A quantum ampere

Review Article

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Quanten-Ampere

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Abstract: The revision of the International System of Units (SI), implemented since 20 May 2019, has redefined the unit of electric current, the ampere (A), linking it to a fixed value of the elementary charge. This paper discusses the new definition and the realisation of the electrical units by quantum electrical metrology standards, which every year become more and more accessible, reliable and user friendly.

Keywords: Metrology, international system of units, base unit, ampere, quantum standard.

Zusammenfassung: Mit der Revison des Internationalen Einheiten Systems (SI) am 20 Mai 2019 ist auch die Einheit des elektrischen Stroms, das Ampere (A), neu definiert worden. Sie ist nun mit einem festen Wert für die Elementarladung verbunden. In dieser Arbeit wird die Neudefinition und die Realisierung der elektrischen Einheiten durch elektrische Quantennormale dargestellt, die immer leichter verfügbar, zuverlässiger und benutzerfreundlicher werden.

Schlagwörter: Metrologie, Internationales Einheitensystem, Basiseinheit, Ampere, Quantennormal.

1 The mechanical ampere: 1948–2019

Electromagnetic phenomena became of industrial interest in the second half of the 19th century, with the exploitation in electrical machines of Faraday's law of induction (1831) [1], which determines the electromotive force developing on a conductor moving in a magnetic field, and the Ampère's force law (1820) [2], which allows to compute the mechanical force between conductors carrying electrical currents. The two interjoined physical phenomena that these laws quantify are the basis of the transformation of mechanical energy—at that time coming from steam or water—into electrical energy, which can be transmitted "istantaneously" at large distances and converted back into mechanical, thermal or chemical energy in an industrial process.

An urgent need for proper and internationally agreed measurement units for electromagnetic quantities arose. International committees and meetings were established with the goal of determining a unique set of electromagnetic units, providing them names (adapted from the surnames of great scientists who discovereed electromagnetic phenomena), symbols, definitions and practical ways for measuring the corresponding quantities.[1] Unfortunately, the communities of physicists and engineers were in disagreement about the best approach to define an electromagnetic system of units, and for several decades different systems coexisted. Oftentimes the same name was assigned to units of different magnitude belonging to different systems, generating a lot of confusion for several decades.

Finally, the International Committee for Weights and Measures [3] agreed on a definition of the ampere implemented since January 1, 1948 and established a metre-kilogram-second-ampere (MKSA) system. The MKSA was a few months later [4] incorporated in the International System of Units (SI). In the SI, all units are derived from a small set of base units (seven in its contemporary version). The base unit for electromagnetic quantities was established to be the ampere (symbol A) [5].

The 1948 ampere definition is directly related to the Ampère's law:

> The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible circular cross-section, and placed 1 metre apart in vacuum, would produce between these conductors a force equal to 2×10^{-7} newton per meter of length. [4]

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1 The International Electrotechnical Congress of 1893 (Chicago, 21–25 August) was particularly significant in this sense, since a definition and practical realisation of the "international" volt, ohm and ampere was established.

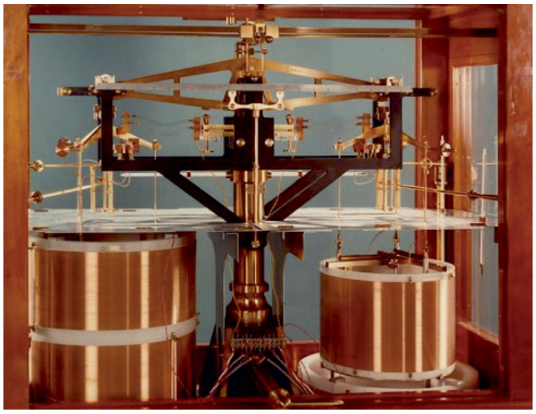

Figure 1: The ampere balance of the National Physical Laboratory. The balance has a symmetric design, with two fixed large solenoids and two movable suspended ones; one large coil has been removed to show the inner one. After more than 60 years of refinements of the device, the best relative accuracy achieved in the ampere realisation was 4×10^{-6} [6].

