and unfolds proteins. Yet it also increases the risk of destabilization through aggregation, a process in which unfolded proteins come together to form clumps.

The strategy for a cook, then, is to move through different temperature windows rather than rely on a sin-

gle one. Higher temperatures are essential at the onset of sauce preparation, as they allow fats to melt and starches to gelatinize, enabling the thickening and mixing of components that stabilize the sauce. But finishing the sauce off the heat allows it to reach its final texture and coat the pasta evenly. A classic example is the technique of *mantecatura*, used in pasta dishes and risotto, in which the dish is rapidly stirred off heat while fats from cheese and butter are incorporated to create a creamy consistency. At that stage, emulsifiers and stabilizing particles coat dispersed droplets without triggering protein aggregation, while tossing and stirring help both reduce droplet size and incorporate air to enhance the sauce's texture. Managing temperature in deliberate stages is therefore one of the most reliable ways to achieve a cohesive, well-balanced sauce.

Into the kitchen

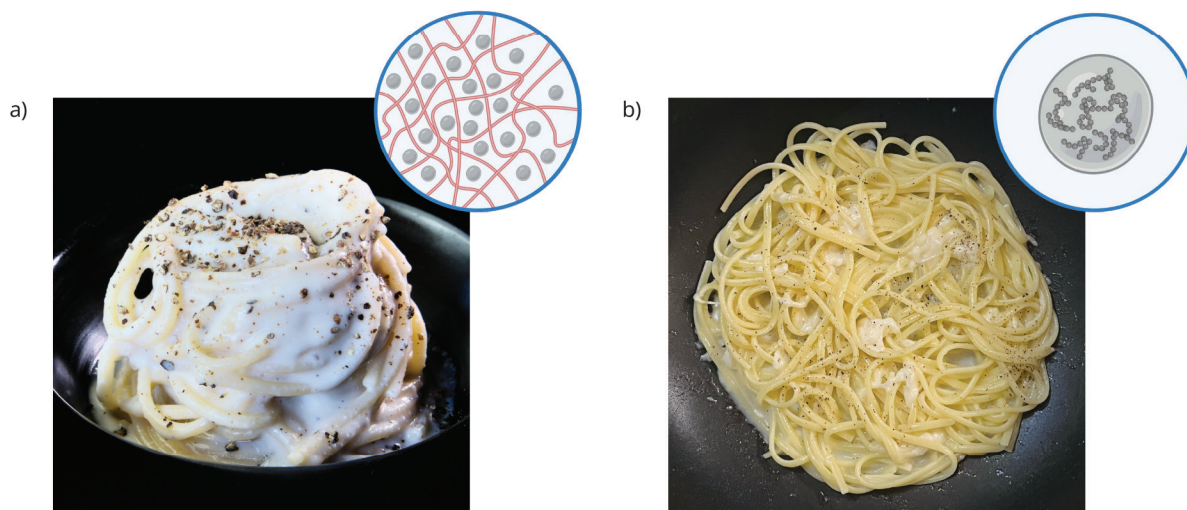
Depending on its ingredients, every sauce will have its own challenges. Protein-rich sauces can experience denaturation, a process in which proteins lose their functional structure and aggregate. A prime example is *cacio e pepe*, a classic Italian dish made with pecorino cheese and black pepper, in which the smooth cheese-based sauce evenly coats the pasta. Pecorino cheese contains whey proteins and casein, which at low to moderate temperatures can adsorb at the interfaces between fat and water droplets and thereby stabilize dispersions.

If present in sufficient amounts, gelatinized starch increases effective viscosity and helps confine fat- and protein-rich droplets; those effects suppress collisions

and phase separation. As a result, the sauce remains smooth and cohesive as it coats the pasta, even at elevated temperatures. Panel (a) of the figure shows a *cacio e pepe* with a velvety sauce clinging to the pasta. Casein is relatively heat stable, but temperatures above about 65 °C can promote protein aggregation and the loss of emulsifying action in cheese-rich mixtures. If the sauce encounters nearly 100 °C pasta without enough starch to provide stabilization, the result can be visible clumping and a stringy sauce, such as the one shown in panel (b) of the figure.

