STANDARDIZATION IN MEASUREMENT: PHILOSOPHICAL, HISTORICAL AND SOCIOLOGICAL ISSUES

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8 TIME STANDARDS FROM ACOUSTIC TO RADIO: THE FIRST ELECTRONIC CLOCK

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In the aftermath of the First World War researchers at the British National Physical Laboratory (NPL) and the American Telephone and Telegraph Company (AT&T) contrived and constructed a new kind of frequency standard. Based on electronically maintained vibrations of tuning forks, their standards suggested hitherto unknown accuracy in measuring high frequencies. Moreover, to ensure the accuracy of these measuring standard they designed another novelty – the first electronic clock. Although the mechanical vibrations of the tuning fork controller continued to determine its pace, designed for and based on electronic technology, the new clock symbolized and helped the turn from mechanical to electronic technology. The transformation to the electronic world is manifested even more clearly with the electronic successor of the tuning fork clock – the quartz clock, in which the hidden electro-mechanical vibrations of the crystal resonator replaced the tuning fork controller.

Notwithstanding the novelty of the new electronic tuning fork standard, it was based on an established tradition of exactitude in the mechanical researc of acoustics. The idea of a tuning fork clock, albeit not an electronic one, also originated in that tradition. This article examines how and why the measuring methods developed within the study of nineteenth-century acoustics were taken for twentieth-century electronic technology. In following the history of the electronic tuning fork it points at three major factors that made this transformation possible. First was the rapid development of electronic radio techniques in the 1910s. Yet, no one designed electronic tuning fork techniques just because new means became available. Researchers, rather, devised new methods to answer particular technological needs, as they were defined by military, commercial and governmental organizations in relations to their goals and the current state of technology. Here, I show that the needs and, even more so, the goals were diverse, and that their particularities shaped the technological solutions. Accuracy became imperative for World War I research on improved wireless devices and ballistics in France and Britain. Yet frequency measurement standards were developed for governmental and commercial civilian needs at the war's aftermath. To coordinate telecommunication within their jurisdiction, Governments needed means for measuring frequencies of radio transmissions, which allowed allocating each to a given wavelength band. AT&T needed a common scale of frequencies to prevent clashes in its elaborated telecommunication system and to allow transferring signals between different methods in its use. As in other cases, accurate measuring standards served for coordinating activities within large networks, where agreement about magnitudes was essential for the functioning of the network as a whole.[2] These contemporary needs were the second factor. A third factor was the strong scientific background of the researchers involved. Mobilized to the war effort and recruited to the novel governmental and industrial research laboratories, physics graduates carried out the research on the new frequency measurement methods. Their academic and practical experience in physics enabled these physicists and engineers to adopt not only methods and ideas but also the ethos of exactitude from nineteenth-century acoustic to the electronic technology of the early twentieth century.[3]

Abraham and Bloch

At the eve of the First World War, the tuning fork was the central device in exact measurement of frequencies for music and scientific ends alike. Since 1834, the tuning fork suggested a portable and thus useful 'measuring stick' for frequencies, calibrated by a few audial and visual methods.[4] Moreover, tuning forks were incorporated in a few mechanical and electromagnetic instruments that allowed maintaining their oscillations and their use for measuring electromagnetic oscillations. These instruments, however, could not be directly used for wireless since tuning forks could not vibrate at the high frequencies (of thousands of cycles per second – Hertz) commonly in use in radio communication. A way to apply the tuning fork for measurements in the new realm was suggested by a new device – the multivibrator.

The 'multivibrator' originated in the French military research on radio communication. Henri Abraham, a physics professor at the *École normale supérieure*, and Eugène Bloch, an active physicists and a teacher at a *lycée*, invented the device. Recruited to help research at the military radio-telegraphy, Abraham and Bloch examined some anomalies with the behaviour of valve amplifiers in use. These amplifiers were based on the novel 'triode': an electronic vacuum valve with an additional third electrode, called 'grid', which controls the electric discharge from the 'cathode' to the 'anode'. Applied for emitting and receiving electromagnetic waves and for amplifying currents, triodes (also known as 'audions') became the basis for wireless communication during the war. They have kept their central role in electronics until the advent of the transistors in the early 1950s. Before the war, AT&T developed triodes, originally invented for transmitting voice over wireless, as amplifiers for telephony, the main business of the corporation. Other researchers refined and applied the improved tube for radio, where it opened up new possibilities. French researchers, however, had not entered the development of triodes until the beginning of the war. Yet, during 1914–15, enjoying American and German knowledge, actual prototypes and the expertise of Abraham and other civil scientists and engineers, the French military radio-telegraphy devised and produced state-of-the-art valves and multi-valve amplifiers. Its researchers continued to spend much effort in their improvement.[5]

Examining such multi-valve amplifiers during 1916–17, Abraham and Bloch 'noticed irregular discharges in these devices'. On further examination they identified the cause of the discharge in the way the triodes were connected to each other. At this point they realized that they could employ this interfering discharge, which they originally tried to remove, to determine high frequencies used in radio, a basic step for further measurements in radio research. Oscillating tens of thousands times in a second, much higher than vibrations hitherto used and studied, radio waves posed a new challenge for frequency measurement. The war research sharpened the challenge as it brought with it significant advancements in radio, and scientists with an interest in exact measurements to its study. Contemporary wave-meters, however, were insufficient for the new requirements as they hardly exceeded an accuracy of one per cent.[6] Abraham and Bloch, therefore, seized the new effect they found in unconventionally connected triodes to improve the accuracy of frequency measurements.