The above definition, fixing the value of the magnetic constant (the permeability of free space) to $4\pi \times 10^{-7}\,\mathrm{NA}^{-2}$, describes an idealised electromechanical experiment which cannot be realised as stated. However, one can think of curling the straight wires into windings having N many turns (thus multiplying the electrodynamic force by a factor N^2). The electrodynamic force can be measured with a well-established device, the beam balance of mass metrology, by equilibrating it with a weight (that is, the force exerted on a mass by the Earth's gravitational field). This experiment is the so-called *ampere balance* (Fig. 1). In metrological language, the ampere balance provides a *realisation* of the 1948 definition of the unit ampere.

The major limitation to the accuracy of the ampere balance lies in the complex shape of the windings, which are three-dimensional helices. The geometry of the helices and their relative position has to be measured with an accuracy better than the target final realisation accuracy of the ampere unit. For example, if the target relative uncertainty is 1×10^{-6} and windings with a size on the order of 10 cm are employed, the mechanical measurements must have an accuracy of a few nm at most. Further, no deformation of the windings (including that due to the very electrodynamic force one wants to measure) above the same magnitude is allowed during the balance operation. The most accurate ampere balances had a relative accuracy of a few parts in 10^6 [6].

An alternative approach is to realise a derived electromagnetic unit instead of the base unit ampere. The *volt balance* [7] is the electrostatic analogue of the ampere balance: the force develops between two electrodes at different electrostatic potentials. The electrodes of the volt balance can have a much simpler geometry than the windings of the ampere balance; they can be flat surfaces or cylinders. Thus, the experimental geometry can be measured with a much higher accuracy and during the balance operation. The drawback of the volt balance is due to the very small magnitude of the force developed. For example, in one of the most accurate experiments [8], which was a couple of meters tall, the force developed by a 10 kV voltage, was equilibrated by the weight of a reference mass of 2 g only.

The *watt balance* [9], since 2016 [10] named *Kibble balance* to honour its inventor Bryan P. Kibble, solves the conundrum of the ampere balance. It has two working modes: a weighing mode, essentially equivalent to the ampere balance, and a moving mode, where a voltage develops on the same windings because of Faraday's law. The combination of Ampère and Faraday laws allows cancellation of the geometrical terms describing the windings from the resulting equation, which limited the accuracy of the ampere balance. The Kibble balance allows to establish the equivalence between the mechanical and electrical unit of power (watt). Ampere, volt, and Kibble balances are big, complex and expensive experiments: unique prototypes which require decades of development by dedicated groups in top-level national metrology institutes.

In conclusion, the 1948 ampere definition leaves no chances: the ampere has a *mechanical* definition, in terms of a mechanical force, and hence ultimate-accuracy *mechanical* experiments are needed to realise the base or the derived electromagnetic units.[2]

2 Quantum electrical standards

2.1 Discovery of quantum electrical phenomena

The idea that the electric charge might be not continuous, but quantised, arose with the discovery of electrochemical phenomena. Chemical reactions occur in discrete amounts, since discrete molecules are formed or de-

2 Impedance units ohm, henry and farad, related together by the unit of time ($1\,\Omega = 1\,\mathrm{Hs}^{-1} = 1\,\mathrm{F}^{-1}\mathrm{s}$), can be realised from the magnetic constant μ_0, or from the electric constant ϵ_0, which has also a fixed value $\epsilon_0 = 1/(\mu_0 c^2) = 8.8541878176\ldots 10^{-12}\,\mathrm{F\,m}^{-1}$ (where c is the fixed speed of light in vacuum). The corresponding realisation experiments are the *calculable inductor* [11, 12] and the *calculable capacitor* [13, 14]. The calculable capacitor exploits an electrostatic theorem of Thompson and Lampard [15] which reduces the number of relevant mechanical dimensions to be measured to a single length, allowing the calculable capacitor to reach an uncertainty of parts in 10^8 [16].

stroyed in fixed proportions. Therefore, in electrochemical reactions, the electrical charge flowing in the circuit should also be exchanged in discrete amounts. Johnstone Stoney [17] was the first to propose in 1881 that these exchanges are mediated by individual particles, to which he gave the name of *electrons*, each carrying the same discrete charge.[3] In the first half of the 20th century, quantum electrodynamics provided a firm foundation for the discreteness and indistinguishability of electrons and explained the quantum nature of electromagnetic phenomena such as light (quantised in photons) and magnetic flux (introducing the *flux quantum*). The fundamental constants that underpin quantum electrodynamics are the quantised elementary charge e and the Planck constant h, the quantum of (mechanical and electromagnetic) action.

