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Gourmet Physics

"The test of all knowledge is experiment."

Richard P. Feynman

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There is more than one way to skin a … beetroot. So, there are many ways to cook and everyone relies on various physical principles and rules. The food we get from each method is also quite different. Sometimes, the same ingredients will even give us a different-tasting result because the temperature is different or there is less stirring or a different sequence or some other parameter. Many gourmet dishes started life as a serendipitous mistake!

In this part we'll visit various cooking methods in turn and observe what happens in the pot, the frying pan, and the oven, and even on a barbeque. We'll also consider various apparently "strange" phenomena that occur in the kitchen and look at how successful food storage depends on physical principles.

But first of all, let's see what happens in the pot.

The Physics of Dissolving

We've talked many times about a food dissolving in a liquid, mainly water. If you think like a chemist, then it's obvious, isn't it? One substance dissolves in another, what is there to add?

But what does "dissolving" actually mean? Well, like many other chemical reactions, it is all guided by electrostatic attraction between molecules, based on quantum mechanical principles. And because of that, the most important question is how "polar" the molecule of the solvent is. In fact, probably the strongest polar solvent is water. As we saw earlier its molecule is made up of an oxygen atom bonded to two hydrogen atoms at a very odd angle, 105°. In fact, this molecule is prone to rotation. This gives the water molecule a strong electric field and makes it strongly polar. So, any other molecule in the water will be attracted by one side of the molecule, to be broken up and maybe reformed differently. AS we saw, water can essentially dissolve almost anything. It has been estimated that the sea contains hundreds of minerals and metals which are frequently extracted for industrial use. For example, magnesium, a very important light metal mainly used to make aluminium–magnesium alloys, but also used in animal fodder and in fertilisers, is nowadays mainly extracted from sea water. Even gold is dissolved in sea water, and although it occurs in miniscule amounts per unit volume, the total amount of gold in all the world's oceans is estimated at up to 1.5 million tons!

So let's see how dissolution of a material takes place in water. When a solid material like common salt (NaCl) is mixed with water, its crystal structure (made up of alternating atoms of sodium and chlorine) is immediately stressed by the electrostatic attraction of the polar water molecule, first weakening the crystal bonds and eventually destroying the salt crystals completely, leaving the ions of sodium and chlorine to swim around freely in the water. If we increase the temperature, the atoms in the crystals and the water molecules vibrate more strongly and therefore the "damaging" effect of the water molecules is even more pronounced, so the salt dissolves more quickly. Similar dissolving processes take place for anything we care to put in water, whether it is a solid or a liquid. Some materials take time, but water eventually dissolves nearly everything we can put in it! But, just like water reforms repeatedly, so do all solutes in it.

Interestingly, when salt (or anything else) is dissolved in water, it has the general effect of reducing the overall polarity of the water, so the solubility decreases until a certain point is reached where there are no more polar water molecules left and no more solute can be dissolved.

In the kitchen, the fact that nearly anything we put in a pot of water will, at least partially, dissolve means that the atoms of the various ingredients can come into close contact and form new compounds. That's how we get sauces (emulsions) and it's how gels and soups develop new tastes. The longer we cook something in a pot, the more uniform the result will be, until eventually we get a smooth, thick soup. In actual fact, under most cooking conditions, what we get are large molecules, similar to the macromolecules of plastics. We'll see how that happens in the next chapter.

Boiling Magic

We saw before that boiling is nothing else than the transformation of liquid water to water vapour, i.e., steam. But how exactly does it happen? If you pay close attention to a pot of water on the fire, you'll notice that bubbles containing steam first form on the walls of the pot. These gradually coalesce together until they are large enough for the buoyancy force—equal to the weight of the displaced water, as Archimedes found out 2500 years ago—to push them up. Finally, they release their contents into the atmosphere when they reach the surface.

Actually, there are two other forces acting on these bubbles. There is the pressure of the water around them compressing them (also due to gravity) and there is the surface tension keeping them stuck on the surface of the pot and making them as hemispherical as possible. In fact, in the International Space Station, where there is almost no gravity, there is only one force, namely the surface tension, and the bubbles do not bubble up but continue growing until they all join up to form a single large, almost spherical bubble surrounded by water. This bubble goes on growing until it has devoured all the water around it, at which point it bursts and releases all the steam at once. Cool. But now let's return to Earth and ask: how do the bubbles form in the first place? I mean, how does the water "know" to start bubbling the way it does?

First of all, there are actually two kinds of bubble. On the one hand we have those that form very quickly and dissipate equally quickly when they reach the surface, as they contain previously dissolved air. On the other hand, there are bubbles which contain steam, which form later, when the water is getting really hot. They tend to form randomly and usually at the bottom and the sides of the pot. If we look carefully, they form at points where there are some tiny imperfections. These are called nucleation sites because bubbles tend to form and grow around them. These are the bubbles that concern us here. How do they form?

There is a bit of magic involved: the magic of quantum physics. It all starts with a single molecule of water that acquires enough energy to escape the bonds of its friends and neighbours and decides to fly around as a gas molecule. But in order to do that it has to somehow persuade thousands of trillions of other neighbouring molecules to do the same, almost in unison. In other words, that single molecule gets enough energy from the heat we apply and starts bumping around and gives some of its energy to its immediate neighbours, and those to their own neighbours, and so on. We don't actually know exactly how this happens, but water molecules are quantum particles and exist simultaneously in a range of energy states themselves. As they acquire more and more energy, the higher energy states spontaneously share some of their energy with neighbouring atoms and an almost instantaneous domino effect takes place which creates that bubble nucleus. Before long these trillions of now gaseous water molecules have formed a visible bubble with a distinct surface at which molecules are continuously being added from the surrounding hot water. They all hold together by their surface tension and the rest is history.

Actually, a hot nucleating surface is not absolutely necessary, and bubbles can start forming in the body of the water instead of on the sides or the bottom of the pot.

Now, when a body of fluid (gas or liquid) gets hot, it expands because the atoms and molecules tend to vibrate more (see later as well for more details) and this takes up more space. This means that the density of the fluid is lower and it rises, just as a large balloon rises when the air inside it is heated. This movement of a warmer fluid in cooler fluid surroundings is the convection we discussed earlier and is what mixes the ingredients in a pot when we heat it. It is also the way a convection heater works. Now, by rising, the warm fluid transports energy from lower regions to higher regions, gradually heating those higher regions. But as it does so, it loses energy and eventually falls back down. This is what is observed when water is boiled in a pot, and we'll have a few more things to say about that later.

Drinkable salts

There are many different salts in drinking water, depending on its origin, containing mainly calcium, magnesium, potassium, and sodium as carbonates, nitrates, bicarbonates, chlorides, and sulfates. All these salts are very important for our nutrition and their presence in healthy water keeps our cells ticking over well. For example, sodium and potassium are critical for ensuring cellular homeostasis, where sodium is exchanged for potassium across the cell membrane. Calcium is of course the main ingredient of bones, while magnesium is necessary for muscle operation.

The total content of salts in water is called its "hardness" and is specified by its TDS value (Total Dissolved Solids) as well as its electrical conductivity, both of which are zero for distilled or deionized water.

By the way, some evaporation happens at any temperature—steam molecules can escape even from cold water or even ice (albeit at a very low rate) since there are always some atoms or molecules that vibrate more violently than others and have enough kinetic energy to escape from the cold liquid or solid. As we increase the temperature and ice melts, the molecules mix more easily and have more energy, so there are even more molecules whose atoms vibrate violently enough to enable their escape.

Evaporation at any temperature is easily observed anywhere there is a water spill. After a few minutes on a dry summer's day or even in winter, the spill will have disappeared, leaving behind a tiny amount of "salt" deposit. Such salt deposits are of course clearly evident inside kettles, where water is boiled and evaporated repeatedly. In areas where water is "hard", meaning there are a lot of salts in the water, it's always a good idea to refresh the water in the kettle frequently and not just top it up before boiling it, otherwise you'll just accumulate a lot of salts. By the way, if you want to clean the salt deposits in your kettle (or anything else), just cover the salt deposits with water, add a glass of white vinegar, heat it a little and leave it. Within 30 min it'll be as good as new. Vinegar contains acetic acid, which dissolves most common salts even those generally insoluble in water. Remember to rinse it out well though, or you'll have vinegar-flavoured tea.

Finally, a few words about the effect of salt on boiling of water. It seems that many people believe that adding salt will substantially increase the boiling point of water. Well, it does increase it, but only by a tiny amount, a fraction of a degree for most concentrations used in cooking, and it happens because salt slightly reduces the vapour pressure of the water.[1] But you might have noticed that sprinkling salt in water which is just about to start boiling (say at about 99 °C at sea level) seems to have the opposite effect: the water will start boiling violently. This seems to indicate that the boiling point has decreased! So what's going on?

Well, the reduction in vapour pressure is not the only phenomenon that occurs in salt solutions. There are two counteracting phenomena. Firstly, salt particles act as nucleation centres for the formation of boiling bubbles. The moment they hit the hot water, bubbles form around them almost instantaneously and often quite violently. That's how rain forms too, around dust particles. But as soon as the salt dissolves in the water, the overall polarity of the water decreases (some of the polar molecules have now been "neutralised"), reducing the overall heat capacity (the energy needed to heat the water), making it easier to reach boiling point. That's why the water appears to boil suddenly. Who would have thought that simply boiling water would be so intricate?

High Cooking

You know of course that water boils at 100 °C, right? Well, this is *only* correct at sea level, when the atmosphere is stable and the atmospheric pressure is about 100 kPa (called 1 bar). During a storm, the atmospheric pressure may be substantially below this value, and it turns out that water will boil at a lower temperature! And if the atmospheric pressure increases on a good day, the boiling temperature will also increase slightly, softening foods in the pot more quickly.[2]

At constant pressure, the boiling temperature remains constant, no matter how much energy one inputs into the system. However, if you feed the steam produced into another container, seal it, and heat it, the temperature of that steam can be increased to more than 500 °C, while its pressure will also increase, with enough energy to drive a generator.

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[1] This is due to the relative entropy of the gas–liquid phases.

[2] That's the basis for driving steam turbines made to turn generators and produce electricity. By heating the boiling water in a closed vessel, the steam temperature and pressure increase hugely which is then able to turn the steam turbines.

At the boiling point of water, many water molecules get enough energy to escape the liquid. Because of the added energy, they begin to move around very fast and become vapour. This is true for any liquid. The escape energy depends on the surrounding atmospheric pressure. So, if this pressure is lower, as happens up a mountain or during a storm, the energy that molecules need to escape is also lower. For this reason the boiling point of water decreases by about 1° every 300 m you go up a mountain.

This means that if you live at a higher altitude, you'll have to boil food longer or rely on a pressure cooker. Without it, potatoes, peas, legumes, and similar foods will never soften at altitudes higher than about 3000 m (where the boiling point of water is about 90 °C), no matter how long you boil them. On the last camp before the top of Everest, at about 8000 m altitude, where the atmospheric pressure is only about 35% of sea level, water boils at about 70 °C, which means you can't even make a hot cup of soup! Even an egg will never come out hard at that temperature.[3] It won't help to increase the energy input to the pot. All you'll do is waste energy, as the boiling will proceed at a constant temperature until all the water has disappeared, whereupon the solids left over will start heating up, probably dissociating and eventually burning if organic. Agreed, you'll have other things to worry about up there, but the laws of physics are unrelenting and uncompromising.

However, there is a way out. By using a closed pot with a tight lid, you can increase the pressure in the pot a little while heating it. This increases the boiling temperature until it becomes possible to boil rice and anything else. The reason is that a larger amount of energy (heat plus pressure) is delivered to the food, breaking down fibres and collagen more quickly. However, you will pay for this by the inconvenience and a slightly reduced taste, as we'll see later.

Most of us are used to atmospheric pressure not too far from sea level, while many bodily functions work differently at significantly different atmospheric pressures. For example, our tastebuds (and all other sensations) have a slightly reduced sensitivity (and electrical and other impulses to the brain are weakened) when we fly in an airplane. This is because the atmospheric pressure in the cabin is kept at about 80% of sea level pressure (equivalent to atmospheric pressure at about 2000 m). The underlying reason is the reduced oxygen in the cabin,[4] reducing the efficiency of various bodily functions. That's why airplane foods need more salt and pepper to make them

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[3] The white only starts hardening at about 65 °C and the yolk at about 70 °C.

[4] Although the relative amount of oxygen in the air is the same, about 21%, the total oxygen available to us is about four fifths of this.

palatable. But there is a silver lining too. When I fly, I often ask for tomato juice. I enjoy this, but only when flying. On the ground I find its taste too intense.

Reduced oxygen in the airplane is also the reason why any alcohol we drink has a quicker and stronger effect on us. The reason is once again the mild hypoxia (less oxygen in the blood) at the decreased atmospheric pressure and reduced rate of metabolism of the alcohol, which remains at a higher level in the blood for longer.

By the way, the reduced pressure in an airplane is also the reason why they always avoid offering too many vegetables and fruit. These can produce wind and discomfort as the pressure difference is greater when flying than it is on the ground.

The Shuffle of Atoms and Molecules in a Pot

You've all seen it. If we add a tea bag to hot water and leave it there without moving it in any way, the tea will take some time to infuse. However, it will eventually do so, although the tea will be tepid by then. This happens because the spread of tea molecules in water is a slow process of "diffusion," i.e., spreading around in the water. As we saw earlier, all molecules vibrate due to their heat energy, whether in water or in air, and they also shuffle and move around incessantly, mixing with the other molecules. But the net motion of the molecules is not completely random. The physical laws of diffusion tell us that there is method in their apparent madness. A molecule will slowly diffuse from an area where the concentration of its particular type is higher to an area where the concentration of its type is lower. You've experienced this many times in the kitchen. Unless you have the extractor on, the smell of cooking will waft around the house gradually reaching everywhere, even the smallest nook and cranny. Where there was no smell before, it will soon appear. Unless there is a draft (e.g. by extraction or at least two open windows), gradual diffusion of the molecules will continue until the whole house smells equally strongly of the kitchen smell. In other words, the concentration of the molecules causing the smell will become equal everywhere.

Bumping atoms

Until 1905, people weren't fully convinced of the existence of atoms and molecules. They couldn't observe them or measure them, so they weren't sure they even existed.

But it had already been noticed by Robert Brown in 1827 that tiny specks of dust or pollen suspended in clean water appear to move in apparently random jerky movements. This "Brownian motion" was used by Einstein in 1905—his amazing "miracle year" when he published 4 foundational papers—to explain and prove the existence of randomly shuffling and scuttling atoms in liquids and gases.

The rate of diffusion is of course related to the amount of energy the molecules have. The higher the temperature, the faster the molecules vibrate and shuffle around and the faster the diffusion will be. Perhaps you've noticed this. In summer, when the air is at a higher temperature, the diffusion of smells from the kitchen is noticeably faster.

You can actually see this happening in liquids too. Gently put a tea bag in a light-coloured tea cup containing hot water. Initially, the tea bag will be surrounded by the darker tea molecules (water with dissolved tea substances), but the remainder of the hot water will remain clear. Gradually, in front of your eyes, the tea molecules will disperse and diffuse until all the hot water reaches the same uniform colour. By stirring to give the molecules a bit more kinetic energy, the diffusion will occur even faster. If you try this with lukewarm water, the diffusion rate is much slower, and with cold water, there will be hardly any diffusion. This is actually a nice experiment one can do to illustrate diffusion in schools. Various coloured substances may also be substituted for tea leaves.

The diffusion of molecules is affected by the viscosity (i.e., the thickness) of the liquid. When we cook, it is always important to stir or baste the food frequently, otherwise the various substances will take a long time to mix and blend correctly. When we add salt to a cooking pot, it will dissolve quickly in the water, but the dissolved molecules or atoms will diffuse too slowly unless we stir it frequently. This is especially important for immiscible materials, such as oil or pepper in water. The diffusion of oil in water is extremely slow, so unless you stir the food, the two will remain separated, or at best in an uncomfortable embrace of tiny droplets, as in a weak emulsion.

Talking of stirring, who can guarantee optimal mixing of thick mixtures? One of the trickiest hand-stirring jobs to get right is béchamel sauce. If one continues stirring in the same direction (e.g., clockwise), all that will be achieved is a thick sauce in the middle and a thin one at the edges. Changing direction occasionally helps a little but is still not perfect. A very good way to homogenise the sauce is to stir in one direction off-centre, moving around gradually, while occasionally changing the stirring direction. This way, the “centre” of rotation itself moves around and the sauce will thicken uniformly. Not even using automatic blenders can guarantee such perfect mixing.

Up Close and Personal

Top quality cooking requires quite accurate temperature control to get the best and reproducible results. The hob settings help, but they are completely misleading if the pot or pan does not make perfect (or at least consistent) contact with an electric hob or if the gas flame is not uniform. Even a slight (sub-millimetre) gap between the bottom of the pot and the electric hob is enough to make a setting of 6 give the same result as a setting of 4. And waste a lot of electricity and money into the bargain.

A key reason for this is the very good thermal insulation properties of air. Air consists of gas molecules, four fifths nitrogen and one fifth oxygen, with a few other gases in very small quantities. These shoot around, occasionally bumping into each other and exchanging a little bit of energy. But even a thin layer of air can insulate one metal from the other because the heat energy exchange between molecules bumping into each other is not very efficient at all. In fact, during collisions in fluids, molecules and atoms do not actually touch each other neither do any materials actually “touch” one another. This is due to their natural mutual electrical repulsion and quantum mechanical rules that only allow certain mingling of their electrons. So, when molecules and atoms do bump into each other, it is not like hard billiard balls at all, but more like soft footballs that have lost much of their air. In any case, just like colliding balls, the faster of the two molecules will lose some energy during the collision while the slower one will gain a bit of energy, keeping the average energy approximately constant. So, only part of the collision energy is exchanged in air and they do not carry the heat energy of the hot surface to the other surface very efficiently. This fact is exploited in producing highly insulating structures for houses, cars, and even padded jackets, by filling them with air pockets.

Actually, in the case of an air gap between a hot hob and a pot this is only half the story. The presence of a thin layer of air not only insulates the pot, but actively carries heat away! The reason is that hot air expands and if it is free to escape, it will do so gladly. In this case, it will escape out the sides and rise around the pot, carrying heat away. And when it does, fresh, cooler air will rush in to take its place, effectively cooling the pot.

This fact is so important that it is always well worth paying good money for good pots with flat, heavy bottoms that will not easily distort or warp. Most pots and pans destined for electric hobs have thick bottoms for exactly this reason. The bottoms are actually made of two or more layers, including a copper layer,[5] which reduce the propensity for distortion. At the same time, the hobs themselves must also be completely level and flat to ensure perfect contact with the pot during cooking. Flat-topped stoves with a glass–ceramic surface may have a similar problem, but induction heating stoves avoid it to some extent, as we'll discuss later.

In fact, because you can never ensure perfect contact between the hob and the pot, professional chefs avoid using electric hobs at all. They prefer gas hobs, since the flame will always make contact with the thinner pot and the food will respond very quickly. It is also much easier to control the cooking process, although not everything is plain sailing, as we'll see later.

Talking of flat-bottomed pots and the need to avoid any distortion, it is never a good idea to pour water in a pan with very hot oil after frying. Frying is done at temperatures way above the boiling point of water and the temperature of the frying oil can easily reach 180 °C. So, apart from the mess it will make (water being heavier it will immediately sink under the oil where it will suddenly heat up to its boiling point and explode as the steam tries to escape), the metal will on one side try to shrink while the other side is still very hot. This is called differential thermal shrinkage (or expansion) and creates very large mechanical stresses in the bottom of the pot which will almost certainly result in some distortion and warping.

