Are There Really Electrons? Experiment and Reality

J. J. Thomson "discovered" the electron a hundred years ago. Eventually, the accumulating experimental and theoretical evidence made it clear to all but the most obdurate skeptics that there really are electrons.

Allan Franklin

Discussing the existence of electrons, philosopher of science Ian Hacking has written, "So far as I'm concerned, if you can spray them, then they are real."[1] He went on to elaborate this view: "We are completely convinced of the reality of electrons when we set out to build—and often enough succeed in building—new kinds of device that use various well-understood causal properties of electrons to interfere in other more hypothetical parts of nature."[2]

Hacking's example was Peggy II, a polarized electron source built at the Stanford Linear Accelerator Center in the late 1970s. Peggy II provided polarized electrons for an experiment that scattered electrons off deuterons to investigate the weak neutral current. Although I agree with Hacking that manipulability can often provide us with grounds for belief in a theoretical entity, his illustration comes far too late. Physicists believed in the existence of electrons long before Peggy II, and I show here that they had good reasons for that belief.

I discuss the grounds for belief in the existence of the electron by examining the early history of experiments involving electrons. This is not a complete history, but rather a reconstruction of the argument that a physicist in the early 20th century might have used to argue for the existence of the electron. I begin with J. J. Thomson's 1897 experiment on cathode rays, which is celebrated this year as *the* "discovery" experiment.

Thomson's cathode-ray experiment

The purpose of Thomson's experiments at that time was to investigate the nature of the then recently discovered cathode rays. He was attempting to decide between the view that the rays were negatively charged material particles and the view that they were disturbances in the aether. His first order of business was to show that the cathode rays carried negative charge. That had presumably been shown earlier by Jean Perrin. Perrin had placed two coaxial metal cylinders, insulated from one another, in front of a plane cathode. Each cylinder had a small hole through which the cathode rays could pass. The outer cylinder was grounded. When cathode rays passed onto the inner cylinder, an electroscope attached to the inner cylinder showed the presence of a negative electrical charge. When the cathode rays were magnetically deflected so that they did not pass through the holes, no charge was detected. "Now the supporters of the aetherial theory," Thomson wrote, "do not deny that electrified particles are shot off from the cathode; they deny, however, that these charged particles have any more to do with the cathode rays than a rifle-ball has with the flash when a rifle is fired."[3]

Thomson repeated the experiment in 1897, but in a form that was not open to such an objection. His apparatus is shown in figure 2. Like Perrin's, it had two coaxial cylinders with holes. The outer cylinder was grounded and the inner one was attached to an electrometer, to detect any charge. The cathode rays passed from A into the larger bulb, but they did not enter the holes at the cylinder ends unless they were deflected by a magnetic field. Thomson concluded, "When the cathode rays (whose path was traced by the phosphorescence on the glass) did not fall on the slit, the electrical charge sent to the electrometer when the induction coil producing the rays was set in action was small and irregular; when, however, the rays were bent by a magnet so as to fall on the slit, there was a large charge of negative electricity sent to the electrometer. . . . If the rays were so much bent by the magnet that they overshot the slits in the cylinder, the charge passing into the cylinder fell again to a very small fraction of its value when the aim was true. *Thus this experiment shows that, however we twist and deflect the cathode rays by magnetic forces, the negative electrification follows the same path as the rays, and that this negative electrification is indissolubly connected with the cathode rays.*"[3] (Emphasis added.)

There was, however, a problem for the view that cathode rays were negatively charged material particles. Several experiments, in particular that of Heinrich Hertz, had failed to observe the deflection of cathode rays by an electrostatic field. Thomson proceeded to answer that objection with the apparatus shown in figure 3. Cathode rays from the cathode in the small bulb at the left passed through a slit in the anode and then through a second slit, both of them in the neck. They then passed between the two plates and produced a narrow, well-defined phosphorescent patch at the right end of the tube, which also had a scale attached to measure any deflection.

