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GASTRONOMY UNIVERSE BY EYES OF PHYSICISTS

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(Adunanza del 4 aprile 2019)

SUNTO. – Dopo un breve inquadramento degli argomenti della presente nota nello scenario di una attività di divulgazione della Fisica attraverso la descrizione di fenomeni che intervengono nella vita quotidiana, si passa a considerare processi legati alla attività culinaria. In particolare, la cottura della carne o degli spaghetti, la preparazione della pizza o di un buon caffè. Sulla base di equazioni quali la equazione di diffusione del calore o del flusso e dei processi di trasferimento dello stesso e della temperatura (dedotte semplicemente attraverso considerazioni di analisi dimensionale) si perviene a formulare i principi che regolano questi processi e a fornire regole di esecuzione aventi validità scientifica.

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ABSTRACT. – After a brief presentation of the general scenario to which the note is connected, the equations involved in some processes related to gastronomy and cuisine activity are derived, only by resorting to dimensional analysis. It is shown how the meat cooking time, or that one for spaghetti preparation can be quantitatively calculated on the basis of the heat conduction or thermal diffusion equations. The processes involved in baking of a good pizza (particularly in a wood oven!) or brewing a good coffee are addressed on the basis of scientific approaches.

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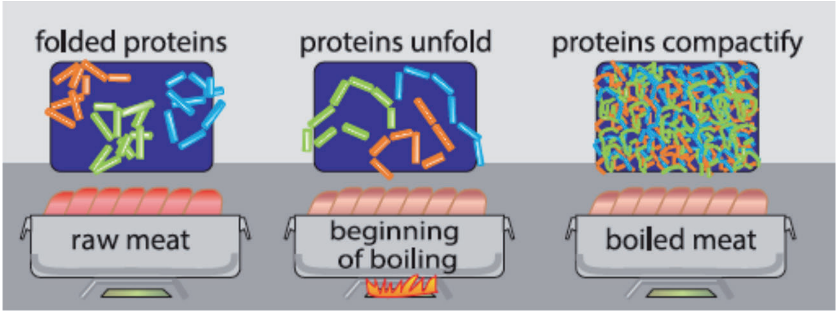
Foreword

The motivation and the roots of the present note go back to more than ten years ago. At that time the authors, strongly involved in researches on superconductivity of strictly scientific character, decided to devote some time to divulgation of Physics, in view of the increasing occurrence of this discipline in the everyday life. Thus several seminars in various institutions arose and finally the authors decided to publish a book. First in Italian language (“**Magico caleidoscopio della Fisica**”, presented to our Istituto) and later on (2014) in an enriched form in French language (“**Le Kaleidoscope de la Physique**” with the additional contribution by Jack Villain, foreign Member of the Istituto Lombardo as well), by the editor Belin in Paris, even this presented and donated to the library of our Istituto).

After that, one of the authors, (A.V.) that is presenting this note to the audience, wanted to somewhat extend the description of the involvement of Physics into other aspects the every-day life, in the kitchen or directly in the preparation of foods typical of the Italian cuisine. Thus, a series of contributions arose and they are collected and deeply illustrated in the present note. As it will be seen, the general transformation of the proteins under cooking, the process of cooking of spaghetti or a big turkey or making a pizza or how to get a good coffee are illustrated, with the help of a few basic equation, still preserving scientific validity.

1. The basic formula of culinary

What does it mean to cook meat? There are biologists in the audience, and I apologize if using oversimplified picture. Meat is mainly composed of proteins. What are proteins? Geometrically, these are folded knots that unfold as the temperature rises. At a certain temperature - each type of meat has its own (for beef it is 74°C, for fish 47°C, for yolk - about 64°C) denaturation (compactification) of these chains occurs: they straighten form some kind of rugs. The difference between cooked and raw meat is whether these rugs have formed or not. So, at a temperature of about 75°C, such compactification occurs in beef, as a result of which boiled meat is obtained.



How does it differ from fried meat? The cooking process starts when we throw the piece of meat into the water. At normal atmospheric pressure, water boils at 100°C in an ordinary saucepan. You can calculate how long it takes for the temperature in the center of a piece of meat to reach the required 75°C and the compactification of proteins will take place in its entire volume. And frying?

Fried or grilled meat is very different from boiled meat. Different color, different taste. It turns out that if the temperature rises significantly above the denaturation one, then the so-called Maillard reaction can occur in the protein carpet. It was discovered in 1912 by the French chemist Louis Camille Maillard and consists of a chemical reaction between amino acids and sugar. It turns out that not all bonds are the same in our rug. In the plane, they are of one kind, across – of the other. At a sufficiently high temperature (for beef it is about 140°C), in the process of the Maillard reaction, some of the bonds are caramelized, which leads to appearance of the characteristic taste of a fried meat. Vegetable oil does not have a specific boiling point, there is a characteristic temperature when it starts to smoke. For olive oil this temperature is about 180°C.

I am not a chemist, and leave this topic, slippery for me. Let's go back to the equations, this is better. Let's formulate a model of the process of boiling a piece of meat. Martin Luther once advised that when bathing a child and pouring water out of the bathtub, be careful not to throw out the child together with the dirty water. This is what a physicist should always think about when formulating a model for some phenomenon. Unlike to mathematician, who solves exact problems, a physicist generally has to make some approximations. The world around us is very complex, and we must come up with a model that will allow both to describe the essence of the phenomenon, and, at the same time, be solved by mathematical methods. Therefore, it is necessary to grasp the essence of the phenomenon and not overcomplicate the task.

Let's start the discussion with the case of a spherical piece of meat. Remember the anecdote about mathematician and physicist at the hippodrome? A physicist meets a mathematician there and asks:

- What are you playing on the sweepstakes?

The mathematician answers:

- No, I'm building a theory of the betting game ...

Physicist:

- Successfully?

Mathematician:

- So far I have managed to solve the problem of the movement of a spherical horse in an airless space ...