For the same reason, it is never a good idea to place anything cold on the hot surface of a ceramic flat-surface stove. Those surfaces are made of a glass–ceramic (a type of strengthened, semi-crystalline glass) and, although they have higher thermal conductivity than ordinary glass, they are still susceptible to heat stresses. At the same time they are also brittle (as are all glasses and ceramics), which means that they can easily develop cracks if they are loaded while also under heat stress. By the way, metals are much more resistant to heat stresses than glasses or ceramics because they conduct heat away very quickly and don't allow it to build up and cause stresses. All these aspects will be discussed later in more detail.

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[5] Copper has one of the highest thermal conductivities of all metals. It also has a very high electrical conductivity, so it's used for wires.

More Edible Plastics—Jellies, Sauces, Syrups, and Creams

Gelling during cooking is often welcome, especially for thickening sauces, various creams, etc. But what exactly is a gel? It's actually a weak food polymer and forms by a type of "polymerisation" reaction. This is of course closer to chemistry than physics, but the underlying mechanisms are all governed by physical laws, as is everything else.

So, what is polymerisation? It's simply the linking up of many small molecules (from a few hundred in food gels to millions in industrial plastics) to form complicated chains. In the case of foods, most of the short chains are organic molecules or pieces of amino acids taken from protein polymers in the food. Polymerisation is quite a complicated process, but in general, it takes a certain time at cooking temperatures, the time for some of the weaker atomic bonds on small food molecules to break (due to the energy input), allowing them to join back together in new ways. Such small molecules could be fats or sugars or parts of proteins. For this to happen in a reasonable amount of time, we need to have an acid in the food which helps to weaken the atomic bonds—lemon, orange, or other fruit juices, or indeed vinegar and even wine (alcohol) will do the trick very well, and then help to form a bridge between the lipid we use and the water. After some time boiling slowly (to make a sauce for example, as in shortening), the oils and fats and other small molecules in the food will join up with the water molecules to form a thick gelled sauce—the longer you leave it, the thicker it becomes.

In some cases, free water does not allow easy gelling—the reason is not fully understood but it is believed to be because of free radicals, highly reactive OH molecules in the water. Slow cooking first boils off most of the free water, some of which is still bonded to the food molecules, and once it's gone, the food molecules can start joining up. That's why, when you make a sauce, always add water very gradually and in very small amounts at a time. If you add too much at a time, the sauce will consist of water with some small gelled pieces here and there, a type of curdling.

By the way, if you don't have much time and you don't mind a bit of cheating, you can add some flour to the sauce. The fine particles of the flour help to bind the free water and "nucleate" polymerization, which then proceeds faster and give greater volume. Personally, I think this is an acceptable short cut, but the sauce will not taste the same because of the watery flour in it. It's essentially a gravy. But in most restaurants, creamy sauces are generally made like this.

Finally, a few words about jelly, something that so many children (and adults) love. The gelling mechanism is about the same, since the powder in the packet includes a “gelling agent” (essentially some acidic substance such as citric acid—artificial lemon) which speeds up the polymerization of sugar and water-containing juice molecules.

Creamy Emulsion or Curdled Mess?

When mixing ingredients in water, we can end up with one of three things. A solution, where the water has dissolved the solute (for example, salt or sugar in water), a suspension where the solids dissolve very little but are light enough to remain suspended in the liquid (e.g., milk), or nothing at all, where the ingredients remain separate (oil or pepper and water). But if you want a smooth, uniform sauce, in which various liquids (and some solids) are well distributed without separating out, you need to work at it. This is called an emulsion, and when it’s done right, it’s always the supreme culinary pleasure. It’s different from gelling and smoother.

The simplest (thin) emulsion is simply a cold mixture of oil and a solution of an acidic agent in water, separated into tiny lipid particles to encourage weak bonding. A very popular one in my country is made simply by whisking or beating together olive oil and lemon juice with added condiments (salt, pepper, chopped parsley, thyme) and is proposed very often in Greece to accompany grilled fish. Because it is made at room temperature, the ingredients cannot react together to form a thick emulsion, even with very strong beating, and they tend to separate to some extent, so this has to be used quickly. Adding some very finely chopped herbs (e.g., thyme or parsley) helps to maintain the gel by including other molecules which act as additional molecular bridges.

But making a creamy emulsion sauce—or any smooth cream for that matter—is not that simple. We want to make sure that the ingredients and dissolved molecules diffuse and distribute well, but gravity and surface tension often throw a spanner in the works by separating out and sinking some of the heavier liquids and solids. For example, when making a béchamel sauce, it helps to first mix the flour very well with the molten butter (or oil)—together with any condiments—before we add the cold milk, and the latter must be non-skimmed milk. Even then, it is still necessary to whisk the mixture strongly, and steadily and very gradually increase the heat to ensure that the ingredients are broken up into very small particles or droplets which remain continuously in touch with one another until they heat up. This will enable them to react and polymerise, thereby increasing their density. At this point, the strength of the (electrostatic) bonds in the polymer sauce will be higher than the surface tension of the individual ingredients, and the sauce or cream will remain smooth.

The most difficult sauces to get right are the ones that contain egg and an acidic ingredient like tomato or lemon. For instance, Hollandaise sauce is prepared without flour, and the use of egg yolks beaten with lemon juice means that it is much trickier to get it to emulsify correctly when we add the lipid. We have to be careful when adding the butter (or oil) at the end, because egg white will react immediately and solidify under heat, destroying the sauce. Albumin is particularly sensitive to heat, so heating must be carried out very slowly while beating all the time to ensure proper distribution of all the molecules. A mayonnaise sauce is made in a similar way, but using vinegar. Actually, the egg white solidifies after the albumin protein has partly unfolded and refolded in a random way, cross-linking all over the place and trapping the water inside to form a gelatine-like structure. That's why, while raw egg is transparent, cooked egg scatters light and appears white. This trapping capability of re-folded albumin protein makes it very useful for forming various foams with other molecules inside, like meringue.

The difficulties with emulsion sauces don't stop there. An emulsion sauce is not a stable configuration. Rather, it is "metastable" and under certain conditions its constituents will try to separate out, sometimes causing curdling or separate phases. In the case of béchamel, its main liquid constituents—butter or oil and milk—are mutually repulsive, since oil and butter are hydrophobic (from the Greek for "scared of water", the opposite is "hydrophilic"), while milk is mainly water. This is why we use a bit of flour to help bond them. But the flour preferentially absorbs water so, if the sauce is reheated too quickly or some acid is added, it will separate out easily, causing curdling.

Hollandaise and similar sauces are even more metastable and can curdle even more easily, both during preparation and during reheating, since they do not use any bonding agent. The secret is to beat them very fast while increasing the heat gradually so that the oily component splits into tiny droplets which then can bind to the watery component long enough to start polymerising. In Greek cooking, we make a similar egg and lemon emulsion sauce[6] without flour. After beating well and heating very slowly by gradually adding hot broth (cooked with olive oil), we add it to the hot pot with immediate stirring and shaking to polymerise it rapidly and create a

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[6] Generally, only the egg yolk is used, but I find using the whole egg gives a smoother texture, as the albumin aids in polymerisation, even if it is trickier.

smooth, very pleasant sauce throughout the pot.[7] It's a really brilliant sauce for any meat or fish soup, or for stuffed vine or cabbage leaves[8] and similar dishes.

Curdled sauces and creams can generally be rescued by adding just a little milk (or lemon or just water), while heating gently and beating continuously to ensure very fine re-dispersion of the oil droplets. I find that gentle heating in the microwave oven helps these sauces not to curdle. Generally, in creamy sauces, it helps to use higher-fat milk or yoghurt, which enhances emulsification.

Pressure or No Pressure?

There is more than one way to put energy into a closed system. What we generally do in the kitchen to cook food is to increase the temperature of the food, thereby increasing molecular vibrations which enhance the reactivity of the ingredients and also help to soften the molecular bonds in collagen and fibres. This works well for nearly all cooking operations. Nutrients dissolve more quickly when we heat up the liquid (usually water), and collagen and fibres soften more readily at higher temperatures. Diffusion of nutrients is also substantially sped up at higher temperatures.

However, heat also has a negative effect on many sensitive nutrients. Many vitamins and other molecules tend to break down (dissociate) at high temperatures, something which we would like to avoid. One possibility is to cook at a lower temperature for longer period. This is what is preferable for game or other tough proteins which must first be softened (partly breaking down fibres and collagen by marinading in vinegar and wine) before we add other ingredients, such as sensitive herbs and spices.

Now, increasing the pressure on the food during cooking by the use of a pressure cooker (or "pressure pot boiler") has the major advantage that food is cooked faster. This brings substantial savings on electricity. But what happens to the food?

Increasing the pressure of a closed system with the same heat input will automatically increase the internal temperature,[9] and also the vapour point and boiling point of water. This means that, difficult to soften fibrous meat

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[7] Alternatively, you can remove some of the hot broth and prepare the sauce separately. I don't, as I like the sauce to diffuse into the food for a while before serving. It adds to the pleasure.

[8] Because it's difficult to get the sauce right, many restaurants just offer béchamel instead, which I consider a bit of a cheat.

[9] According to the ideal gas law that we discussed before, for a closed system $PV = cT$, where P is the pressure, V the volume, T the temperature, and c a constant. In a pressure cooker, V is constant,

and vegetables will cook more quickly and with less water (since the steam does not escape). Sauces also tend to polymerise more quickly in a pressure cooker because of the additional energy that is made available to the food. Diffusion is also faster when there is more energy around, and this means that blending of tastes is also accelerated. This is useful for making legume soups since you don't need to soak the legumes (beans, chickpeas, etc.) overnight.[10] It is also very useful for boiling potatoes and corn and other simple operations. Interestingly, certain very stable spices, such as nutmeg, cumin, and others, need this higher temperature to release their active ingredients, so foods made using such spices come out with more intense flavours, and you can use much smaller quantities.

Toxic spicy pleasures

It's worth remembering that most spices (and many herbs) are actually toxic in large amounts and should be used with caution by people with health issues, especially those with an oversensitive central nervous system or impaired liver or kidneys. For example, cinnamon contains cumarin, which can damage the liver and kidneys, while nutmeg contains a strong psychogenic compound (myristicin) with potentially serious complications.

The toxicity of many plants is a protective evolutionary strategy developed in parallel with many plants' distinctive smell and colour. Foraging animals attracted to a smell or colour remember very clearly which plants are nutritious and which ones give them digestive problems, or worse.

On the other hand, many nutrients break down more readily in a pressure cooker because of the higher temperature. And not only nutrients, but many sensitive herbs tend to break down faster, well before the rest of the food is ready. It doesn't matter how low we have the heat setting on the pressure cooker. Even at the lowest setting, pressure will gradually build up due to the accumulation of steam until the internal pressure reaches the set point of the valve, which is usually twice atmospheric pressure. The water then starts boiling. At this pressure, the boiling point of water is higher than 120 °C.

And therein lies the problem with pressure cookers. To benefit from the convenience of speed, all ingredients are added together in a pressure cooker. But foods don't all cook at the same rate and most foods require careful stirring, which is impossible in a pressure cooker. Molecular (and atomic)

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so increasing P will increase T. It's the same law that results in a bicycle tire getting hotter when we pump it up.

[10] However, you should always throw away the "first" water (after soaking or initial boiling for 10 min) to reduce various indigestible compounds and avoid excess generation of gases later on.

diffusion rates are very different between meat and vegetables, and fibrous foods take much longer to soften than starch. For this reason it's nearly impossible to boil pasta in a pressure cooker to the correct "al dente" consistency. By the time the pressure has built up, the pasta is already soft and may stick together. This necessitates pre-cooking certain foods before placing them in the pressure cooker, or adding them part-way through, which seems to cancel out much of the convenience. Moreover, you cannot see what is happening inside the cooker, so you cannot take any steps to make corrections to the food. Most complaints about pressure cookers centre on that fact. For example, if you add too little water or too much water at the beginning, there is little you can do to correct for that.

There are other limitations too. Although oil-based sauces polymerise and thicken more quickly in a pressure cooker, it is impossible to make sauces that require intense beating, such as béchamel, hollandaise, or similar. It is also inconvenient for foods that require initial stir frying of onions and garlic, followed by wine or vinegar, before adding other ingredients, such as when making bolognaise and similar sauces and many stews. Finally, many stews and soups require thickening at the very end, which we encourage by adding an acidic component such as lemon to catalyse polymerisation of the lipids. If we add it earlier, the soup thickens before it is ready, which reduces diffusion of ingredients, since larger macromolecules diffuse more slowly. This situation, together with the need to add less water (all steam is recycled in the pressure cooker), explains why a pressure cooker often leaves a thick, half-burnt residue at the bottom, no matter what the food.

In general, pressure cookers are certainly convenient and you can make a satisfactory soup or a simple stew, but they are not something that I would use for making a more intricate dish.

Cooking by … Radar

Wouldn't it be nice to be able to gently and deeply cook the inside of a thick piece of meat or vegetable (e.g., an aubergine or potato) without burning the outside first? Well, there is. It's the microwave oven,[11] and it is probably one of the most efficient and convenient machines we have for heating food (especially water-rich foods), since little energy is lost in the process. Microwave photons have a wavelength of about 12 cm and just the right amount of energy to be able to penetrate up to about 1–2 cm into food (depending on

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[11] Microwave heating was first discovered over 60 years ago, during the development of radar, which also uses microwaves, as we'll discuss later.

its water content) and heat it from within. That's why they are so quick and efficient at heating up moist foods and soups—very little energy is wasted in heating the surroundings. Compare this with ordinary infrared electric ovens, where the air and the metal panels are heated more than the food, and the net efficiency is hardly more than 30%. Microwave ovens can reach efficiencies of more than 70%.

We'll discuss the way microwaves work in more detail later, but let's look first at how they are used for cooking. The way they heat foods is very different from other methods of heating. They do not share their energy by collisions between the IR photons and surface atoms as all other heating methods do, after which we must wait for the slow energy transfer inwards. They do so by direct "excitation" of the dipole water molecules. In the same way as you can use a magnet to jiggle the needle of a compass, so microwaves can jiggle water molecules billions of times a second, precisely because they are polar, with a positive end and a negative end. Since molecules also vibrate and move around randomly, the jiggling of the molecules increases the vibrations of other polar molecules around them and this adds energy to the system. It's as simple as that, and it works with all kinds of polar molecules, but not with non-polar molecules, since they have no positive and negative ends to be jiggled by the microwave radiation. You can experiment yourself to find out which foods "absorb" energy from microwaves and which don't. For example, many saturated lipids, such as butter and fat are slightly polar and are readily heated by microwaves.

But what happens to food when it is heated (irradiated[12]) by microwaves? The first thing to remember is that microwave photons do not have enough energy to make food crispy or produce a tasty crust on meat or vegetables.[13] All they can do is heat up water, butter, and some oils. So very dry foods cannot be heated in a microwave oven, no matter how long you are prepared to wait. They also have too little energy to polymerise oils to produce sauces. And certainly, they have far too little energy to "damage" any nutrients, as some claim. Considering their very low energy, it is quite surprising to hear concerns about the supposed danger of minute amounts (less than 2 mW, a millionth of the power of a MW oven) "leaking" from mobile telephones.

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[12] I guess it's the word "irradiated" that may have given MWs a bad name. People somehow associate irradiation with X-rays or γ-rays and forget that we are all irradiated all the time by visible photons with much higher energies than MW.

[13] As we saw earlier, microwave photons have thousands of times less energy than infrared (heating) photons and millions of times less energy than visible light.

In any case, microwaves are particularly useful for uniform and very rapid reheating of water-containing foods, especially leftovers, which would otherwise dry up or burn in an ordinary oven, while incurring the usual waste of energy. It is very easy to heat milk or melt chocolate or butter. One can also cook soup fairly quickly, but the difficulty in stirring the food inside the oven makes it a bit cumbersome.

Cooking meat and vegetables with microwaves is also very efficient, although the final colour is a highly unappetising grey since they cannot be crisped and cannot produce the pleasant golden brown colour from the Maillard reaction. This can be accomplished separately under a hot grill or on a hot plate for a few seconds after microwave cooking. This results in a very tender core to the exact level requested—rare, medium rare, or whatever—but with a nicely browned surface, and all this without drying it out. In many busy restaurants (even haute cuisine), the meat or vegetables are generally cooked separately and then smothered by the sauce, so any greyness is not much of a problem (don't look under the sauce).

For the same reason, microwave heating is also very useful for adjusting the core of oven-baked roasts or grills, when the surface of the meat or vegetable or fish has browned sufficiently but the inside is still red or uncooked. This is particularly useful for cooking thick and fibrous vegetables, such as aubergines and potatoes, while maintaining their shape and nutrients, something that cannot be done properly by boiling in water.

Wine, Vinegar, and Lemon—A Dashing Trio

I have already mentioned that the preparation of a smooth sauce without flour requires the addition during boiling of an acidic agent as a catalyst for the polymerisation reaction. Dry wine does the job too, as it also contains various bridging molecules, giving a thinner, but quite smooth sauce, as long as it is added at the initial "light frying" stage. For example, when we prepare seafood (shells, octopus, prawns, calamari, etc.) by briefly frying in oil, as soon as the water has mostly evaporated and the seafood is sizzling slightly, we can pour a small cup of white wine on top of the very hot oil. This immediately reacts with both the sea food and the hot oil to produce a thin, smooth sauce. At the same time, the alcohol evaporates and the remaining ingredients of the wine (sugars and aromatic substances) will diffuse into the seafood, giving it that special taste and even texture. This must all be allowed to go on for at least five minutes (longer is better, but do not allow any more frying). However, it must be completed before we add chopped tomato, peppers, or other vegetables or herbs. By the way, if you add the wine while there is still water in the pot, it will not react and the food will have a wine and alcohol flavour which can be a bit annoying.

Stronger alcoholic drinks may also be used, and in this case they can be added at any time. They have a quite different effect because the alcohol has time to diffuse into the seafood before it evaporates completely, while at the same time inducing polymerisation to thicken the sauce. If you combine this with starch, the effect is quite striking. When I make prawns (or calamari, or cockles, etc.) with pasta, I add a substantial amount of ouzo or raki[14] during early boiling of the seafood, wait for a bit for diffusion, and then add the pasta. The dill and salt are added just before the end. The starch dissolved into the water thickens the sauce very well,[15] so what we have here is a combination of polymerisation and gelatinisation.[16] By the way, pasta should only be added when the water is boiling to avoid prematurely dissolving the starch and the gluten. Because it does not contain gluten, rice can be added with the water at the beginning.

Vinegar (containing acetic acid) and lemon (citric acid) are both used as polymerisation agents, but they also have other effects on ingredients. Being acids, they soften and even partially break down fibres in various vegetables, making them more digestible. For example, all legumes (peas, beans, chickpeas, lentils, fava, etc.) as well as leeks, carrots, celery, celeriac, and other fibrous vegetables can benefit from the addition of vinegar or lemon during the early stages of boiling as this softens them and allows the acid to diffuse within them. Olive oil is added afterwards together with more lemon to thicken the sauce. Aubergines can also be cooked in a stew this way, as long as the cooking is at a low temperature. For example, in a pork stew, the meat must first be pre-cooked (with onions, carrots, and garlic) to partly dissociate the proteins, then fried lightly in its own fat, and only then do you add the aubergines with vinegar or lemon and continue to cook slowly till soft. Sensitive herbs are always added last (to avoid oxidation and dissociation of aromatic molecules), except bay leaves and allspice, which go in earlier to enable sufficient diffusion. If you want a thicker sauce, add some potatoes or celeriac before the aubergines to gelatinise the sauce.

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[14] Both are quite strong aperitifs from the eastern Mediterranean, with 40% or more alcohol. They are both made by double distillation of grapes with skin and stalks, but while ouzo has a strong aniseed aroma and flavor, raki is more fruity. Other similar drinks are pastis, raku, tsipouro, and arak.

[15] For the cooks out there, I also add chopped onion, garlic, and tomatoes too, plus salt and pepper with the ouzo, and boil at least 10 min before adding the pasta.