When Hertz had performed the experiment, he found no deflection when a potential difference was applied across the two plates. He therefore concluded that the electrostatic properties of the cathode rays are either nil or very feeble. Thomson admitted that, when he first

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FIGURE 1. JOSEPH JOHN THOMSON (1856—1940), photographed some time around the turn of the century. (Courtesy AIP Emilio Segrè Photo Archive.)

performed the experiment, he also saw no effect. "On repeating this experiment [that of Hertz] I at first got the same result, but subsequent experiments showed that the absence of deflexion is due to the conductivity conferred on the rarefied gas by the cathode rays."[3] Thomson then performed the experiment at lower pressure and, indeed, observed the deflection. He also demonstrated that the cathode rays were deflected by a magnetic field.

Thomson concluded, "As the cathode rays carry a charge of negative electricity, are deflected by an electrostatic force as if they were negatively electrified, and are acted on by a magnetic force in just the way in which this force would act on a negatively electrified body moving along the path of these rays, I can see no escape from the conclusion that they are charges of negative electricity carried by particles of matter."[3] (That's the well-known "duck argument." If it looks like a duck, quacks like a duck and waddles like a duck, then we have good reason to believe it is a duck).

Having established that cathode rays were negatively charged material particles, Thomson went on to discuss what the particles might be. "What are these particles? Are they atoms, or molecules, or matter in a still finer state of subdivision?"[3] To investigate this question, he made measurements on the charge-to-mass ratio of cathode rays. He employed two different methods. The first used the total charge carried by the cathode-ray beam in a fixed period of time, the total energy carried by the beam in that same time, and its radius of curvature in a known magnetic field.

Thomson's second method eliminated the problem of leakage, which had plagued his first method, and used both the electrostatic and magnetic deflection of the cathode rays. His apparatus was essentially the same as the one he had used (figure 3) to demonstrate the electrostatic deflection of cathode rays. He could apply a magnetic field perpendicular to both the electric field and the trajectory of the cathode rays. By adjusting the strengths of the electric and magnetic fields so that the cathode-ray beam was undeflected, Thomson determined the velocity of the rays.

Turning off the magnetic field allowed the rays to be deflected by the electric field. From the measured deflection, the length of the apparatus and the electric and magnetic field strengths, Thomson could calculate the ratio m/e for cathode rays. He found a mass/charge ratio of $1.3 \pm 0.2 \times 10^{-8}$ grams per coulomb. (The modern value is 0.56857×10^{-8} gm/C; Thomson used more old-fashioned units and gave no explicit error estimate.) This ratio appeared to be independent of both the gas in the tube and of the metal in the cathode, suggesting that the particles were constituents of the atoms of all substances. It was also far smaller, by a factor of 1000, than the mass/charge ratio previously measured for the hydrogen ion in electrolysis.

Thomson remarked that this surprising result might be due to the smallness of m or to the bigness of e. He argued that m was small, citing Philipp Lenard, who had shown that the range of cathode rays in air (half a centimeter) was far larger than the mean free path of molecules (10^{-5} cm). If the cathode ray travels so much farther than a molecule before colliding with an air molecule, it must be very much smaller than a molecule. Thomson concluded that these negatively charged particles were also constituents of atoms.

Millikan and his oil drops

Thomson did not use the term "electron" to refer to his negatively charged particles; he preferred the term "corpuscle." "Electron" had been introduced by the Irish physicist G. Johnstone Stoney in 1891, as the name of the "natural unit of electricity," the amount of electricity that must pass through a solution to liberate one atom of hydrogen. Stoney did not associate the electron with a material particle, and physicists at the time questioned whether or not electricity might be a continuous homogeneous fluid. Lord Kelvin, for example, raised this question and commented that "I leave it, however, for the present and prefer to consider an atomic theory of electricity . . . largely accepted by present day workers and teachers. Indeed Faraday's laws of electrolysis seem to necessitate something atomic in electricity."[4]

The early determinations of the charge of the electron had not established that there was a fundamental unit of electricity. That was because the experiments measured the total charge of a cloud of droplets, without showing

