Scientia Canadensis
Canadian Journal of the History of Science, Technology and Medicine
Revue canadienne d'histoire des sciences, des techniques et de la médecine

Reading Galvanometers: Reflecting on the Infrastructure and Instrumental Practice of Electrical Metrology at the University of Toronto

Erich Weidenhammer, Victoria Fisher, Chen-Pang Yeang, Ava Spurr, Patrick Finnigan

Volume 45, Number 2
Artifacts & Opportunity: Science and Technology Collections in Canada
Science et technologie en contexte militaire

Published: 2024 December 31
DOI: 10.29173/scientia10

Abstract: The methodology of experimental reenactment has typically been used by historians to better understand landmark experiments. In this paper, we apply this approach to the galvanometer, an instrument so fundamental to the study of electricity that we may consider it infrastructure underlying the teaching of physics and engineering through the 19th century and well into the 20th centuries. We study a selection of galvanometers from the University of Toronto Scientific Instruments Collection, using them to explore their institutional context. Finally, we operate a representative galvanometer to explore several of the teaching experiments undertaken by engineering and physics students of the late 19th and early 20th centuries.

Keywords: Galvanometer, University of Toronto Scientific Instruments Collection, Metrology, Physics, Engineering, Education, Experimental reenactment

Résumé : La méthodologie de la reconstitution expérimentale a généralement été utilisée par les historiens pour mieux comprendre les expériences marquantes. Dans cet article, nous appliquons cette approche au galvanomètre, un instrument si fondamental pour l'étude de l'électricité que nous pouvons le considérer comme une infrastructure sous-jacente à l'enseignement de la physique et de l'ingénierie tout au long du XIXe siècle et pendant une bonne partie du XXe siècle. Nous étudions une sélection de galvanomètres de la collection d'artefacts scientifiques de l'Université de Toronto, en les utilisant pour explorer leur contexte institutionnel. Enfin, nous utilisons un galvanomètre représentatif pour explorer plusieurs des expériences d'enseignement entreprises par les étudiants en ingénierie et en physique à la fin du XIXe siècle et au début du XXe siècle.

Mots clés : Galvanomètre, Collection d'instruments scientifiques de l'Université de Toronto, Métrologie, Physique, Ingénierie, Éducation, Reconstitution expérimentale

ISSN 1918-7750

UNIVERSITY OF ALBERTA
LIBRARY

Reading Galvanometers: Reflecting on the Infrastructure and Instrumental Practice of Electrical Metrology at the University of Toronto

Erich Weidenhammer, Victoria Fisher, Chen-Pang Yeang,
Ava Spurr, Patrick Finnigan

Abstract: *The methodology of experimental reenactment has typically been used by historians to better understand landmark experiments. In this paper, we apply this approach to the galvanometer, an instrument so fundamental to the study of electricity that we may consider it infrastructure underlying the teaching of physics and engineering through the 19th century and well into the 20th centuries. We study a selection of galvanometers from the University of Toronto Scientific Instruments Collection, using them to explore their institutional context. Finally, we operate a representative galvanometer to explore several of the teaching experiments undertaken by engineering and physics students of the late 19th and early 20th centuries.*

Résumé : *La méthodologie de la reconstitution expérimentale a généralement été utilisée par les historiens pour mieux comprendre les expériences marquantes. Dans cet article, nous appliquons cette approche au galvanomètre, un instrument si fondamental pour l'étude de l'électricité que nous pouvons le considérer comme une infrastructure sous-jacente à l'enseignement de la physique et de l'ingénierie tout au long du XIXe siècle et pendant une bonne partie du XXe siècle. Nous étudions une sélection de galvanomètres de la collection d'artefacts scientifiques de l'Université de Toronto, en les utilisant pour explorer leur contexte institutionnel. Enfin, nous utilisons un galvanomètre représentatif pour explorer plusieurs des expériences d'enseignement entreprises par les étudiants en ingénierie et en physique à la fin du XIXe siècle et au début du XXe siècle.*

Keywords: **Galvanometer, University of Toronto Scientific Instruments Collection, Metrology, Physics, Engineering, Education, Experimental reenactment**

The galvanometer is a scientific instrument designed to measure electrical current. Like the microscope or precision balance, it is founded on a basic physical principle whose utility made it standard in laboratory work across many scientific disciplines. A historical collection of scientific artifacts associated with a university or college will likely contain a conspicuous quantity and variety of galvanometers, representing a range of different uses in the measurement of electricity. As a result, surviving galvanometers provide a useful vantage point from which to explore the culture of electrical metrology in those settings. Given their utility and ubiquity, galvanometers may be viewed in several disciplines as what some Science and Technology Studies (STS) scholars have called "infrastructure." This term refers to the systems, techniques, organizations, and artifacts that support and enable our activities, and need not be reconsidered when undertaking a new venture. As scholars have shown, examining infrastructure can help unveil social and technical structures, the nature of membership, conventions, or practice, or standards in a scientific or technological system.[1]

Erich Weidenhammer, Victoria Fisher, Chen-Pang Yeang, Ava Spurr, Patrick Finnigan, "Reading Galvanometers: Reflecting on the Infrastructure and Instrumental Practice of Electrical Metrology at the University of Toronto," *Scientia Canadensis* 45, no. 2 (2024): 42-68.

As infrastructure, the galvanometer's function and operation was fundamental knowledge for professional work in a variety of disciplines, including electrical engineering and physics, and thus formed part of a university education in those areas. The galvanometer was understood by its early users as a "direct descendant of the magnetic compass."[2] Its mechanism involves the interaction between the magnetic fields of an electromagnet and a permanent magnet. Depending on the design, one is stationary and provides a radial magnetic field. The other is mobile, suspended by a fine filament or wire within the magnetic field of the other. When a current is applied to the electromagnet, the mobile element deflects in proportion to the strength of the current, permitting its measurement. Use alongside other electrical equipment extends their utility beyond current measurement.