[16] Restaurants do something similar, but instead of pasta, they add starch (or water saved from boiled pasta) so they have a ready sauce to add to any type of pasta or rice or other carbohydrate.

Vinegar, wine, or lemon juice are also used to marinate and tenderise game meat (but also any other meat, fish, or vegetables) for the same reason: diffusion into the cells and gradual breakdown of collagen and fibres while imbuing the flesh with aromas and flavours. The longer the marinade, the more tender and more aromatic the result, even at low temperatures. In this case, the cooking time can be reduced and the meat eaten rarer than normal as the marinade sterilises the meat as well. The remaining liquids can of course be further cooked with olive oil and perhaps tomato and herbs, and made into a smooth sauce with additional lemon.

Salt and Sugar—A Love–Hate Relationship

Salt (sodium chloride, NaCl) is one of our most critical nutrients. In fact, the sodium ion is one of the most critical elements for life, as it is crucial for regulating blood pressure and heart and muscle function, as well as a healthy nervous system and a balanced immune system. We require a minimum of about 2–4 g of salt per day (about 1–2 teaspoons) for the needs of our body, depending on the amount we lose in sweat and urine (both diffusion-controlled). So don’t scrimp on added salt, unless there is a medical reason or you regularly eat ready-made meals or processed foods, which generally contain too much salt.

Salt has many functions in cooking and it has different effects depending on timing, i.e., exactly when it is added to the food. Let’s first look at the properties of salt that are independent of other agents.

Salt (and sugar) is a strongly hydrophilic molecule so it desiccates all foods. It sucks out water from meat by diffusion and osmosis (diffusion across a membrane till the concentration of salt is the same on both sides), so it tends to make meat drier and tougher. It’s always better to add salt after braising or barbequing meat or fish, rather than before. It does the same with vegetables, but in this case we do need to remove some of the water, so it helps to add salt at the start. When you start a casserole or a stew by frying onion and garlic, always add a pinch of salt to draw out the water earlier and slightly caramelise the vegetables more quickly, without burning them. The remaining salt is added much later, with the vegetables. Potatoes and celeriac are special cases, as they have a strong affinity for salt and will even preferentially absorb salt from the sauce. If you ever discover you’ve added too much salt in your soup or stew, just add a potato for a few minutes, stirring frequently. It will suck out all the excess salt, saving your reputation (but not if you serve the potato).

Because salt is such a strong desiccating agent, it can be used very successfully for keeping chips and other fried foods crispy for a little longer. Right after you fry something, sprinkle a bit of salt on it. It will absorb all excess water from the surface of the fried food. Because all forms of life (including microbes and fungi) depend on water, salt is also an excellent preservative, as generations of salted cod fishermen and connoisseurs will certify. We'll talk more about this again later.

Taste sensors

There seem to be (more or less) specific tastebuds for each of the five tastes: sweet, sour, bitter, salty, and umami. Each of them is connected to the brain via a different neuron, but the brain often processes their signals in tandem with signals from the olfactory centre.

The taste buds sense a particular molecule by binding to it (transiently reacting with it) and generating a small voltage signal "signature" which is passed along to the brain along the corresponding neuron. In the brain's processing region (the "thalamus"), the signal is then compared with a previously stored signature to determine the strength and quality of the substance.

Now, salt has a strange effect on our tastebuds. It is not fully understood why, but a tiny amount of salt enhances both the sweet taste of sugar and the taste of umami. In other words, using a tiny bit of salt in chocolate makes it taste sweeter. It may have to do with its desiccating ability again, because somehow the electric signals from our tastebuds are strengthened and arrive enhanced at our taste centre in the brain. I hypothesise that this happens because the non-electrically conductive water is reduced at the point where our tastebud molecules encounter a sweet molecule, removing a point of electrical resistance. This only works when the amount of added salt is tiny, otherwise the sense of saltiness will overpower everything else. Ready meals companies know that, and when they prepare fat-free meals, they add quite a lot of sugar, umami, and salt just to give them some taste. You see, fat-free meat is practically tasteless and without that combination of additives it would be inedible. The misconceived trend for ultra-low-fat foods has played into the hands of ready-food manufacturers. Fat spoils more easily (it oxidises readily at room temperature but is also the preferred growing place for bacteria), so by removing fat and adding salt and sugar, they can increase the shelf life of processed foods and ready meals while reducing the possibility of food poisoning.[17] At the same time, you feel hungry more quickly since sugar has far less energy content than fat and it is also digested and metabolised much more easily.

Salt is also very important for improving the colour of fresh bread. It does that by first increasing caramelisation due to the oxidation of natural sugars in the starch, probably by desiccating the starch. Secondly, it slightly reduces the (oxygen-free) fermentation reaction of the yeasts. Both of these effects produce a nice brown crust more quickly.

Salt is also added to most cheeses and yoghurt as a means of controlling the fermentation reaction by their corresponding moulds. And it is added to processed meats (ham, sausages and the like) to make them look pink and more palatable. In reality, processed meats are a horrible grey colour so the addition of (unfortunately) relatively large amounts of salt increases the conversion of nitrites to nitric oxide (because of the free Cl ions from the dissociation of NaCl), thereby changing the colour.

Ideally, salt should be from the sea or at least iodised, as we need iodine for the correct operation of our thyroid gland. This is probably an evolutionary leftover from the primordial times when our ancestors lived in the sea. Sodium is also quite a critical trace element in catalytic enzymes and we should always include it in our diet.

Both salt and sugar have very good antibacterial properties, at sufficiently high concentrations. No bacterial growth or fungal growth is possible in salted fish, nor in properly made jams (provided that all free water is eliminated during boiling). The main reasons are their desiccating effect on the microbes due to osmotic pressure—without water all bacteria die—and the deadly effect of free Cl on the cell membranes and on bacterial DNA, but not in our blood where it serves important functions.

Looking Through the … Syrup

Sugar has had a bad press for a long time but for a dubious reason. As I mentioned above, because of the need to add taste to otherwise unpalatable or even bitter fizzy drinks, ready meals, and processed foods, manufacturers tend to add relatively large amounts of sugar (together with salt), leading to over-consumption and serious problems of metabolism.

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[17] That's not all. Since sugar is no match for the high energy content of fats and other lipids, it cannot sustain us till our next main meal.

However, sugar in moderation is extremely important in nutrition (and the brain) and it is certainly needed in cooking. In certain stews and other pot dishes using tomatoes, sugar helps to balance out the sourness of fresh tomatoes, giving a very agreeable sweet-and-sour taste. It is important to allow the sauce to boil for a while so that the sugar and water can react with the acidic agent in the tomato to give a smooth tomato sauce.

Sugar also serves to stabilise and lighten the batter in cake mixtures before baking, so that the ensuing carbon dioxide has a chance to diffuse through the structure, something that we'll discuss later.

Mediterranean baking of sweets and cakes such as baklava, kadaifi, revani, samali, orange cake, spoon sweets, etc., often involves making thick syrups, and here sugar comes into its own, at least the unprocessed, brown sugar everyone should use. A syrup is another light polymer, made by reacting sugar with water in the presence of an acidic catalyst like lemon, orange, alcohol, etc. By boiling the mixture for 5 min or so, sugar (sucrose) splits into glucose and fructose, which bind with water molecules in the presence of the catalyst. This type of syrup is called inverted[18] sugar syrup and it is particularly thick if made with brown sugar which brings in additional molecules.

When making this syrup, an interesting optical phenomenon occurs. As soon as the sugar has been added at relatively low temperature, the solution becomes semi-opaque (cloudy) because the sugar splits into glucose and fructose before bonding with the water molecules. While this is happening, light is being dispersed throughout the liquid, giving a cloudy, bright appearance. This continues for a while as the solution is heated, but as soon as bonding with the water molecules is complete, the solution very suddenly becomes transparent. If you don't add lemon or another acidic agent, the phenomenon takes longer, but the transition from semi-opaque to transparent is equally sudden.

Sugar's antibacterial and anti-fungal properties have been known for thousands of years. As I mentioned in the previous chapter, the sterilisation mechanism is mainly due its desiccant effect, but it's also due to its ability to damage the cell membranes of microbes and viruses by forming strong bonds with membrane proteins and lipids. It is the same damage that wreaks havoc on healthy cells in the bodies of people with uncontrolled blood sugar levels.

Honey also displays desiccant osmotic capability, as well as being quite acidic. In ancient times (definitely in Greece and China but elsewhere too), deep wounds were treated by mixing honey (rich in glucose and fructose)

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[18] It has the opposite optical polarization rotation to the original sucrose.

with olive oil and lemon (to enable bonding), along with various herbs (thyme, origanum, and others), and leaving it on the wound for some time. All of the ingredients work by multiple routes and all are able to destroy bacterial membrane proteins by electrostatic interactions. Apparently, there is even a substance in honey that affects communication between bacteria so that they cannot develop resistance to it. Some honeys also contain hydrogen peroxide, another potent antibacterial agent with highly reactive oxygen ions.

Denatured Scum Always Rises to the Top

Do you like soup? The making of soup is probably the oldest form of proper cooking (I discount simply placing meat on a fire) and it's no wonder it has evolved to yield literally hundreds, globally probably thousands of different types. And yet, the basic principles are still the same. All soups are made by slowly boiling some protein food with a lipid (I always use olive oil and sometimes mix in some fresh butter[19]), adding vegetables and herbs. The end result is a broth which can be converted to a creamy or veloute soup, or, after clarifying, into a clear consommé soup which may be slowly reduced. The various phenomena present are interesting and incorporate some enlightening chemistry and physics.

Proteins are all rather complex polymers made of thousands of amino acids (basic protein units), coiled into very specific shapes. There are hundreds of thousands of different protein types in foods, all made by strict instructions in the food's genome (the collection of genes in the DNA), but that's another story. During heating in water the protein molecules get to vibrate strongly and eventually the hydrogen bonds holding the protein together weaken, the structure partly breaks down, and, by releasing stored energy, it uncoils permanently into a loose polymeric structure, sometimes with fresh cross-linking of the remaining short-chained amino acids.[20] This is called denaturing (it's mostly irreversible) and any acidic or alkaline agent or an alcohol can speed up and intensify the process by weakening the bonds. However, the amino acids remain mostly intact and therefore the total nutritional value of the food is not affected. Heating an egg demonstrates this process very well. Throwing an egg in boiling water immediately denatures it

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[19] Never margarine—it spoils the taste and I definitely do not believe it is as healthy an alternative as so much marketing would have us believe.

[20] Cross-linking is a random, complicated form of chemical bonding between different macromolecules, creating a rigid structure. Most hard polymers and epoxies are cross-linked, as are body cartilage and similar structures.

and the egg white becomes solid. However, if we first beat the egg strongly using a whisk or a fork with a bit of water, the proteins in the egg bond temporarily to the water and then we can add it to a hot soup without it solidifying.[21]

The same happens to meat when you boil it for a soup or a stew. The proteins are quickly denatured and re-form by cross-linking in a more-or-less random manner, making the meat hard. During that early period, some of the surface proteins rise to the surface and form an ugly-looking "scum" which, however, is simply an insoluble mixture of loose amino acids with some fat. If you are making a stew or a broth, you can just let it mix in and it will soon be re-absorbed in the soup, although it'll probably remain in the form of small particles. If, however, you want a clear soup (e.g., a consommé), then it's probably a good idea to remove it right away as it will affect the clarity of the soup. Unlike a broth or a stock, a consommé must be completely clear. You can also filter it to remove particles, before reducing it by extensive boiling.

Further boiling the soup will gradually dissolve some of collagen allowing the meat to soften again, at which point you should stop the process as any further cooking will result in severe cross-linking of the proteins and very hard meat. By the way, cross-linking is the reason why overcooked meat appears to shrink as it hardens, even if it's still in the soup. And it's also the reason why overcooked steaks on the barbeque or in the frying pan shrink and become tough.

Denaturing of proteins also occurs when meat and vegetables are slowly marinated in wine with added vinegar. This also dissolves any collagen. After marinating, cooking should be carried out at lower temperature and for shorter time to avoid shrinking and hardening of the proteins.

I mentioned clarifying a consommé and it is worth looking at the process a bit more closely. In order to make a very clear soup (meat, fish, or vegetable), we need to make sure that all protein particles are removed, including those from the denatured proteins in the scum. We can do that by filtering of course, but a lot of the nutrients will probably be absorbed in the filter paper and I'm not sure whether the paper itself might not affect the soup.[22] The correct way to do this is by cutting all the solid starting ingredients into tiny particles—everything including meat, vegetables, herbs, the lot—and then adding them to cold water. Boiling should be done over a low heat for a few

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[21] An egg denatures every time we heat it. A very simple method I use for cooking an egg is in the microwave. I use a round shallow dish (a glass "petri" dish from the lab is perfect). Without oil, it will cook in under 1 min (at half power) to a perfect consistency. Go on, try it. You'll never go back to frying.

[22] Even the clearest of consommés will contain many particles at the nanometer size (a billionth of a metre), and these can easily stick to the filter paper.

hours, with very gentle stirring. You will notice that very soon all the finely cut ingredients float to the surface, because they still contain some air pockets, and they will stay there because of the surface tension of water. Each particle is very light, and as most foods are slightly hydrophobic because of their lipid content, they float around, behaving just like those insects that walk on water,[23] as we saw earlier. If you continue boiling softly (with very gentle stirring), the collagen and other nutrients will very gradually dissolve in the water, which remains clear since all solid particles remain at the surface.[24] After a few hours (!) of slow boiling, everything that can dissolve will have and you can then remove and discard the remaining husks, leaving a very clear but quite dense (and extremely tasty) consommé. Salt and pepper corns may be added at the beginning, but ground pepper and other condiments should be added on the plate as they will cloud the clear soup. No oils are used in this soup and the meat must be very lean[25] as oils and fats reduce the surface tension of water[26] and the finely cut ingredients will simply sink after a while.

At the opposite extreme, as we discussed earlier, to make a creamy or velvety soup, you need to add oil or butter (or use non-lean protein) and use as much of the collagen and protein and fat as you can. All of this will help to thicken the soup, together with emulsifiers such as lemon and egg. In that case, it is perfectly fine to use the scum and I never bother removing it, but take pleasure in re-incorporating it back into the soup. In fact, fish soups are an excellent source of edible collagen which is concentrated in the scum, especially the skin, heads and bones of larger fish like cod and tuna.

Dragged Over the Coals or Trial by Fire?

I guess the earliest cooked meal by an ancestor must have been a piece of meat thrown on a fire, or perhaps dropped accidentally on a fire, or simply discovered half-burnt. Funny how many people still do exactly that. It must be the worst way to cook as it destroys the food, unless it is carefully controlled to keep the temperature below a certain limit and avoid all naked flames.

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[23] They are the "water striders" we saw earlier. A few species have evolved to do that, including long-legged flies and a few types of spiders. And, of course, some fish have also evolved to nab them from below.

[24] In fact, most of the solutes (the nutrients) in such small pieces dissolve faster than if you use larger pieces, because their specific surface area is very large, allowing faster diffusion.

[25] Fish consommé also works well with young cod, scorpion, and similar lean fish. Sea bream, grouper, and sea bass make excellent rich, velvety soups.

[26] They affect the electrostatic repulsive forces of the water molecules.

That is because all proteins can be destroyed very easily at high temperatures and especially in the presence of a flame, and so can fats and carbohydrates (starches and sugars) at higher temperatures. They are all carbon-based fuels and they can burn (oxidise) quite happily as soon as the water is removed.[27] In fact, the proteins start breaking down because of the excess heat quite early on, long before any actual burning. When burning starts (and the surface of the food has converted to primary black coal), it is too late to save it. It is indigestible and in fact it probably contains many aromatic hydrocarbons, all quite toxic.

The only way you should broil food on a barbeque is using charcoal, never directly on wood flames and wait until the wood has converted to coal,[28] and only when all flames have completely subsided.[29] The temperature at the surface of the meat or vegetable should not be higher than about 200 °C to ensure heating without burning. Any flames (e.g. from dripping fat catching fire) must be put out immediately (cold or wet salt works fairly well as it has a high heat capacity and absorbs the heat) to avoid burning the food.

Because of buoyancy (a gravitational effect), hot air rises so a barbeque does not need a lot of hot coals to do a good job, and they certainly do not need to be red hot. Well-prepared hot coals are grey, without any covering of ash, which is an excellent thermal insulator. Ash prevents heating of the air and stops all infrared radiation from reaching the food above, so it should be removed as quickly as it forms.[30] In fact, ash is such an excellent insulator that hot coals in a fireplace retain their heat well enough to be used to start a new fire the next day. Nomadic people cover hot coals with ash, to protect them from further oxidation, and transport them in a skin bag until the end of the trip, when the coals are uncovered and can be used immediately for cooking as they will have retained their heat very well, even days later.

To reduce the rate at which the coals burn, you can reduce their oxidation. While at the beginning you supply a good flow of air to start combustion, once the coals are red hot, you can reduce the air supply to an amount that will give you just the right temperature. This will also reduce the rate of production of ash.

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[27] As soon as all water evaporates, food converts to and emits various gases which ignite, before final pyrolysis, which ends with carbon.

[28] Wood fires emit many toxic gases, especially hydrogen cyanide (HCN).

[29] Initially, coal will oxidise only partially, producing carbon monoxide (CO) another toxic gas. Later, it will produce carbon dioxide, assuming there is an ample supply of fresh air.

[30] A vibrating barbeque would do the job very well, by occasionally shaking the ash off the coals. I wonder if anyone has thought of it.

Back to the kitchen, cooking over a gas fire is of course very ordinary in many places in the world, and many barbeques work with gas fires.[31] I'll discuss gas fires later, but they produce a different cocktail of gases when they burn, so the meat (or vegetable) actually has a slightly different taste to that broiled with coals. In addition, it is more difficult to control the fires produced by dripping fat and it is easier to block the gas grid, although some barbeques try to reduce such problems. Heating occurs by both rising hot air and IR radiation.

Another method of high temperature cooking—maybe the original method—is by slowly rotating a large piece of meat (usually a whole animal or bird) on a spit over a large coal fire on the side.[32] A smaller version is available in home ovens (a rotisserie) and heating is generally by radiation as the hot air is guided to the side of the meat. Instead of a whole animal on the spit, various arrangements are used in Greece with pieces of meat ("kontosouvli") or even grease-paper packets ("exohiko", with meat, potatoes, onions, cheese, herbs, and spices—vegan versions are possible). In the latter case, cooking is enabled by conduction from the hot grease-paper to the contents, gradually building up the pressure of the vapour from the ingredients to produce an interesting combination of broiling and steaming.

Apart from the meat-above arrangement of a barbeque or a spit, there are other ways of cooking with a fire. In many countries, vertical broiler rotisseries[33] are now common, producing shredded "gyro", a type of heavily spiced (and very tasty) meat or chicken, compressed together to make a large barrel-shaped mass. In this case, heating is mainly by infrared radiation from vertical gas fires, and the gyro (Greek for "rotate") is gradually broiled on the outside. The latter is cut off and served which enables broiling of the next layer, as meat is a very weak heat conductor.

Another unusual method of cooking with a fire is by covering the meat (including condiments and herbs) with grease-paper, burying the packet in the ground together with hot coals, and allowing very slow cooking over many hours. The result is another delicious combination of broiling and steaming. Burying ensures that the coals remain hot for a long time, since the surrounding soil is an excellent thermal insulator, especially when dry—that's why underground cellars or caves have a constant temperature throughout the year. It also reduces the amount of smoke produced.

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[31] I often wonder if the current situation in which the climate has been destabilised would have been milder or occurred more slowly if gas hobs (and air-conditioners too) had never become so ubiquitous. In many countries, they are used in up to 90% of homes.

[32] To be found everywhere at Easter in millions of Balkan homes and farms.