Consequently, the two physicists changed the goal of their research. Instead of using the triodes for amplifying alternate current without changing its frequency as they initially tried, they used triodes to multiply known frequencies. Rather than eliminating the discharge as needed for their original goal, they augmented it by coupling the triodes in a new manner: connecting the grid of each triode to the anode of the other triode through a capacitor (Figure 8.1). This connection generated periodic discharges between the valves. The new device could generate electric oscillations in many frequencies that are exact integer multiplications of the input frequency. Following the way they appeared (and heard) in acoustics, students of periodic phenomena dubbed such oscillations 'harmonics'. According to Abraham and Bloch their new device 'is true extraordinary rich in harmonics reaching an order of 200 or 300. [Therefore] we gave this device the name *multivibrator*, which reminds this remarkable property'. Due to its production of high harmonics, the multivibrator allowed generating high frequency oscillations from low frequency oscillations. Since precise and stable low frequency vibrations were easier to produce, the method offered high frequency oscillations of higher stability than could be produced by direct means. These oscillations could be the basis for a new frequency meter for radio frequencies.[7]

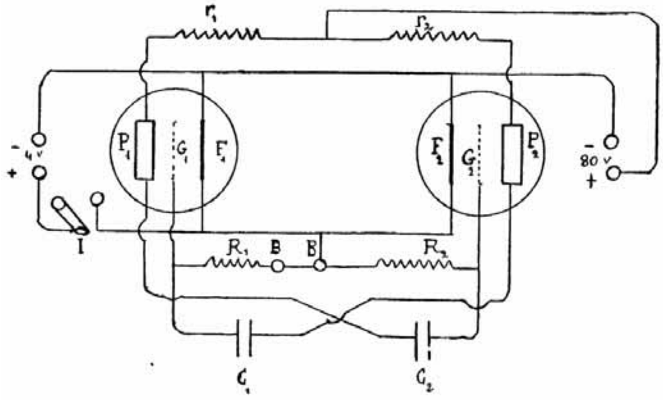

Figure 8.1: The multivibrator. The two circles are the triodes, where F is the cathode (filament), P the anode (plate) and G the grid. Notice that the grid of the left triode (G_1) is connect to the anode of the right triode (P_2) through a capacitor (C_1) and vice versa. The figure includes also resistors and direct current power sources.

***Source*: Abraham and Bloch, 'Measure en valeur absolue', p. 214.**

Abrahams and Bloch chose the tuning fork as the reference for the low frequency multiplied by the multivibrator. Thereby, they employed its mechanical precision for the novel electronics. During the nineteenth century scientists, like Ernst Chladni, Jules Lissajous, Herman von Helmholtz and Lord Rayleigh and instrument makers like Rudolph Koenig, studied and improved the stability, purity and exactness of the tone produced by the U-shape tuning fork in common use by musicians. In their hands it became the most precise device to measure frequencies. They also employed it to regulate the production of sound pitch and as a timer for short intervals.[8] By employing the tuning fork, Abraham and Bloch connected the new field of electronic oscillations to the established tradition of physical research on mechanical vibrators.

Yet, the multivibrator could not be directly connected to the mechanical vibration of the tuning fork, but only to electric oscillations. Thus, Abraham and Bloch connected the multivibrator to a circuit whose frequency was equal to that of the tuning fork. To ensure the equality, they transduced the electro-magnetic oscillations of the electric circuit into mechanical wave, i.e. sound, through a telephone receiver, a common tool in early electronic laboratories. Comparing the sound heard through the telephone with the tuning fork's pitch, they reached a deviation of no more than one-thousandth between the two, as higher differences produced audible beats. This mechanical-electrical transduction reduced the accuracy in one order of magnitude, since the frequency of their 1,000Hz (near Soprano do) tuning fork was stable to within one in ten thousand. As common in the acoustic tradition, the latter frequency was determined through a comparison to a clock, since frequency is the inverse of time, and time was determined more exactly than any other magnitude. Using a known method, Abraham and Bloch, recorded the vibrations of the tuning fork on a photographic film and compared them to the second beats of an astronomical clock. In this method, they connected the tuning fork to a small synchronous motor to reduce the rate of its marks on the film. The harmonics produced by the multivibrator-based tuning fork could be served as a high frequency wave meters, of about one order of magnitude more precise than those in common use.[9]

Shortly thereafter, researchers dispensed with the audial comparison, which reduced the precision, and incorporated the tuning fork into an electronic circuit. Interestingly, at about the time they developed the multivibrator, Abraham and Bloch invented a triode circuit that oscillated at the frequency of an embedded tuning fork. Still they did not suggest connecting this circuit to the multivibrator. In their method, the mechanical vibration of a tuning fork (or a pendulum) induced alternating magnetic force and consequently an electric current at its period in induction coils, placed in proximity (Figure 8.2). Simultaneously, alternate electric current in the coils induces a changing magnetic field, which exerts a force on the magnetic tuning fork. At suitable frequencies this alternating force maintains the mechanical vibration of the tuning fork against damping. Since the triode electric circuits were flexible enough to oscillate in a range of frequencies, the mechanical vibration forced the frequency of the electric current in the circuit to its own period.[10]

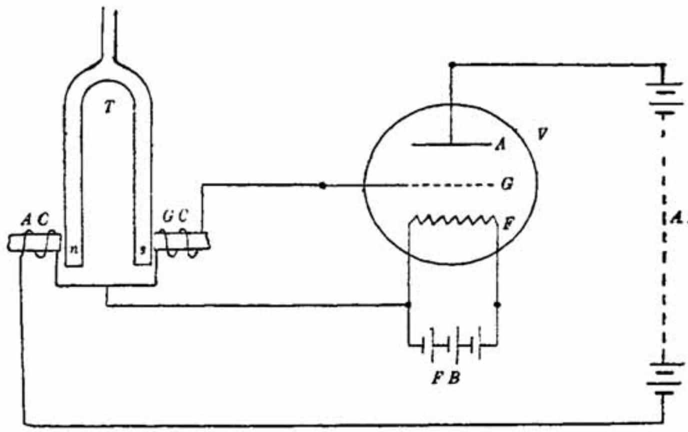

Figure 8.2: A triode-maintained tuning fork. T is a permanently magnetized tuning fork, AC and GC are two induction coils, connected to the triode (V), one to its cathode (F) and the other to its grid (G), A is the Anode.