After their invention in the 1820s, galvanometers became emblems of precision measurement.[3] In the 1850s, William Thomson's development of a highly sensitive galvanometer to detect weak signals in transatlantic cables saw both an increase in laboratory use and the wide introduction of precision instrumentation into telegraph engineering, an important early industrial application.[4] In the 1880s, further design developments offered increased sensitivity and scientific utility.[5] Following the expansion of power grids and electrical communication networks in the 1870s-90s, galvanometers spread into electrical engineering workshops and into the field as testing and maintenance tools, where different features were required for rougher conditions.[6] By the turn of the 20th century, galvanometers were standard, all-purpose metrological apparatus for research and engineering available in a range of types offering better practicality, resistance to electromagnetic interference, or greater sensitivity, as appropriate to their settings.[7] Handbooks on electrical metrology from the period such as that of James Swinburne (1888), Ernst Berg and Walter Upson (1916), and Albert Campbell and Ernest Childs (1935) all include detailed descriptions of the construction, features, calibration and operations of a variety of galvanometers, showing their diversity and ubiquity.[8]

Despite this ubiquity, the typical galvanometer is not trivial to operate. Most examples are delicate, owing to the fine filament from which the moving element is suspended. This arrangement requires accurate levelling to permit it to rotate freely. Unlike direct reading instruments such as modern multimeters that indicate measurements in the appropriate unit, the typical galvanometer requires users to derive results mathematically from a simple incremental scale. This requires an understanding of the particular instrument's electrical characteristics. The operation of galvanometers therefore required significant technical and mathematical training for budding electrical engineers, physicists, and others.

In this paper, we explore training in galvanometer use during the instrument's heyday, from 1890 to 1970. Using the close study of artifacts drawn from the University of Toronto Scientific Instruments Collection (UTSIC), and an experimental re-creation using those artifacts, we explore the changing culture of electrical metrology in physics and electrical engineering at the University of Toronto. Instead of focusing on a specific historical event, we trace, through inspections of historical artifacts and related textual sources, the adoption of what became a pervasive metrological instrument, showing its arrival as a specialised research instrument and development as a teaching and industrial tool.

Our paper contributes to scholarship associating educational institutions with the development of physics and electrical engineering, and infrastructure to electrical metrology during this period, particularly in the realm of instruction. Graeme Gooday found that the emergence of physics at teaching laboratories in Victorian Britain was configured by researchers' need to train students for precision measurement. Such training drove metrology into the core of experimental research in physics.[9] Thomas Hughes argued that the rise of college programs in electrical engineering in the UK, US, and Germany from the 1870s to 1900s—especially the emphasis on accurate and scientific lab work—assisted the development of electric-power networks as a technological system.[10] In Canada, scholars including Michelle Hoffman, Danielle Ouellet, and Victoria Fisher have investigated the emergence and development of physics in educational and institutional settings through instrument collections. Such work highlights practical instrument-based education, which was seen as crucial to national development of technical expertise in Canada.[11] Similarly, Yves Gingras and Fisher have pointed to the close relationship between early engineering and physics in the country.[12] Following these scholars, we seek to contribute to the history of the subjects through our focus on a Canadian university in the late 19th and early 20th centuries.

Methodology

Our study draws methodological inspiration from scholarly investigations centering on instruments, especially those using artifacts as sources. Especially germane is the work of Charlotte Connelly and Hasok Chang, who investigated the galvanometer collection in the Whipple Museum of the History of Science at Cambridge University. They used the notion of "many lives" of scientific instruments to follow galvanometers' changing designs and uses over the 19th and 20th centuries.[13] While many artifacts in Connelly and Chang's study were research instruments, we focus on the study of teaching, following, for instance, Paoli Brenni who traced teaching practices in 19th century Europe using the design and diffusion of instructional instruments and textbooks.[14] Similarly, Jean-François Gauvin explored physics teaching in the 1960s through pedagogical "toys" in the Collection of Scientific Instruments at Harvard University.[15]

Following these examples, we focus on instruments from a single source, the physics and electrical engineering laboratories of the University of Toronto, now part of the historical collections at the university.[16] Inspired by material culture methodologies including object biography and artifact reading, we examine four particular instruments dating from the 1890s to the 1960s, exploring their significance to their purchasers and users and the broader culture of Canadian electrical metrology.[17] These four galvanometers represent four phases of teaching and research at the University of Toronto, as well as their relations with the changing culture of electrical metrology more broadly.

We complement this material inspection by replicating basic experiments undertaken by undergraduate engineering students at the university in the early 20th century.

Historians of science have used replication of historical experiments as a method of historical inquiry to complement the research on textual sources.[18] Their goals have varied from clarifying and materializing ambiguous texts on recipes or procedures and settling controversial scientific claims to demonstrating empirical phenomena described in historical documents but abandoned in modern scientific texts and exploring why scientists observed what would be later considered contradictory effects.[19] In following this path, we seek what Otto Sibum sought to discover in replicating James Joule's experiment on the mechanical equivalent of heat: the "tacit" or "gestural" knowledge, embodied skills, and other aspects of practice not mentioned in published texts but crucial to experimental success.[20]

Through this artifact-led, collection-specific approach, we discover that the galvanometers became instrumental infrastructure for the University of Toronto via two paths as it was developed into a full-fledged educational institution in the first part of the 20th century. On the one hand, prestigious, high-precision galvanometers were employed into emerging cutting-edge experimental research in physics, epitomizing the institution's transformation into a research university. On the other hand, "workhorse," standard galvanometers were integrated into undergraduate engineering lab teaching, marking the university's expanding and standardized engineering education. Our study and replication of the teaching experiments surrounding galvanometers also demonstrate how the instruments were designed into the engineering pedagogy for practice-, procedure-, and artifact-based understanding of electrical principles.