[33] Believed to have originated in Greece to produce the gyro. Also used for doner kebabs in Turkey and shawarma in the Middle East.

I have concentrated on meat, but broiling fish on coals is an excellent way of getting the most taste out of them, as well as being particularly convenient and smell-free. Generally, fish broils very quickly, but only whole fish can be broiled as the flesh has an open structure and dries out very easily. The convenient thing is that the skin heats up (and burns) quickly on coals and, due to the difference in thermal expansion,[34] it separates from the underlying flesh, so it's easy to peel off. For this reason, many fishermen don't even bother to clean fresh fish when cooking them over a makeshift fire on the beach. An added bonus is that, since fish skin is not eaten and once it dries it shields the flesh, the effect of flames from dripping fat is less important. This means that, with care, fish can be cooked quite successfully in a matter of a few minutes over an open fire, without waiting for hot coals to form. The same is true for chicken, if you don't eat the skin, which is a pity actually as it is full of collagen and other nutrients.

Fat on Fire

Lipids of all types (animal and vegetable) are a very important part of our nutrition and the source of most of our energy. That's why the body stores fat so carefully as soon as it has the slightest opportunity, or finds it in excess, or when it has lower energy needs. In fact, it hoards fat very selfishly and happily (even converts excessive sugar not used up into fat) and only uses it for energy when other sources are all but dried up. People who try to lose weight will vouch for this: how easy it is to gain fat and how difficult it is to lose it.

Indestructible fat cells

Fat (lipid) cells (both "brown" and "white" ones) in the body are fascinating and almost indestructible. They resemble little balloons which fill up with lipids and empty them out as needs arise in the body. Because of the great importance of fat for the generation of energy in mitochondria and elsewhere, lipid cells can easily increase in number, but are very difficult to eradicate by fasting. The best we can do to lose weight is to use up their contents temporarily.

While white fat is used only for long-term storage, brown fat is used to produce emergency energy for maintaining body temperature and when needed suddenly. For this reason the corresponding cells contain a very large number of mitochondria which use the hydrogen atoms in the stored lipid to increase internal heating in a cold environment.

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[34] As mentioned before, thermal expansion of materials is due to the greater vibration of atoms when heated. Ceramics and glasses expand a little, metals more, polymers and food even more, and liquids much more.

It is all the brain's fault. As we saw earlier, the brain uses glucose almost exclusively for its energy needs, and this can be obtained fairly easily from fat by a simple enzymatic transformation. So, as soon as it detects excess fat in the body (not used up for daily needs), it makes sure it is stored and very well protected until it is needed. Interestingly, the brain converts all excess sugar into fat as well, because it is easier and safer to store fat than the rather toxic glucose. If you want to lose weight, reduce your sugar intake and hold on for a few days, while continuing to use up energy (e.g., exercising and thinking hard). The brain will then be forced to convert stored fat into sugar for its huge needs. But you have to persevere, as the brain will easily go back to its bad (survivalist) behaviour of directing the storage of fat as soon as it can.

The lipids we eat can very easily be damaged beyond reasonable usefulness by cooking the wrong way and by oxidation in a warm environment. Here, a chemical transformation is to blame. Overheating is the main culprit and high-temperature frying the main cooking route to damaged fat. Let's see how these problems occur.

Most everyone loves the taste of fried chips ("French fries") or steaks, but do you know why? It's a drug, of sorts. During deep or shallow frying, starch from potatoes or flour is converted to certain kinds of sugar, which are of course very palatable. But at high temperatures (e.g., during frying) starch is converted to a brown chemical called acrylamide which gives potatoes and bread their lovely golden brown colour. As mentioned before, it is also a bit toxic,[35] so it's a good idea to stop frying when the chips are lightly golden, not browned. The reason why acrylamide is so easy to form by frying is because most oils boil at over 180 °C, while water boils at just 100 °C (at sea level). By heating the oil to about 180–190 °C, the surface water on the food (say potato chips) boils and evaporates violently, the surface of the potatoes is quickly crisped, and the potato is sealed, thereafter reducing oil absorption. Shaking the basket with the potatoes helps to expose new surfaces to the hot oil for an even crisping. During frying, the temperature of the oil–water–potato mixture remains just above 100 °C until all free water has evaporated. At that point, the oil temperature starts increasing fast and the starch starts overheating, gradually converting the now desiccated surface starch to acrylamide. If you wait too long, the acrylamide will get darker and darker, eventually turning black and becoming inedible as more and more of the hydrogen and nitrogen break away and only the core carbon atoms remain. In fact, acrylamide starts forming once the temperature of the oil in the pot has climbed above about 130 °C. This gives us a quick way of telling that it's

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[35] Lots of high-temperature transformations in the kitchen give slightly toxic but tasteful by-products. It's a case of balancing taste with safety while our liver expertly eliminates them over time.

time to remove the chips. By the way, chip size matters and they should be up to about 7 mm thick. The problem is that, if the potatoes have been cut too thick, the core will not be properly cooked before too much acrylamide has formed on the surface. If they are cut thinly, they will become very crispy without too much acrylamide—just like crisps in a packet.

While the chips are still frying, it's a good idea to shake them in the basket to loosen them. Acrylamide is quite a hard and adhesive compound and forms tiny bridges between chips (I once observed them under a microscope), bonding them together.

Finally, it is worth noting that most oils also start breaking down (dissociating) above about 160 °C, so frying should only be done using oils that have a higher dissociation temperature, for example sunflower or safflower oil. High quality olive oil should be avoided for shallow frying as it breaks down at much lower temperatures (about 110–120 °C) and in any case it's such a waste to destroy the fruity taste of such olive oil, especially the "extra virgin" type. It should only be used in salads and in pot cooking, where the temperatures never go above 100 °C. By the way, "extra virgin olive oil" is a formal designation to indicate extraction only by the—centuries old—cold-pressing method, without the application of any heat. This is important because olive oil extracted by thermal methods (which give almost twice the yield) is already affected by heat and has already lost much of its fruity aroma and taste, although it can be used for frying.

The air fryer is a recent development which aims at reducing oil absorption, but presents its own problems. The potatoes are placed in a metallic basket and hot air is blown on them at about 160 °C, quickly sealing the potatoes and gradually cooking them internally. The problem is that acrylamide starts forming almost immediately and not at the end as with deep oil frying, while the potatoes still have to be heated for some time to make sure they are cooked properly inside.

Barbequing meat presents another problem, rather more serious. At high enough temperatures, e.g., during grilling on a barbeque with a free flame, fat is converted to various toxic compounds called cyclic aromatic hydrocarbons which are certainly bad for health (proven carcinogens). It's mainly the result of any flame that is produced by dripping fat onto the hot coals, so make sure you put out any fire immediately by sprinkling wet salt on it or a good dose of beer. As I mentioned earlier, salt puts out a fire very effectively, simply by soaking up large amounts of heat and thereby cooling it down. In physical terms we say that it has a high specific heat capacity (energy that needs to be absorbed per kilogram to raise its temperature by one degree) and it is something of a champion in this regard. The value for salt is only about a quarter of that for water, but still very high. Water has the highest specific heat capacity of all normal materials (only hydrogen and helium gases have higher values). This is in fact the basic reason why life arose on our planet, whose average annual temperature (about 15 °C) is ideal for water in its liquid state, providing the perfect conditions for life to get a grip and develop. Water's very high heat capacity and its very high "latent heat of vaporisation" which we discussed earlier means that it can't be heated up and evaporated too easily by the Sun, allowing life to get a firm hold on the early Earth.

Batter Matters

Everyone likes pancakes and honey puffs, I think. And surely everybody likes Wiener schnitzel. I like them both, not only because of their taste, but also because of the fascinating physics underpinning them. In fact, everything that requires coating has interesting features. Let's look at them in more detail.

First of all, let's see how pancakes (or honey puffs or dumplings) are made. We simply make a batter of flour with water (perhaps adding some baking powder or bicarbonate of soda[36] or even some beer) and then throw a spoonful into very hot oil at about 180 °C. If the oil is very shallow (or we use a hotplate at this temperature), we get a pancake but in deep oil we get a batter puff. But what exactly happens?

The flour–water mixture (essentially starch with gluten and perhaps some short fibres if we use whole wheat flour) becomes a thin glue which, on contact with the oil at about 180 °C, immediately converts to acrylamide. The latter is strong and hard, encasing and protecting the soft batter inside, which has since filled up with carbon dioxide and air. At the same time, the batter tries to minimize its surface area (like a balloon), resulting in a disc or spherical shape, and the puffs are ready in a few seconds. The added baking powder forms carbon dioxide bubbles which cannot burst straight away, giving a light, swollen pancake or honey puff. Beer does the same, as it contains (and generates) carbon dioxide bubbles itself, but it's better to wait a few minutes in this case to allow for the batter to swell a little before frying. I have already discussed the effects of using alcohol in cooking.

By the way, flour with a very little water is well known as a glue because of the gluten it contains. In olden times, carpenters and other wood workers used to make their own glue from very fine (gluten-rich) processed (white) flour and water. It had to be used very quickly as it coagulated and

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[36] Both contain carbonates which quickly decompose above about 160 °C to give off carbon dioxide.

dried quite fast. But wood stuck with that could remain well glued for many years.

We use this property when we fry fish or schnitzel or calamari. The problem is that fish or calamari are very sensitive and will dehydrate and shrink in seconds in hot oil, so we need to delay this process until the flesh is cooked. For this we employ a thick batter or simply dip and coat the slightly wet fish in flour and allow it to dry slightly to make a strong coating before frying. As soon as the flour starts converting to golden acrylamide, we know that most of the internal water has been eliminated and the food is ready to be served.

In the case of a schnitzel (or a chicken leg for that matter), the added beaten egg and crumbs after the flour give added taste, but they also offer some protection to the sensitive thin slice of meat inside and ensure that it stays moist during shallow or deep frying in oil.

Drink and be Bubbly and Merry

We've already discussed the catalytic effect of a little alcohol on the polymerisation of lipids when making smooth sauces. It does this by being slightly polar. This allows it to bond equally well with water and various lipids, while at the same time breaking down some proteins, which thickens the sauce even further. But alcohol also has a number of other effects on food and food preparation.

As I mentioned above, beer lightens up batter by including carbon dioxide bubbles as it contains various foaming agents. It can even lighten up heavy batters (e.g. bread) because it generates bubbles and at the same time strengthens the bubble surfaces by the presence of a small amount of alcohol, which binds the water with the oil. Allowing the batter to swell a little before baking or frying increases the subsequent swelling substantially.

Fizzy wines (or champagne) also work fairly well too, as the greater amount of alcohol tends to strengthen the additional bubble surfaces and raises the batter better during frying. The additional taste left over by the wine or champagne makes for an extra special treat.

The strength of the water–gluten bonds makes it difficult to create a flaky batter or dough with white flour. A way to achieve this is to use a stronger alcoholic drink—whisky, rum, brandy, vodka, raki, ouzo, etc., all with about 40% alcohol—and stir the batter or knead the dough a bit more. The larger amount of alcohol and the substantial amount of sugar results in weakened water–gluten bonds but stronger oil–water binding, and the batter or dough becomes flaky during frying. In each case, the alcohol is added to the almost ready batter or dough and folded over many times before frying or baking. This is how croissants are made, adding butter as well.

Strong alcoholic drinks are also used for various flambé dishes, for example in Banana Foster or crème brûlée. The alcohol is ignited and the flame envelops the dessert, but the temperature on the dish itself is not very high, so browning by the Millard or caramelisation reactions is minimal. The alcohol binds the dish while evaporating, and once the alcohol has burnt off, all that's left is the aroma and the taste of the drink.

Swelling Pressure and Architectural Perfection

Imagine a world without carbon dioxide (CO_2). Actually, it's impossible, since every bit of life on the planet depends on the availability of this simple molecule: a carbon atom flanked by two oxygen atoms, in addition to water. Plants and algae grow by taking in carbon dioxide from the atmosphere and converting it with the help of sunlight (via amazingly complicated but fascinating endothermic reactions called photosynthesis) to sugars and proteins. Actually, it's another interesting physical process that allows this to happen: the conversion from CO_2 to sugars would take years if it wasn't for the presence of a metal catalyst that accelerates the reaction by millions of times to enable plant growth. Such catalytic acceleration of the CO_2-to-sugar reaction has a number of intermediate stages and for many years it was not understood. In fact, as we discussed before, all life depends on catalysis of biological reactions, enabled by the enzymes in all living bodies. Many of the vitamins and minerals we need for a health life are actually catalysts which enable the necessary processes of life. There is strong evidence that such catalytic processes depend on the quantum mechanical characteristics of the system at the molecular and atomic levels.

But I digress again. We were discussing carbon dioxide. Animal life produces CO_2 continuously by the exothermic reaction between carbon in our food and oxygen in the atmosphere. It's a good thing that plants are able to use this carbon dioxide to produce sugars and other compounds with the help of sunlight. But let's disregard all that for a moment and see where we find it in the kitchen. First of all, we breathe it out all the time and it is also produced by the combustion of the gas in the hob or the oven, as long as the hob is clean and there is sufficient oxygen.

In the kitchen, we depend on the production and controlled release of carbon dioxide for numerous cooking and baking processes. A cake would never rise, and would therefore remain dense, if it wasn't for the pressure inside millions of bubbles of carbon dioxide gas in the moist starch–gluten mixture. This gas is produced by the dissociation of baking soda molecules (sodium bicarbonate, consisting of a sodium atom with a hydrogen, a carbon, and three oxygen atoms) or baking powder, which is a mixture of baking soda with a weak acid like sodium phosphate. As soon as the wet cake mixture reaches about 150 °C in the oven, these will start dissociating and releasing carbon dioxide, creating bubbles in the cake and making it swell and rise.

Actually, much more is involved in making a cake or bread. If we put the cake in a cold oven and let it heat up gradually, it will not rise because the carbon dioxide will gradually seep out at a lower temperature (from about 140 °C) and not do its job properly. It's critical that the cake mixture be put in a pre-heated oven at a high enough temperature (at least about 175 °C), so that the top layer dries out very quickly and forms a barrier to any gas seeping out too quickly. The gas in the bubbles is under pressure from the surface tension of the bubble skin and all the bubbles together push against the surface of the cake. This is exactly how a balloon works: it expands until there is equal pressure inside and outside, taking into account the elasticity of the balloon. Once the cake has risen enough, the temperature of the oven can be reduced slightly (to about 160 °C), so as not to overbake the surface of the cake but still allow the evaporation of the water and the reaction between the starch, sugars, etc., to proceed. Finally, all the water will dry up as it diffuses to the surface and evaporates away, and the cake will retain the puffed-up appearance of the dried bubbles.

Biscuits and cookies are made much the same way, but most of them nowadays, especially the ones referred to as "soft", are first dried and pre-baked in a conveyor microwave oven and then passed under a normal infrared oven to given them a slightly crusty outer surface.

Before we leave cake making, a word about aromatics in cakes and biscuits. Most aromatic compounds are very volatile molecules and are extremely sensitive to baking. They dissociate very easily and their aroma is all but lost if the temperature is too high or baking takes too long. Examples are various "essences" such as vanilla, orange, lemon, etc. In my experience most such essences are lost during baking and we might as well not use them at all.

However, there are a number of ways out of this conundrum. The first is to add the aromatics in a slightly coarse, solid form, and make sure the batter is dense so that the baking time is short and some of the compound remains behind. Examples are small particles of mastic, vanilla, cinnamon, orange, or lemon rind, etc. Alternatively, you could reduce the original amount of sugar in the cake and add the aromatics after baking, in a thin syrup which produces a soft, moist cake of the kind made in many countries of the Eastern Mediterranean or Middle East. Finally, if the aromatic is particularly sensitive, it could be sprinkled on afterwards. An example would be rose or orange "water".

What about bread? Well, the overall mechanism is exactly the same. We need a sticky dough (the more starch and gluten, the stickier it will be) with good surface tension, and we need something to produce carbon dioxide to create bubbles. It's actually quite possible to make bread using baking powder and baking soda, but it won't taste like real bread. Lots of cheap bread products use these and they taste strange or downright awful. For real bread, we need to use yeast, a type of fungus. This is actually a living mould-like colony of millions of spores that produces carbon dioxide by a fermentation reaction, even at quite low temperatures. In fact, real bread is made by allowing the dough to swell at a very mild temperature (about 35–40 °C is sufficient) for about 1–2 h and then immediately baking it in a pre-heated oven at about 180–200 °C. The big difference with cake is that swelling ("raising") must be completed (up to 100% of the starting volume) before baking begins. Indeed, baking does not produce any more carbon dioxide as the yeast is killed at high temperatures. By the way, many porous cheeses such as Swiss emmentaler are produced using the same principle. Various kinds of cheese yeast produce carbon dioxide. This increases the pressure inside the cheese mass, which swells as it tries to equalise the pressure inside and outside, being assisted of course by the strength of the cheese mass around the pores.

Interestingly, 100% whole wheat bread or cake can never be made to swell as much as white bread, or even at all. Because of the additional fibres and reduced starch and gluten, it is impossible to seal the surface and the bubbles completely, and carbon dioxide seeps out well before the bubbles can expand. The best that can be managed is about a 20–30% expansion to make so-called "German bread". For lower contents of whole wheat flour, the sealing of the bubbles is sufficient, so swelling up to 100% is possible again. Interestingly, oat flour is gluten free, but its starch content is high so it forms strong and elastic bubble walls and it can replace up to about 30% of the white flour if preferred, with only a minor effect on the swelling. To get the same swelling, add more yeast.

The science of fracture

There is a whole scientific field called fracture mechanics, which deals with the way that materials deform and fail. The whole field is based on the way materials absorb energy as the atomic lattice deforms, and also on how they dissipate fracture energy in order to sever atomic bonds at the point of fracture. It has been crucial in recognising that thick structures are not necessarily strong, as they can fail by the extension of tiny preexisting flaws. It has also shown that, in many structures, toughness (energy dissipation) is more important than strength in determining reliability.

In the case of composite materials, fracture mechanics explains that hard, blocky inclusions in a "matrix" reduce the strength, but if they are elongated or tough, they can increase the energy needed for a crack to propagate thereby delaying final fracture. Ever since its development 60 years ago, fracture mechanics has been instrumental in the development of large, tough, and lightweight ships, very tall buildings, safer cars, safe pressure vessels, and reliable ships among other structures.

Yeast cannot be mixed with baking powder as some of the sodium carbonate decomposes early in the watery mixture, producing caustic sodium hydroxide (NaOH, a strong base) which kills the yeast.

Bread or cake containing nuts or olives or raisins or anything else that we like to add behaves the same as when adding whole wheat flour as far as rising and final shape are concerned. You can add up to about 10% of such tasty morsels, but you should expect a slightly denser final result because some of the carbon dioxide will diffuse out more easily. This is due to new channels opening up through the mechanical action of these added foods. Adding more yeast or baking powder helps a bit, but not much.

But the biggest effect of adding nuts, raisins, etc., is on the strength and toughness of the final cake or bread. These added ingredients tend to weaken the structure, so expect the cake or bread to come out a bit crumbly, especially if the pieces are too large. Interestingly, adding small currants or raisins to cake has a toughening effect: the currants tend to bridge the cracks and the cake becomes less crumbly. Nut s and larger fruit usually act as "flaws" in the structure, weakening it. On the other hand, oat flakes have a strengthening effect, because of the large amount of starch that acts as additional glue. The strongest and tastiest olive bread should have a lot of whole wheat (I use about 60%), with long, thin slices of olives. The fibres in the whole wheat flour act as millions of tiny bridges across the gluten-rich white flour, giving great strength on top of the fantastic taste and being very healthy. Try it and you'll see.

I sometimes illustrate the difference between strength and toughness to students by using hard chocolates. A normal chocolate breaks apart directly – it is brittle like a ceramic. But the same chocolate with raisins will crack while not separating immediately: it is tougher.