***Source*: S., 'The Maintenance of a Vibrating System by Means of a Triode Valve', *Proceedings of the Physical Society of London*, 32 (1920), pp. 345–60, on p. 345.**

Originally, Abraham and Bloch developed the pendulum-controlled triode circuit to maintain steady alternating currents of a few cycles per second, in order to amplify low frequency oscillations for unspecified needs of the military radiotelegraphy.[11] Coupling a pendulum to an electromagnet was common in electric pendulum clocks.[12] Abraham and Bloch's novelty lay in coupling the mechanical vibrator to an electronic circuit based on the new triode valves. Once they had a low frequency circuit based on the pendulum, extending their method to the tuning fork was a simple step. Beginning with Lissajous and Helmholtz in the 1850s, scientists and instrument makers had already suggested magnetic coupling of vibrating tuning forks to electric circuits. The connection of the tuning fork to electromagnetic systems was, thus, common within a tradition of exact measurement. Moreover, in 1915, Amédée Guillet, a lecturer at the Sorbonne, devised the first electric tuning fork chronometer, based like Abraham and Bloch's device on magnetic coupling. Yet, unlike Abraham and Bloch, Guillet did not use electronic valves, but employed, instead, a carbon microphone as a current rectifier. His device was exact only for short intervals, but probably satisfied its role for laboratory measurements. As a student of Gabriel Lippmann, Guillet had a strong interest in metrology especially of electromagnetic units but also of time. His chronometer incorporated a method for keeping the vibrations of tuning fork, which he had previously developed for exact measurement, with a new method for counting the electric oscillations. Since Guillet published his suggestion, and moved in the same circles as Abraham and Bloch, they must have heard about his method.[13] Yet, they did not need Guillet's particular suggestion to know that one can couple tuning forks to electric circuits.

Eccles, Jordan and Smith

The war research on improving wireless led also the Brits William Eccles and Frank Jordan to invent a similar method of 'sustaining the vibration of a tuning fork by a triode valve', independently. Interestingly, Eccles and Jordan developed the method to measure the magnifying power of valve amplifiers, a goal for which Abraham and Bloch designed the multivibrator. Later, Eccles traced the origins of this work to commercial motivations. Namely, in 1914, he suggested the use of tuning fork to circumvent a patent of the German firm Telefunken, which allowed using only one amplifier for both sound and radio waves regardless of the differences in their frequencies. It reduced, thereby, electric consumption and expenses on additional amplifiers and thus threatened to dominate radio. Eccles tried unsuccessfully to utilize the harmonics of a tuning fork to reach both audial and radio frequencies from one vibrator. He had already been a notable expert on radio communication both in its theoretical understanding and in its practical uses. A reader at University College London, he had carried out many studies on a range of radio topics from wave detectors to the ionosphere.[14]

During the war, Eccles consulted a few military arms on the radio. For the needs of his new clients, he modified the tuning fork circuit, most importantly by incorporating a triode. With the help of Jordan, an 'electrician' and a 'lecturer of physics' at the City and Guilds College in which Eccles became a professor of applied physics and electrical engineering in 1916, he 'found that a generator of remarkable constancy [in voltage and frequency] had arisen'.[15] While the constancy of the frequency stood at the centre of their design, the precise value of the frequency was less important for their measurements. Yet, they soon found another military application for the triode-maintained tuning fork – secret transmission of pictures, which hinged on precise synchronization of frequencies.

A few methods for transmission of pictures by electromagnetic signals were known at the time. Eccles and Jordan based their system on the 1904 method of the German physicist Arthur Korn. As with most facsimile methods, in Korn's method an electric 'eye' moved in front of the picture, scanned it and translated its luminosity into electric signals. A light beam repeated the motion of the 'eye' in the receiver, producing a copy of the picture on a chemical paper. Korn suggested a mechanism by which the motion of the source controlled the motion in the receiver to ensure synchronization. Instead, Eccles and Jordan controlled the period of each end through a separate tuning fork, dispensing with the need to send signals about their motion. Since one could not reproduce the picture without knowledge of the period of the 'eye', the system could be used for secret signalling.[16] The system required high degree of agreement in the frequencies of the two tuning fork circuits. Since the mechanical period of the 'electric eye' was much lower than that of a tuning fork, Eccles and Jordan needed a mechanism to reach lower frequency. This was easy to find; a means to couple the tuning fork to low frequency electric oscillators was well known. In 1875, a Danish inventor Poul la Cour had invented the phonic wheel – a kind of electric motor that turns at a known fraction of a tuning fork's frequency – for synchronization in telegraphy. Rayleigh claimed to have invented the device independently for his needs in acoustical research, three years later.[17] As with Abraham and Bloch, the novelty of Eccles and Jordan was in connecting known mechanic and electric methods to the new triode valve.