It happens that you take a boiled chicken and its meat is still raw near the bone ... I wish this did not happen and the denaturation process took place in the entire volume of the "meat ball". So, I have a spherical piece of meat with a diameter d, with an initial temperature of T_0, and it enters the environment with a temperature of $T_c = 100°C$.

It is clear that a heat flow begins to spread from the surface inward. To correctly describe this process, it would be necessary to write a differential equation known as the *heat conduction equation*. This equation states that at any point the time derivative of temperature is equal to the *thermal diffusivity* of the medium multiplied by the temperature Laplacian calculated at the same point

$$\frac{\partial T(r,t)}{\partial t} = \frac{\kappa}{\rho c}\frac{\partial}{\partial r}\left(r^2\frac{\partial T(r,t)}{\partial r}\right)$$

I think that several people sitting in the hall understood what I mean. And yet, we will not solve the differential equation, let's carry out its dimensional analysis.

In physics, many things can be understood without solving equations. It is enough to analyze the dimensionality of physical quantities: the dimensionality on the left side of the equation must coincide with that one on its right side. This allows one in many cases to understand what is happening. An intelligent student often manages to pass an exam without even being prepared in advance for the question asked, if he is able to write the correct formula from dimensional analysis. It is better if a person is able to write an estimate by dimensionalities, showing that he understands the essence of the phenomenon, than simply is able to memorize.

Let us try to figure it out by ourselves using the dimensional analysis method. The temperature of denaturation of meat coincides by an order of magnitude with the boiling point of water (differs from it by 20 – 25%). Therefore, we assume that the time of "delivery" of the necessary temperature to the center of the solid sphere depends only on its material parameters and size: the thermal conductivity of the meat, its density, specific heat and radius. Therefore, we seek the dependence of the required time on the size of the sphere in the form:

$$\tau = \kappa^{\alpha} \rho^{\beta} c^{\gamma} R^{\delta}.$$

By comparing dimensions, we write:

$$[\tau] = [\kappa]^{\alpha} [\rho]^{\beta} [c]^{\gamma} [R]^{\delta}$$

The dimension of the thermal conductivity $[\kappa] = \frac{kg \cdot m}{s^3 \cdot K}$. Substituting it, side by side with the dimensions of density ($[\rho] = \frac{kg}{m^3}$), specific heat ($[c] = \frac{J}{kg \cdot K}$) and radius ([R] = m), and then comparing them in the right- and left-hand sides, one finds: $\alpha=-1$, $\beta=\gamma=1$, $\delta=2$. Thus, we conclude that

$$\tau = C_0 R^2/\chi,$$

where $\chi = \kappa/(\rho c) = 1,4 \cdot 10^{-7} \frac{m^2}{s}$ and C_0 is an unknown constant of the order of unity.

From this formula is clear that if I take a ball with twice larger the diameter, then the time it takes for the required temperature to reach the center will quadruple.

You see, I, without straining you too much, got a nice formula. But there are more accurate people. One Englishman, Peter Burham, was not too lazy, and for boiling soft-boiled eggs, he derived the exact formula. How? He took the equation I wrote for you, rewrote it in elliptical coordinates (an egg is an ellipse with good accuracy), solved it carefully and got the exact formula:

$$t = 0.15d^2 \log 2\frac{(T_b - T_0)}{(T_b - T_f)}.$$

(in addition, it includes the initial temperature of the egg, the temperature of compactification of the yolk and the boiling point of water).

Now let's imagine to be in the USA. Today is the penultimate Thursday, of November, Thanksgiving day, about 40 million turkeys will be eaten. Usually, when you buy a turkey at the supermarket, the packaging says how long it needs to roast. However, each housewife has her own recipe. At times I have heard the advice for every pound of extra weight to add 15 minutes of turkey's stay in the oven. This is not true, we have already seen that the time of "temperature delivery" to the center depends on the mass nonlinearly, the obtained above equation for cooking time can be rewritten as:

$$\tau = C_1 \frac{c \cdot \rho^{1/3}}{\kappa} M^{2/3},$$

I went online and found this table of recommended times there:

Mass M (pounds)	Baking time τ (*hours*)
8	3,5
12	4,5
16	5,5
20	6,5
24	7,35

From the first glance I do not see the correlations here. The mass has grown by 4 times, and the cooking time has grown a little more than 2.

Let's use our formula. How the experimentalists elaborate their data? It is very important to choose the coordinates corresponding for the task. In our formula, we time appears in the first power while the mass appears in the power 2/3. It is why I propose to take the table and plot the corresponding data in the form of a graph in coordinates of time *versus* mass in the power 2/3. Look at what a nice straight line they fit!

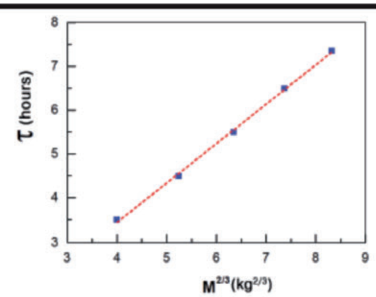


Fig. 21.2: Linear dependence of cooking time τ on the turkey mass M taken in power 2/3.

But this is not just the triumph of theory over practice. First of all, it is clear that from the linear dependence slope I can determine the thermal conductivity of meat yet is not the point now. It is much more important where this line goes. It can be seen that, with good accuracy, it goes to 0. This means that in reality only minutes are needed to undergo the denaturation process and the Maillard reaction. All hours of the turkey's stay in the oven are needed for the required temperature to reach the depth. What temperature? The temperature corresponds to the Maillard reaction, 140°C, if we want to eat baked turkey, not boiled one. And you need this turkey to be baked in full. You could set a higher temperature in the oven, but then there is a high probability of burning the turkey. The temperature should be set just above the required 140°C so that the heat wave goes inward but does not burn the periphery. Often, to save the surface, the turkey is pulled out of the oven, poured with fat, and then sent back. We will talk a lot about surface temperature when discussing the physics of pizza. In cooking, it is often necessary to try on two conflicting requirements: on the one hand, bake, on the other hand, do not burn.