Finally, a quick word about pastry and pies and puddings. All of them are also made of different types of dough, but the mechanism of swelling is approximately the same. Croissants and dumplings rely on repeated layering by folding the dough (a very long process), which encloses hot butter or another lipid and keeps the thin layers separate. During baking, the different layers swell and shift or slide separately, giving the fluffy structure we enjoy. In my part of the world we don't bother with folding but we use many layers of very thin dough (called "fyllo", Greek for "sheet") with which we make pies, or the famous syrup-laden sweets like baklava, etc.

Pasta is of course a type of pastry made by extrusion of very elastic dough through dies, using exactly the same manufacturing extrusion method as is used to make minced meat, plastic cutlery, accessories, and toys as well as aluminium and steel bars and structural bricks with holes. After extrusion, the pasta is dried at low temperature, mainly using microwave driers, to preserve the nutrients. When boiling pasta, which must be done by throwing it in boiling water at high temperature to avoid it becoming soggy and oxidised, water diffuses into the structure, swelling it and softening it again. A pasta pie or lasagne with a topping of béchamel cream[37] or melted cheese is very popular in Greece and Italy, as the pasta is protected from oxidation and from drying by water diffusion while adding a further tasty layer.

Fine Delicacies—Mouldy Yeast and Tasty Microbes

It is a well-known fact nowadays that our health depends on our gut bacteria. Not a day goes by without some new discovery on how our gut "microbiota" controls many of our bodily functions or how the bacteria need some specific nutrients to stay healthy. They control many of our normal digestive functions and they manufacture various hormones and other chemicals important to maintain our health and immune system. They even adjust our behaviour and responses to outside influences. Most hide in our guts where oxygen levels are very low because they are mainly anaerobic (they cannot use

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[37] Coarse pasta mixed with a mince and tomato sauce ("Bolognaise"), topped with béchamel and cheese is an extremely popular dish in Greece called "pastichio". I personally prepare it layered with lasagna.

oxygen for energy like mitochondria do for us). The important thing is that these bacteria are critical for breaking down starches, fibres, and potentially toxic molecules from foods to smaller molecules which then diffuse through the intestinal wall into the bloodstream. They also synthesise vitamins B and K and many amino acids using the raw materials we give them. And all they ask to stay healthy is a reasonable amount and variety of fruit and vegetables. An unhealthy microbiota leads to an unhealthy body.

Our friends, our gut bacteria

Our "microbiota" is the flora of our gut (especially in the thick intestine), which consists of trillions of bacteria of many different types, in a close symbiotic relationship with us.

Until recently, our gut bacteria were considered a nuisance, even parasitic. However, it is now recognised that each type of gut bacteria produces different chemicals and hormones, all of them essential for our health. Even some allergic or auto-immune disorders appear to be connected to an unhealthy or weak microbiota. It therefore pays to keep them healthy.

To that end, it is worth remembering that there is quite strong evidence that all they need is a diet fairly heavy in fruit, vegetables, and dietary fibre. Just like the famous Mediterranean diet.

Bacteria and fungi are everywhere. On our skin, on every utensil in the kitchen, and on every bit of food we eat. They also exist in the water we drink and every breath we take. The vast majority are completely innocuous, unless they penetrate our skin and manage to find a rich environment where they can proliferate, like our blood and cells. Many even protect us from various dangerous bacteria, viruses, and fungi. And a few of them are edible.

Edible bacteria and fungi exist naturally in many different foods such as yoghurts and sour milk as well as in various mixtures such as the Japanese miso. Probiotics (mixtures of various beneficial bacteria) are also now added regularly to natural foods as well, in an effort to improve our gut microbiota, which is often damaged by diets poor in vegetables and fruit.

The interesting thing from a physicochemical perspective is how these probiotic bacteria can manage to proceed almost unharmed through our digestive system and eventually reach our gut. It's quite an obstacle course, especially with the strong acid in our stomach. They apparently do this by shielding themselves using a thick mucus which reduces diffusion and even neutralises the acids long enough to allow them to reach our intestines alive. The nature of this mucus is not fully understood but it may be a type of fungus working synergistically with the microbes.

At the same time, edible fungi are also an important raw food in many dishes. Mushrooms and truffles are actually huge synergistic communities of fungal spores that have evolved to look like a single organism.[38] Structurally, they are held together by chitin, the same material as the exoskeleton of crabs, prawns, and lobsters. Yeast is the most common fungus we eat and a very important one, but it is only used for producing carbon dioxide for breads and is not directly edible.

In most cases mushrooms and truffles are eaten for pleasure (especially for their aroma), not for their nutrients. A lot of what they are made of, especially chitin, is largely indigestible, even by our gut microbes. After boiling, very little of the chitin dissociates, but frying does break down much of it, allowing for some limited decomposition and digestion.

Slow Food Versus Fast Food

As far as I'm concerned, food should always be cooked slowly and carefully. The ingredients must be added at the right moment and allowed sufficient time to blend and mutually diffuse to obtain the best result. Damaging chemical reactions due to high temperatures, which result in oxidation, dissociation, etc., must be controlled and kept to a minimum by cooking at the lowest temperature possible. Sauces need their own good time to polymerise and diffuse through, and reduction must be done very gradually. Nothing should be rushed. Meat must first be softened by gradually dissolving the collagen or breaking down the fibres before sensitive vegetables are added, and water must be allowed to diffuse through to make sure starches are softened, and so on. In general, slow food is a synonym for good food.

Normal cooking of a stew or a soup in a pot or a casserole in the oven is slow cooking with all its benefits. But is there a way to slow cook a thick steak of beef or salmon uniformly and succulently without drying it out? Of course there is. One method is called sous vide (French for "under vacuum") and it simply means that you place your steak or fish fillet in a plastic bag under vacuum[39] and cook it in hot water up to 90 °C for an extended period, i.e., a minimum of about one hour to get a medium-rare result for a thick fillet or steak. Sensitive fish fillets need lower temperatures, but one shouldn't

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[38] Isn't this what every living being is? All living bodies are huge symbiotic collections of trillions of individual cells, after all.

[39] This is done with vacuum-sealing apparatus that uses plastic bags of high density polyethylene (HDPE) or polypropylene (PP), never polyvinyl chloride (PVC) or low density polyethylene (PE). We'll discuss the various types of plastics and their properties later.

cook anything at less than about 65 °C to ensure proper sterilisation of the food. Vegetables can be prepared like this as well and they lose none of their nutrients and aroma, as they tend to do in the pot, even if steamed. Boiled eggs can also be cooked this way to obtain a soft but not runny consistency. The main problem with this method is that meat comes out, well, boiled, so a steak still needs a quick searing in a frying pan or on a hot plate to brown it by the Millard reaction. As a student I used to boil sausages directly in their vacuum-sealed bag in the kettle with very good results.

On the other hand, “fast food” has come to mean burgers or fried chicken and similar, and refers to something quick and often a bit rushed. Not to mention dubious quality in some cases. Of course, not all such “fast food” deserves a bad reputation since many street foods all over the world are actually well prepared and carefully cooked. Fast food may be thought of as any type of high temperature cooking, from frying to grilling, and lots of physics and chemistry occurs in a frying pan as we’ve seen. But because of the serious protein changes occurring during frying and grilling, I personally prefer slow cooking in the pot or in casseroles.

Casseroles are an interesting case in point. They combine high temperature surface cooking with normal pot cooking. While the main body of the food cooks just like in a pot, the surface cooks a little like under a grill, exploiting the Maillard reaction to a gentle extent. In fact, there are dishes that cannot be made any other way. For example, anything that requires layering can only be made in the oven.

An example of casserole dishes which benefit from oven baking are various au gratin dishes where the cheese needs to melt and bind the protein (e.g., cauliflower with or without béchamel) before browning. Because of the low thermal conductivity of such foods (they contain a lot of air pockets), it is necessary to precook them (including heating the glass dish) before baking them. Exemptions are various vegan dishes like the Greek “briam” (a type of ratatouille) dish, where many different vegetables (e.g., zucchini with aubergines, carrots, potatoes, and tomato) are baked at high temperature to break up some of the tough fibres, and stirring is carried out regularly.

Lasagne with cheese topping or the popular Greek dishes pastichio or mousaka,[40] both with cheese-béchamel topping, are good examples of layered dishes requiring some precooking, followed by oven baking to ensure that heat penetrates sufficiently inwards. The dish must be assembled very quickly after preparing the ingredients (meat sauce, pasta or vegetables, and béchamel) and baked immediately so as to avoid losing too much heat.

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[40] The name—but apparently not the dish—comes from the Arabic “mousaqqa” which means something like “pounded” or “cold”.

For the same reason, namely the low thermal conductivity of most vegetable foods, many stuffed vegetable dishes are also cooked in the oven after some precooking. Two good examples are the dish "papoutsakia" (Greek for "little shoes"), consisting of stuffed aubergines topped with a cheese-béchamel sauce, and various popular stuffed zucchini or other vegetable dishes.

Be that as it may, in certain situations it does pay to speed things up a bit when cooking, or at least to accelerate cooking at specific times to obtain certain unusual results. We have already seen a few examples of this: crunchy fried chips, surface caramelisation, etc. The overarching objective in most cases is to form a protective skin which shields sensitive foods from desiccation or dissociation until they are properly cooked. Speeding things up in this case usually means frying, but it can also mean faster boiling, as when we want to evaporate an excess of water in a stew.

In most such cases, we create a physical barrier that is made of a different material from the main body of the food, for example, hard acrylamide on starchy potatoes or bread. Such physical barriers are dry and allow only a limited amount of heat into the body of the food. For example, by throwing potatoes in very hot oil we are aiming to rapidly form a hard crust which will protect the inside till it is properly cooked. If the oil is not hot enough then we tend to desiccate the potatoes and eventually even introduce too much acrylamide and oil into them—not a good idea.

In certain other cases, we want to encourage a certain additional aroma or taste, as in the caramelisation of onions (oxidative pyrolysis of the sugar) when we fry them lightly before introducing meat or fish or other vegetables into the pot. By the way, I like to caramelise carrots too, sometimes together with the onions. They tend to release a very nice aroma, and they also get sweeter by a transformation reaction.

The timing of accelerated cooking is important. For example, when we make a stew or a casserole, we want to go slow at the beginning until the meat (or other protein) is partly cooked but not dry, then increase the heat and fry it in oil in order to form a thin protective crust, before we add vegetables and slow the cooking down again to increase diffusion. At the end, we will probably want to increase heating again to enable thickening (polymerisation) of the sauce by adding some acidic substance.

Cooking with a wok on a hot flame is a case in point as it combines many of the above mechanisms. Here we are essentially frying very thinly sliced meat and vegetables in such a way that we encase the soft centres in a hard crust in a matter of seconds, while the large surface area of the finely cut ingredients and caramelisation of the proteins enhance the overall aroma. At the same time, we shake and stir the food all the time, which increases the contact between the ingredients and enhances diffusion. Because of the very short time (which should be) involved when we cook with a wok and the minimum amount of oil we (should) use, the overall effect is healthier than deep or shallow frying.

On Thin Ice—Chocolate Baked Alaska

Everybody loves ice cream (don't they?) and surely everyone loves chocolate. That's why chocolate chip ice cream is so popular. But what about a choc-coated melted ice cream bomb that explodes in your mouth?

It's one of the nicest summer treats you can prepare (and an impressive dessert) and it all relies on microwave energy being able to penetrate dry foods as easily as if they were not there. You'll need a few small ice cream balls (or bells) with dark chocolate coating and a very cold plate. If you cannot find them in the shop, you can easily make them by dipping scooped balls of ice cream into molten dark chocolate and re-freezing them. Now, put a few of them on the cold plate without touching them and immediately microwave them for about 15 seconds. The result is a cold, hard chocolate ball containing molten ice cream that explodes with one bite in your mouth. The MW energy penetrates the cold hard chocolate—which contains very little water—as though it wasn't there, and heats up and melts only the ice cream inside, with a delightful result.

The same thing happens when you heat up any food with a crust but a soft interior such as a pie or a dumpling. In fact, microwaves heat up the interior rather than the exterior of any food, even a soup. The reason is that, just like any form of light, they can also be reflected, and a shiny, wet exterior reflects light better than a dry crust. When reheating a soup or a stew in a MW oven, it's a good idea to stop every thirty seconds or so and stir it to allow heat distribution. Alternatively, reheat it at half power for double the time[41] and let thermal conductivity do the job of distributing the heat evenly in the food.

Finally, when I make the original baked Alaska, I aim for a similar effect, but instead of chocolate, I cover very cold ice cream balls with meringue and put it directly under a very hot grill for a few seconds to set the meringue (solidify the albumin by cross-linking the macromolecules) and

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[41] "Half power" in MW ovens does not mean exactly that. It just means full power applied intermittently (i.e., "half the total energy"), as we'll discuss later too.

slightly brown it. This gives a crusty protection with a soft ice cream centre. Nice, but I prefer the chocolate version.

Stretchy Dough

There are lots of occasions when we want to create unusual cakes or breads or pies, and for this we need to produce a strong, stretchy dough. What is the physics behind this?

The basic ingredients are deceptively simple: flour, water, and a lipid—butter or oil. But if you combine them all together at the same time, you often get a crumbly, or at best non-elastic dough. Indeed, if you add water first, you get crumble. The reason is that the water combines preferentially with the flour, closing all pores and excluding the oil, making the dough crumbly and poorly homogenised. Because water is a polar liquid while oil is a non-polar, hydrophobic liquid, the two will always try to exclude one another. Once the flour has absorbed the water, it will not be able to absorb the oil, which is critical for the elasticity.

What is needed is a binding agent and this is the job of the flour, up to a point. The only way to ensure a strong, elastic dough, is to first mix the flour very well with the oil (or molten butter), until it is well bound (salt helps a little) and then introduce the water gradually. The oil will become even better distributed and will not easily separate from the flour as it tries to avoid the water. At the same time the water, being polar, will adhere very strongly (both electrically and mechanically) to the flour, and this will ensure that the whole dough gets very evenly homogenised. It’s a synergistic effect. For best results you need to leave the dough in the fridge well covered for at least one hour to enable sufficient diffusion and to stop the lipid from melting and diffusing around in the dough. The end result is a very stretchy, very elastic dough you can use for pitas, pizza or pies. If you use whole wheat flour as I do (about 50:50, and up to 70:30, which gives tasty results but is trickier), you need to use a little more lipid to start with as the fibres tend to lock-in quite a bit of the oil.

When making croissants or other kinds of very flaky pies or fibrous bread (such as the “tsoureki” sweet bread popular in Greece), then even the above basic stretchy dough is not sufficiently elastic. In such cases, we need to add a slightly beaten egg, whose albumin aids in bridging the oil and the water even better because of its electrical affinity for both. The egg must be added to the flour first and mixed well, and then the oil or molten butter is added and mixed in well before the water and the salt and any other aromatics are added. After an hour in the fridge, this dough is extremely elastic and can be folded over many times (oiling the surface every time) *without kneading* to create a croissant or puff pastry dough. Even though it looks like a single mass, when baked these folds will separate out into multiple layers because of the physical action of the intervening lipid, just like many layers of fyllo put together. In fact, even the baked product behaves quite elastically because of the relative sliding of the multiple layers. It's the same principle that allows a laminated brittle material to bend without breaking.

Wholesome Food

The benefits of using whole grain flour (or rice) cannot be overstated. Apart from the beneficial effects on our own digestive functions, the husk and fibres are the ideal slow food for our gut bacteria, keeping them healthy and producing critical hormones and other compounds that our own cells cannot. In addition, the use of whole grain flour delays the conversion of starch to sugars in the body, allowing for more uniform and longer acting metabolism while reducing any sugar spikes after eating. It appears also that gluten from whole grain flour has a much reduced allergic effect on people with gluten sensitivity.

Concerning the flour for breads and cakes mentioned above, I actually use a mixture of whole grain and white (refined) flour at a ratio of more than 50% whole grain flour, usually with added cracked or floured oats, barley, and various seeds. Ideally, I'd like to use 100% whole grain flour, but to get a nicely raised bread I'd need a lot of yeast (at least triple the amount)which alters the taste a bit. As we saw, this is because whole grain dough tends to leave open pores and much of the carbon dioxide escapes early before it has a chance to raise the bread. Indeed, this situation gets worse on exposure to a high temperature in the oven. For this reason, the white flour (about 30–40% in most cases) serves to close the pores and allow to raise the dough without using excessive yeast. Commercial whole grain breads usually contain a much larger proportion of white flour, up to 80%, in order to raise the dough further and produce a light, fluffy bread. Of course, I'm referring to real bread, not the sticky industrial glop that passes for bread and is not made with yeast (the sliced "bread" for toast).

Whole grains (of wheat, barley, or any other cereal) include the husk of the seed which, being almost completely fibrous, has very different water absorption properties to the inner seed. In fact, the husk has evolved in order to protect the seed from premature dissociation or decomposition, as well as attack from moulds (omnipresent in the air), so it must first be broken down by extensive cooking before the seed itself can start cooking, something almost impossible at reasonable temperatures and in reasonable times. Even during soaking, the husk absorbs water by diffusion and swells without allowing too much of the water to diffuse inwards. Any mould spores tend to be stopped and broken down at the husk as well. For this reason, to use whole grain flour for baking we have to grind the whole grain, which breaks it up and exposes the seed. Even then, whole grain bread requires much more yeast, longer baking times, and slightly higher temperature than ordinary flour.

A good example of how different (and tasty) whole grain bread can be is the well-known vollkornbrot German bread mentioned earlier, made using one of the original, ancient wheat species, the einkorn wheat, a little sugar, and beer. One can also make it with a little molasses instead of sugar, which (with the beer) is used to increase the metabolism and carbon dioxide output of the yeast.

Whole grain rice is another healthy food for the same reasons as the whole flour, and in this case, there is no gluten. Even the sticky "glutinous" rice used in Chinese cooking actually contains no gluten at all. Because of its husk, whole rice (sometimes called brown rice) requires at least twice the amount of time to cook at boiling temperature to hydrolyse the husk before the seed can start cooking.

Explosive Food

Earlier, I mentioned that slow food is generally the best food, but there are times when we need to speed things up a bit. That's when we sometimes get explosions in the kitchen, some of them spectacular.

In fact, it's not that unusual for some food to explode during cooking, mainly as a result of steam pressure building up in an enclosed space. Sometimes we even try to create some controlled explosions, for example, to create foamy foods or other interesting concoctions. Let's look at some examples of both uncontrolled and controlled explosions.

Everyone knows that you shouldn't attempt to boil a raw egg (in the shell) in the microwave. The shell is mainly made of calcium and magnesium carbonate, which are non-polar and dry. This means that they are completely transparent to microwaves and don't absorb any energy. On the other hand, the water inside the egg (more than 80% of the total mass) readily absorbs microwaves and immediately starts heating and evaporating.[42] Very quickly (within a few seconds, well before the egg white has time to heat up and coagulate and solidify), the steam pressure will build up beyond the internal stress that the shell is designed to withstand and it will explode quite violently, making an absolute mess of the microwave oven.

In fact, even an open egg without the shell can explode in a microwave oven, as I have found out not infrequently when cooking very fresh eggs. A very fresh egg yolk is covered by quite a strong lipid membrane,[43] made of non-polar molecules and therefore transparent to microwaves. That's why a fresh egg yolk sits almost spherical in a bowl. In an older egg, however, the lipid structure will have been weakened (hydrolysed) by the water inside and outside, and the yolk sits flatter in a bowl because the membrane is weak and easy to bend and break. Microwaving a very fresh egg (the fastest and healthiest way to cook it—no need for any oil at all) needs to be done at a low power setting to avoid overheating and exploding the yolk, whereas an older egg can be cooked quite safely at the maximum setting.

Leidenfrost's dancing drops

Have you ever noticed that a single small drop of water on a hot plate will dance around and take some time to evaporate completely? But if you spread it out it will disappear immediately?