When one considers macroscopic conductors, and voltage or current magnitudes of interest for the applications, the quantum nature of the electromagnetic phenomena is typically hidden from direct observation. Nonetheless, in the second half of the 20th century, macroscopic quantum phenomena in solid-state devices were discovered: the *Josephson effect* (1962) [18] and the *quantum Hall effect* (1980) [19].

The Josephson effect occurs in structures composed of two superconductors separated by a nanometer-thick spacer of normal metal or insulator, called *Josephson junctions*. The junctions are biased with an ac current (possibly also an additional dc bias is employed). At each cycle of the current, one flux quantum $\Phi_0 = h/2e$ develops across the Josephson junction. The inverse of the flux quantum $K_J = \Phi_0^{-1} = 2e/h$ is called the *Josephson constant*. Since flux is the integral of voltage over time, the time-averaged voltage which develops across the junction is proportional to the ac current frequency f through the relation $V = \Phi_0 f = f/K_J$. The Josephson junction is therefore an ideal frequency-to-voltage converter.

In 1888 E. Hall discovered the Hall effect: if a conducting slab carries an electric current I, and a static magnetic field B is applied orthogonally to the slab surface, a voltage V develops across the slab, perpendicularly to both the current direction and the magnetic field. The ratio $R_H = V/I$ is called the *Hall resistance*; in the normal Hall effect its value is proportional to B and dependent on the slab material, thickness and temperature. Nearly a century later, Klaus von Klizing discovered the unexpected *quantum Hall effect*: in samples where a two-dimensional layer of conduction electrons is present, for sufficiently high B and low temperatures, the Hall resistance becomes quantised, and its value is no longer dependent on the device material or the temperature: it is a simple fraction, with a small denominator, of a constant of nature, the resistance quantum $R_K = h/e^2$, also called the *von Klitzing constant*.

3 The electron was actually discovered only several years later (1897) by J. J. Thomson.

2.2 Exploitation of quantum electrical phenomena

Since their discovery, the metrology community is making strong efforts to exploit the quantum electrical phenomena into robust and practical quantum electrical standards.

2.2.1 Josephson voltage standards

Josephson junctions can have dimensions of several μm, and can be fabricated with litographic techniques derived from the semiconductor device industry. Modern nanofabrication techniques allow the large scale integration of Josephson junctions in single chips operating at frequencies of the tens of GHz. Josephson voltage standards [21, 22, 23, 24, 25] evolved into two different streams:

– Programmable Josephson Voltage Standards (PJVS) are based on a large array of Josephson junctions in series (up to 500 000 [26]). The array is made of binary sections ($1, 2, 4, 8, \ldots$ junctions) which can be individually switched to generate positive, zero or negative voltages by an external control signal. The PJVS is thus a binary digital-to-analogue converter (DAC), which can be programmed to generate quantized voltages within a large range (e. g., from –10 V to +10 V). Both dc or low-frequency (up to kHz) ac voltages can be generated. Commercial PJVS are available, also in dry cryocooler versions, thus allowing a metrology laboratory to have a turn-key quantum voltage standard permanently available.
– In Josephson Array Waveform Synthesizers (JAWS) [24, Sec. 2.2] a sequence of RF pulses at a high (around 10 GHz) repetition rate is applied to a Josephson array (Fig. 3). The array quantises each RF pulse into a voltage impulse (integral of voltage over time) of exact magnitude Φ_0; the individual impulses are time averaged by filtering out the RF component, and are available as the output voltage. By applying proper RF pulse sequences arbitrary voltage waveforms of quantum accuracy can be generated, with an output bandwidth up to the MHz range. JAWS are of more recent development than PJVS and are not yet available commercially.