Four Representative Artifacts: the development of electrical metrology at the University of Toronto

In university settings, experimental physics and engineering have intertwined histories. At the University of Toronto, as at many other universities in North America, these disciplines emerged contemporaneously in the last quarter of the 19th century, and shared overlapping programs preparing students for electrical work in further study or in the workplace.

Material evidence of these programs can be found in the University of Toronto collection, which holds thousands of instruments from a variety of scientific departments across the university, including galvanometers from many research and teaching fields and contexts. Unfortunately, most of the material legacy of Engineering was lost in a fire at the Sanford Fleming building in February 1977.[21] Physics instruments have survived comparatively well. Consequently, we use galvanometers from the Department of Physics to explore the material culture of both fields.

Supplementing this record, textbooks, student assignments, university calendars and photographs from the University of Toronto Archives and Records Management Services (UTARMS) show that students in research and teaching laboratories of electrical engineering and physics worked with a variety of galvanometers. These ranged from common workhorse instruments suitable for teaching and basic electrical measurement, to those perceived as rare, costly, or otherwise more specialized experimental tools. Despite their differences, we consider either of these types to be infrastructure. Galvanometers of both kinds were introduced to students as standard arrangements, suggesting their common attributes and capabilities were considered basic building blocks in electrical work from classrooms to laboratories.[22] Exploring diversity among galvanometers permits us to discuss the themes and context represented by this form of instrument.

In this section, we present four galvanometers from the University of Toronto scientific instruments collection. In exploring each instrument's acquisition, design and use amid the broader setting, we unravel a narrative that traces scientists and engineers at the university through distinct phases and themes of a transformative era for electrical metrology.

The Carpentier Ballistic

Among the older instruments in the University of Toronto collection is a ballistic galvanometer fabricated in the mid-1890s in the Parisian workshop of Jules Carpentier (1851-1921).[23] Manufactured by one of the leading electrical makers of the 19th century and of a specialised design, it points to the aspirations of the early university and the establishment of electrical metrology there.[24]

The Carpentier galvanometer (Figure 1) is an impressive assembly of wood, brass, and steel that exemplifies the hand-crafted instruments of the period. The mechanism is set inside a wooden frame featuring mounting points for wall hanging. The same points are used to set the mechanism on its accompanying wooden stand. The instrument was provided with a removable wooden front cover with a rectangular window to view the mirror.[25]

This galvanometer embodied a shift in technology. Earlier galvanometers equipped with moving magnets were susceptible to magnetic interference from external sources. One solution was to swap the position of coil and magnet, surrounding a coil suspended on a conductive filament with a powerful magnet. This created what early commentators described as an artificial field that negated ambient interference.[26] The result, known after its designers as the D'Arsonval-Deprez galvanometer, was a sensitive and reliable general-purpose mechanism that formed the basis for subsequent electrical-measuring instruments.

This instrument features a large and wide moving coil, a characteristic of many ballistic galvanometers. Rather than measuring a steady current, ballistic galvanometers measure the total quantity of charge over a period using the large moment of inertia of the moving element; this instrument's coil produces an oscillation lasting around eight seconds. At the time when it was made, such instruments would have been among the few means to measure transient or fluctuating currents.[27]

The Carpentier ballistic galvanometer is one of several Carpentier instruments which survives from the early years of engineering and scientific research at the University of Toronto. Like many comparable institutions, the university's physics program emerged in the latter part of the nineteenth century through an effort to emulate the model of laboratory research associated with German scientific education and spreading through the US.[28] As elsewhere, this involved the acquisition of teaching instruments from specialized manufacturers in Europe.

The key figure in provisioning the University of Toronto's physics workshop was James Loudon (1841-1916). Loudon was appointed Professor of Mathematics and Natural

Galvanomètre Deprez d'Arsonval
à miroir - modèle balistique. 150 frs

EXPOSITIONS UNIVERSELLES
RUDOLPH KOENIG
QUAI D'ANJOU, 27
PARIS

Paris, le 13 Octobre 1895

Cher Monsieur Loudon

Voici les explications sur le galvanomètre balistique que je vous avais annoncées dans ma lettre du 10 courant, et que je viens de recevoir à l'instant même de Mr Violet.—

Mille amitiés

Rudolph Koenig
27, Quai d'Anjou

P.S. La lettre du bursar n'est pas encore arrivée.

Figure 1: *(Right) The Carpentier ballistic galvanometer. [Credit: University of Toronto Scientific Instruments Collection] (Left) Part of the associated correspondence between James Loudon and Rudolph Koenig preserved at the University of Toronto Archives. [UTARMS B1972-0031-004(11)]*

Philosophy in 1875, becoming the University's first Canadian-born professor. He spearheaded the effort to establish laboratory instruction in physics, equipping the Physics Laboratory with an array of high-quality Parisian instruments. [29] He first purchased electrical apparatus in the 1880s, mostly from Carpentier.[30]

The acquisition of the ballistic galvanometer is documented in correspondence between Loudon and his Parisian agent, maker Rudolf Koenig, beginning October 1895.[31] For Loudon, this Carpentier instrument likely represented prestige; not only a well-known maker, Carpentier had been one of the first manufacturers of the D'Arsonval-Deprez galvanometers.[32] Loudon's purchase formed part of a broader adoption of moving coil galvanometers, which began to disseminate in the early-to-mid 1880s, first appearing in the University of Toronto's engineering calendars in 1888.[33]