Another famous pasta dish, carbonara, is traditionally prepared with egg yolks, pecorino, and guanciale (cured pork jowl). The sauce's stability relies on molecular emulsifiers, primarily lecithin and yolk proteins, that lower interfacial tension and coat dispersed fat droplets. (The same mechanism is responsible for stabilizing mayonnaise.) The mechanism is rapid and efficient but sensitive to heat. Above 65 °C, yolk proteins coagulate as a result of the yolk's lecithin losing its emulsifying properties, and the emulsion can fail. Failures tend to result in a grainy or greasy texture rather than the dramatic curdling seen in *cacio e pepe*.

Interfacial and rheological principles also extend to sauces with garden-grown ingredients. Tomato sauces, for example, are polymer-rich dispersions in which pectin, sugar, and other dissolved solids increase viscosity. Evaporation during the cooking process and the addition of starchy pasta water can enhance coating by further increasing effective viscosity. Pesto, on the other hand, behaves as a particle-stabilized dispersion, where nut fragments, herbs, and grated cheese accumulate at oil-water interfaces during mixing and



▲ Visualizing stabilization in *cacio e pepe*, a traditional Italian sauce made with pecorino cheese and black pepper. (a) A velvety sauce has gelatinized starch, which forms a viscoelastic network that traps dispersed fat and protein (as depicted in the inset) and maintains a smooth, cohesive texture. (b) A separated sauce has clumping caused by protein aggregation (visualized in the inset) at high temperature. (Panel (a) photo by Simone Frau; insets created using BioRender.)

form a weak network that slows the growth of large oil drops.

Perfecting, not by accident

Even for cooks who understand the science behind an expertly executed sauce, things can go wrong. Knowing how to identify problems in a sauce can make it possible to deploy targeted fixes. Loss of gloss indicates inadequate interfacial coverage—in other words, the effective surface tension is too high to prevent oil droplets from merging into visible oil beads. A cook can remedy that problem by applying moderate shear through mixing the sauce with a spoon and adding small amounts of an emulsifier, such as a knob of butter, or a gelatinized starch. Grainy clumps are a signature of protein aggregation caused by excessive heat. To fix that, a cook should return the sauce to a lower temperature window, gently dilute it with starchy water to separate the aggregates, and mix it again to restore a smooth dispersion. When those adjustments fail, a blender can provide the needed shear.

Bound together, the ideas in this article provide a compact guide for making perfect sauces. Whether cooking aglio e olio, pesto, or another sauce, cooks can achieve the desired consistency by following scientifically reproducible cooking techniques.

We thank the coauthors of and contributors to our 2025 Physics of Fluids paper on cacio e pepe phase behavior for their help and support.

PT

Additional resources

- ▶ E. Dickinson, “Hydrocolloids as emulsifiers and emulsion stabilizers,” *Food Hydrocoll.* **23**, 1473 (2009).
- ▶ Q. Zhu et al., “Review on the stability mechanism and application of water-in-oil emulsions encapsulating various additives,” *Compr. Rev. Food Sci. Food Saf.* **18**, 1660 (2019).
- ▶ P. Fischer et al., “Rheological approaches to food systems,” *C. R. Phys.* **10**, 740 (2009).
- ▶ G. Bartolucci et al., “Phase behavior of cacio e pepe sauce,” *Phys. Fluids* **37**, 044122 (2025).
- ▶ V. D. Kiosseoglou, P. Sherman, “Influence of egg yolk lipoproteins on the rheology and stability of O/W emulsions and mayonnaise 1. Viscoelasticity of groundnut oil-in-water emulsions and mayonnaise,” *J. Texture Stud.* **14**, 397 (1983).

Daniel Maria Busiello is a researcher at the University of Padua in Italy, and **Vincenzo Schimmenti** and **Ivan Di Terlizzi** are postdoctoral researchers at the Max Planck Institute for the Physics of Complex Systems in Dresden, Germany. Di Terlizzi also has a postdoctoral appointment at Ludwig-Maximilian University of Munich.



LOOKING FOR A JOB?

Job ads are now located throughout the magazine, alongside the editorial content you engage with each month. Also find hundreds of jobs online at jobs.physicstoday.org



LOOKING TO HIRE?

Enjoy the power of print plus online bundles any time as well as impactful exposure packages & discounts for our special Careers issue each November. Post online-only jobs anytime at employers.physicstodayjobsnetwork.org

PT PHYSICS TODAY JOBS NETWORK

Questions? Contact us at: employers.physicstodayjobsnetwork.org/contact-us

AIP