The imperfect toaster

Despite what numerous manufacturers of small kitchen appliances have promised in the past, I have yet to own a toaster that really works. Even when I don’t touch the settings, my toast can come out with a huge range of toastiness, from faintly tanned to thoroughly carbonized. Maybe I just keep buying cheap toasters or maybe there is something more fundamentally difficult with automating the toasting of bread.

The basic design of the toaster has remained essentially unchanged since 1919 when Charles Strite patented the automatic, pop-up toaster. Strite’s invention brought together a number of ideas in one machine, notably a heating element on a timer linked to a spring powered pop-up mechanism. At the heart of the toaster though is another invention, that you can still see glowing brightly in a modern toaster, nichrome wire. The very first toaster, invented in 1893 by Scotsman Alan MacMasters used coils of steel wire through which electricity flowed to produce the heating needed to toast the bread. Unfortunately, the steel wire would get too hot, react with oxygen and burn away. The company manufacturing the toasters, and MacMasters himself, did not do well from his invention. Then in 1905 nichrome wire came onto the scene. If you make a mixture of 80 per cent nickel and 20 per cent chromium the resultant alloy has a couple of very important properties. Firstly, it can be heated to very high temperatures

without it burning away like steel; instead nichrome forms a protective layer of chromium oxide. Secondly, nichrome turns out to be a slightly rubbish conductor of electricity. You may think that this is a hindrance for use in electrical devices. However, it is this resistance to the flow of electricity that makes nichrome wire essential in most electrical heating appliances. If electricity runs through a wire of nichrome, this resistance to the flow of the electricity manifests as heat, and lots of it. These two properties combined make nichrome the ideal material to convert electricity into heat, so much so that the inventor Albert Marsh was magnificently declared the Father of the Electrical Heating Industry.

So, if the toaster itself is such an essentially simple device, why does it continue to be produced in a form that produces such variable results? The answer lies not in the toaster, but in the bread. The perfect toast, in my estimation at least, is hot, crispy and golden brown all over. The hot and crispy bit is relatively straightforward to achieve, but the colour change is more tricky.

The chemistry of this change, called the Maillard reaction, has been extensively studied as it is fundamental to many cooking processes. As you heat up a slice of bread (or a potato, or a coffee bean, or a steak) protein molecules begin to react with some varieties of sugar, like glucose, lactose and maltose – but not sucrose. This reaction produces a whole slew of new, complex, brown coloured and very tasty molecules. It is these molecules that we are striving to make on the surface of our toast. Heat it too much though, and you move the reaction further, producing bitter tasting caramelization and ultimately carbonization. The problem with making toast is the extent of the Maillard reaction depends critically on the amount and type of sugar and protein in the bread. This is why even the best, currently available toaster in the world will be unable to reliably produce a perfect slice of toast every time. Even between similar loaves of bread there will be enough variation to make a difference. Furthermore, purely physical things like the temperature of the bread before it goes in the toaster and the thickness of the slice will have a major impact on the Maillard reaction. It turns out that making toast is harder than it seems, which is maybe why the evolution of toaster technology has stagnated for nearly one hundred years.

Kitchen scales and the kilogram

Digital kitchen scales are, in my opinion, one of the twenty-first century's great gifts to humanity – they take up little space, they are incredibly easy to use, they can flick between imperial and metric and you can zero them with any size bowl sat on top – and yet, they almost certainly lie.

If I plonk a lump of cheese on my scales and it says 153 grams (about five ounces), is that really 153 grams? If you look

closely at the scales, or maybe in the manual, it will give you its degree of accuracy, which on my scales is plus or minus five grams, or for the imperialists among you, that is a range of about a third of an ounce. So, my lump of cheese could in reality be anywhere from 148 to 158 grams. This is probably not going to make much difference to my cooking, but it does raise the question of how do I know that even this range of weights is correct? Is it possible to ever know the weight of anything precisely and with 100 per cent certainty? The answer is yes, but only for one, small object in the universe.

My scales were almost certainly made somewhere in the Far East. Inside the scales is a device called a strain gauge that converts the weight loaded onto the scales into an electrical signal. Strain gauges are made from lots of parallel, incredibly thin strips of metal foil. When the gauge is squashed by a weight, the thin foil is stretched and gets even thinner. As it does its resistance to electricity changes, and the microprocessor within the scales detects this and converts it into numbers on the display. During construction in the factory, the microprocessor is set up so that it knows what reading the strain gauge gives for zero grams and what reading for one kilogram. From this the microprocessor can work out the weight of anything placed on top of it. To do this set up, the factory will have a test weight that is exactly a kilogram – except of course they only know it is a kilogram because they weighed it on a more accurate set of scales made in a different factory, and so it goes on. Each weighing device is calibrated using a standard kilogram that is in turn weighed on a more accurate device. Since each set of scales has an inherent degree of inaccuracy, each subsequent standard kilogram will have a bigger and bigger variation in its measured weight. So, where does it end? If you keep going back up this chain where do you get? Eventually, the calibration of my scales goes back, through the Far Eastern manufacturer to a suburb of Paris, France.