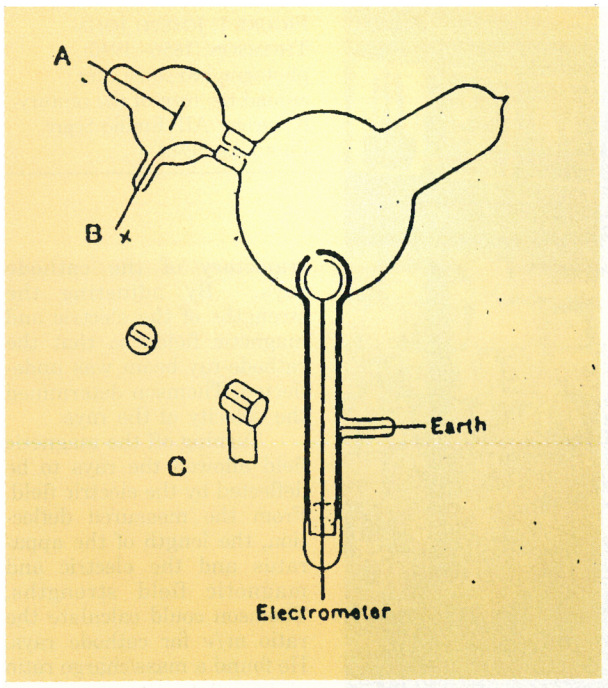

FIGURE 2. J. J. THOMSON'S 1897 APPARATUS for demonstrating that cathode rays have negative electric charge. The slits in the cylinders are shown. (Adapted from ref. 3.)

that the value obtained was anything other than a statistical average. The same was true for Thomson's measurement of e/m for a beam of cathode rays.

It was the experimental work of Robert Millikan at the University of Chicago, beginning in 1909, that provided the next step in establishing the electron as a fundamental particle. Millikan not only demonstrated that there was a fundamental unit of electrical charge; he also measured it accurately.

Millikan's experimental apparatus is shown in figure 5. He allowed single oil drops to fall a known distance in air, and measured the duration of the fall. He then turned on an electric field and measured the time it took for each drop to travel the same distance upward. (The oil drops were traveling at constant terminal velocity.) These two time measurements let him determine both the mass of the drop and its total charge.

The charge on the oil drop sometimes changed spontaneously, by ionization or absorption of charge from the air. Millikan also induced such changes with either a radioactive source or x-radiation. One could calculate the change in the charge on a drop from successive ascent times with the field on. Millikan found that both the total charge on a drop and the changes in that charge were small integral multiples of e, a fundamental unit of charge.

Millikan wrote, "The total number of changes which we have observed would be between one and two thousand, and in not one single instance has there been any change which did not represent the advent upon the drop of one definite, invariable quantity of electricity or a very small multiple of that quantity."[5] Millikan's final value for e was $(4.774 \pm 0.009) \times 10^{-10}$ esu. (The modern value is $4.803\ 207 \times 10^{-10}$ esu.)

Despite his claim to the contrary, Millikan did not publish *all* of his oil-drop results. Many drops he excluded because he was not sure that the apparatus was working properly; some because of experimental or calculational difficulties; some because they simply weren't needed (he had far more data than he needed to improve the measurement of e by an order of magnitude); and a few seem to have been excluded solely because they increased the experimental uncertainty. One drop, which gave a value of e that was 40% low, was also excluded. For that one, Millikan wrote "won't work" in his notebook. I speculate that this exclusion was simply to avoid giving Felix Ehrenhaft ammunition in the charge-quantization controversy.[6] Later analysis has shown that the data for this drop were indeed unreliable.[7]

Millikan also discarded some of the data from accepted drops, and he engaged in selective calculation. But the effects of all this cosmetic surgery were quite small. If one includes all the good data and does all the calculations as advertised, the value of e changes by only a part in a thousand, with an insignificant increase in the experimental uncertainty.