The late 1880s and 1890s saw an emerging culture of electrical metrology at the university. In 1887, various galvanometers and associated equipment, were mentioned in the university calendar among the electrical equipment available at the Physical Laboratory.[34] In 1895, William J. Loudon, nephew of James, and John C. McLennan, future head of the Department of Physics, published *A Laboratory Course in Experimental Physics*, which discussed the sine, tangent, Thomson, and Deprez-D'Arsonval galvanometers, along with several methods for calibrating them.[35] While James Loudon did not publish research involving electricity, William Loudon, McLennan, and others did, meaning electrical instruments were increasingly necessary.[36]

To support this work, Loudon looked to the emerging electrical industry, hiring technician and instrument maker John S. Plaskett in 1890. Plaskett, a Canadian, had worked in the manufacture of electrical dynamos in Thomas Edison's Schenectady factory.[37] Plaskett's name appears inked on the face of an earlier Carpentier ammeter—also a form of galvanometer—indicating his recalibration of the instrument.[38]

Plaskett's background in electrical engineering was especially valuable because during this period the Physical Laboratory also taught students from the School of Practical Science (SPS), the engineering school at the university that had opened in 1878. Loudon himself had been involved with the School's foundation.[39] This close relationship between physics and engineering instruction echoed other arrangements found across Canada.[40] Students studying both engineering and physics through the early 20th century went on to hold jobs in the burgeoning electrical industry after graduation.[41]

At the University of Toronto, however, divisions were beginning to emerge. In 1888 the SPS hired its first lecturer in electrical engineering, Thomas R. Rosebrugh, but descriptions of electrical classes in the SPS calendar remained focused on the offerings of the Physics Laboratory.[42] In 1895, the year the Carpentier instrument was ordered, the School opened a large galvanometer laboratory occupying a ground-floor room previously used for ore dressing, and classes in electrical engineering were for the first time split between the SPS and Physics (Figure 2).[43] This trend continued until 1905, when the instruction of engineering students at the physics department ceased.[44]

A specialised instrument, the Carpentier galvanometer was likely used only by advanced students, in lecture demonstrations, or in research rather than in laboratory teaching experiments. Its purchase came at a time when Paris was losing its market dominance in instrument making, and prowess with electrical research was more associated with Germany, the UK or the US; yet Carpentier products like the D'Arsonval-Deprez galvanometer were perceived as prestigious and up-to-date.[45] Its purchase, therefore, can be seen as representing the aspirations of an emerging scientific institution, and likewise the changing relationship of the Toronto physical laboratory with students interested in electrical engineering.

The Cambridge Instrument Company Paschen Galvonmeter

Despite the widespread adoption of moving coil galvanometers, moving magnet galvanometers were far from obsolete. The second notable galvanometer in our examination is a Paschen-type moving magnet galvanometer, made by Cambridge Scientific Instruments Ltd. around 1914 (Figure 3).[46] This sensitive research instrument represents the emergence of a research culture of precision measurement and at the University of Toronto between 1900 and1920. Devised by German physicist Friedrich Paschen (1865-1947), it could measure minute currents on the order of 6 x 10^-10 amps.[47] It is a more complex machine than the Carpentier example, with numerous electrical connections, and several screws and knobs for fine adjustment.

The instrument's sensitivity is, in part, the result of the moving magnet arrangement. Where moving coil galvanometers require a comparatively massive conductive suspension and coil, a moving-magnet instrument can use a variety of lighter non-conductive suspension materials. The Cambridge Paschen galvanometer used extremely fine