This happens because some of the water on the surface of the drop evaporates immediately and, once it does, the ensuing steam insulates and cushions the drop from the hot plate, making it jump and dance around. This is called the Leidenfrost effect, after its discoverer.

The same protective surface-localised evaporation effect allows you to dip your hand in liquid nitrogen (at a temperature of – 196 °C) or even a cold hand in molten lead (+ 327 °C) for half a second or so without any harm. But please definitely don't try it at home!

Similar explosions can occur with all sealed vegetables in the microwave oven, especially potatoes (some fresh ones can crack or even explode within 2–3 min) and aubergines (egg plants).

A dangerous explosion can happen whenever high energy input is not balanced by an equivalent energy release. Microwave ovens are not the only potential culprits. A dangerous situation can also occur if frying oil is heated up too much and we add a load of wet potato chips. The surface water on

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[42] All materials evaporate, even at much lower than boiling temperatures, because of the random energy distribution of the molecules.

[43] It's the membrane that sperm need to penetrate and fertilise the egg. As soon as one manages it — not a mean feat—the membrane reforms by cross-linking to form a hard, impervious structure.

each potato will heat up and boil almost immediately, creating thousands of steam bubbles which join up and expand rapidly, suddenly pushing the whole oil mass upwards. If the oil overflows the pot, it will catch fire, and it can even explode if it seeps between the pot base and the electric hob plate. If we are not sure whether the oil temperature is correct, it's always a good idea to add chips in gradually. Then, if it's too hot, it has a chance to cool down a bit before adding the rest.

An explosion can also occur even inside a pot full of otherwise gently boiling stew with rice. This can happen if there is no stirring, or inadequate stirring, and the rice (or flour, as in bechamel sauce) settles on the bottom of the pot, creating a seal beneath which some liquids continue boiling. Because rice is a good thermal insulator and seals well, little heat is conducted through it, and all the while, steam will build up underneath. Eventually, that layer of rice may suddenly rise or even explode inside the pot. So it's a good idea always to stir the rice frequently if you do not use a rice steamer.

Other explosions can occur because of the flammability of various food stuffs, such as icing sugar, flour, etc., in a very dry environment. All such foods have such a small particle size (nanometre-size) and, as we discussed before, their very large specific surface area means that they can readily react with oxygen to cause a fire. Even simply throwing dry flour or icing sugar directly on a gas flame or a hot stove or frying pan can start a fire.

On the other hand, we sometimes cause controlled explosions in the kitchen for particular baking creations. We may even consider a cake to be an assembly of thousands of small explosions in which baking powder releases carbon dioxide in closed cells, thereby causing the whole cake to rise.

In another example, during the final stages of making a thick sauce like béchamel, bubbles burst through the top like small explosions, telling you it's time to stop heating and remove the sauce from the hot plate.

Finally, frying often causes minor explosions on specific foods. Calamari and similar sea foods, even after cleaning, are covered by thin but strong membranes containing water which persists even after coating them with flour. When frying in oil, the trapped water can overheat and it's not unusual for small explosions to make a mess of your clothes. This means an apron is highly recommended in such cases. Vegetables with thick external skins, such as aubergines, can also give the same explosive result during frying.

Overcooking Trouble

I've talked a lot about the chemical conversions that occur during frying at high temperatures or when exposed to fire. The added energy from the fire transforms many compounds in the food by pyrolysis (Greek for "dissolution by fire"). Starch converts to acrylamide, meat after the Milliard reaction converts to various toxic chemicals,[44] and fruit and other sugars caramelise[45] before charring. Normal heating and cooking do not necessarily produce all these chemicals. It's only when water has been evaporated away and the proteins are exposed directly to the hot plate or fire. In all these cases, the atoms absorb too much energy and vibrate violently enough to cause the proteins to quickly uncoil, be damaged, and then reform. Even when removed from the energy source, the damaged proteins (or separated amino acids) can reform into different chemicals or, more likely, remain denatured. For this reason, the golden rule in cookery is to stop when a little water still remains (except when making soup). This point may not always be obvious, of course, but we can get a good idea by watching the behaviour of the food. In the pot, all free water[46] has evaporated and the stew is ready when boiling becomes explosive or the food starts sticking to the bottom, as can be felt by a wooden spoon. In the oven, a pie or a casserole is ready when the former becomes golden and starts shrinking away from the sides of the tray and when the latter's surface boiling becomes explosive. In all these cases these observations indicate that the free water has evaporated and the temperature is already climbing above 100 °C.

If the protein molecules persist on the hot surface or fire, then all the side bonds of these proteins and amino acids will be destroyed by pyrolysis. The hydrogen and oxygen ions will happily combine to create water and the various nitrogen and metals ions will also be oxidised into gases or converted to foul smelling compounds such as sulphates, nitrates, etc. All that will be left is the skeleton of the proteins, consisting solely of black carbon atoms.

Overcooking food doesn't just alter its chemistry and produce toxic chemicals. It alters its taste and makes it indigestible as well as dangerous. One might as well eat a few pencils—that's also carbon.

But what can one do when asked to prepare something "well done"? My own immediate reaction is always to refuse—I don't want to destroy the food

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[44] Heterocyclic amines (HCAs) and polycyclic aromatic hydrocarbons (PAH) among others. All of them are dangerous, with strong indications of carcinogenicity.

[45] Releasing the "nutty" smelling chemical diacetyl.

[46] Free water is water that is not bound up with other chemicals or mechanically bound within cells and other structures in the food.

and poison my guests. The most I will ever cook food is to a brown colour, allowing some of the transformation reactions to take place and only on the surface.

I can't honestly believe that anyone really enjoys overcooked food. One possible reason some people ask for "well done"[47] is because they are worried about the possible presence of bacteria, especially in meat. In that case, if you cannot trust the quality of your meat, boil it, or better, microwave it first for a minute or two until the internal temperature reaches 65^0C, which essentially sterilises the food, before frying or grilling it for a short time to give it colour. For the same reason, if you cannot be sure of the freshness and quality of your eggs, cook them to at least 65 °C for a minute or two, at which temperature they only just start denaturing and solidifying. By the way, a soft (almost runny) omelette like the tortilla Espanola (with potatoes) can be made easily and safely (properly sterilised) by beating the egg slightly in some milk (but not completely breaking up the albumin proteins), pouring it in a hot, oiled frying pan with the already fried potatoes, and stirring continuously only during the first 15 or so seconds to make sure all the egg has been well heated up before becoming fully set. Finally, put it under a hot grill for another half a minute for the perfect soft tortilla omelette. I often add a bit of cheese, origanum and perhaps some thinly sliced meat.

Shaken, Stirred, Beaten, Kneaded, or Whisked?

Mixing and blending of ingredients is one thing, but sometimes we need to introduce more mechanical energy to enable better mixing or to force ingredients to bond. However, the amount of energy we put in has to be controlled, otherwise the result will end up all over the place.

The lowest energy mechanisms of mixing and blending are simple shaking or stirring. We use them when the ingredients must simply come into contact with each other and we must avoid too great a chemical reaction between them. The weakest is shaking, which leaves solid food intact in the pot or casserole and only circulates a liquid around it. It is used when we introduce an emulsification agent that must circulate, but is very sensitive and cannot be stirred too much because it can easily curdle. A lemon–egg emulsification agent poured on stuffed vegetables laid out in rows in the pot is a good example.[48]

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[47] What a misnomer. It should rather be called "badly done" or overdone or destroyed food.

[48] Greek vegan stuffed vine leaves (dolmadakia) or filled cabbage leaves (lahanodolmades) are good examples.

Next up in energy input, stirring, introduces more energy into the food. It forces the ingredients to come into contact with each other and with the hotter base and sides of the pot. Stews, ratatouilles, and simple soups are good examples where the cooking temperature should be controlled. Just letting the soup boil on its own and hoping that it will result in a good blend does not work well because of the high temperatures on the sides and bottom of the pot and the internal circulation currents set up in the pot during boiling.

Beating a mixture of liquids introduces even more energy and is mainly used in cases where the liquids are largely immiscible and require energy to get them to blend well. Beating whole eggs helps to break down the lipid membranes and mix them with the protein and the albumin. But beating can go too far and give the wrong result. If we are making an omelette, we need the lipids and the albumin to remain mostly intact so as to form the mechanical structure keeping the omelette fluffy during frying. Mixing in a little full-fat milk while keeping the beating to a minimum, preferably using only a fork, is best. If on the other hand we want to prepare a smooth sauce like béchamel, then we want all membranes and albumin to be fully mixed with the protein, so the beating (or better, whisking) must be vigorous, whether with a hand or electric beater. Intense initial beating of sugar, eggs, and butter is also necessary when we prepare a cake mixture, otherwise the albumin will fail to emulsify the oil with the water in the cake. But the flour and other agents must be added by soft mixing or folding.

Bread dough presents special problems as there is not enough water to give good bonding with the gluten without long and strong kneading to mix in the water and blend the ingredients. If we want to add egg to the dough then it needs to be beaten well first and then added to the initial mixture before kneading well to bond with the gluten–water mixture.

Finally, making frothy or fluffy creams (Chantilly) requires whisking or beating so that the albumin bonds with the water in the protein and forms intricate semi-rigid networks containing air. This is only possible with very vigorous beating and whisking which provides a lot of energy. Extra icing sugar (if desired) should only be added after beating, otherwise it will immediately react with the albumin, breaking the polymer chains and not allowing any thickening.

Making Food Last

We've already discussed the sterilising and preserving effects of salt and sugar. Both work mainly by desiccating the protein, thereby removing the water needed for parasites to grow. But they are not the only means of ensuring that moulds (fungi) and bacteria will not multiply or thrive in our prepared foods. And if you, like me, love left-overs, we need to make sure the prepared food is as uncontaminated as possible before eating it. Most left-over soups, stews, and casseroles taste better the next day or two (as long as they have been stored in the fridge) because diffusion of nutrients continues, even in the fridge. This ensures a better homogenisation of sauces as well.

The main parasites that invade all cooked foods—and all foods in general—are thousands and thousands of different types of moulds. Mould spores are everywhere—in the air we breathe, the water we drink, and the food we eat. There is absolutely no way to avoid them, no matter how clean we keep our kitchen. In fact, nearly all cases of "food going off" involve moulds of some sort. Many fruit and vegetables are susceptible to moulds to varying degrees, especially if their protective outer skin has been damaged somehow. The way they work is by injecting special enzymes into the fruit or vegetable or meat which break down everything—proteins, sugars, fats—into their smallest units (amino acids or even simple molecules) and then reabsorbing them for their own metabolism. In order for the enzymes to be injected and work their damage, they use water as the diffusion carrier.

Interestingly, the way moulds grow and spread within the food is often different in various species of fruit and vegetables. For example, a small scratch on most apples will quickly (in a matter of 30 min!) spread through the flesh and the characteristic mouldy smell and taste will contaminate the whole apple very quickly. This is because apple cells tend to communicate with one another, and their cell membranes are easy to break down. The enzymes sent by the mould break down the cell structure and denature all proteins to a liquid mixture of amino acids and water that can be absorbed and metabolised by the mould. On the other hand, the cell structure of pears and peaches is quite different, with limited diffusion paths and hardier walls between cells, so a mouldy area on a pear or a peach can be cut out and the remainder eaten safely, if you catch it early enough. The same is true for oranges and mandarins and other similar fruit. If any section is infected, in most cases the rest of the fruit is unaffected, unless it's the green, hairy type of mould attacking the outside of oranges or lemons. Because those particular types of mould extend long tendrils inwards, the whole fruit is quickly contaminated. Vegetables also vary widely in their response and sustainability with regard to mould infection and we'll discuss their response below.

We breathe in and swallow mould spores all the time, but it's rare to get a fungal disease.[49] We should be thankful that our immune system has evolved over millions of years to be very well focused and expert in killing them, so we hardly ever notice them.

Most types of food are susceptible to bacterial or fungal contamination, except dry foods where water has mostly been removed by high temperature frying or grilling. Dried herbs, vegetables, fruit, pasta, rice, and nuts (if mould-free to start with) are also mostly impervious to any bacterial contamination. Drying meat or fish (protecting and drying with salt and spices) is a common method of preserving food and it has been known for thousands of years.[50] Smoking ("curing") has also been used to preserve different protein and fat-rich foods, because wood smoke and raised temperatures kill most bacteria and gradually dry the outside of the food. Alcohol is another agent that destroys bacteria by dissolving their membranes. This is what preserves wine, beer, etc. Finally, most modern processed foods contain various chemical preservatives that work by destroying bacterial membranes, although they do change the taste and may not be as safe as we wish.

Cooking well essentially sterilises all food. No mould or bacteria[51] can survive boiling temperatures in a pot or the scalding temperature in a frying pan or an oven.[52] However, in general, boiled vegetables and fruit are much more susceptible to mould contamination later since half the job of breaking down the cell structure has already been done by the cooking and moulds can more easily gain a foothold and spread. Any contamination of jams, sauces, etc., by mould spores (possibly) or bacteria (very rarely) will thus happen after the food is cooked and has cooled down and only in the presence of free water.[53] If there is any free water on the surface of the food, mould spores will immediately grab the opportunity to embed themselves and start growing and multiplying, aided by the nutrients below. For this, they need

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[49] But not impossible. Immune deficiency may allow fungal infections, but most are relatively easy to treat.

[50] Interesting examples are "biltong" from Southern Africa, "kilishi" from Nigeria, and "beef jerky" from the USA.

[51] There are some extremophile bacteria that can survive boiling, but they are extremely rare and certainly unheard of in a clean kitchen.

[52] All bacteria (microbes, viruses, spores, parasites) are enclosed in membranes made of various lipids which dissociate easily above 65 °C or in alcohol or under exposure to sunlight, resulting in their death.

[53] It is mainly moulds we should be concerned with in the kitchen, since bacterial contamination of cooked food is very rare unless it pre-existed in the ingredients and cooking was incomplete.

water and some air, so we need to exclude either or both of these to stop moulds growing.

Breathing water

Water in the form of extremely small droplets and steam is easily dispersed and held in air in a humid environment. We specify the relative humidity (RH) as the amount air actually holds divided by the maximum it can hold at each temperature. At 100% humidity, the air cannot hold any more and condenses everywhere, so nothing dries.

It's remarkable how much water air can hold. The maximum amount depends on the temperature, but in a typical kitchen at 30 °C it can hold up to 30 g of water per cubic metre of air. If the relative humidity is 80% the air holds about 24 g of water, so we breathe in about a teaspoon of water every minute.

Because we rely mainly on sweating to cool down (by losing latent heat via the evaporation of sweat), a simple dry thermometer reading is a very poor indicator of comfort in humid environments. Much better is the "wet-bulb" thermometer reading, which takes into account the evaporation. The "dew point" (the temperature at which water condenses) calculation is also a better, but a bit more extreme indicator.

This means that a way must be found to stop any contamination, and the simplest way is to reduce all free water on and in the food. Freshly cooked food must be cooled down completely before covering and storing in a fridge, to reduce the energy available for parasites to grow. Cooling down for an hour before storing reduces any condensation that may form on the underside of the container lid because of the difference between the temperature inside the container and the temperature inside the fridge. As an added precaution, after a few hours in the fridge, carefully dry out the condensation from inside the lid. Condensation is also reduced if you minimise the amount of air in the container before closing it.[54] Freezing of cooked food should be done only after a day in the fridge and removal of all condensation. "Freeze drying" of flaked or powders food in factories is done at very low humidity and at very low temperatures which ensures almost zero free water.

Condensation of steam is actually present everywhere in the kitchen, during and after cooking, whenever steam meets a cooler surface: on the underside of the pot cover, the walls, the windows, etc. If the extractor fan is not extracting the steam properly (see later), we'll also have condensation on the underside of the fan, which can easily drip back into the pot. This is

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[54] Some condensation will occur in a humid atmosphere anyway, even if you cool down the food to room temperature. Transparent covers help to monitor any condensation so that you can remove it in time.

because the fan casing is cooler than the surrounding air so any steam will easily condense on it if there is insufficient extraction. In general, condensation is almost distilled water so it is almost sterile and cannot do any harm if it falls back into the pot from its lid during cooking.[55] But not condensation from the extractor above.

The pressure of air

The pressure of the kilometers of air above us (and everywhere around us) is very high. At sea level, it is about 100 000 N/m^2 (100 kilopascal). That's equivalent to 200 kg squeezing your open palm! We don't feel it of course, because we are adapted to it and because it squeezes us equally from all directions ("isostatically").

Many sensitive foods are vacuum packed, which helps to keep them fresh and makes them last longer. They are usually packed at only about 1% of atmospheric pressure, so the atmosphere squeezes and seals the food with a pressure of about 99 kPa. That's why it is so difficult to open a vacuum-packed jar or packet.

How else can we reduce the amount of free water in contact with spore-filled air in food? For soups or stews or boiled vegetables, an excellent way of doing this is to add a thin layer of oil, something which happens automatically if we use a sufficient amount of oil in the food when cooking. The portion which is not bound in the sauce will sit on top of the food since it is lighter. All oils have a lower density than water so they float on top, forming a barrier that is toxic and impervious to most bacteria and moulds (oils break down their lipid membranes). Almost nothing grows in oil so this is a quite safe protective barrier, although it does oxidise over long periods of time. In many Mediterranean homes and restaurants today (and in ancient times as well), nearly all pot and oven dishes are made with a slight excess of olive oil, both for taste and for preservation. Olive oil is also an excellent preservative for pickled foods, olives, and all types of dips and sauces. For added safety, pickles and vegetables should be kept at low pH (less than 4) with some vinegar, because moulds and bacteria cannot grow under such conditions.

Moulds, like all life, depend on water to grow, but many depend on the availability of oxygen as well. Reducing or removing the air from a container not only reduces the available water but stops metabolism of parasites. The food industry utilises this principle widely, and vacuum-packed foods are

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[55] Apparently, some people believe that drinking distilled water is healthy. It is nothing of the sort and actually quite dangerous in sufficient quantities as it destabilises the sodium/potassium balance across cell membranes.

now the norm if extended shelf life is needed, for example, for pre-packed cheeses, processed meats, etc., which use special multilayer plastic films. Be that as it may, all plastic materials are ultimately pervious to oxygen, so even vacuum-packed foods cannot be preserved indefinitely. The oxygen transmission rate (OTR) is an important quality parameter for plastic films used for packaging. They need to have an OTR thousands of times lower than ordinary cling-film. Simple kitchen cling-film (now made mainly of low density polyethylene, LDPE[56]) cannot keep a vacuum, as it is quite pervious even to water and must be used only as temporary packaging. More expensive aluminium-coated plastic films have almost zero OTR and are used for aromatic or sensitive materials such as ground coffee, chocolate, croissants, etc.

The vacuum packing method cannot be used for ready meals, nuts, dried fruit, etc., because it would dry them out completely.[57] Instead, food manufacturers pack ready meals in a nitrogen atmosphere at atmospheric pressure, thereby excluding oxygen, but the OTR of the barrier must still be very low to ensure oxygen doesn't leak in by exchanging with nitrogen molecules. They also flash freeze prepared dishes very soon after producing them to reduce the possibility of bacterial or fungal growth.

Modern food cans (or tins) need to preserve food for years and are made of aluminium or tin-coated or chromium-coated steel, but metal contact with food is generally avoided by coating the inner surface with a special plastic barrier with high OTR.[58] The barrier needs to have other properties too, such as mechanical tear strength, wear resistance, temperature and chemical stability, etc. Glass packaging, fully sterilised, is used for all acidic or liquid foods, such as sauces, jams, etc., which are usually vacuum packed too.