2. Spaghetti and physics

Now the physics of pasta will be discussed. Today I will talk about the pasta of cylindrical shape. These are: capelli d'angelo - angel hair, the thinnest pasta with a diameter of only 0.85 mm, spaghettini, spaghetti, vermicelli, bucatini. All types of cylindrical pasta without a central hole along the axis of the cylinder vary in diameter from only one to two millimeters. Already when the diameter reaches 2.7 mm (bucatini), such a hole turns out to be necessary for some reasons. Below we will try to understand why.

What does it mean: to cook pasta? First, the pasta needs to be heated. If I put the pasta in cold water, it will not become eatable. Secondly, I have to soak its bulk with water, if I just put it into the oven, then the pasta also will not become eatable.

Above I discussed the problem of a heat transfer, here we must additionally solve the problem of the delivery of water to the center of the cylinder. The pasta was specially dried at the factory, and in the process of cooking one has to restore the water contents in it. You've already seen a beautiful equation of heat conduction. The diffusion equation that describes how the concentration of water changes with time, turns out to be mathematically equivalent to the heat conduction equation. The same equations – the same solutions. When considering the issue of cooking pasta, it turns out to be more convenient to work not with the mass, but with the diameter, so we can rewrite the formula for cooking time as

$$\tau_{sp} = ad^2 + b.$$

The coefficient a is determined by the thermal conductivity and the diffusion coefficient, but this is not important to me, I will determine it empirically. As for the parameter b, we saw that for a turkey it is practically equal to 0. In the case of cooking pasta, the parameter b, as we will see, differs from zero, and I claim that its value depends on the nationality of the eater. Do you believe that Germans or Americans cook pasta for as many minutes as the Italian manufacturer writes on the wrapper? No, if they consider the pasta as the side dish. At the same time Italians undercook pasta, even compared to what is written on the wrapper! Why? Because the pasta, after being thrown into a colander, must still go to the pan with the sauce. And there it will still be cooked. Therefore, it is necessary to cook pasta for a minute or two less compared to what is written on the pack. Hence, for Italians, the coefficient b must be negative. I'll prove it to you now with numbers in my hands.

What does the term pasta "al dente" means? In my model, this corresponds to the fact that the water and temperature do not reach the cylinder axis. The spaghetti center remains uncooked. In practice, of course, this is not entirely true. We understand that complex physical and chemical processes take place in the dough during cooking - diffusion, heating, denaturation of starches... My model is simple - to deliver water and the required temperature almost to the center. Let's see if I am not throwing out the child with the dirty water, if I can build a reasonable theory.

I went to a supermarket and bought all the cylindrical pasta that was there: Capellini no. 1, Spaghettini no. 3, Spaghetti no. 5, Vermicelli no. 7, Vermicelli no. 8, Bucatini. The latter are already so thick that there is a hole in them. Then I went to the laboratory of my friend experimentalist, took a caliper and measured diameters of all of them. The results are collected in the following table:

Type of pasta	Diameter, external/internal (mm)	Experimental cooking time (min)
capellini no.1	1.15/-	3
spaghettini no.3	1.45/-	5
spaghetti no.5	1.75/-	8
vermicelli no.7	1.90/-	11
vermicelli no.8	2.10/-	13
bucatini	2.70/1	8

In our formula for cooking time there are two unknown parameters - a and b. I will not search for them on the Internet, they can be found in a simple way. Namely, I will take Spaghettini no. 3 and Vermicelli no. 8 as reference points (the extreme rows of the table should not be taken, this can lead to a larger error). For optimal preparation of spaghetti, the manufacturer recommends 5 minutes (as written on the pack). Let's take this as the value of the experimentally verified cooking time. For vermicelli no. 8 the corresponding time is 13 minutes. So, I have two equations connecting the known cooking times of two types of cylindrical pasta with their known diameters. The parameters **a** and **b** remain unknown. Solving two algebraic equations with two unknowns, we obtain

$$a = \frac{t_2 - t_1}{d_2^2 - d_1^2} = 3.4\,\mathrm{min}/mm^2$$

$$b = \frac{d_2^2 t_1 - d_1^2 t_2}{d_2^2 - d_1^2} = -2.3\,\mathrm{min}\,.$$

Using the found parameters, we can "predict" the cooking times for all the other types of pasta we have. We can see that my formula works great in the middle of the table and fails at the edges. Indeed, it doesn't go well with Capellini: we have 2.2 minutes instead of the recommended 3, but with Bucatini, it's a big problem - here our formula gives 25 minutes instead of 8. Let's try to figure it out.

Let's start with bucatini. Please tell me what do you think, why it is the hole in its center? There are two possible reasons. First, if there is a hole, then there is no need to deliver heat up to the very center through the outer surface, since water will fill in there anyway. As a second explanation, perhaps someone will tell me that, thanks to the inner hole, there will be two flows of heat, one from the outside, the other from the inside? Do you think there will be a heat flow from within or not? No, it will not. For occurrence of the heat flow it is not enough for the water inside the bucatini to have a temperature of 100°C. Take a pot of boiling water and place a small saucepan in it, will the water boil in the latter? No, it will not boil! It is not enough to be surrounded by media with temperature 100°C, it is necessary to have constant flow of energy from the external source. The same thing happens with the long bucatini. Water really enters at the first moment with a temperature of 100°C, but then where to get energy for heat transfer into the dough? Therefore, I will take my formula for cooking time of cylindrical pasta which takes into account only the flow from the outside, and subtract in it the size of the internal hole from the diameter, which no longer needs to be heated, there is already water with its 100°C. In result I get the theoretical cooking time as 7.5 minutes instead of the recommended 8. This is really great!

We see that I came up with a theory, it works in a certain range, but as soon as I went beyond it, the theory stopped working. In 25 minutes my dough will just turn into porridge! Then I extended my theory, take into account the central hole, and the theory works great again. This is a good example that shows how a theoretical physicist works. You come up with a certain model, it works within some limits, which you must stipulate in advance, but at the borders of the region it may fail, then the theory must be revised.