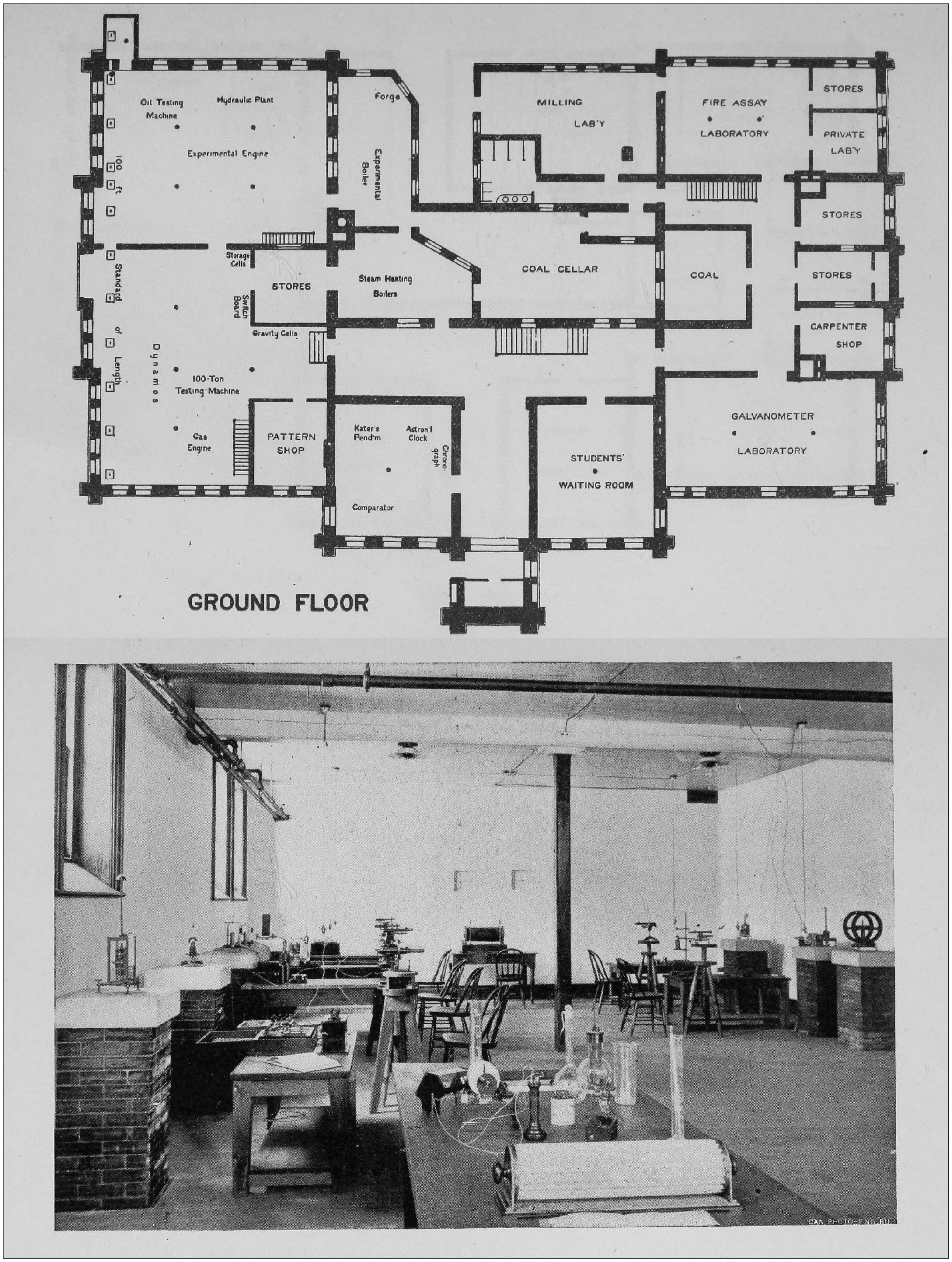


Figure 2: *(Top) The ground floor layout of the School of Practical Science shows the galvanometer laboratory established in 1895. (Bottom) A corresponding image of the laboratory. Note the variety of galvanometers. School of Practical Science,* ***Calendar of the School of Practical Science of the Province of Ontario, Toronto, 1896-1897*** *(Warwick Bros. & Rutter, 1896), 7, 21. Digitized and published to Internet Archive by University of Toronto Archives & Records Management.*

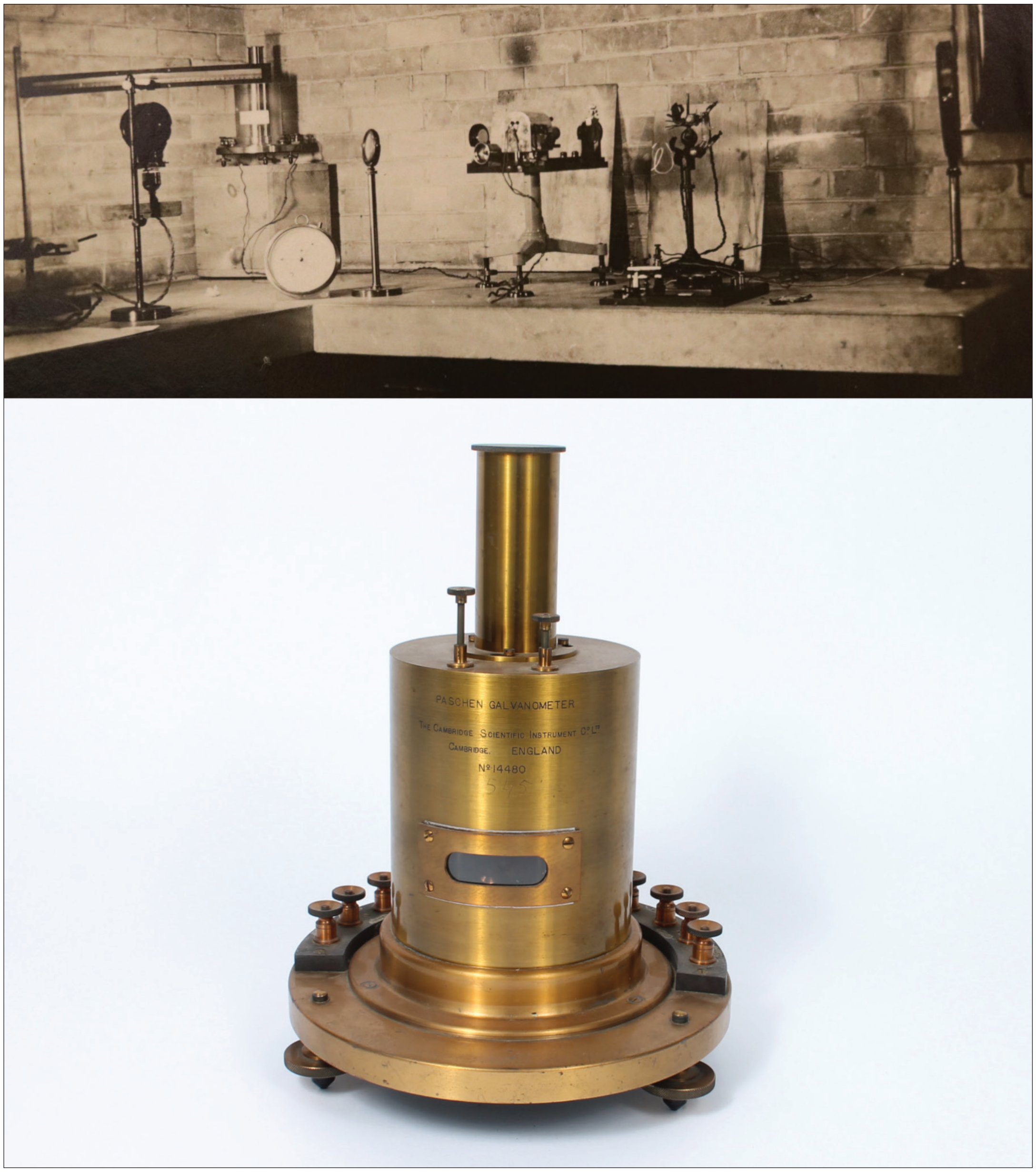


Figure 3: *Above: The apparatus described in Raymond Dearle's 1916 thesis. Below: Cambridge Scientific Instrument Paschen Galvanometer (2019.ph.228), likely the same instrument depicted in the thesis photograph. Raymond C Dearle, "Lines in the Infra-red Spectrum of the Mercury Arc" (MA Thesis, University of Toronto, March 1916) Western University Archives A07-032-001, Fig. 4, Arrangement of Apparatus.*