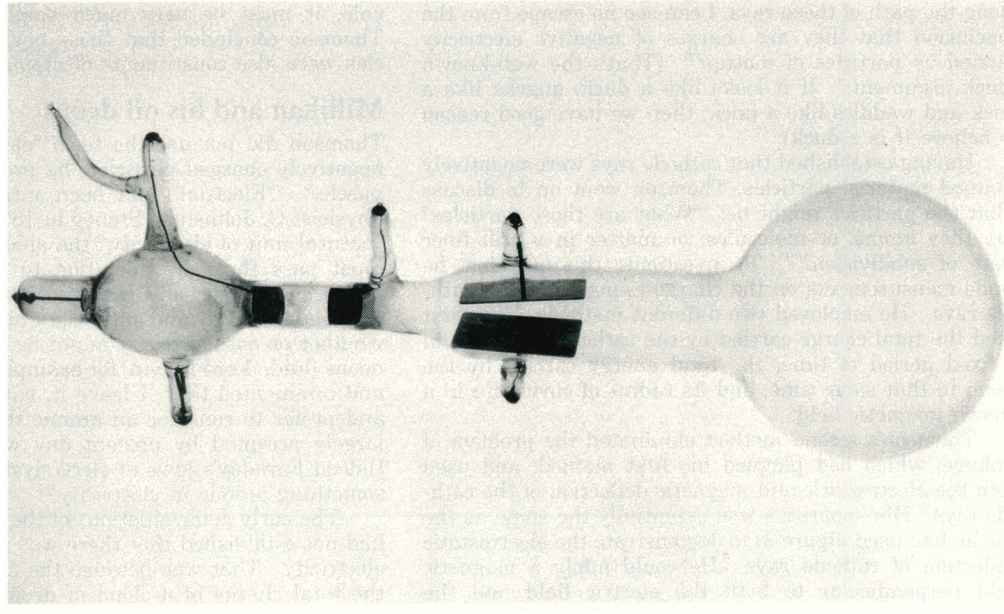

FIGURE 3. THOMSON'S TUBE for demonstrating that cathode rays are deflected by an electric field. It was also used to measure e/m. (Courtesy of Cavendish Laboratory.)

FIGURE 4. ROBERT MILLIKAN (1868–1953) as a postdoctoral student in Germany, in 1895–96. (Courtesy of California Institute of Technology.)

Millikan associated his measured e both with the charge on Thomson's corpuscles and the charge on the hydrogen ion in electrolysis. He combined his value for e with contemporary measurements of e/m by electrolytic and cathode-ray techniques to determine that the mass of Thomson's corpuscle was 1/1845 that of the hydrogen atom—surprisingly close to 1/1837.15, the modern value. Now one had both a definite mass and a definite charge for this would-be fundamental particle, and it behaved exactly as one would expect a negatively charged particle to behave. There was now good evidence for believing that it was a constituent of atoms—in other words, the electron.

Bohr's theory of atomic electrons

In 1913, not long after Millikan's oil-drop results, Niels Bohr was constructing a theory whose confirmation would provide support for the view that the electron was both a fundamental particle and a constituent of atoms. Bohr began with Rutherford's nuclear model of the atom, with a small, massive, positively charged nucleus orbited by electrons of mass m and charge $-e$. Noting that classical electrodynamics would not allow such a system to be stable, he postulated that the electron could, nonetheless, exist in stationary orbits without radiating energy. He calculated that the binding energy W_n of the nth such stationary bound state around a nucleus of charge Ze would be

$$W_n = 2\pi^2 m e^4 Z^2/h^2 n^2 ,$$

where h is Planck's constant. He further assumed that the electron emitted radiation only when it made a transition from one stationary state to another and that the transition energy from the nth to the n'th state was in the form of a light quantum of energy,

$$E = h\nu = W_{n'} - W_n ,$$

where ν is the frequency of the quantum of light.

This gave the formula for the Balmer series in hydrogen, including the empirical Rydberg constant. Using the best available values for Planck's constant and the electron's mass and charge, Bohr calculated the spectroscopic proportionality constant

$$N = 2\pi^2 me^4 Z^2/h^3 = 3.1 \times 10^{15}\ s^{-1} ,$$

in good agreement with $3.290 \times 10^{15}\ s^{-1}$, the measured spectroscopic value at that time.

Somewhat later, Millikan discussed the same issue:

> The evidence for the soundness of the conception of non-radiating electronic orbits is to be looked for, then, first, in the success of the constants involved . . . If these constants come out right within the limits of experimental error, then the theory of non-radiating electronic orbits has been given the most crucial imaginable of tests, especially if these constants are accurately determinable.
>
> What are the facts? The constant N of the Balmer series in hydrogen . . . is known with the great precision obtained in all wave-length determinations and is equal to $3.290 \times 10^{15}\ s^{-1}$. From the Bohr theory it is given by the simplest algebra as $N = 2\pi^2 me^4 Z^2/h^3$ . . . As already indicated, I recently redetermined e with an estimated accuracy of one part in 1000 and obtained for it the value 4.774×10^{-10} [esu]. As will be shown in the next chapter, I have determined h photoelectrically with an error, in the case of sodium, of not more than one-half of 1 per cent, the value for sodium being 6.56×10^{-27} [J s]. The value found by Webster, by a method recently discovered by Duane and Hunt, is 6.53×10^{-27}. Taking the mean of these two results, viz. 6.545×10^{-27}, as the most probable value, we get with the aid of Buecherer's value of e/m . . . which is probably correct to 0.1 per cent, $N = 3.294 \times 10^{15}$ [s^{-1}], *which agrees within a tenth of 1 per cent with the observed value.* This agreement constitutes the most extraordinary justification of the theory of non-radiating electronic orbits.[8] [Emphasis added.]