Now let's deal with the second nuisance. Capellini are thin and have a diameter only 1.15mm. The recommended time is 3 minutes, but we got 2.2. Why this 30% discrepancy? The matter of fact, that from our formula follows that there is such a thickness of cylinder at which you can eat corresponding pasta just raw. "*Al dente*" in my model means that the heat flow does not reach the center. Let's see how thick the pasta should be in my model in order to be eaten raw. The cooking time is set equal to 0, therefore

$$ad^2 + b = 0.$$

Here **a** is a positive value, and **b** is negative, therefore this equation has a real solution. We find that the corresponding critical value of d is 0.85 mm. Hence, according to my logic, a hypothetical pasta with a diameter of 0.85 mm does not need to be cooked at all. The value 1.15 mm is already very close. One can see that, when the diameter was 2 mm, everything is fine, but when we approach 1 mm, the theory breaks down.

Pasta serves the industry as well. One day, a Swiss firm set out to learn how to knit fishing nets. The company's engineers made a mathematical model from which it followed that the most dangerous places in terms of the break are these in the nodes. And they decided to test it experimentally, but they didn't succeed on the experiments with a real network. In those days, they did not have a fast enough camera, and they could not keep track of how the nylon breaks. Then an ingenious solution was proposed. The engineers took spaghetti, boiled it, doused it with olive oil, tied it in knots and began to study the tearing process on a slow camera.

Has anyone seen pasta knotted during cooking? Nobody has seen. Why don't they knot? Do you think it's that simple? I asked myself the question, how long should the spaghetti be to make it knotted? Why does the wire from the headphones always get entangled but no pasta? Moreover, out of 5,000 amino acids, only few are knotted. I have a colleague and friend, Alexander Grossberg, a great expert in knots. Many years ago he was a professor at Moscow State University, now he is a professor in New York. Once I asked him to answer the above questions, but he said that the problem of knotting a long rope has not yet been fully solved. A formula has not yet been found that would analytically determine the knotting probability. There are numerical models, but no good theory.

From the general principles of statistical mechanics, it is clear that the probability of self-knotting of a cord is determined by the exponential to the power of which its length is divided by some quantity of the dimension of length $\gamma\xi$, all with a minus sign:

$$w = 1 - \exp\left(-\frac{L}{\gamma\xi}\right)$$

What is ξ here, and what is γ? The quantity ξ is the characteristic length of the cord at which it can change its direction to 90°. With headphones, the wire bends very easily, we can say that ξ is less than one centimeter. So, ξ is the characteristic length of the material, which characterizes its elasticity in bending. And γ is the numerical coefficient that is still obtained only as a result of computing on a computer. Surprisingly, γ turns out to be huge - about 300, a rare case. But that's why spaghetti and amino acids don't entangle. Let's estimate the likelihood of knotting for spaghetti. Let's take ξ = 2-3 cm. Then, in order for spaghetti to knot with a 10% probability, their length should be about 1 m. And the standard for pasta is 23 cm.

Finally, I would like to conduct an experiment. Everyone knows about the Nobel Prize. Thanks to journalists, everyone probably knows about Ig Noble Prize awarded by Harvard University. The Ig Nobel Prizes honor achievements that make people laugh, then think. The prizes are intended to celebrate the unusual, honor the imaginative — and spur people's interest in science, medicine, and technology. The Ig Noble Prize of 2007 was given to two Frenchmen, Basile Audoly and Sebastien Neukirch of the Université Pierre et Marie Curie, for their analysis that explains why uncooked spaghetti breaks into several pieces when it is bent.

Take the spaghetti by the ends and bend it into an arc. It seems obvious that with further bending, sooner or later it, somewhere near the middle, will break into two parts. It turns out that in this case our intuition lets us down, there will almost always be three or more fragments.

This unusual property of spaghetti attracted the attention of many scientists, among whom was Richard Feynman. And only quite recently, in August 2005, thanks to the research of two French physicists, Audoly and Neukirch, a quantitative explanation of this phenomenon appeared, which, possibly, will find its further development in the science of the strength of materials and applications in construction. Scientists have investigated the behavior of a thin elastic bar under bending deformation. To do this, they used the so-called Kirchhoff equation, writing it down for a curved elastic rod, first with two fixed ends. They then studied what would happen to the stress distribution in the bar when it breaks at an arbitrary point. The solution turned out to be possible to find only numerically, however, this also allowed understanding physics. Let us assume that, as a result of the applied mechanical bending stress, the first fracture occurs at the weakest point of the spaghetto. It would seem that after it both formed parts should return to their equilibrium positions. However, this process takes place in a very complex and ambiguous way. Immediately after the first fracture, elastic bending waves appear in both parts of the bar, which propagate along them. They lead to an increase in certain areas of the bar of the local bending stress in comparison with the already existing static bending preceding the first fracture. As a result, in these places of growth of the bending stress, further fractures of the bar can occur. Of course, such elastic waves, generated by the first kink, decay with time, however, at a certain ratio between the length of the rod and its elastic properties, they can lead to subsequent fragmentation of the rod. It is remarkable that, having carried out their complex calculations, the scientists were convinced of the correctness of their conclusions with the help of slow-motion shooting of experiments with spaghetti with a high-speed movie camera.

3. Pizza physics

In ancient Egypt there was a tradition to celebrate the birthday of the pharaonic by eating cakes sprinkled with aromatic herbs. The ancient Greek historian Herodotus in his writings mentions Babylonian recipes for various kinds of tortillas baked from flour.




Virgil describes the process of making tortillas in the hearth by peasants from the time of ancient Rome, much like the baking of modern pizza. Apparently, the modern Italian word “pizza” has a Latin etymology: it is consonant with “pinsa” - the past participle of the verb “pinsere”, which means “to crush, to grind” in Latin. Traces of dishes similar to modern pizza can be found in historical documents from the Middle Ages and Renaissance of various Mediterranean countries. But she found her true home, from which pizza set out to conquer the world, in the labyrinths of Naples’ alleys in the first half of the 18th century.