filaments (0.00075 of a mm in diameter) of drawn quartz. The magnets were fine pieces of cobalt steel, arranged along the suspension in two groups of thirteen—using many smaller magnets decreased the moment of inertia.[48] The suspension weighed about 80 milligrams.

Long experience with developing galvanometers had permitted designers to maximize the output of the coils relative to their resistance through a complex arrangement of four coils, or two opposed pairs. Each coil winding consisted of wires of six sizes. The sensitivity of the instrument was determined by adjusting the distance between the coil and suspension as one set of coils was mounted on a sliding rail.

The challenges of the moving magnet system are evident in the instrument's design. The inner mechanism is shielded by a heavy brass lid with a window for viewing the galvanometer mechanism. Large bell-like covers weighing up to 46 kg could be purchased to further isolate the instrument from ambient magnetic fields.

The Paschen galvanometer is one of many instruments derived from William Thompson's four-coil astatic galvanometer introduced in 1858 developed to detect the minute signals from a transatlantic telegraph cable. This was the first to employ two pairs of coils, each oppositely wound and paired with oppositely directed magnets, in order to partially compensate for the effects of the earth's magnetic field. Later experimenters transformed Thomson's galvanometer from a detector into an extremely sensitive measuring instrument.

Introduced in 1894, Paschen's instrument had been developed for his spectroscopic research.[49] Widely pursued among physicists in this period, this research program employed photoelectric cells to measure spectral emissions as electrons shifted between atomic orbitals. Sensitive galvanometers measured the electrical signals given off by these photoelectric cells. The University of Toronto's Paschen galvanometer was likely acquired around 1914 when J.C. McLennan, then the Director of the Department of Physics, had committed to the pursuit of spectroscopy and equipped the physics lab accordingly.[50] This photoelectric method was one of several experimental approaches employed by McLennan's lab to study atomic spectra.

At least one published paper features this instrument. "On the Infra-Red Emission Spectrum of the Mercury Arc" was published in 1915 by McLennan and his graduate student Raymond C. Dearle. These experiments sought to resolve uncertainty surrounding the emission lines of mercury in the infrared region. The apparatus used a mercury arc lamp, a spectrometer with a rock-salt prism, a bismuth-silver thermopile, and a galvanometer described as one "specially designed by Paschen," a likely reference to this artifact.[51] Photographs in Dearle's thesis, on which the article was based, show an identical instrument.[52]

By the end of the 19th century, galvanometers were central to laboratory work due to the need for precision measurement in spectroscopy and newly discovered x-rays and radioactivity. At the time, this work was most prominently underway at Cambridge University's Cavendish Laboratory. The subsequent emergence of the Toronto Department of Physics as a centre of original research was closely bound to work at Cambridge.

McLennan had studied under James Loudon at the University of Toronto before researching electricity in 1898-99 at the Cavendish Laboratory under J. J. Thompson. Following his return to Toronto, he advanced from laboratory demonstrator to Associate Professor and finally, in 1904, to Director of the Physical Laboratory.[53] In 1912, he hired John Satterly, a Cambridge demonstrator trained at Imperial College London, who revamped the undergraduate program and took charge of purchases.[54] Together, he and McLennan equipped the department mainly with English-made instruments, including the Paschen galvanometer.[55] Its manufacturer, the Cambridge Scientific Instrument Company, had emerged in the 1880s as the predominant supplier to the Cavendish laboratory, making it a familiar choice for McLennan and Satterly.[56]

The Cambridge Paschen Galvanometer represents a new phase at the department—one seeking to establish a specific scientific research culture. Like the Carpentier, it was a specialised and sensitive laboratory instrument, whose purpose suited the physics laboratory's goals more than in engineering training. After engineering ceased sending students to Physics in 1905, classes offered tended to be designed to suit the industrial jobs most graduates would take.[57] In 1905, galvanometers and metrology were covered in the context of machinery, circuits, standards and fault location and the galvanometer laboratory hosted several interference-resistant D'Arsonval-Deprez instruments but only a single sensitive Thompson galvanometer.[58] By the 1910s, the engineering calendars exhibit a focus on laboratories devoted to heavy machinery and calibration, which were supplied with equipment from the increasingly important American electrical behemoths Westinghouse and Weston.[59] As well as simply showing a shift in attention, such heavy machinery would have interfered with nearby highly sensitive instruments like the Paschen galvanometer.[60]

Accordingly, we interpret the Paschen galvanometer as representing a point of divergence for electrical metrology at the University of Toronto, where the differing needs and expectations of physics and engineering education drove different classroom cultures of metrology. This divergence was driven by differing needs, one increasingly research focused, the other dedicated towards practical education.

The Tinsley Portable

A utilitarian 1950s mirror galvanometer made by the British firm H. Tinsley & Co. (Figures 4 and 5) provides an interesting contrast to the Paschen example. It belongs to a category of instrument that integrates the scale into a single unit.[61] This arrangement sacrifices one advantage of the mirror galvanometer, the precision of a long "pointer" formed between the detached mirror and scale, for portability and convenience.