Frank E. Smith, the head of the NPL division of electrical standards and measurements, used Eccles and Jordan's triode-maintained tuning fork to measure very short time intervals. Smith did not try to improve telecommunication, but ballistics. In his war project he measured projectiles' velocities. With David Dye he recorded the electric current induced by projectiles passing through coils on running cinematograph paper and compared their marks with steady marks of time. For the latter end Smith 'used first a purely electrical arrangement, and found that a very constant frequency (about 1,000 per second) could be obtained … For certain reasons, however, it was thought desirable to employ a tuning fork, and one of those had been borrowed from Professor Eccles'. The marks made by the tuning fork attained 'an error not greater then one fifty-thousandth of a second'.[18] This was probably the first application of an electronic circuit for precise time measurement, although the tuning fork had already been used for timing before in mechanic and electromagnetic instruments. Smith's transformation of the electronic tuning fork method from frequency to time measurement displays the close connection between standards of time and frequency.

Dye and the NPL

Ballistics was not part of the regular expertise of the NPL's division of electrical standards. Normally, the division engaged with studies related to electromagnetism and its commercial use. With the development of radio communication, frequency measurements became a central concern of the division, answering a growing interest from the government, the military and private companies. With the end of hostilities the military remained the major user of wireless communication with high stakes in measuring and controlling frequencies. High frequency (by contemporary standards), stability and accuracy of senders remained a central concern of the Admiralty, which requested apparatuses for measuring wavelengths from the NPL throughout the 1920s. With the rapid development of civilian wireless broadcasting, the British post office, responsible for civilian communication joined the request for high frequencies standards at the middle of the decade; towards its end a commercial company like Marconi's Wireless Telegraph Co. deemed the field useful enough to fund research carried out at the NPL.[19]

Until 1921, wireless was used overwhelmingly for point-to-point (or to a few points) two-way communication by the military arms, a few commercial companies and amateur operators. The swift emergence of public broadcasting, i.e., transmitting signals from one broadcaster to a large number of listeners who are unable to transmit signals back, posed new challenges for governments. Along with the growth of two-way transmission, the emergence of broadcasting stressed governmental interest in dividing the useful electromagnetic spectrum to many communication channels. To this end governments had to allocate a relatively small band for each station. Interference between transmissions at overlapping, or even nearby, wavelengths posed another problem for the allocation and regulation of the electromagnetic spectrum.[20] Such regulations meant standards in two senses of the term: as specifying the technical requirements, like the deviation of the actual frequency form the allocated one, and as providing the means to check whether these rules are kept. The latter required refinement in the precision and accuracy of measuring methods.

Within the NPL, frequency standards became the expertise of Dye. Dye joined NPL's electrical measurement division in 1910, after studying engineering at the London Guilds Technical College. 'A brilliant but rather irascible scientist', 'he showed … a wonderful instinct for measurements of the very highest accuracy; and especially for the attainment of this accuracy by means of perfection of the mechanical construction of his instruments'. Thus, upon Smith's departure in 1919, the thirty-two-year-old Dye succeeded him as the head of the division. While heading the division Dye returned to formal studies, attaining a Doctor of Science degree in 1926.[21]

The war-related research provided Dye new techniques for measuring high frequency. In 1919 he adopted Abraham and Bloch's multivibrator and their methods in examining extant standards of radio frequency. Improving on the inventors he combined, probably for the first time, the multivibrator to the triode-maintained tuning fork, on which he had learnt from Eccles and Jordan. Well familiar with the use of the latter from his research on ballistics, Dye saw its combination with the multivibrator as a simple step.[22] He regarded the combined system as the future standard for high frequency and continued improving it in the following years. Dye directed his efforts into two main goals: increasing the precision of the system, and extending its use for higher frequencies. By 1922 he could measure frequencies of 10^7Hz. To this end he connected two multivibrators in cascade.[23] Already in 1921 the NPL was satisfied enough with the accuracy to adopt the tuning fork–multivibrator device (with a one multivibrator) as its standard for radio frequency in its reliable range of up to 150 KHz (below broadcasting range). Yet, as is common in the work on standards, which includes recurrent refinements, Dye continued examining the precision of the apparatus, and especially its most important component – the electronically maintained tuning fork. He experimented with variations in the frequency of a tuning fork under changing physical conditions like temperature, magnetic field and modifications in the triode circuit, comparing the affected tuning fork to one that was 'kept invariable as possible' under constant temperature and pressure.

But how does one know that a tuning fork circuit under invariable conditions actually keeps a constant frequency? To this end it should be compared to a stable standard. Since frequency and time are two sides of the same periodic motion, the tuning fork periods could be compared to those of a standard astronomical clock. Therefore Dye needed a way to count the tuning fork's vibrations. He constructed a more elaborate system than Abraham and Bloch who marked the vibrations of the tuning fork on a cinematic tape and compared them to those of a standard clock. Forty years earlier, the instrument maker Rudolph Koenig designed a mechanical clock controlled by tuning fork. Like Dye, Koenig did not have a direct interest in horology but devised a clock to determine his tuning forks' frequencies by comparing the rate of the clock to that of a standard pendulum clock.[24] Dye followed a similar track, yet he relied on the new triode technology. With that technology, Dye constructed what was arguably the first electronic timekeeper.[25]