In the triumphant procession of pizza, two of its ingredients were decisive: mozzarella cheese and tomatoes. The first appeared in Naples thanks to the Germanic tribe of the Lombards, who, after the fall of the Roman Empire, descended from the North to Campania and brought herds of buffaloes with them. It is from the fatty milk of buffaloes in the vicinity of Naples that the true mozzarella is still produced. It is very tender not only in taste - mozzarella is afraid of cold (after being in the refrigerator it becomes "rubbery") and lives only a few days, floating in its own whey.

The second ingredient - tomatoes - was brought to Europe from Peru by the Spaniards during the colonization of America. In the 16th century, the Spaniards also ruled Naples; one of the positive consequences of their rule was the mountains of tomatoes on the shelves of greengrocers in the old city. At first, conservative Italians were distrustful of the overseas vegetable, but the Campanian climate turned out to be favorable for him, and gradually the tomato began its triumph in Italian cuisine, becoming the basis of many pasta sauces and, later, the most important ingredient in pizza.

Since the beginning of the 18th century, numerous shops, called "pizzerias", have opened in Naples, where, among other things, pizza is baked. Due to its cheapness and its wonderful taste, pizza is becoming an affordable dish both poor and rich. Soon the fame of pizza reaches the ears of the King of Naples and the Kingdom of the Two Sicily Ferdinand Bourbon, who, in order to taste this dish, neglects palace etiquette and goes to one of these pizzerias. From this moment on, pizzerias come into fashion, become establishments where only pizza is prepared. The most popular pizza in Naples at this time is the sailors' pizza - "Marinara". In its present form, it arose around 1730. To this day, this pizza is a flat disc of simple dough (yeast, water, salt and flour), covered with thinly chopped tomatoes and garlic, drizzled with a little olive oil, sprinkled with oregano (origan). Before getting on the table, Neapolitan pizza spends a couple of minutes in a hot oven, next to hot logs (the temperature is such that it's close to the melting of the aluminum shovel, with which the *pizzaiolo* puts the pizza into the oven: 450-480°C).

Another popular pizza recipe from this era dates from 1796 - 1810. Here, tomatoes, mozzarella and basil leaves are placed on a base of the same unleavened dough. These colors repeat the colors of the tricolor (vertical green, white and red stripes) popular in northern Italy at that time. In 1861, Garibaldi unites Italy, and the tricolor becomes a national symbol.



In 1889, the King of Italy Umberto I and his wife, Queen Margherita, came to Naples. According to legend, the best pizza maker in the city, Raffaele Esposito, bakes three different pizzas for them. Of all the three, the queen appreciated the pizza in the colors of the flag of Italy, so much so that since then this pizza has been named after her - "pizza Margherita". In 1989, the coauthor of this note A.V. was fortunate enough to be in Naples during the celebration of the centenary of Margherita pizza, when the whole city was celebrating the anniversary, the walls of houses were painted in red, white and green, and pizza was handed out on the streets for free.


In the process of the mass emigration of Italians at the beginning of the 20th century, pizza from southern Italy moved to northern Europe and overseas, conquering Grenoble and Hamburg, New York and Chicago, Tokyo and Melbourne. Pizza has taken root there so much that many are convinced of the American origin of pizza.

Having moved from Naples to Rome, I (A.V.) did not immediately recognize my favorite dish. In Roman pizzerias, instead of soft, fluffy, with towering wrapped edges of Neapolitan pizza, they usually serve thin, drier, the size and thickness of a thick pancake (4 - 5 mm), the so-called Roman pizza. On its surface, as in the case of Neapolitan pizza, all sorts of tasty things can lie: both mozzarella with ham and mushrooms ("Prosciutto e funghi"), and the contents of the same "Margherita", but still decorated with circles of peppered salami ("Diavola") , and a collection of four different cheeses ("Quattro formaggi") ... Served in Rome and "Napoli" - pizza with tomato, mozzarella, capers and anchovies. In Naples, on the contrary, pizza of such content is called "Romana" - Roman. It seems that you can combine anything with anything. However, this is not the case, there are classic combinations in Italian cuisine, and there are strict restrictions on imagination: for example, no one will sprinkle seafood with Parmesan cheese, mix fish and meat. This, however, does not apply to American pizzerias: pay for two "toppings" (This is the name of the agreed menu for the standard pizza toppings.) And in the kingdom of the "dibs" they will at least mix a herring with nutella.

"The neophyte is holier than the Pope," says the old proverb. Following her, I began to diligently delve into the secrets of making pizza. The first commandment that I heard from Italians is to try to always go to a pizzeria equipped with a wood-burning oven, not an electric oven. Good pizzerias take pride in their "forno", where the entire cooking process takes place in front of your eyes. Pizzaiolo masterly "sculpts pizza", puts it in the oven with a wooden or aluminum spade, in a moment - and it is already appetizingly bubbling with boiling cheese in front of you, calling to be immediately eaten and washed down with good beer.

Every time I (A.V.) visited the same "Two Lions" pizzeria near my home, I soon received valuable advice from a friendly pizza maker: come in for dinner either before 8 pm, or after 10 pm, when the place is half empty. This was also confirmed by behavior of one of the "lions" - a fat, smoky-gray cat, feeding at a pizzeria "client" [In ancient Rome, clients were called free citizens under the patronage of a patron - a noble citizen, often patrician]; during the influx of people, he went for a walk and was not at all interested in the contents of the plates sitting at the tables.