When making marmalades, jams, or sauces at home, it is important to sterilise the glass jars as well as possible, otherwise moulds will find a way to grow on even the tiniest amount of free water, e.g., condensation. The classic method to ensure that is to boil them standing upside down for an hour, but you still can't be sure you won't pick up some spores afterwards. There is a simpler method. Just add a few drops of alcohol (vodka or ouzo will do fine) into the jar, close it tightly, shake it and leave it for an hour while you are making the jam. When ready, pour in the hot jam, fill to the brim and close the jar tightly. As it cools down the little bit of air trapped

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[56] They used to be made of softened poly vinyl chloride (PVC, also used extensively for plastic containers until recently) until it was discovered that the phthalates used to soften PVC are very dangerous.

[57] Water would readily diffuse out of the food onto the surface until it reaches vapour balance.

[58] It used to be bisphenol-A-based plastic (BPA, an epoxy), but now other plastics are used, as BPA has also been found to be very dangerous.

inside will contract creating a moderate vacuum[59] containing a little alcohol vapour. Nothing survives that and the jars can be stored in the cupboard for months.

But how can you tell if something has been attacked by a mould? As I discussed previously, there are literally hundreds of thousands of different mould species and they all just need water and a few nutrients to grow. Many appear hairy (like the green mould on lemons and oranges, and also the invasive moulds on yoghurts) others are just slimy. Many, but not all, have a characteristic "mouldy" smell. But they all have one thing in common: they inject special enzymes which break down fats and proteins—even the hard, skin proteins of fruit—into their very basic constituents in order to be able to absorb and metabolise them, and they also liberate water in the process. So if you see a very soft, watery patch on a vegetable or fruit which is broken and has lost its normal smell—even if there is no obviously visible mould or slime around—it is usually the result of a mould (or microbe) and you can try cutting around it before eating the rest, provided the rest smells and looks normal.[60] Tomatoes and cucumbers are susceptible to moulds but they are rarely affected beyond the immediate vicinity of the attack. Over-ripeness sometimes looks like that, but the fruit or vegetable still has a completely normal smell. In this case, it helps to refrigerate it to help keep longer.

Fermented Shark, Anyone? Heat-Free Cooking

Have you ever heard of kiviak (or kiviaq)? It is an Inuit delicacy from Greenland. It is made by stuffing many whole Auk birds into a fresh seal skin (with the fat layer still intact), sealing it, and leaving it in a cold environment for months. In winter when food was scarce and difficult to obtain, the Inuit would actually survive eating kiviak and similar fermented foods. Very successfully preserved even if not easily enjoyed.

Fermentation is the only exothermic process which does not require oxygen. Nearly all heat-producing processes, such as metabolism, on Earth need oxygen, but fermentation does not (neither do nuclear and atomic processes, but that's another story). A gas fire burns gas in oxygen exothermically and the same is true with a wood fire. Without oxygen there is no fire.

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[59] A half-filled plastic water bottle in the fridge will crumple and collapse for the same reason. This method is of course used by many industries to vacuum-pack jams and similar foods. When you twist the jar open (difficult, as you are working against atmospheric pressure—use a blunt knife under the rim), you hear a click telling you that you have "broken the vacuum" and let some air in.

[60] The general advice is that very young children, along with older, vulnerable people and everyone with weak immune systems, should be extra careful with any moulds.

That's how fire-fighting liquids or foams work, by excluding oxygen from the fire. In fact, the more oxygen you add to a fire, the higher the temperature and the stronger (and faster) the fire. There is some evidence that millions of years ago the atmosphere contained more oxygen than now (up to 28% compared to 21% now). This would have allowed fast and strong growth of plants (and animals) in wet climates. When the climate changed though, huge fires swept through everything, but many plants had little access to oxygen and produced half-burnt wood (similar to brown charcoal). Over many millions of years, this converted to vast deposits of coal and gas and petrol that became the fossils we have been using over the last 150 years to produce energy (and pollute the atmosphere). Electricity is unfortunately still largely produced by coal, petrol, or gas combustion with oxygen. Hopefully, the next few decades will see a complete decarburisation of energy production.

But let's get back to fermentation. Since it is an exothermic reaction, the heat it produces can actually cook the fermenting food very slowly, even in the absence of oxygen. I haven't had the dubious pleasure of eating kiviak yet (and I'm not sure I would want to, hearing about it from people that have tried it), but it is a fascinating process. Fermentation also happens in the body, but it produces much less energy than oxygen metabolism by our mitochondria.

Left-Overs Taste Better

If your cooking and storage methods are correct, you'll have no problem keeping a meal in the fridge for a few days and enjoying it again. It makes both financial and culinary sense. As I mentioned earlier, reheated fresh food (in the microwave oven of course) often tastes better because of further co-diffusion and co-absorption of ingredients and nutrients. Even at the low temperature of the fridge (about 4 °C, if it is working as it should), ingredients can diffuse around and some reactions can even proceed further.

The danger with reheating food from the fridge is the possible growth of moulds and, in very rare cases, bacteria, due to the presence of free water at the interface between the water and the air. Moulds almost never grow inside the food (unless there are air pockets with some water), but always on the surface, where they will be clearly visible.

In any case, it's probably a good idea to eat left-overs within a few days at the most. As a rule of thumb, foods containing a creamy sauce (e.g., béchamel) in a full, tightly closed container can keep happily for up to 3–4 days in the fridge, while freshly stored meat or vegetable stew or casserole or tomato-based sauce can easily keep for 5–6 days as long as free water is kept to a minimum and the container is as full as possible and well closed. Always choose the smallest container possible that will fit all your left-over food, as this minimises the amount of air above it. Simple boiled foods like pasta or rice can keep even longer if fairly dry. Fried or grilled foods, being even more sterilised by the high temperature frying, can keep for up to a week, but they will probably dry even more by that time.

When reheating left-overs, it's always a good idea to let them reach room temperature before reheating them thoroughly in a microwave oven, stirring occasionally as necessary to homogenise the food and distribute the heat evenly. The thermal conductivity of food is very low and heat will take a long time to distribute itself throughout by conduction alone. Using a glass container with a well-fitting lid will give you very good results. It's not a good idea to use plastic containers (except PP) in the microwave oven for reheating, as it is not fully established that their constituents do not leach out at the hot spots.[61] A food-grade PP container is as good as glass as long as you don't overheat the food.[62] Keep the lid only slightly open to allow steam to escape, but not so much that the food dries up.

Reheating in an oven is never a good idea as it will just heat up the surface of the food, while the inside will remain cold. If you are forced to use an oven, cover the food well with aluminium foil and place it in the centre of the oven. It will eventually heat up your food, but you'll wait a long time and waste a lot of electricity or gas. In the absence of a microwave oven, pasta and rice can be reheated fairly effectively by adding a little water or milk and heating them in a pot, while stirring continuously. The liquid will pick up heat from the base and help to distribute it throughout the food more or less evenly.

Always Store in a Cool Dry Place?

The general advice "store in a cool dry place" is good practice, of course, but it's not enough for food. As soon as food has been properly cooked, it is completely sterile, but it does not remain so for long at room temperature, and needs to be well protected to avoid contamination by bacteria, and even more so moulds. Apart from everything noted above about removing

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[61] Even with a rotating table, some microwave ovens form hot spots on the food. The ones with convex or concave reflectors are better as they distribute heat more evenly.

[62] Polypropylene (PP) can be used up to about 100–120 °C, but microwave hot spots can reach higher temperatures. Glass presents no problem at all, even at much higher temperatures.

free water and air, we enhance its longevity by reducing the energy content of the food, i.e., by substantially reducing its temperature. The lower the temperature, the lower the rate of all chemical reactions, including natural dissociation reactions and bacterial and fungal growth. The underlying physical mechanism is always the energy availability of the molecules. Below the freezing point of water, the diffusion of molecules through ice is heavily curtailed, reducing reaction rates even further. Below about − 18 °C, chemical reactions have all but ceased and protein-rich foods will remain as they are for weeks or months. All good freezers (with at least 3* indication) work at − 18 °C or a bit lower. Deep freezers work at even lower temperatures, but offer only limited additional benefit.

All protein-rich foods—raw as well as cooked—should be stored in the refrigerator whenever the ambient temperature is above about 20 °C, even if they are going to be used within the next few hours. This is particularly important for fish and fatty foods, which are more susceptible to bacterial contamination and growth.[63] In fact, even if you'll use the meat or poultry or fish after just a few days, it's better to place it in the freezer and defrost it in the fridge for 12 h before cooking. If the kitchen temperature is less than 20 °C, then you can defrost it outside, carefully covered.

Raw game meat needs particular attention since most wild game meat (and sometimes river fish) is riddled with parasites. If very fresh, game meat needs draining of all blood, and then it must first be left hanging in the open air (sunlight is optional) for at least 24 h, protected behind a fine mesh.[64] Afterwards it should be placed in the freezer at about -18 °C. At least 2 days before use it should be thawed and marinated while covered in the fridge with plenty of vinegar, onion, and oil (as well as wine and other herbs, according to taste) for at least 2 days turning, over occasionally. Deep diffusion of the marinating liquids will break down their cell walls and kill all parasites and their eggs deep inside the meat, and also initiate the breakdown of strong fibres within the meat, which helps to tenderise it.

While discussing preservation, I'd like to add some comments about "expiry dates" on foods. I have struggled to understand the real purpose of expiry dates or "best before" dates on so many food items. Generally, well-stored fresh foods do not lose their nutrients or become infected for many days. More often than not, perfectly eatable[65] food gets thrown away because

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[63] Lipids dissociate much more quickly than proteins, even under bacteria-free conditions, as their molecular hydrogen bonds are weaker.

[64] You can ignore this for butcher-supplied game.

[65] Eatable means nice to eat, whereas edible means safe to eat.

its so-called "expiry date"[66] has lapsed. This is an incredible waste, environmentally unsustainable, and certainly a financial burden. I often wonder if companies are abusing this originally well-meaning concept to increase their sales. I personally trust my senses much more than any such overcautious approach. Let's look at a few simple examples.

Yoghurt and milk sold in shops is always pasteurised (treated briefly at very high temperature to kill bacteria) and sealed in an anoxic (oxygen-free, usually nitrogen) atmosphere. Milk can either be designated long life (UHT, extended pasteurisation at very high temperatures) or fresh. In the latter case, it's given 5–6 days' life which is erring heavily on the side of caution. Even after 7 or 8 days in the fridge, the milk is generally still safe, unless it was contaminated during packaging. Under normal conditions, the worst that can happen to it is that it should go slightly sour, which is not dangerous at all. Even if it curdles, it's still edible, although not as pleasant. Sour—slightly acidic—milk products (e.g., kefir) are available and apparently aid the immune system. Curdled milk is the next stage, when these acidic agents bind the proteins together with the water to make frothy, solid masses, usually floating in the milk. Yoghurt, cheese, and kefir are the next stage, made with special bacteria. All of these stages are perfectly edible, although not always palatable.

Oxidation is another threat, but milk cartons are multi-layered with an intermediate aluminium barrier and plastic inner layer which stops all oxygen permeation. Yoghurt pots are made of thick polypropylene[67] and the sealed lid is aluminium, both of which are practically impervious to oxygen. Yoghurts are given about 2–3 weeks expiry dates, but if there is no obvious mould, they can be eaten or used well after that date. I regularly do myself. Vacuum packed processed meats and cheeses are covered in polypropylene or some other oxygen barrier membrane and given a few weeks' life, although they can easily last months, especially in the fridge. And so on, and so forth.

The "best by date" is one step lower in recommendation and generally means that the vegetable or fruit or whatever may have lost some of its expected nutrient content, usually be oxidation or reactions with atmospheric humidity or exposure to sunlight. In reality, only a few nutrients are seriously affected by air over a few days or even a couple of weeks, even if the vegetable or fruit looks wilted. Surface proteins, trace elements, and sugars

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[66] In most cases, "expiry dates" are recommendations, not restrictions, but you wouldn't know it by listening to so much nonsense "advice" online and offline.

[67] For a brief introduction to various materials, see later.

can be affected by oxidation,[68] and the amounts of certain water-soluble vitamins (mainly A and some of the B complex) will be reduced by the presence of humidity. UV exposure (sunlight) also affects the same vitamins,[69] but also dries foods and initiates some dissociation of protein polymers.

All in all, my opinion is that the expiry date concept is overused and misleading and buyers should use their own judgement. I think that having only production dates imprinted on every product and smelling the food should be sufficient to determine whether something is eatable or even edible, as long as people use their common sense. If in doubt, don't throw it away, but think sustainably and ask for advice. It'll save you money as well. I personally grew up without expiry date information and still rely on my common sense to determine if something is eatable (or edible) or not. If a vegetable or fruit looks right, smells as it should naturally and there is no visible contamination or infection, then it is most probably eatable no matter what the "expiry date" says.

Of course, this is not strictly true for raw meat, poultry, fish, and similar uncooked proteins. In such cases, a natural smell should be aided by making sure it is heated right through to a temperature of about 65 °C. This is the only way to be sure that the vast majority of bacteria, parasites, and moulds that the food may contain have been eliminated.

Finally, a word about tinned foods. Few food items are nowadays sold in tins, but some people still prefer them. It is a huge change from just 30–40 years ago when a supermarket used to have aisles full of tinned foods. The main worry about a tinned food is the presence of the bacterium Clostridium botulinum which causes botulism (very rarely now) and the tell-tale sign is a badly swollen tin which indicates that the food has reacted and produced a large amount of gases inside. This may be caused by the tin having been crumpled, cracking the internal protective membrane. Get rid of it without opening.

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[68] Oxidation of foods by ozone (O_3) is much quicker than with ordinary oxygen (O_2) so it's an excellent antibacterial and antifungal agent. It is also a pollutant generated by older types of electric motors and everywhere where there is electric arcing and very intense sun light.

[69] The high energy of UV photons can easily break up some of the vitamins' weak bonds. It can also affect proteins and even carbohydrates.

When Freezing Goes Wrong

Of course, we can preserve foods in the fridge for a few days and in the freezer for weeks. The problem is that this doesn't work for everything, as the conversion of water to ice results in damage to certain fresh foods. Let's consider some of them.

Nearly all slow-cooked foods (soups, stews, casseroles, etc.) can be safely frozen. The proteins have been denatured by cooking, the vegetable cell walls have dissolved, and the food sauce is a smooth mixture. Meat products and fish can also be frozen safely for weeks on end with minimal effect on structure and taste. The secret is to freeze all such foods as soon as possible before natural dissociation and decomposition reactions have started breaking down the proteins. This is especially true for fish whose fat is particularly prone to decomposition.

However, many vegetables and fruit cannot be frozen. Freezing water-heavy vegetables such as lettuce, tomatoes, and cucumbers, as well as most fruit, destroys their cell structure, because of the expansion which occurs when water freezes to ice. This expansion happens because the atomic structure of ice has many open spaces between the molecules as compared with liquid water. Recall our earlier discussion on the shape of the water molecule H_2O. The H–O–H angle is about 105°, which means that the molecules cannot fit comfortably next to one another. When the water temperature drops, their vibrations reduce and at about 0 °C, the molecules can no longer move freely, but must find a stable, rigid position. The result is a hexagonal atomic structure, but because of the unusual H–O–H angle, the hydrogen bonds between H and O are stronger than the bonds between the molecules, so the structure is slightly distorted (see figure) and more open than would have been the case otherwise. The result is that ice has about 9% lower density than liquid water and expands by that much when it forms. One consequence of this is that ice floats in water.[70] Another is that everything that contains water will swell when placed in the freezer, and indeed, not just swell, because the expanded ice will break cell walls and thus cause damage to vegetables and fruit.

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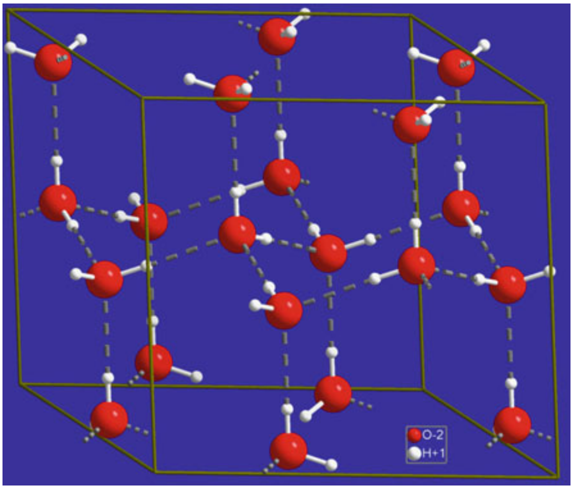
[70] For any iceberg, only about 1/11 of its mass is visible above the surface. The rest is underwater.



The atomic structure of ice

Not all water turns to ice at 0 °C. In order to freeze, water must at least contain some particles, for example dust or food particles, which act as nucleation sites for ice to start forming around them. This is called heterogeneous nucleation and has a much lower activation energy (minimum energy to start nucleation) than homogeneous nucleation (i.e., without particles) under identical conditions. If water is particularly clean (e.g., distilled), nucleation of ice crystals is delayed until the temperature drops to a much lower level than 0 °C (even down to − 30 °C in some cases) and the water then becomes "supercooled". Try an experiment: place very clear distilled water (or deionized) in the freezer and do not shake it as you remove it from the freezer. If you now touch it or shake it slightly, it will suddenly freeze in less than a second. Since condensed water on the underside of a lid is essentially distilled, it freezes at a much lower temperature than 0 °C and may remain liquid allowing mould to grow even in the freezer.[71] Before you freeze any cooked food, make sure you remove any condensed water from the underside of the lid.

But ordinary water can also remain liquid below 0 °C if it contains in solution certain salts such as common salt (NaCl) or $CaCl_2$.[72] In this case the mechanism for remaining liquid is different. The water molecules break up the salts and the ions float around disturbing the balance between the water molecules leaving and joining the ice at the interface. The more ions are swimming around in the water, the more they block liquid water molecules

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[71] Moulds and slimes are known to grow happily even in Antarctica.

[72] Both are generally used to defrost ice on roads and other surfaces.

from entering and solidifying, and the freezing temperature of the solution is therefore reduced.

Some food plants also contain natural anti-freeze compounds. Vegetables in the brassica family (cabbage, kale, broccoli, Brussels sprouts, etc.) and also carrots contain many calcium ions, which depress the freezing point of water. They also produce special antifreeze proteins which obstruct the formation of ice crystals, another way to stay liquid. The net effect is that cabbage and kale and similar vegetables can withstand severe frost and much lower fridge temperatures than most other vegetables, although not freezer temperatures. In fact, many of them taste much sweeter after strong frosts (even Brussels sprouts), because some of the antifreeze proteins can convert other proteins to sugars.

Tastebuds Never Lie—Or Do They?

Is taste due to chemistry or physics? I think a bit of both. Taste is essentially the way our brain perceives an excitation reaction that occurs on thousands of microsensors (receptors) on the tongue and at the back and on the roof of the mouth when particular molecules touch it. Let's see how it works in some detail.

Neuron whispering

Neurons don't actually touch one another in order to deliver their message. Electrical signals, called action potentials, travelling along the neuron "jump" across very small gaps called "synapses" between tendrils and adjacent neurons. By connecting many neurons via synapses, a signal travels from the brain to the periphery and vice versa.

The jump can be either electrical (here the synapses almost touch via special proteins and the signal is transmitted almost instantaneously) or chemical, where neurotransmitter molecules "carry" the signal across a gap, which gives a slight delay. By repeating the signal, the synapses can be "strengthened" by increasing the number of neurotransmitters.

It's interesting to speculate why synapses did not all evolve to be instantaneous (electrical). The short delay in chemical synapses must offer some adaptive or protective benefit.

Food consists of various molecules, not all of which excite the taste sensors, while some excite more than one type of sensor. As you probably know, there are five tastes: sweet, bitter, sour, salty, and umami (or savoury). The taste we feel is sent to the brain by specialised neurons, where it is appropriately "translated" by the brain according to the excitation potential signature. When a molecule of sugar (or glucose or fructose, etc.) is dissolved in saliva, it reacts with a sweetness receptor which produces a small voltage signal. The more molecules react with it, the more voltage is produced, giving a measure of the amount of sugar. This is then transmitted along the neuron to the brain, where it is processed by the brain neurons and understood as something sweet. The more voltage reaches the brain, the sweeter the food is perceived to be.