Following Eccles and Jordan's design for secret facsimile, Dye employed a twenty-tooth phonic wheel to reduce the 1,000 Hz vibration of the tuning fork. The phonic wheel drove a 50:1 worm wheel, which closed an electric circuit 'once each 1000 alternations', marking thereby a dot on a chronograph tape, in a manner similar to that suggested by Smith to record the motion of projectiles. Moreover, by adjusting the electromagnetic properties of the circuit, the motor that drove the chronograph was put in synchronization with the tuning fork. 'In this way the tuning fork records its own frequency directly on the chronograph without any attention and with extreme accuracy'. Comparing the 'second' dots made by the tuning fork with those marked by a standard second pendulum clock, Dye observed the accumulated error in the period of the former. With assistants he continued to carry such comparisons for longer intervals of up to a week on the same tape. By 1932 '[t]he frequency stability over hourly periods [was] of the order of 5 parts in 10^8, and over weekly periods, 3 parts in 10^7'; the latter was at the same order of magnitude as the best mechanical pendulum clocks of the time, and the short-range accuracy approached that of the most exact electro-pendulum clocks.[26]

Beyond the purposes of wireless communication, for which he had begun the research, Dye regarded the tuning fork circuit as a precision time standard. As such he deemed it useful for measuring relatively short intervals of time (as he had done with Smith), possibly even 'to observe variations in the hourly rate of standard clocks'.[27] He had not, however, connected the tuning-fork-controlled phonic wheel to a clock mechanism that would allow continuous reckoning of time and its continuous display. That Dye did not take this step does not seem to originate in technical difficulties. It rather reveals his lack of interest in making such a continuous display tuning fork clock, as it did not seem to serve any concrete aim, and its construction did require meticulous work.

Bell's Tuning Fork Clock

While state agencies sought exact standards of frequency for coordinating wireless communication under their jurisdiction, AT&T needed them to integrate its extended telecommunication system, known as the 'Bell system'. During the 1910s the world's largest telecommunication company introduced electronic technologies to its network. These included new radio techniques, which allowed transmission of the human voice over a distance, to complement its extensive wired network and the array of services it provided. It also developed new methods to multiply the number of conversations that could be transmitted over its wired network (called multiplex telephony). A common standard for measuring these oscillations was a prerequisite for coordinating the expanding number of methods in use, as it was necessary for attaining smooth transmission of signals between them. Accurate standard allowed also increasing the number of transmission in multiplex telephony, and in the wireless waveband allocated to the corporation, as each could be confined to particular frequencies. Its construction was a task given to a group of researchers with backgrounds in physics and engineering headed by Joseph Warren Horton, a physics graduate, at the corporation's research department.

For the basic frequency standard of the Bell system, Horton's team adopted the French and British novel triode maintained tuning fork technologies, albeit in a modified arrangement suggested by researchers of the American Bureau of Standards (BoS). Since the Bell system required precise knowledge of a wide range of frequencies, Horton's group invested much effort in refining the stability and accuracy of their standard, and in methods for multiplying its value. To allow sensitive measuring of frequencies to within 100 Hz at a wide range, the group chose a tuning fork of that period (ten times lower than Dye's), and devised a special system for reaching any multiplication of its value up to 100,000 Hz. Still, the accuracy of the system clearly depended on that of fundamental tuning fork. Within the tradition of exact measurements in acoustic and independently from Dye, Horton suggested comparing the tuning fork, which should have 'the general characteristics of a good clock', with the astronomical timekeeper. Unlike Dye, Horton was not satisfied with connecting the tuning fork only to a tape chronograph; instead he suggested controlling a clock mechanism by the tuning fork.[28] By June 1921 Bell's tuning fork drove a clock mechanism through a synchronous motor and a commutator that reduced the frequency of Horton's design. Unlike the chronograph, the tuning fork clock moved continuously, allowing the observation of small errors as they accumulated over time. The same mechanism that transferred the tuning fork vibration into a mechanical rotation for driving the clock allowed marking of time signals on a chronograph for monitoring possible fluctuations over shorter intervals. The researchers invested much effort in developing a suitable synchronous motor for driving the continuous clock mechanism.[29]

Arguably, the coupling of the basic frequency standard to a clock was the greatest and most important novelty of the system. The idea and the means to accomplish it had precedents. Still, both the linkage of radio frequency to continuous time measurement and the construction of a clock on an electronically maintained tuning fork (which suggests a steadier operation than Guillet's earlier microphone mechanism) were important original steps of the group. Dye followed a similar track but was satisfied in comparing the NPL's frequency standard to a timekeeper over limited intervals. Horton's group, however, conceived AT&T's frequency as a continuous reference for tuning and measuring frequencies of electric oscillations at the Bell system. The NPL, on the other hand, regarded its central standard as a means for calibrating other devices used as secondary standards; its continuous operation was not deemed important for its main purpose. Since Bell's frequency standard operated continuously, its researchers sought a continuous method to inspect its performance.[30]

By comparing the tuning fork clock to the laboratory clock, the group concluded that the former is exact to within 'about 6 parts in 1,000,000', well within the needs of the Bell system, set in 1923 at one part in 100,000. Still, the group continued improving the accuracy of its standard, reaching an accuracy of three parts in 1,000,000. Since this accuracy was higher than that of their laboratory electric pendulum clock, the researchers established it by direct comparison with the radio signals from the naval astronomical clock. The accuracy of the tuning fork clock was only one order of magnitude lower than that of the BoS's standard clock. Still in 1927, Horton's group suggested improvements in the mechanism that would increase the accuracy by about twenty-fold; as mentioned, such accuracy was attained later by the NPL in its chronometer. The increase interest of the Bell group in horology can be seen in its use of the clock fork for exact time measurements. In January 1925, Warren Marrison at the laboratory recorded the timing of the total solar eclipse at different locations in the northeast USA. Stations at each of these locations sent a signal through telephone line to the laboratory in New York, where it was marked against the time signals from the tuning fork.[31]