Enclosed mirror and needle-type galvanometers (which replaced the mirror with a physical pointer) shared a niche with another form of moving coil electrical instrument: the "Weston" indicator type that became popular for most common tasks in the opening decades of the 20th century.[62] Both are portable and self-contained. However, a Weston-type instrument replaces the delicate suspension of a typical galvanometer with a sturdier jewelled pivot.[63]

Enclosed galvanometers were common workhorse instruments in this period; the University of Toronto collection has several examples dating back to the 1920s. These instruments include a replaceable suspension. Though we lack detailed trade literature from H. Tinsley & Co., a very similar component is found in catalogues from an American company, Leeds & Northrup, which was selling instruments with this arrangement in 1912, and possibly earlier.[64] There we see that, in hard-wearing portable units, galvanometer components were small, robust, and interchangeable. When the suspension needed repair the user would mail this part to the manufacturer rather than having to replace or repair the suspension themselves. These features made them practical instruments that were easy to use in classroom and workshop settings.

This modular arrangement embodies a trend in which, over the middle of the 20th century, the mechanisms of fundamental instruments, including optical microscopes,

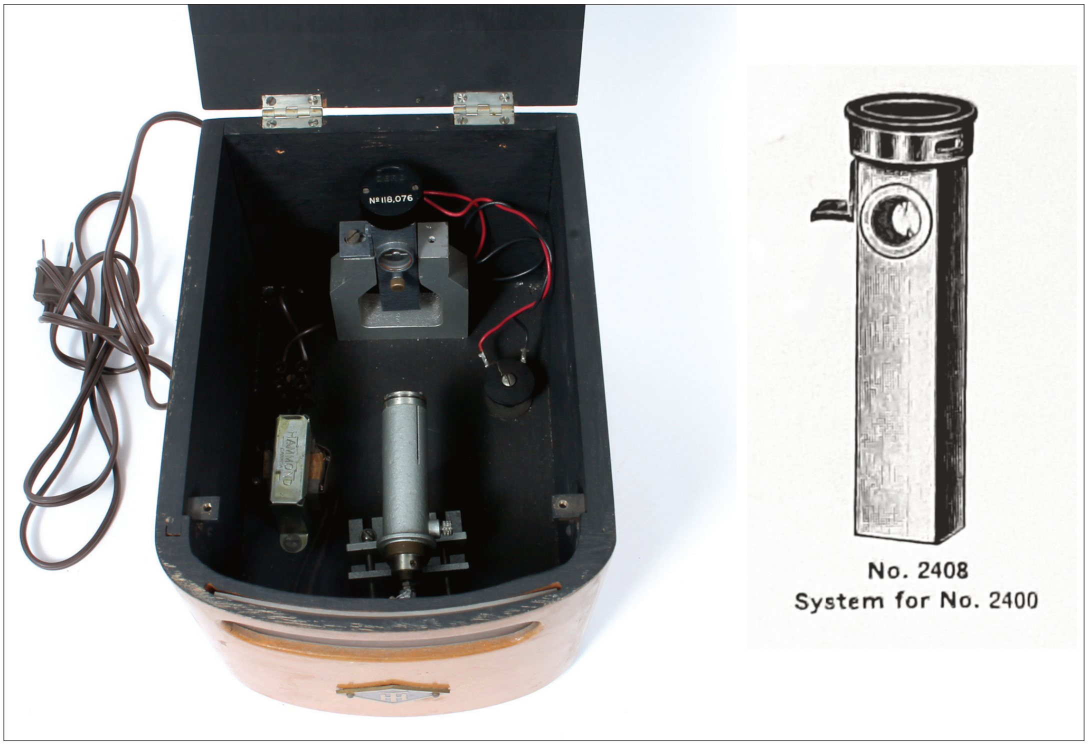
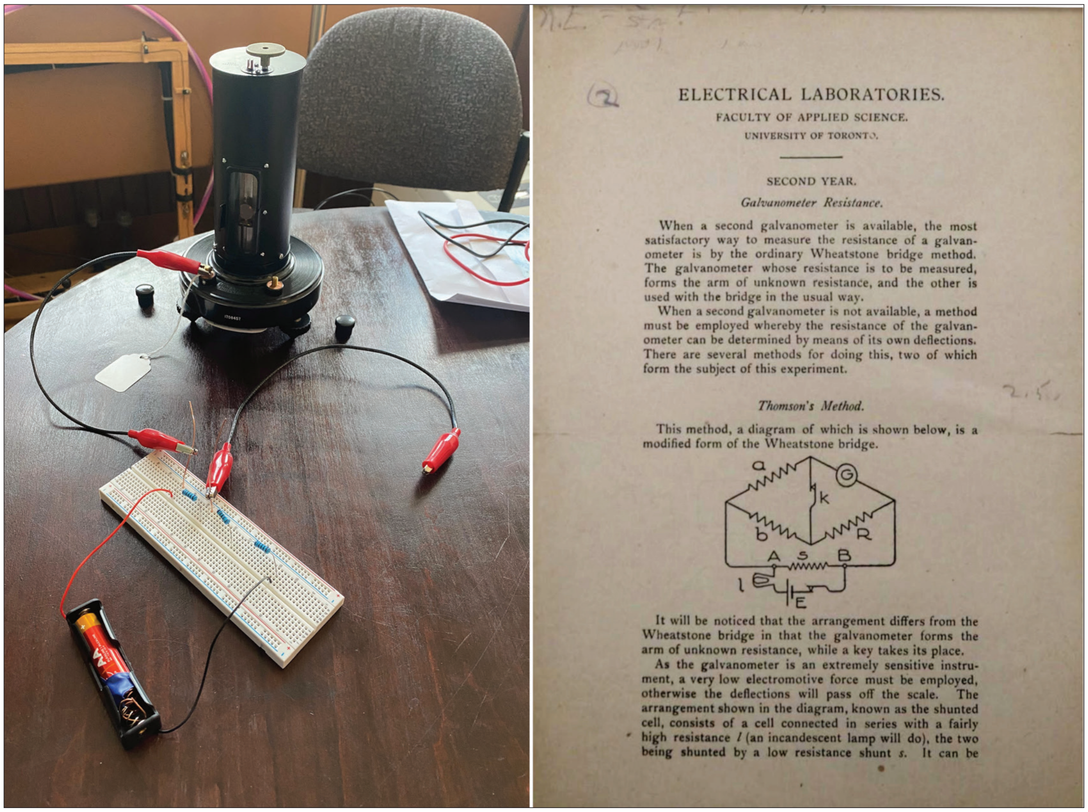