The reason for this limitation turned out to be very simple - in the throughput of the furnace. As the same pizzaiolo explained to me, the optimum temperature for the Roman pizza he makes in a wood-burning oven with a refractory brick bottom is 325-330°C. [This temperature, of course, depends on how the dough is prepared and stored. Friend Antonio prepares the dough in advance - a day before baking a pizza from it. After kneading well, he leaves the dough to "rest" for a couple of hours, then divides it into portions (for Neapolitan pizza - 180-250 g, for Roman pizza - less) - one per pizza, - and puts it in a wooden box in the form of balls. The dough ripens for another 4-6 hours, then it can already be planted in the oven. But in our case, it is sent to the refrigerator.] At the same time, thin, Roman, pizza "matures" in the oven for 120-130 seconds. Thus, even putting them in the oven two at a time, the pizzaiolo will be able to serve 50-60 visitors per hour. And at "rush hours" there are about a hundred of them in the hall, and even a dozen people are piling up near the cash register, wanting to take the pizza, blazing with heat, home. Here Antonio, for the sake of the owner's income, raises the temperature in the oven to 390°C, pizzas fly out of the oven every seventy seconds, but their quality is not the same - the bottom and edges are slightly burnt, and the tomatoes are still damp ...

Since it is often difficult to find a pizzeria with a wood-burning stove (you need a chimney, but how can you make it in a multi-storey modern building?). Let's figure out what are its advantages over an electric oven, and is it possible to improve the latter so that he still made a passable pizza.

Let's start from afar. Imagine that your temperature rises, and your thermometer is broken during the last cold. Mom will put her hand to your forehead, hesitate and say: you have a cold, you have a fever, you are not going to school tomorrow. In physics, in order to understand a phenomenon, the problem should always be simplified first. Imagine that your mother is measuring the temperature of your forehead not with her fingers, but by touching her forehead to her forehead. Moreover, if the temperature of your forehead is 38°C, and her forehead is 36°C, then it is quite clear from the symmetry of the problem that on the border between the two foreheads the temperature will be set at 37°C, which mother will feel, because a heat flow will flow to her from your hot forehead.

Now let's imagine that the mother has a "copper" head, and the temperature is still the same 36°C. Then, it is intuitively clear that the temperature at the interface will drop, say, to 36.5°C: a copper head that conducts heat well (due to its high thermal conductivity) will take your heat away from the border between the foreheads into the depths. At the same time, it is clear that the removal will be the better, the less heat is required to be left in the border area; it increases (and the boundary temperature decreases) with a decrease in the specific heat capacity of the material.

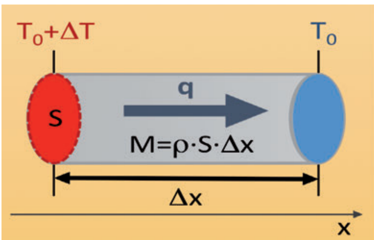
In order to move from conversation to business, we remind the reader of the basic concepts and results of the physics of heat transfer. The term heat (heat energy) usually means the part of the body's energy associated with the movement of its atoms, molecules or other particles of which it is composed. We inherited the concept of heat from the past of physics, heat, as scientists say, is not a function of the state of the body, its value depends on how the body came to this state. Heat, like work, is not a type of energy, but a quantity convenient for describing its transfer. The amount of heat required to raise the temperature of a unit mass of a substance by one degree is called the specific heat of the substance.

It is clear that in the SI system of units, the specific heat is measured in J kg^{-1} K^{-1}. When two bodies with different temperatures are brought into thermal contact, the heat from the more heated one rushes to the less heated one. In the simplest case of a homogeneous non-uniformly heated body, the heat flux q, *i.e.* the amount of heat flowing per unit of time in the direction of temperature change through a unit area perpendicular to this direction is

$$q = \frac{cM\Delta T}{S\Delta t} = c\rho\frac{(\Delta x)^2}{\Delta t}\left(\frac{\Delta T}{\Delta x}\right) = -\kappa\frac{dT}{dx},$$

where ρ is the mass density. Assuming that Δx is small, we identified the value in parentheses as the derivative of the temperature by the coordinate x and took into account the fact that the temperature decreases in the x direction. In the general case, q is a vector and the derivative should be replaced by the gradient of T, which describes the rate of temperature change in space. The coefficient κ is the thermal conductivity, which describes the ability of a material to transfer heat when a temperature gradient is applied. The presented equation expresses mathematically the so-called Fourier's law, which is valid when the temperature variation is small.

Next, let us analyse how a temperature front penetrates a medium from its surface, when a heat flow is supplied to it (see *Figure*).



Assume that during time t the temperature in the small cylinder of the height L(t) and cross-section S has changed by ΔT. Let us get back to the equation and rewrite it by replacing Δx by L(t):

$$\frac{c\rho L(t)\Delta T}{T} = \kappa\frac{\Delta T}{L(t)}.$$

Solving it with respect to the length one finds:

$$L(t) \sim \sqrt{\frac{\kappa t}{c\rho}} = \sqrt{\chi t},$$

i.e., the temperature front enters the medium by the square-root law of time. The time after which the temperature at depth L will reach a value close to that one of the interface depends on the values κ, c, and ρ. The parameter $\chi = \kappa/(c\rho)$, as already was mentioned above, is called the thermal diffusivity or coefficient of temperature conductivity. The heating time of the whole volume can be expressed in its terms: $\tau \sim L^2/\chi$.

Of course, our consideration of the heat penetration problem into a medium is just a simple evaluation of the value L(t). A more precise approach requires solution of differential equations. Yet, the final result confirms our estimation just correcting the numerical factor:

$$L(t) = \sqrt{\pi\chi t}.$$

Now that we know how heat transfer works, let us get back to the problem of calculating the temperature at the interface between two semi-spaces: on the left with parameters κ_1, c_1, ρ_1 and temperature T_1 at $-\infty$,and on the right with parameters κ_2, c_2, ρ_2 and temperature T_2 at ∞. Let us denote the temperature at the boundary layer as T_0. The equation of the energy balance, *i.e.*, the requirement of the equality of the heat flowing from the warm, right semi-space through the interface to the cold, left semi-space, can be written in the form

$$q = \kappa_1\frac{T_1 - T_0}{\sqrt{\pi\chi_1 t}} = \kappa_2\frac{T_0 - T_2}{\sqrt{\pi\chi_2 t}}.$$