In autumn 1927, when Horton and Marrison announced the higher new accuracy of their tuning fork clock, it had already been eclipsed by their own new quartz clock. Soon, workers in the field adopted quartz frequency standards, as they proved more stable and could reach wider range of frequencies that became useful for electric communication than the tuning forks. Although based on different physical phenomenon – piezoelectricity, the mutual influence of electricity on pressure in crystals, the research on the new quartz standards continued that on the tuning fork. Many of the electronic techniques in use were very similar. In particular, Marrison followed the work on the tuning fork standard in developing a quartz clock to monitor the period of the piezoelectric frequency standard. With their high accuracy, quartz clocks became the most popular device for exact timekeeping, replacing the pendulum clocks, and apparently obstructing the development of tuning fork clocks. Tuning fork controllers became important again with the minimization of electronics after the advent of the transistor. An electronic tuning fork watch developed in the late 1950s paved the way for the quartz watch, which has since became ubiquitous, as the electronic tuning fork clock paved the way for the quartz clock in the 1920s.[32]

Conclusions

The triode-maintained tuning fork clock, the first electronic clock, resulted from an accumulation of small steps. Innovations consisted of quite minor additions and modifications of previous methods, which in retrospect often seem straightforward or even trivial. Once the triode became a central powerful device of wireless technology, connecting the hitherto electromagnetically maintained tuning fork to the electronic valve was quite straightforward; although Abraham and Bloch did not connect the new device to their multivibrator, to Dye such a connection seemed quite trivial. Since the idea of comparing tuning fork frequency to a clock was well known, it seems simple to connect its electronically maintained version to a chronograph; the means to do so were known and only required some modifications: the phonic wheel motor, the chronometer and the mechanism for marking dots on tape. Driving a clock dial, and not only a dot-marking mechanism from the phonic motor, did not require much imagination, especially as the phonic wheel had already been used for timers. Arguably the only innovation that was not based on a previous device was that of the multivibrator, which still relied on a known idea of producing harmonics. This gradual process does not offer great 'Eureka' moments, yet it represents many important inventions.[33] And, indeed, it was a process of invention. It was not merely a process of refinement and improvement, as the end result – a highly accurate electronic clock and a system of radio frequency standards – is clearly different from the original electromagnetic tuning fork. Moreover, this electronic device opened the way for overthrowing centuries-old mechanical horology by the quartz clock.

Still, carrying out these small steps required specific reasons for contriving the innovations, knowledge of and preferably experience with the related technologies, and some ingenuity. Otherwise many more researchers would have suggested each innovation. To take an example: that two resourceful researchers like Abraham and Bloch did not connect their own multivibrator and triode-maintained tuning fork suggests that the step required some ingenuity. That Guillet did not incorporated triodes in his new electromagnetic tuning fork clock suggests the crucial role of the inventors' experience with electronic technologies, in addition to their knowledge of the tuning fork methods, of which also Guillet was an expert. The researchers discussed in this article designed their methods for specific aims, like measuring amplification power of triodes, synchronization in secret signalling, measuring velocities of projectiles, or the frequencies of different radio waves. The crucial role of their specific aims is well illustrated by the difference between the otherwise equivalent uses of the tuning fork frequency standard at the Bell system and at the NPL. Since only Bell required continuous reference to measure frequencies in its system, Horton's group constructed the first electronic clock, while Dye was satisfied with a chronometer.

Most, but not all, of these specific technological goals originated in efforts of improving methods of wireless communication for military, commercial and governmental interests. Under the pressure of the Great War, scientists and engineers applied their expertise in exact measurements and in electronics for military aims, resulting in triode tuning fork methods. Nevertheless, Dye, Horton and their colleagues developed the electronic tuning fork frequency standards for the novel needs of telecommunication as a mass technology. Precise knowledge of frequency was necessary for an efficient coordination and integration of large telecommunication system, providing an immediate reason to construct accurate frequency standards. Exact frequency standards answered the commercial interest of AT&T and the social interest of the government in regulating and fostering radio communication. While standardization had a social function, its roots were in scientific practice. Scientists and scientific instrument makers had turned the tuning fork into a high precision instrument for laboratory measurements of acoustics and time. It was scientists and academic engineers who transferred the tuning fork from a research instrument to a central device of wide scale telecommunication, which required precision hitherto limited to the scientific laboratory. While Horton, Dye and their colleagues developed basic tuning fork standards for the techno-social goals of their institutes, like good metrologists they sought to improve the precision of their standards, also beyond their practical goals. That the major use of the tuning fork clock qua clock was to help investigating natural phenomenon (sun eclipse) suggests that the precise instrument still had a scientific value, even when it served the technological need of a giant corporation.