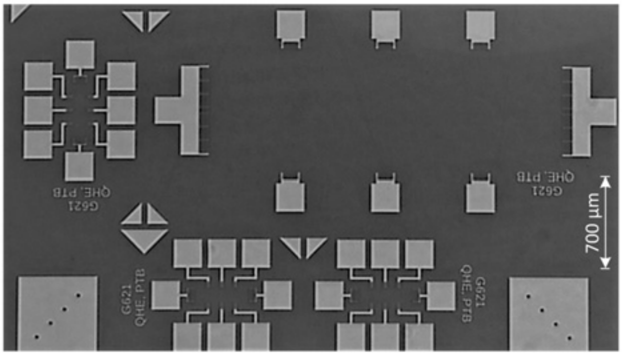

Figure 2: Four graphene QHE devices of different size on a single silicon carbide substrate, fabricated at Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany. The Hall bars are rectangular, with eight electrical contact on the sides: three have a width of 100 µm, a larger one of 650 µm. Graphene is invisible in the micrography. Measurements show [20] a resistance quantisation accuracy better than 5×10^{-10} at a temperature of 4.2 K under a magnetic field of 7 T. Photo courtesy of Mattias Kruskopf, PTB.

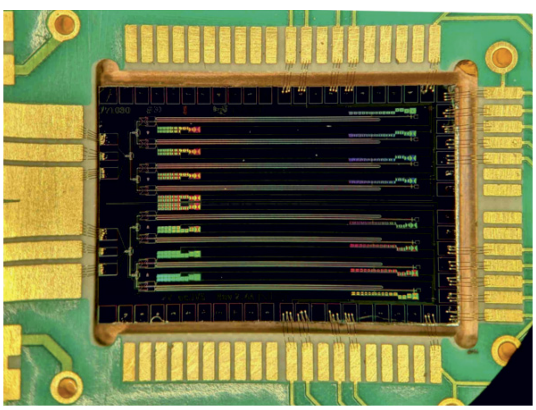

Figure 3: A Josephson Array Waveform Synthesizer (JAWS) chip. The rf pulses generated by room-temperature high-speed electronics enter the chip from the left, are split by on-chip rf dividers and fed to the arrays of Josephson junctions (the thin horizontal lines); after on-chip filtering, the resulting voltage waveforms are available at the pads on the right. When generating sinewaves, the chip can reach a rms voltage up to 2 V. Photo courtesy of the National Institute of Standards and technology (NIST), Boulder, USA. The JAWS system is available as a NIST Standard Reference Instrument.

2.2.2 Quantum Hall resistance standards

Von Klitzing discovered the quantum Hall effect in silicon devices [19], in a dedicated scientific facility that allowed to reach magnetic fields of 18 T and performing the measurements with a current limited to 1 µA. A decade later, robust gallium arsenide (GaAs) heterostructures were developed [27], displaying the effect at a magnetic field (less than 10 T) reachable with a superconducting magnet, and at higher measurement currents (> 50 µA), better suited for the calibration of artifact standard resistors. The applications of quantum Hall effect as a primary standard of resistance and impedance fluorished [28, 29, 30, 31, 32]. The temperature required by either Si or GaAs devices (typically 1.5 K) remains very low,[4] but can nowadays be reached by a dry cryomagnet. Commercial quantum Hall resistance standards are available, although they are large and expensive machines.

The discovery of graphene (2004) [34] initiated research to exploit the quantum Hall effect in this new material. Operation of graphene QHE devices (Fig. 2) at lower magnetic fields (5 T or lower), higher measurement currents (up to hundreds of µA) and higher temperatures (5 K) was demonstrated [35]. These conditions allow to implement tabletop quantum Hall resistance standards using small, inexpensive dry cryocoolers [36, 37], suitable to be continuously operated in a calibration laboratory. Research is now focusing on achieving better reproducibility of fabrication and long-term stability of the devices.

The value of the quantum Hall resistance R_H is fixed by nature, and direct calibration of resistor having decadal values (e.g, 100 Ω, 10 kΩ, . . .) versus QHE requires the measurement system to embed an accurate ratio device. The ratio device is a complex and expensive component of the system itself and may require calibration. This limitation prompted research on *quamtum Hall array resistance standards* (QHARS) [38, 39], which are integrated circuits composed of several QHE elements interconnected. Proper design [40] allows to generate, with a limited number of elements, resistance values very close (better than 1×10^{-6}) to the decadal resistor to be calibrated, thus allowing measurements by 1:1 comparison.