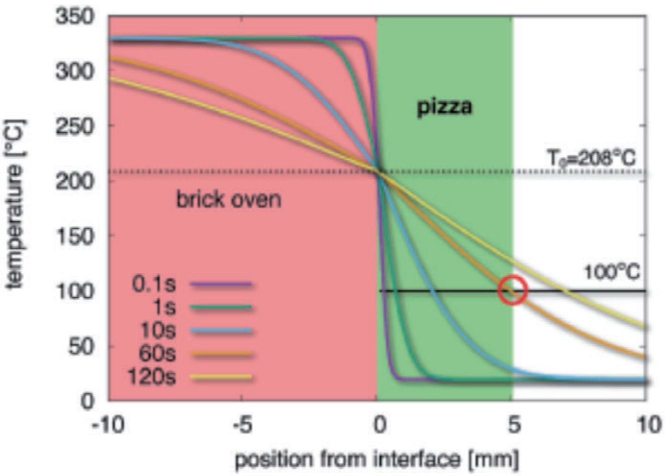
Here we simplified the problem assuming that all temperature changes happen at the corresponding temperature dependent length. Solving this equation with respect to T_0 one finds that

$$T_0 = \frac{T_1 + \nu_{21}T_2}{1 + \nu_{21}},$$

where

$$\nu_{21} = \frac{\kappa_2}{\kappa_1}\sqrt{\frac{\chi_1}{\chi_2}} = \sqrt{\frac{\kappa_2 c_2 \rho_2}{\kappa_1 c_1 \rho_1}}.$$

First of all, we note that time was not included in our formula, *i.e.* in the first approximation, the temperature at the boundary does not change. Thus, we quantitatively substantiated the intuitive answer given at the beginning at 37°C for the temperature at the border between two identical foreheads. If the right, cold, forehead is copper, then for him the temperature of the cold copper forehead almost does not increase from contact with the hot usual.



We are now ready to discuss the benefits of a wood-burning stove. Let's calculate the temperature at the bottom of the pizza we put in the wood-burning oven. All parameters necessary for us are given in the table.

Material	Heat capacity $c\,[\frac{J}{kg\cdot K}]$	Thermal conductivity $\kappa\,[\frac{W}{m\cdot K}]$	Mass density $\rho\ 10^3[\frac{kg}{m^3}]$	Temperature conductivity $\chi\ 10^{-7}[\frac{m^2}{s}]$	ν_{21}
dough (2)	$2{-}2{,}5 \cdot 10^3$	0,5	0,6–0,8	2,5–4,2	1
steel (1)	$4{,}96 \cdot 10^2$	18	7,9	45	0,1
fire brick (1)	$8{,}8 \cdot 10^2$	0,86	2,5	4,0	0,65

Assuming the initial temperature of the pizza dough as 20°C, the temperature inside the oven, as our pizzaiolo claimed, being about 330°C, and the ratio $\nu_{d,fb}$ = 0,65 we find for the temperature at the boundary layer between the oven surface and pizza bottom

$$T_0^{bp} = \frac{330°C + 0{,}65 \cdot 20°C}{1{,}65} \approx 208°C.$$

As we know from the words of the pizzaiolo, a pizza is perfectly baked in two minutes under these conditions. Let us now repeat our calculations for the electric oven with its baking surface made of steel. For an electric oven the ratio $\nu_{d,s}$ = 0,1, and if heated to the same temperature of 330°C, $T^{eo}_1 = T^{wo}_1$ = 330°C, the temperature

$$T_{0*}^{eo} = \frac{330°C + 0{,}1 \cdot 20°C}{1{,}1} \approx 300°C.$$

That is too much! The pizza will just turn into coal! This interface temperature is even much higher than in Naples pizzerias, where oven temperatures between 400 – 500°C are common.

Well, let us formulate the problem differently. Let us assume that generations of pizza makers, who were using wooden spade to transfer pizzas into the oven, are right: the temperature at the (Roman) pizzas bottom should be about 210°C. What would be the necessary temperature for an electric oven with steel surface?

The answer follows from our equation with the coefficient $\nu_{d,s}$ = 0,1 and solved with respect to T^{eo}_1 when the temperature at the bottom of the pizza is the same as in the wood oven: $T^{eo}_0 = T^{wo}_0$. The result of this exercise shows that the electric oven should be much colder than the brick one: T^{eo}_1 = 230°C.

Of course, as always in physics, in order to understand the essence of the phenomenon, we considered the simplified model. It is not always possible to install the correct wood-burning stove, and not all visitors will understand the difference between very good and good pizza. Therefore, engineers use tricks: in a modern professional electric oven, they make a bottom made of special ceramics, imitating the bottom of a wood-burning oven, in order to fry pizza evenly, they make the bottom rotate, thermal ventilation is added to the radiation from the oven walls, and other tricks are also invented. But still, the dry heat and the smell of the wood of the old stove remain the ideal to which any imitation and improvement can only strive.

4. THE PHYSICS OF GOOD COFFEE

One of the most common home-brewed coffee makers in Italy is the moka. It consists of three parts of the lower truncated cone (heater, combi steamers), where water is poured, a metal filter, where coffee of medium fine grinding is placed, and, finally, the upper truncated cone, where the finished drink is collected. This coffee maker is already designed to prepare a drink of a certain consistency: water should be poured up to the level of the valve in the heater, the filter is filled with a full one - about 6 grams per serving in 50 ml of water.

The process of making moka coffee is very entertaining. After filling of moka by water and coffee powder the along the upper and lower cones are tightly twisted, the upper strainer covers the filter cylinder. Additional insulation from the outside is provided by a rubber gasket between the top and bottom cones. The coffee maker is put on low heat. The preparation process consists in bringing water to a boil in a heater, then running it through the coffee powder contained in the filter, further lifting the drink prepared in this way through the tube and draining it into the volume of the upper cone. The coffee is then ready to be dispensed into cups through the spout.