E. Trizio (2013), 'Calibration: A Conceptual Framework Applied to Scientific Practices Which Investigate Natural Phenomena by Means of Standardized Instruments', *Journal for the General Philosophy of Science*, 44 (2013), pp. 263–317.
5. See Soler et al, 'Calibration'.
6. H. M. Collins, *Changing Order: Replication and Induction in Scientific Practice* (1985; Chicago, IL: University of Chicago Press, 1992), pp. 100–6.
7. Collins, *Changing Order*, pp. 104–5.
8. For illustrations, see the references given in L. Soler, F. Wieber, C. Allamel-Raffin, J. Gangloff, C. Dufour and E. Trizio (2013), 'Calibration: A Conceptual Framework Applied to Scientific Practices Which Investigate Natural Phenomena by Means of Standardized Instruments', *Journal for the General Philosophy of Science*, 44 (2013), pp. 263–317, sections 2.3.2 and 2.2.4.
9. See, e.g., J. Woodward, 'Data and Phenomena', *Synthese*, 79 (1989), pp. 393–472, or N. Rasmussen, 'Facts, Artefacts, and Mesosomes: Practicing Epistemology with the Electron Microscope', *Studies in History and Philosophy of Science* (Part A), 24:2 (1993), pp. 227–65.
10. See, e.g., Rasmussen 'Facts, Artefacts, and Mesosomes', who explicitly categorizes some episodes involving the two models of microscopes under the heading of 'calibration'.

8 Katzir, Time Standards from Acoustic to Radio: The First Electronic Clock

1. I wrote this article while I enjoyed a Marie Curie fellowship of the Gerda Henkel Foundation.
2. S. Schaffer, 'Rayleigh and the Establishment of Electrical Standards', *European Journal of Physics*, 15 (1994), pp. 277–85; B. J. Hunt, 'The Ohm Is Where the Art Is: British Telegraph Engineers and the Development of Electrical Standards', *Osiris*, 9 (1994), pp. 48–63; A. Hessenbruch, 'Calibration and Work in the X-Ray Economy, 1896–1928', *Social Studies of Science*, 30:3 (2000), pp. 397–420.
3. On the ethos of exactitude see M. N. Wise (ed.), *The Values of Precision* (Princeton, NJ: Princeton University Press, 1995); J. L. Heilbron, *Weighing Imponderables and Other Quantitative Science around 1800* (Berkeley, CA: University of California Press, 1993).
4. M. W. Jackson, *Harmonious Triads: Physicists, Musicians, and Instrument Makers in Nineteenth-Century Germany* (Cambridge, MA: MIT, 2008).
5. L. S. Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876–1926* (Cambridge: Cambridge University Press, 1985); M. Amoudry, *Le général Ferrié et la naissance des transmissions et de la radiodiffusion* (Grenoble: Presses universitaires Grenoble, 1993), pp. 162–95.
6. Anon., *Circular of the Bureau of Standards, No. 74: Radio Instruments and Measurements* (Washington: Government Printing Office, 1918), pp. 96–109; H. Abraham and E. Bloch, 'Amplificateurs pour courants continus et pour courants de très basse fréquence', *Académie des sciences (France). Comptes rendus* (hereafter *Comptes rendus*), 168 (1919), pp. 1105–8, on p. 1106.
7. H. Abraham and E. Bloch, 'Mesure en valeur absolue des périodes des oscillations électriques de haute fréquence', *Journal de physique théorique et appliquée*, 9 (1919), pp. 211–22, on pp. 212–13. They described their results in confidential reports in 1916 and 1917.

8. D. Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-century Paris* (Dordrecht: Springer, 2009), pp. 22–25, and passim; J. H. Ku, 'Uses and Forms of Instruments: Resonator and Tuning Fork in Rayleigh's Acoustical Experiments', *Annals of Science*, 66 (2009), pp. 371–95.
9. Abraham and Bloch, 'Mesure en valeur absolue'.
10. H. Abraham and E. Bloch, 'Entretien des oscillations méchaniques au moyen des lampes à trois électrodes', *Comptes rendus*, 168 (1919), pp. 1197–8; H. Abraham and E. Bloch, 'Entretien des oscillations d'un pendule ou d'un diapason avec un amplificateur à lampes', *Journal de physique théorique et appliquée*, 9 (1919), pp. 225–33.
11. Normally, triode valve circuits oscillated at much higher frequencies.
12. On electric clocks see, e.g., M. Viredaz, 'Horloges électriques', at http://www.chronometrophilia.ch/Electric-clocks/francais.htm [accessed 28 February 2014]; R. Stevenson, 'Mechanical and Electrical Clocks', in D. Howse (ed.), *Greenwich Time and the Discovery of the Longitude* (Oxford: Oxford University Press, 1980), pp. 213–19. Ku, 'Uses and Form', p. 376.
13. M. Lavet, 'Propriétés des organes électromagnétiques convenant aux petits moteurs chronométriques a diapason', *Annales Françaises de chronométrie*, 15 (1961), pp. 183–96; N. Hulin, 'Un mutualisme pédagogique au tournant des XIXe et XXe siècles. Informer, échanger, centraliser', at http://www.aseiste.org/documents/53f9941495beb59b3ecf87631053f420.pdf [accessed 26 June 2012]; A. and V. Guillet, 'Nouveaux modes d'entretien des diapasons', *Comptes rendus*, 130 (1900), pp. 1002–4; A. Guillet, 'Roue à denture harmonique, application à la construction d'un chronomètre de laboratoire à mouvement uniforme et continu', *Comptes rendus*, 160 (1915), pp. 235–7; see also the list of Guillet's publications in Web of Science. On Lippmann's metrology, see D. J. Mitchell, 'Measurement in French Experimental Physics from Regnault to Lippmann: Rhetoric and Theoretical Practice', *Annals of Science*, 69:4 (2012), pp. 453–82.
14. J. A. Ratcliffe, 'William Henry Eccles. 1875–1966', *Biographical Memoirs of Fellows of the Royal Society*, 17 (1971), pp. 195–214, quotations on p. 198; W. H. Eccles, 'The Use of the Triode Valve in Maintaining the Vibration of a Tuning Fork', *Proceedings of the Physical Society of London*, 31 (1919), p. 269
15. Jordan's affiliation is mentioned in his patents, e.g., 'Improvements in application of thermionic valves to production of alternating currents and in relaying'. GB 155854, filed 17 April 1918. 'A list of the principal reports of experiment and investigation received by the Board of Invention and Research from August 1915 to February 1918', National Archives Britain (hereafter NAB), ADM 293/21, also in 212/159.
16. A. Korn, *Elektrische Fernphotographie und Ähnliches*, 2nd edn (Leipzig: S. Hirzel, 1907), pp. 66–9. Eccles's recollection quoted in Ractliffe 'Eccles', p. 198; 'Fourth Periodical Schedule of Reports Concerning Experiment and Research', NAB (ADM/159). Unfortunately, I could not locate Eccles and Jordan's report itself. Therefore, the description of the system is my reconstruction.
17. J. W. Strutt, Baron Rayleigh, *The Theory of Sound*, 2nd edn (New York: Dover 1945), pp. 65–70.
18. First quotation from S. Eccles, 'The Use of the Triode Valve', second quotation from *Annual Report of the National Physical Laboratory for the Year 1919* (Teddington: National Physical Laboratory, 1920), p. 50. This part refers to a work done in 1918.
19. On the request from these bodies see *Annual Report of the National Physical Laboratory for the Year 1919* (Teddington: National Physical Laboratory) for the years 1920 (p. 63), 1923 (p. 84), 1924 (p. 77), 1926 (p. 11), 1928 (p. 13), and D. W. Dye, 'A Self-