In 1960, at the eleventh *Conférence Générale des Poids et Mesures* (General Conference on Weights and Measures) the gathered dignitaries announced *Le Système International d'Unités* or SI Units as it became known. This consisted of the definition of seven fundamental units and how to measure them. The system has been updated since then, and for all but one of the units the definition is something that can be counted, with some difficulty, in nature. For example, the metre is now defined as the distance travelled by light, in a vacuum, in one 299,792,458th of a second. The second is the time taken for 9,192,631,770 cycles of the radiation coming from a specific type of caesium atom. The single, odd one out unit of measurement is the kilogram. The kilogram is defined, in absolute terms, as the weight of a lump of platinum and iridium, made in 1889 and currently sat in a vault in Sèvre, on the outskirts of Paris in France. Calling it a lump of platinum and iridium is somewhat underselling it. The International Prototype Kilogram, as it is called, is a perfect, flawless cylinder 39.17 mm tall (about 1.54 inches) and with an identical diameter of 39.17 mm. Copies of the International Prototype Kilogram were made and distributed around the world where national institutes of weights and measures use these first generation

copies to make more, inevitably slightly less accurate, second generation copies – and so it goes on all the way back to my kitchen scales. With each step away from the International Prototype Kilogram, the weighing device becomes more and more inaccurate. When my kitchen scales confidently tell me that a lump of cheese weighs 153 grams, the chance that they are not lying is incredibly slim.

Egg white, not see through

Consider this: when you cook an egg, be it chicken, duck or quail, the egg white, or albumin to give it its correct name, turns from completely clear and liquid to a solid, translucent white. On the other hand, the yolk remains the same colour even though it too changes consistency. Why should the transparency of one change, but not the other?

The egg of a bird like a chicken is packed with the protein, fat and minerals needed to make a baby chicken. The yolk contains the majority of the calories in an egg and is the primary source of nutrition for the developing embryo. It's the bit that has all the fat, unlike the albumin of the egg that is almost pure protein mixed in water. The albumin is there to support and protect the yolk, although eventually it too is used up in the process of creating a baby chicken. The proteins within the uncooked albumin of the egg are made up of long chains of hundreds of amino acids. Along the length of these chains are charged chemical groups that will stick to other charged groups along the same chain. Consequently the proteins roll themselves into tiny little balls as all the charges pair up and glue it together. The albumin of an egg is a solution of these protein molecules floating about in water.

You now need to get your head around what makes something transparent or the opposite, opaque. On a molecular level, uncooked egg white is packed with molecules of water and protein, each of which is made up of constituent atoms. At this scale it seems unlikely that light could penetrate far, let alone pass through. However, go beyond the scale of the atom and into the realm of subatomic particles and all this changes. All atoms are made up of a central nucleus, surrounded by a cloud of orbiting electrons and the nucleus takes up a tiny portion of the space inside the atom. There are numerous popular analogies to illustrate this involving sports stadia and peas, but the core concept is that inside an atom, there is very, very little stuff, it is mostly just empty space filled with a cloud of electrons.

When a ray of visible light hits an atom it is almost certainly not going to hit the nucleus, but will pass through the cloud of electrons. Since we are now talking about things at the sub-atomic scale, we have entered the realms of quantum effects. Electrons can only exist in certain predefined energy levels. The reason behind this, without delving into too much quantum weirdness, is analogous to electrons possessing several resonant

frequencies. The energy levels possible depend on the type of atom and what else it is joined to.

A ray of light has a particular amount of energy associated with it, defined by the wavelength or colour of the light. When light passes through electrons, the electrons can absorb this energy, jumping to one of their higher energy levels, but only if it's exactly the correct amount of energy. An electron can't jump halfway to a new energy level, or overshoot a bit. The energy has to be just right. It turns out that in egg white, full of water and proteins, all of the electrons have energy levels that are spaced out too far. When visible light hits the egg white, it has the wrong energy to be absorbed by the electrons. Since it is not being absorbed, it passes straight through and the egg white liquid appears transparent to light. It should be noted that water, and raw egg albumin is not transparent to higher energy, ultraviolet light. This kind of light does have the right amount of energy for the electrons and is consequently absorbed.

All of this changes though when you start to heat the egg white. At about 60 °C (140 °F) the first proteins begin to change their structure. By the time you hit 80 °C (176 °F), there is a mass breakdown of order within the egg white. The curled up balls of amino acids, that make up the proteins, are shaken so violently by the heat that the chemical bonds holding them together as little balls start to come apart. The balls unravel and our egg white is filled with long chains of amino acids that become entangled and stick to each other. The upshot of this is twofold. First, since the protein molecules are all stuck together and tangled, they can't now freely move about, and the egg white becomes a wobbly solid. The second thing that happens is that the possible energy levels within the electrons in the egg white change, so that they can absorb visible light. Now, when a ray of light hits the egg white, it doesn't pass through, its energy is absorbed and the egg white appears opaque.

It's worth wondering what happens to all this absorbed energy. Well, it's released by the electrons, as they sink back to their lower energy levels, in the form of light. However, it's released in all directions, not necessarily the direction the original ray of light was traveling. While some of it will carry on into the egg white, at least half will be reflected back towards the original light source. All of which makes the egg opaque and white.

So, now that the transparency of egg white becomes clear, pun intended, what of egg yolk, why is this not clear? In this case it's a bit less complicated than it having the wrong electron energy levels. Egg yolk is not just water with protein dissolved in it, in addition, it's chock full of tiny blobs of fat. When light hits these it reflects off the surface of the blobs, scattering the light.

Given how many things need to be just right for a substance to be transparent, it's remarkable that anything is. Don't even get me started on how a solid, like glass, manages this trick.