Joining graphene QHE and the QHARS principle [41, 42, 43] can be the next step to achieve simple, reliable, economic and easy to operate quantum resistance standards suitable for operation in an industrial calibration center.

2.2.3 Electron counting devices

In the 1990s nanodevices which allow the counting of individual electrons were introduced. These devices are based on the Coulomb blockade phenomenon: an electron charge on a conductive island has an electrostatic energy $E = \frac{1}{2}e^2/C$, where C is the capacitance of the island.

4 In recent experiments it has been shown that performances acceptable for routine calibrations can be achieved also at higher temperatures [33].

Displacing the charge to or from the island requires the application of a voltage $V \approx e/C$. If the island is sufficiently small (in the 100 nm range or smaller, such that C is in the fF range) and at sufficiently low temperature ($T < 100$ mK, to avoid its random charging because of thermal fluctuations), individual electrons can be moved in and out of the island by applying proper control voltages to gate electrodes. In an electron pump, one electron is moved through the island at each cycle of the ac control voltage(s) at frequency f: the current pumped is thus $I = ef$.

At present, electron pumps can achieve currents in the 100 pA to nA range [44], which must then be amplified with an accurate ratio device by a large factor to be of interest for typical calibrations. Further, the low operating temperature make these devices very expensive to implement and operate. These limitations might be overcome in the future: if the fabrication technologies will allow the fabrication of even smaller devices in large-scale integration. Equivalent C in the aF range could raise the working temperature to the K range, and setting many devices in parallel could increase the current output by orders of magnitude.

3 The revision of the SI

The increasing reproducibility, robustness and diffusion of the quantum electrical standards prompted a reconsideration of the definition of the unit ampere.

3.1 Conventional electrical units: 1990–2019

A first step towards the acceptance of the superiority of a quantum definition of electrical units was taken in 1990. At that time, the reproducibility of the Josephson voltage and quantum Hall resistance standards was already well established, and much better (parts in 10^9) than that of the mechanical realisations of the corresponding units (parts in 10^7). A definition of electrical units in mechanical terms was thus a strong limiting factor in the accuracy of comparisons between different laboratories. Therefore, *conventional* values, with no uncertainty, for the Josephson and von Klitzing constants K_J and R_K were introduced by the International Committee for Weights and Measures (CIPM), with effective date January 1, 1990, to be employed as *representations* of the volt and the ohm with the quantum effects [45, 46].

These conventional values, $K_{J\text{-}90} = 483\,597.9\ \mathrm{GHz\,V^{-1}}$ and $R_{K\text{-}90} = 25\,812.807\ \Omega$, were denoted with a "-90" suffix; the values chosen were those of the most recent determination of the same constants [47] in SI units, removing the determination uncertainty.

The adoption of the conventional values introduced *de facto* new non-SI units A_{90}, V_{90}, Ω_{90}, W_{90}, et cetera. In 1990 this was not a problem, since the size of the conventional units was the same as the SI units.

Over the time, the determinations of K_J and R_K in SI units improved, and the determined values shifted with respect to the conventional fixed values $K_{J\text{-}90}$ and $R_{K\text{-}90}$. In 2017 the shift was about 1×10^{-7} for the volt, and 2×10^{-8} for the ohm.

3.2 The quantum ampere: 2019–

The existence of a parallel system of conventional electrical units, having a magnitude slightly different from the SI ones, was a major problem of the SI (the main one being the suspected instability of the international prototype kilogram, which defines the unit of mass); the need for a revision of the SI was already pointed out at the turn of the century [48]. The revision was finally approved by the 26th General Conference of Weights and Measures in November 2018 [49] and implemented on 20 May 2019, the *implementation day*. The SI is now based on a set of seven constants with exactly specified numerical values.