Millikan could barely contain his enthusiasm for Bohr's theory. He challenged critics to present an alternative that fit the experimental results: "It demonstrates that the behavior of the negative electron in the hydrogen atom is at least correctly described by the equation of a circular non-radiating orbit. If this equation can be obtained from some other physical condition than that of an actual orbit, it is obviously incumbent on those who so hold to show what that condition is. Until this is done, it is justifiable to suppose that the equation of an orbit means an actual orbit."[8]

Obviously Millikan did not expect them to be able to do so. He was also adopting a clearly "realist" position about the Bohr atom. Millikan was not always so sanguine that satisfying an equation proved the existence of the postulated underlying entities. Discussing Einstein's postulation of photons to explain the photoelectric effect, Millikan wrote, "Despite then the apparently complete success of the Einstein equation, the physical theory of which it was designed to be the symbolic expression is found so untenable that Einstein himself, I believe, no longer holds to it."[8]

Both Millikan and Bohr thought that the existence of the electron, as both a fundamental particle and as a

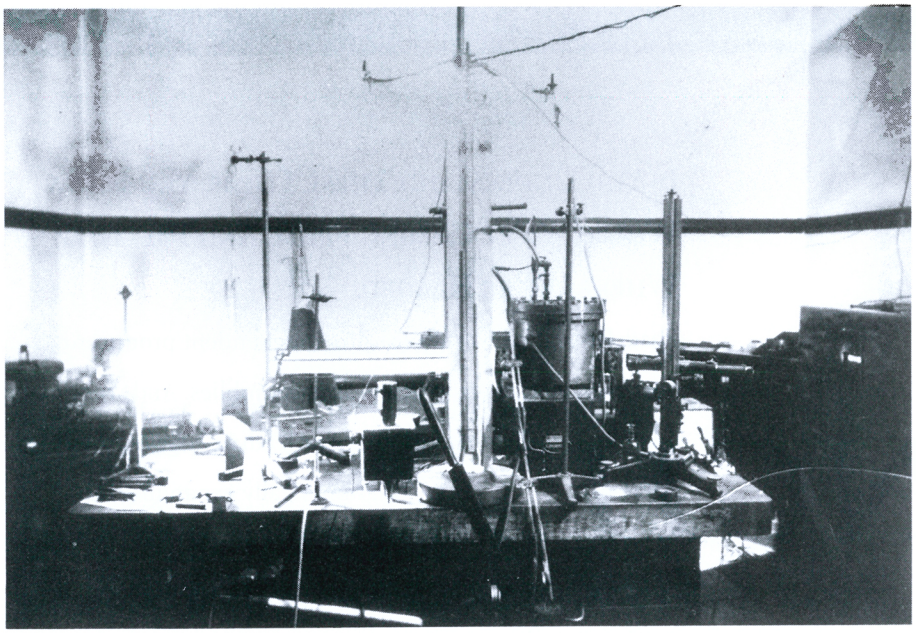

FIGURE 5. MILLIKAN'S OIL-DROP APPARATUS for measuring the charge on the electron. (Courtesy of California Institute of Technology.)

constituent of atoms, was already so well established that they didn't even argue that this spectacularly successful prediction supported it. Instead, they argued that the result supported the more controversial assumptions of Bohr's theory. This is a good example of the view that to have good reason for holding a theory is, *ipso facto*, to have good reason for believing in the existence of the entities postulated by that theory.

The skeptical reader may ask what happened to that argument when the Bohr theory was superseded, a decade later, by the quantum mechanics of Erwin Schrödinger and Werner Heisenberg. The answer is simple: Nothing happened. The Schrödinger equation also assumes an electron with charge e and mass m, and it gives exactly the same prediction as the Bohr theory for the Balmer series.