Everything seems simple and clear, but what is the driving force behind the described process? Fire, of course. First, it heats the water to a boil, then the boiling process occurs in a confined space, where the water occupies much more space than the steam above its surface. The temperature surpasses through 100°C, the steam above the water surface remains saturated all the time, its pressure exceeds 1 atm and continues to grow. The external pressure, at the upper level of the filter, is equal to atmospheric. The saturated steam with a temperature above 100°C in volume V begins to play the role of a compressed spring, forcing slightly overheated boiling water through the coffee powder contained in the filter. In this process, those aromas, oils and other components are extracted from it that turn water into a wonderful drink. It is clear that the properties of this drink depend both on the coffee powder itself in the filter and on the temperature of the water and the time it flows through the filter. The secrets of mixing, roasting and grinding coffee beans are the secrets of every manufacturer, based on talent, work and centuries of experience. What determines the time of fluid flow through the filter, we can understand without industrial espionage, proceeding only from the laws of physics.

In the middle of the nineteenth century, the French engineers A. Darcy and J. Dupuis made the first experimental observations of the movement of water in pipes filled with sand. These studies laid the foundation for the creation of the theory of filtration, which today is successfully used to describe the movement of liquids, gases and their mixtures through solids containing interconnected pores or cracks. In addition to creating the first perfect water supply system in Europe in the city of Dijon, A. Darcy formulated the so-called linear filtration law, which today bears his name. It relates the volumetric flow rate of the liquid through the filter with its length and area, with the characteristics of the porous medium filling it, as well as with the pressure difference on both sides of the filter. Today it is one of the basic laws applied in the oil extraction. It is not difficult to apply Darcy's Law to the study of our moka. For example, you can calculate to what temperature boiling water overheats at the bottom of the coffee maker. This temperature can be estimated from the pressure difference between the bottom and top sides of the filter, which is included in the Darcy formula and looking at the dependence of the boiling point pressure on the external pressure. To do this, it is enough to note the time during which the drink fills the upper vessel and measure the characteristic dimensions of the mocha filter. A little more searches in the tables of water viscosity, bewilderment where to find the porosity coefficient of coffee powder in the filter, a brilliant idea to replace it with the corresponding value for medium-grained sand (which is in the table for oil engineers) and now, according to the above graph, it can be seen that the corresponding boiling point of water is 115-120°C, depending on whether the moka is on low or strong fire.

Moka coffee turns out to be strong and aromatic, without sediment, but it is still inferior in its taste to "espresso", which is served in a good bar. The main reason for this, apparently, is the relatively high temperature of boiling water forced through the filter by superheated steam. Therefore, the recipe for improving the quality of coffee when preparing it in mocha is as follows: put the coffee maker on very low heat. In this case, the filtration process will go slower, however, the steam in the lower vessel will not overheat too much.

Antique Neapolitan coffee maker ("Napoletana") resembles a moka, but uses gravity filtration instead of excess steam pressure. It also consists of two vessels stacked one on top of the other and a filter filled with coffee between them. The water in the lower cylinder is brought to a boil, then the coffee maker is removed from the heat and turned over. Filtration occurs under the action of a column of water pressure of the order of several centimeters. The process of making coffee here is noticeably slower than in moka. It is possible to experiment with brewing the same amount of coffee in both coffee makers and, based on the inverse proportionality of the coffee brewing time to the applied pressure following from Darcy's law, check our previous estimate of the pressure in the mocha heater. However, in practice, for "Napoletana" coffee is chosen with a larger grind than for mocha, otherwise the drink will be ready in half an hour and already cold.

Experts say that coffee from "Napoletana" is tastier than from mocha: here, although the filtration process is slower, there is no harmful effect of overheated boiling water on coffee. However, the high pace of modern life leaves no time for philosophical conversation on the terrace overlooking Mount Vesuvius and the beautiful Gulf of Naples, in a pleasant anticipation of finally having a cup of wholesome drink. This luxury remained in old paintings from Neapolitan life and in the works of Eduardo di Filippo.

Not all Neapolitans were patient in times gone by. They say that in the last century one of those residents of the capital of the Kingdom of the Two Sicilies, could not calmly wait coffee brewed in "Napoletana", persuaded his friend, an engineer from Milan, to design a fundamentally new coffee machine that prepares an individual portion of a wonderful fragrant, thick drink for half a minute. Each good cup of coffee is a repository of the secrets of growing and harvesting coffee beans, making a mixture and roasting it, grinding ... Behind the pinnacle of coffee art - a small cup of Italian "espresso" - there is also high technology. The espresso machine is much larger in sizes

and more impressive than its counterparts described above. Usually such machines are in bars and restaurants, but for connoisseurs and lovers of coffee there are also home versions of this machine.

In an espresso coffee maker, water with a temperature of 90-94°C is forced under a pressure of 9-16 atm through a filter with coffee powder of a special grinding, even finer than for mocha.

The whole process takes 15-25 seconds, resulting in 1-2 servings of coffee, 20-35 ml each, for you personally and, perhaps, your interlocutor. The process of fluid flow through a filter with coffee powder is described by the same Darcy's law as in moka, however, the pressure difference applied to the filter is 50 times greater here, and the temperature, on the contrary, is below 100°C. These parameters are specially selected so that do not destroy unstable fractions of the coffee drink with high temperature. The relatively short time of interaction of water with the powder, together with high pressure, leave excess in it and extract all the best from it: emulsions of coffee oils form the drink that cannot be achieved in any other way; its aroma is preserved by the presence of a foam that does not allow volatile components to disappear.

Espresso, oddly enough, contains less caffeine - due to the short contact of water with the powder (20-30 seconds *versus* 4-5 minutes in the filter) and the smallness of its volume, all the caffeine does not have time to be extracted. The first example of an espresso machine was exhibited in Paris in 1855. In modern stationary devices that make up the equipment of bars and restaurants, water is supplied under the required pressure using a special pump in the design. In a classic espresso machine, hot water from the heating cylinder, by lifting the handle, fills the chamber above the filter and then is forced through the filter manually by lowering the handle; high pressure is generated by the dynamic resistance of the coffee filter and the leverage effect that multiplies the hand force.

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