The definition of the ampere reads today as (Fig. 4)

> The ampere, symbol A, is the SI unit of electric current. It is defined by taking the fixed numerical value of the elementary charge e to be $1.602\,176\,634 \times 10^{-19}$ expressed in the unit C, which is equal to A s, where the second is defined in terms of

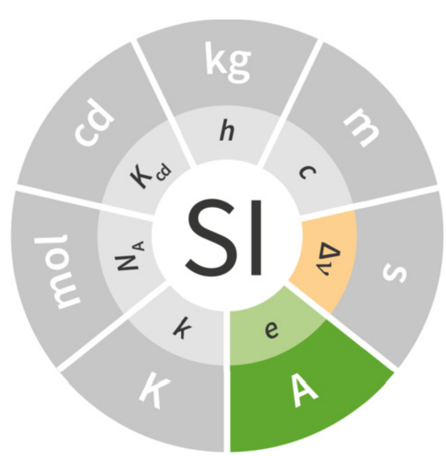

Figure 4: A pictorial representation of the SI, highlighting the base unit ampere (A) and the fundamental constants that enter the definition, the elementary charge e and the hyperfine transition frequency of the caesium atom $\Delta\nu$.

$\Delta\nu_{Cs}$ [where $\Delta\nu_{Cs}$ is the hyperfine transition frequency of the caesium atom].

The SI fixes also, in the revised definition of the kilogram, the value of the Planck constant to be $h = 6.626\,070\,15 \times 10^{-34}$ J s. As a consequence, the Josephson and von Klitzing constants have also fixed values with no uncertainty. The quantum nature of the SI units becomes apparent: the quantum experiments (Josephson, Hall, electron counting) are, after the revision, *realisations* of the electromagnetic SI units volt, ohm, ampere.

The values of e and h fixed by the revised SI correspond to the best last determination [50] of the same constants in the previous SI; in this way, there are no (significant) changes between units realized from the past and the revised SI definitions.

Unfortunately, the calibration certificates of the last thirty years were expressed (although often not explicitly stated) in the conventional 1990 units. Hence, a small step in the values of maintained electrical standards (calibrated in terms of the quantum standards both before and after the revision) occurs after the implementation day. For voltage and resistance standards, the step ($+1.067 \times 10^{-7}$ for voltage, $+1.779 \times 10^{-8}$ for resistance [51]) has the same small magnitude of the difference between the conventional and SI constant values, and is unnoticeable by the vast majority of the SI users.

4 Outlook

The definitions of the units in the 2019 SI do not refer to any specific physical effects; hence, *any* experiment that directly links a quantity value to one or more of the seven fixed constants through known physical laws can be considered a realisation of the unit of the same quantity in the SI. The realisation accuracy does not necessarily have to be the best possible; what is relevant is that it suffices for the measurement purpose.

Electrical metrology research in Europe is coordinated by the European Association of National Metrology Institutes (EURAMET), and several joint research projects have been devoted to develop implementations of the electrical quantum standards of higher performances, smaller size, better engineereed and less expensive, and easier to operate by the inexperienced user. The outcomes of these projects, as remarked in Sec. 2.2, are now considered ready (or close) for calibration in industrial environments and a few are also now available commercially.

Integration of multiple quantum standards allows to realise several SI electrical units. For example, the project *GIQS - Graphene Impedance Quantum Standard* [52], recently started, aims to integrate graphene quantum resistance standard (working in the ac regime) and multiple-channel JAWS to provide a quantum standard for impedance (ac resistance, capacitance, inductance) in a single cryogenic environment.

New quantum phenomena in solid-state physics are being considered for exploitation in electrical metrology. The so-called *quantum anomalous Hall effect* in ferromagnetic-doped topological insulators has shown resistance quantisation even with zero applied magnetic field [53]. *Quantum phase slip* is a predicted [54] dual of the Josephson effect, that should generate quantised current steps in ultrathin superconducting nanowires under microwave irradiation. A direct observation of these steps is not yet conclusively confirmed. Only time will tell whether new discoveries in quantum physics will evolve into new quantum electrical standards or not.

In the near future, European industries and research institutions will have a major role in the development of novel quantum electrical metrology standards, measuring systems, sensors. In October 2018 the *Quantum Flagship*, a 1 b€ and 10 yr initiative, has been launched. *Quantum metrology and sensing* is one of its three pillars, and the draft strategic research agenda [55] explicitly includes "[…] application targets here are for enhanced measurement and metrology of current, resistance, voltage and magnetic fields […] integration of quantum electrical standards for self-calibration in instrumentation providing highly-accurate measurements […]". The revised International System of units is ready to underpin these challenging goals.

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