In the 1920s, another intrinsic property of the electron emerged. In 1921, Otto Stern and Walther Gerlach used the already known properties of the electron to design an experiment to search for spatial quantization of atomic orbital states, as predicted by Arnold Sommerfeld's elaboration of the Bohr theory. Stern wrote that "the experiment, if it can be carried out, will result in a clearcut decision between the quantum-theoretical and classical views." Sommerfeld, for one, did not expect the experiment to succeed. But, as every physics major knows, Stern and Gerlach did find that a beam of silver atoms split into two components as it passed through an inhomogeneous magnetic field. This remarkable result, they concluded, established the existence of spatial quantization.

A few years later, following the suggestion of intrinsic electron spin by Samuel Goudsmit and George Uhlenbeck, it was realized in retrospect that the Stern–Gerlach experiment had actually provided evidence for such an intrinsic spin, with a magnetic moment of 1 Bohr magneton.

Is it all the same electron?

In the 1920s the charge e of the electron was $(4.774 \pm 0.009) \times 10^{-10}$ esu.[9] Its mass m was 1/1845 that of the hydrogen atom,[8] and it had a magnetic moment indistinguishable from $eh/4\pi m = \mu_B$, the Bohr magneton. If we look at the most recent edition of the *Review of Particle Physics*,[10] a 720-page blockbuster, we find that the charge of the electron is $(4.803\ 206\ 8 \pm 0.000\ 001\ 5) \times 10^{-10}$ esu and its mass is $(9.109\ 389\ 7 \pm 0.000\ 005\ 4) \times 10^{-31}$ kg, approximately 1/1837 the mass of the hydrogen atom. The electron's magnetic moment is $(1.001\ 159\ 652\ 193 \pm 0.000\ 000\ 000\ 010)\ \mu_B$, in exquisite agreement with what quantum electrodynamics predicts.

Allowing for improvements in both the precision and accuracy of these measurements, it seems fair to say that the properties of the electron have remained constant. That is not to say that we haven't learned a lot about the properties and interactions of the electron in the intervening time, but rather that its defining properties have stayed the same. It is still a negatively charged particle with a definite charge and a definite mass. It has spin 1/2 and is a constituent of atoms. The electron, as an entity, has remained constant even though the theories we use to describe it have evolved dramatically. Thomson's early work used Maxwell's electromagnetic theory. That was followed by Bohr's old quantum theory, the new quantum mechanics of Schrödinger and Heisenberg, Dirac theory, quantum electrodynamics, and most recently the Glashow–Salam–Weinberg unified theory of the electroweak interactions.

Are electrons real? Is van Fraassen?

At first glance these two questions might seem to be answerable in very different ways. Most people would say that, of course, there is a real Bas van Fraassen. (He is a philosopher of science who does not believe that we can have good reasons for belief in the existence of particles such as the electron.[11]) We can see him, hear him and in other ways detect his presence with our unaided senses, and we could also measure his height, weight and eye color. That should surely convince us that there is such a real person. It would surely be bizarre, then, to limit oneself to saying that "the world is such that everything is as if there were a real Bas van Fraassen."

The electron, on the other hand, is an entity that can be observed only with instruments. Yet why should one such give special status to unaided human sense perception? True, the original meanings of words are often tied to unaided sense perception, but generalization of meaning is a key feature of language. Furthermore, sense percep-

FIGURE 6. THE AUTHOR on his way to visit an electron, which, in addition to being the lightest of the charged leptons, is also one of the smallest towns in western Washington state.

tion can, on occasion, be quite unreliable. Think of mirages, drugs, sleep deprivation or dreams. Eyewitness identifications in criminal trials are notoriously unreliable. "Is it live or is it Memorex?" we were asked in a television ad for a brand of audiotape.

Most people believe that "seeing is believing," and that one need not make an argument for the correctness of human sense perception. I believe they are wrong. The arguments that one should make to validate a sense perception are precisely the same as those one should, and does, provide to show the validity of instrumental observation. If we are willing to believe that there is indeed a real Bas van Fraassen, then I believe we should grant the same status to electrons.

Figure 6 shows the author on his way to visit an electron.

A longer version of this article will appear in the Dibner Institute series on the history of science and technology.

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