Interestingly, we now know that sweet and bitter tastes are perceived by specific parts of the brain (i.e., they are hard-wired in the brain), but the other three tastes appear to be processed by a mixture of sensors in different brain areas, we don't know why yet. We also don't know how the brain actually learns to identify tastes or smells. My own understanding is that it has something to do with the fact that each sequence or chain of synapses (connecting points between neurons) produces a specific electromagnetic "signature" which inductively couples with (or "senses") some permanent sequence of synapses which formed previously when the same taste was first experienced and "saved" in the brain. Comparing the two sequences brings on a recall by association and we identify the taste or the mixtures as similar to the one experienced before. For example, if we encounter a very pleasant taste, the brain creates a chain of synapses with a specific electric field "signature". If the taste is strong enough (or is repeated frequently enough, e.g., licking a chocolate ice cream), these synapses strengthen and become permanent, persisting for years in many cases and now associated in the brain with a name or some other characteristic (also saved by another sequence of synapses). If now we happen to encounter the same food again, the brain will create a similar electric field signature which will inductively stimulate (or resonate with) the older one, and suddenly we have recall or a sense of déjà-vu. Anyway this is all speculative but it may explain all sorts of memory recall.

Certain unusual molecules are perceived as mixtures of different tastes and are sometimes easy to distinguish, sometimes not. Bitter orange marmalade contains molecules which excite both the sweetness and the bitterness sensors, giving this unusual bitter–sweet flavour. A sweet-and-sour sauce excites other combinations of sensors. The brain is actually sensitive enough to distinguish many different tastes in parallel—exactly what we aim for when we prepare an intricate stew or sauce.

Another interesting situation arises when a receptor is over-excited by too many molecules, e.g., by a very sweet food. The signal is saturated (too much voltage is produced), causing a negative perception in the brain which we sometimes call a "cloying" taste.

Colourful Food and Colour Surprises

All materials reflect incident light whether they are solids, liquids, or gases, but how is colour produced? And how come so many ingredients change colour during cooking? For example, red meat very quickly becomes grey when boiled and beautiful green herbs soon turn black.

The answer is related to both the material atomic structure and our own brain's perception of what it sees, all driven by physical phenomena. Let's look first at reflected colour.

As I mentioned before, sunlight that reaches the surface of the Earth includes most wavelengths around the visible region, from IR, through the visible part and UV-A to most of the UV-B region. There are also some microwaves. All of the visible waves are perceived by our brain (though our eyes) as different colours from deep red (in the near IR region, of wavelength about 750 nm) all the way to deep violet (in the UV-A region, of wavelength about 400 nm). But how do some foods (fruit, vegetables, meat, and others) appear coloured or even iridescent in the first place?

It all has to do with which of these waves are absorbed by the food when sunlight strikes it. The first thing to note is that most foods have a cell structure with the cells separated by very thin membranes. The cells are mostly water (containing various compounds and a few pigments), which makes them appear almost transparent when viewed by microscope under transmitted light. When a material is illuminated by sunlight, some light penetrates deep into the cells and encounters pigments which absorb specific wavelengths depending on the atomic structure and elements the pigments contain and their electron energy levels. All other wavelengths are simply reflected away, so the compound appears to be the colour of the reflected photons alone. If nothing is absorbed, the food appears white. If all visible wavelengths are absorbed, the food appears black.

Foods are coloured mainly because of five families of chemical compounds: blood haemoglobin (absorbs all wavelengths except the red colour, as in meat, fish, etc.), carotenoids (yellow, red, and orange in carrots, oranges, tomatoes, etc.), chlorophyll (green in lettuce, parsley, broccoli, etc.), flavonoids (red, blue, and purple, in raspberries, etc.), and betalains (red, yellow, and purple, in beetroots, etc.). Many foods contain combinations of these compounds, so the resulting colour we actually see may be a mixture of these non-absorbed colours, as in mauve or purple aubergines, for instance.

Certain fish can also appear beautifully coloured and many are iridescent by reflection of specific wavelengths and by multiple reflections and prismatic splitting through semi-transparent scales and skin cells. In fact, changing our viewing direction gives different reflected colours in this case.

Naturally, if the incident light contains only specific wavelengths (for example certain artificial lights), the resulting colour we see may be very different. Plants illuminated in red–blue light (in many modern hot houses) appear black because there is no green wavelength to be reflected back.[73] Finally, when the ambient light is very weak, there is hardly enough to be reflected back and most foods (or any other material) appear dark grey or black.

Now, during cooking, two things may happen. If the temperature is very high (as occurs in frying or baking), some of the pigment compounds may dissociate, and the element that gives it colour (e.g., iron oxide in haemoglobin) may change atomic structure. In the case of haemoglobin in meats, after a few minutes cooking covered in a pot, it gets deoxygenated (loses some of the oxygen) and the iron compound changes from ferric oxide (Fe_2O_3), which is red, to ferrous oxide (FeO), which is black, as we discussed earlier. That's why meat looks grey–black after a few minutes in a pot with water. However, on hot coals or under the grill, there is enough atmospheric oxygen for the meat to retain or strengthen its reddish colour longer.

Some compounds retain their colour even after cooking. For example aubergines, carrots, and tomatoes hardly change their colour during cooking, but they do become darker as they oxidise, because the slight change in their structure means they absorb more wavelengths. This also happens with many green herbs and lettuces, which all become nearly black when cooked.

Toast Always Lands Butter-Side Down, but Gravity has Its Good Side Too

Don't you sometimes wish that gravity didn't exist? Then we wouldn't drop things, breaking them or making a mess. And a slice of toast wouldn't land with the, heavier, buttered-side down. Well, be careful what you wish for. Gravity is critical for our everyday life. In the kitchen, we would hardly be

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[73] One can say that green is a useless wavelength for the growth of plants. The same happens in some highways illuminated by monochromatic "yellow sodium arc lamps"—all cars other than yellow appear black.

able to cook and eat if it wasn't for the support and direction that gravity gives us.

As Newton first realised, gravity is the mutual attraction between any two or more bodies. Because the Earth is so much larger than us, everything looks like it is attracted to the floor. When we let go of anything, it invariably falls down, bouncing, breaking, or making a mess. We live in and are completely used to this gravitational "field". All our lives revolve around the need to accommodate and mitigate this strong force acting on us at all times. That's why the muscles that hold our back up are so strong. But gravity is not the same everywhere. Its strength depends on the planet we are on, and in particular, its mass and its diameter. On the Moon, gravity is about a sixth of what it is here on Earth, so a man would weigh only about 15 kg there. That's why the astronauts could be seen hopping around during their walkabouts on the surface of the Moon. On Mars, gravity is about a third of what it is on Earth.

On a space station revolving around the Earth, gravity is artificially arranged to be close to zero, by making the station revolve at such a high speed (about 17000 km per hour) around the Earth that the centrifugal force exactly counteracts the Earth's gravitational attraction. If it stopped revolving, it would immediately fall back to Earth. It's very easy to get used to living without gravity. In fact, astronauts say it's great fun not having to worry about dropping things and being able to move or lift huge things with no effort. But coming back to Earth can be a bit of a shock. Once I spoke to an astronaut at the European Space Agency who had come back to Earth after about six months in the International Space Station and he said his biggest shock was that in the first few days he was always dropping things because he didn't expect them to fall if he let go of them! He thought it was terribly funny, but also very disorientating that gravity would act on him all the time. He had already broken one or two cups that way.

But I digress again. Now let's get back to our kitchen and reflect on how important gravity is there. Our lives and actions are so well adapted to gravity that we don't even notice it. Think about it for a moment. If it wasn't for gravity, water would never stay in a glass and food would never sit in a pot while cooking. And boiling would be impossible. In fact, the pot itself would never just sit on the hot plate, but would start floating around. Water would just shoot out of the tap due to the pressure behind it and splash all over the place, instead of just going downwards into the glass. It wouldn't even be funny. When you turn on the gas on the stove, it would not burn upwards but would go all over the place, causing fires, because the buoyancy of fluids and gases depends on gravity. This means that a lighted gas flame, being lighter than air, prefers to go upwards only because gravity is acting. If gravity were removed, as soon as it came out of the gas pipe and there was no force acting on it, it would go downwards, left, or right unpredictably.

But let's assume that somehow we are able to hold a pot on a hot hob and attempt to cook something. Again, without gravity, the water and anything else we put in the pot will not make proper contact with the bottom of the pot, making it impossible to heat it up.

Let's take this idea further and assume we fill up the pot completely and close it tightly, so that the water and food has nowhere to go and has no choice but to boil. Now we have another problem. While the bottom of the pot gets hot, there is no actual boiling since there is no buoyancy. Bubbles form randomly and will not rise as expected. This means that the food will not be heated uniformly as happens in a gravitational field. Even trying to stir something in a pot will be very tricky, since the stirred food will not fall naturally back down, mixing with the rest, but will stay where you put it.

We've already mentioned that, without gravity, water coming out of a tap would not fall downwards but would splash all over the place. But what about swallowing? Could we still swallow normally? Well, here things are not so tricky. Thanks to our mouth's sucking action, a low-pressure is created behind our mouth, which means that food and water are sucked in normally and forced downwards into our stomach. Just don't expect to be able to pour water "down" your throat. When it reaches the stomach, it must still stay there, which it doesn't always like to do, and many astronauts report feeling nauseous or even suffer from regurgitation for the first few days in a gravity-free environment. Burping is also very difficult.

What about eating on a plate? Again, it is almost impossible without gravity. That's why most food on the space station is contained in tubes or sealed bags and either sucked out or eaten directly out of containers or tins. Food will not stay (unless stuck) on any plate, and the plate itself would float around happily, making it impossible to use your fork or knife, which are also floating around, of course. In fact, any attempt at cutting something with a knife would simply result in the food and the plate moving in the opposite direction to the cutting knife.

What about trying to clean something with soap and water? Again, without gravity it's a very tricky problem. The water would wet the plates and the pot with difficulty and the soapy water would again float around aimlessly, instead of wetting the dirty surfaces. Better to use paper plates.

In a nutshell, we should be glad we have gravity to show us where up and down are, keeping food on our plate and drink in our glass.

What Every Coffee and Tea Lover Should Know

Do you enjoy your morning coffee or tea? I'm sure you do, like me and many millions of others. It's one of the sweet pleasures that we look forward to every morning (and mid-morning, midday, afternoon, etc.). But there are a couple of interesting aspects of both coffee and tea that are worth knowing in order to enjoy them to the full and get maximum benefit from them.

Coffee and tea contain dozens of compounds that range from caffeine to polyphenols and flavonoids, which are considered to be anti-oxidants. Interestingly, if you enjoy a dark coffee or dark tea for their "fuller taste" (whatever that means), you are probably sacrificing many of these compounds because of the high-temperature treatment that is required to make them dark. In particular, dark coffee contains only a fraction of polyphenols and other compounds that are contained in lightly-roasted coffee, and the same is true for tea.

The reason is that high temperatures increase the atomic vibration of the atoms that make up these (rather sensitive) chemical compounds, leading to dissociation in many cases. This is exacerbated in the presence of very hot water when you make your brew. Tea in particular is very sensitive to such dissociation, which explains why many teas require only moderate water temperature for maximum benefit, some green teas as low as 60 °C. This essentially means that, if you want a strong pick-me-up in the morning, use lightly ground coffee or green tea, both made with moderately hot water and short brewing time. And if you just want a nice, tasty coffee or tea before bedtime and then enjoy a good night's sleep to boot, by all means have a dark coffee or tea made with nearly boiling water.

Making a cup of coffee involves a number of interesting phenomena and each method of making it has a different taste as a result. Let's consider some of the methods used to produce coffee drinks—actually coffee suspensions, since they all consist of solutions of soluble compounds mixed with suspensions of non-soluble compounds.

The simplest method is filtered coffee. Boiling water, at a temperature above 100 °C since it is heated under some pressure in the machine, is poured through the filter holding the coffee in the form of a loose, coarse powder. This coarse powder has a rather low specific surface area (about 1 m^2/g) and the water remains in contact with the coffee for a very short time, so a high temperature is necessary to enable some diffusion of the caffeine and other compounds into the water. This means that many of the most sensitive, aromatic compounds are dissociated and lost. The result is that filtered coffee acquires a slightly over-heated flavour and loses nearly its entire aroma. Not for me.

Instant coffee also compromises aroma for the sake of convenience. It is made by boiling, distilling, and drying ground coffee, so the granules we see are porous agglomerates of nano-sized particles of very high specific surface area (over 100 m^2/g) and therefore appear to dissolve completely in water. In reality it is a solution plus a suspension of nano-sized coffee particles. The taste can be very strong since it is made by distillation, but it has almost no coffee aroma. Using water at 90 °C recovers some of the aroma but only for very short time and it has a very limited taste. No again, thank you.

Espresso coffee is made very differently. The coffee is ground very finely (below 10 μm) so its specific surface area is moderately high (over 10 m^2/g) and packed quite tightly in the machine. At the same time the water is heated to only about 90 °C, but forced under high pressure through the packed powder. This gives limited flow and a limited amount of liquid. The result is a highly aromatic and very dense coffee, but a very small amount of it. Much better. Macchiato is similar and even more intense with added drops of milk.

Nanoparticles old and new

Micro and nanoparticles (generally speaking anything smaller than about 5 μm) are everywhere around us in the form of fine dust, soot, pollen, shed skin cells, etc., and most of it is non-degradable and indigestible. When we breathe it in, our lungs can get inflamed, covering it with mucus and trying to expel it before it causes damage. If we swallow it, some of it gets dissolved and digested, but most goes right though us.

Plastic micro and nanoparticles present a particular problem, as many polymer chains are extremely stable. The ones that are bio-based (cellulose, polylactic acid, etc.) are probably broken down and digested to some extent, but most of the synthetic plastics are probably not and pass right through. However, when they are particularly small, smaller than about 30 nm, they can diffuse through the intestine walls and eventually reach various organs. The jury is still out whether such, otherwise inert, materials can cause serious health problems, although animal studies indicate that they can.

Greek coffee is quite different again. The coffee is ground very finely (below 2 μm), so its specific surface area is quite high (over 50 m^2/g) and a much smaller amount is used than in espresso. It is added directly into a small boiling pot with water, stirred well and allowed to heat up slowly and boil only momentarily so that it preserves most of its aroma. The Turkish method uses the same type of coffee but the coffee drink is allowed to boil for a while, so it has less aroma but a stronger taste, since more compounds have time to dissolve or diffuse into the water. Both these methods result in a rather dense solution with a suspension of nano-sized coffee particles. My favourite, of course.

Lately, there have been a number of articles presenting research findings that all hot coffee and tea (and other hot beverages) sold in plastic-coated containers contain billions of plastic nanoparticles, probably leached out from the inner surface of the cups. While this is certainly a cause for some concern, it is also true that all such beverages contain billions of their own coffee and tea nanoparticles, mostly in the form of agglomerates of certain compounds. In fact, all filter coffee and tea beverages (and of course all Greek- and Turkish-style coffees) contain not only huge numbers of nanoparticles but lots of particles at the micrometre level as well, all of which we ingest. I know people that actually love to eat those fine sediments and would never consider discarding them.

Storm in a Teacup

When I make a cup of tea or coffee, it is fun to observe the various physical phenomena that go with it. We've talked about the diffusion of tea or coffee compounds into the water, but there are other interesting physical phenomena too.

First of all let's look at the shape of the tea surface as you stir. When you stir it, its surface gradually climbs upwards around the cup circumference (by the centrifugal force of the rotation), but forms a hole at the centre. The faster you stir, the higher it climbs and the lower the centre hole gets, right down to the bottom of the cup. You have created a vortex. If you look at this vortex shape from the side (an electrical stirrer in a transparent glass cup of tea with milk shows it very well), it looks like a smooth curve. The shape of the vortex is a paraboloid, one of the most commonly encountered types of curve in nature. The exact shape is the result of the need for the momentum of the tea in the middle to keep up with that at the edge. It's the same shape of curve as many flower petals (lilies, etc.), the curve of the rainbow, and the curve of the vortices made by a body moving fast through water. It is also the shape of the distortion that masses make in space according to Einstein's general theory of relativity (gravitation theory). Not bad for a cup of tea.

Let's look at what milk does in hot tea. Milk is also both a solution of water-soluble nutrients and a suspension containing solids and, in full-fat milk, various lipid molecules. If you pour skimmed milk in tea, it mixes very easily, but you can still see the vortices forming as the milk goes in. Full-fat milk is more interesting. Vortices form very quickly and remain stable for some time while the lipid molecules gradually melt but stay separate from the water. Eventually, the lipids form islands on the surface as their density is lower. Adding just a drop of brandy or other alcohol (or an acidic substance like lemon) will quickly help to bond the lipids with the water and smooth out the ugly islands. Or just use skimmed milk.

Talking about milk in tea, there is a lot of discussion about which is correct or preferable: to pour the milk before or after the tea? I think it is a case of personal preference, but I also think that pouring very hot tea (freshly brewed in a teapot) onto a small amount of milk will scald it and dissociate the molecules in it, but not the lipids. Pouring milk onto tea is less damaging since the tea has already had a chance to cool down. You can get the same result by pouring tea at less than 90 °C onto milk. I personally only drink tea without milk. But there's no accounting for taste, of course. All the above are of course also valid for coffee with milk.

Now let's leave the milk out for a moment, stir, and observe the tea leaves. Can you see them making a "boiling" cyclic ("helical") movement while you are stirring? They move to the outer periphery, sink along the outer edge, move a little towards the centre and then rise again in the middle.[74] What is happening is that the leaves get thrown sideways by centrifugal force, meet some friction at the periphery, slow down, and sink to the bottom. They then move inwards, hit the rising part of the liquid, and rise to the top to complete the cycle. But why do they move inwards at the bottom?

Let's look a bit more closely. In the same cup of tea without milk, observe the movement of tea leaves at the bottom of the cup as you stir a little and then stop. Initially, the leaves move to the periphery, but as soon as you stop, they drop down and start congregating at the centre. Fascinating and entertaining. But why?

This is a rare demonstration of the centripetal force pointing towards the centre of the rotation. Generally, the centripetal and centrifugal forces are always balanced (as when you swing a ball on a taut string around your head). In the case here, when the tea leaves reach the bottom and you stop stirring, they encounter some friction, but the liquid still rotates, so the centripetal force on the leaves is now greater than the centrifugal force and they slowly move to the centre. If you don't stop stirring, the tea leaves meet the faster-rotating vortex at the centre and get pulled up, away from the bottom surface, following the parabola to complete the cycle. Interestingly, the same phenomenon occurs in the sharp curves of rivers, where stones tend

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[74] Use green tea leaves or add a few drops of lemon to lighten up the tea (by bonding with some of the tea molecules) in order to see their motion more clearly.

to congregate at the inner bank of the river, not the periphery. A slightly counter-intuitive fact, but quite true.

Let's now add some milk and observe the surface of the tea as it cools down. If you use normal milk, you'll see some floating "scum". This is the bane of all tea drinkers and occurs even in black tea. It's different from soup scum and what happens is this. All tea leaves (in fact, nearly all leaves) are covered by various insoluble waxy compounds which, when you pour in hot water, are released and float to the surface. In addition, in areas of hard water, various carbonate minerals (especially calcium carbonate) in the water bond preferentially with the waxy substances, exacerbating the scum problem. Even worse, when you add non-skim milk to hot tea, on cooling, tiny fat globules tend to separate out and coagulate with any waxy or salt substances, making your tea look terrible when it cools down. The best solution is to drink your tea hot.