Contained Standard Harmonic Wave-Meter', *Philosophical Transactions of the Royal Society of London. Series A,* 224 (1924), pp. 259–301, on p. 300.

20. E.g., S. J. Douglas, *Inventing American Broadcasting, 1899–1922* (Baltimore, MD: Johns Hopkins University Press, 1987), ch. 9, pp. 292–314; C.-P. Yeang, 'Characterizing Radio Channels: The Science and Technology of Propagation and Interference, 1900–1935' (PhD dissertation, MIT, 2004), pp. 327–56.
21. E. V. A. [Appleton], 'David William Dye. 1887–1932', *Obituary Notices of Fellows of the Royal Society (1932–1954)*, 1 (1932), pp. 75–8; quotations from Louis Essen, *Time for Reflection*, ch. 2, unpublished memoirs, 1996, in Ray Essen's personal library; L. Hartshorn, 'D. W. Dye, D.Sc., F.R.S.', *Proceedings of the Physical Society*, 44 (1932), pp. 608–10.
22. Dye casually mentioned the use of the tuning fork circuit in the 1919 NPL report (p. 51). Only in the 1921 report did he add that its combination with the multivibrator was 'an improvement first introduced at the Laboratory' (p. 75).
23. NPL Reports for 1922 (p. 83), 1923 (p. 85), H. R. Slotten, *Radio and Television Regulation: Broadcast Technology in the United States, 1920–1960* (Baltimore, MD: Johns Hopkins University Press, 2000), pp. 1–42.
24. The idea of a mechanical tuning fork clock preceded its use for calibration, and it continued to be used also for other ends. D. Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-century Paris* (Dordrecht: Springer, 2009), pp. 100–5.
25. By electronic I mean here circuits whose mechanism relies to some extent on the properties of discrete electrons, as distinct from other electromagnetic properties.
26. D. Dye, 'The Valve-Maintained Tuning-Fork as a Precision Time-Standard', *Proceedings of the Royal Society of London. Series A*, 103 (1923), pp. 240–60, on p. 257; D. W. Dye and L. Essen, 'The Valve Maintained Tuning Fork as a Primary Standard of Frequency', *Proceedings of the Royal Society of London. Series A*, 143 (1934), pp. 285–306, on p. 306.
27. Dye, 'Valve-Maintained Tuning-Fork', pp. 259–60.
28. J. W. Horton, N. H. Ricker and W. A. Marrison, 'Frequency Measurement in Electrical Communication', *Transactions of the AIEE*, 42 (1923), pp. 730–41, quote on p. 731.
29. J. W. Horton, N. H. Ricker and W.A. Marrison, 'Frequency Measurement in Electrical Communication', *Transactions of the AIEE*, 42 (1923), pp. 734–36, Marrison Notebook (NB) 1112–2, pp. 38–41, in AT&T Archives.
30. The tuning fork of AT&T standard 'ran continuously from April, 1923, to May, 1927, except for four intervals totalling about three days'. J. W. Horton and W. A. Marrison, 'Precision Determination of Frequency', *Proceedings of the IRE*, 16 (1928), p. 139.
31. J. W. Horton and W.A. Marrison, 'Precision Determination of Frequency', *Proceedings of the IRE*, 16 (1928), p. 141, Horton, Ricker, and Marrison, 'Frequency Measurements', p. 736; W. A. Marrison, 'The Evolution of the Quartz Crystal Clock', *Bell System Technical Journal*, 27 (1948), pp. 510–88, 528–530, second quote on p. 529; Marrison NB 1444, pp. 97–105 (24.1.25). Bureau of Standards, *Standards Yearbook* (U.S. Govt. Print. Off., 1927), p. 44.
32. S. Katzir, 'Pursuing Frequency Standards and Control: The Invention of Quartz Clock Technologies', *Annals of Science* (forthcoming); C. Stephens and M. Dennis, 'Engineering Time: Inventing the Electronic Wristwatch', *British Journal for the History of Science*, 33 (2000), pp. 477–97.
33. The steam railway seems as a famous example for such a gradual invention.