Figure 4: *(Left) The interior of the Tinsley enclosed galvanometer. (Right) The equivalent replacement galvanometer mechanism from Leeds & Northrup. [Credit: (Left) University of Toronto Scientific Instruments Collection; (Right) Leeds & Northrup Company, "Catalogue No. 20" 1927, p10 (Ingenium Library and Archives ELTRN L4847 3004 1927)*

telescopes and precision balances, were miniaturized and integrated as subcomponents of more complex instruments. Within the collection, instruments featuring galvanometer components range from electrical seismometers used in geophysics to medical electrocardiographs.[65] The proliferation of the miniaturized, black-boxed galvanometer embodies the elaboration and streamlining of laboratory instrumentation, as well as the spread of the culture of electrical metrology to disciplines other than physics and engineering.

The purchase of an instrument from a British-owned company continued the Physics department's commitment to buying British instruments, which had begun with the Paschen galvanometer. However, the Tinsley galvanometer is among the few commercial electrical-measuring instruments in the collection to have been manufactured in Canada. It represents a period where Canadian industrial research and development was accelerating in the post-Second World War boom. Its manufacturer's label reads "H. Tinsley & Co. Ltd., Saint-Jérôme, Québec," appointing toward the town located about 50 kilometres north-west of Montreal.

In a newspaper feature about the plant's opening, Tinsley's UK-based Director, D. C. Gall, described a two-year search for a Canadian location that involved consultations with existing Canadian users and with federal officials. He noted the ready market provided by federal departments and Canadian industrial laboratories and described the Canadian plant as an opportunity to reduce dependence on the United States for necessary instruments;American companies such as General Electric, Westinghouse



(2)

ELECTRICAL LABORATORIES.

FACULTY OF APPLIED SCIENCE.

UNIVERSITY OF TORONTO.

SECOND YEAR.

Galvanometer Resistance.

When a second galvanometer is available, the most satisfactory way to measure the resistance of a galvanometer is by the ordinary Wheatstone bridge method. The galvanometer whose resistance is to be measured, forms the arm of unknown resistance, and the other is used with the bridge in the usual way.

When a second galvanometer is not available, a method must be employed whereby the resistance of the galvanometer can be determined by means of its own deflections. There are several methods for doing this, two of which form the subject of this experiment.

2.5

Thomson's Method.

This method, a diagram of which is shown below, is a modified form of the Wheatstone bridge.

It will be noticed that the arrangement differs from the Wheatstone bridge in that the galvanometer forms the arm of unknown resistance, while a key takes its place.

As the galvanometer is an extremely sensitive instrument, a very low electromotive force must be employed, otherwise the deflections will pass off the scale. The arrangement shown in the diagram, known as the shunted cell, consists of a cell connected in series with a fairly high resistance *l* (an incandescent lamp will do), the two being shunted by a low resistance shunt *s*. It can be

Figure 5: *(right) Initial set-up of galvanometer connected to breadboard. (left) "Thomson's Method" of measuring galvanometer resistance. Electrical Laboratories Faculty of Applied Science, University of Toronto Second Year – Galvanometer Resistance [class pamphlet], c. 1912-1915, R.H. Lloyd Fonds B1988-0065 Box 2 File 1, University of Toronto Archives.*

and Leeds & Northrup dominated the electrical market of the time.[66] Such arguments likely refer to Canada's role as an overseas centre of British military research and production before and during the Second World War. In the early 1950s, Canada was still enmeshed in the British defence sphere, so production of British metrological instruments may have helped achieve commonality among military contractors.[67]

We speculate that the Quebec facility served as a waypoint for assembling and calibrating instruments using prefabricated components, in order to avoid shipping instruments from Europe in a bulkier and more fragile completed (or near completed) state. The North American facility would have permitted local repair and replacement of working components. Other components—such as the wooden enclosure and the instrument's electrical transformer—were more certainly Canadian-made. The latter bears the maker's mark "Hammond," a Canadian company that still manufactures electrical enclosures and transformers. Despite initial ambitions, the competition with American or more established Canadian-based companies seems to have been too much for the Tinsley outpost; the company departed St. Jerôme in 1957 for Smiths Falls, Ontario and had left Canada entirely by 1961.[68]

This instrument also evokes an important aspect of the material culture of physics as well as the diffuse frontier between electrical engineering and certain other scientific disciplines. Its lid features a Dymo-type label that reads: "Wheatstone Bridge Galvo –

J.M. Perz." When contacted, retired physicist John M. Perz, who was active at University of Toronto from the 1960s, suggested that this had likely been a workbench instrument used to select matched resistors for the construction of experimental apparatus.

The capacity to build equipment was a crucial part of the advancement of numerous scientific disciplines, including physics and engineering. Design of analogue electrical equipment was, for part of the 20th century at least, a key skill and electrical-measuring instruments necessary tools. As noted, the University of Toronto's Physics department hired J.S. Plaskett specifically because of his electrical experience, and workshops similarly emerged in engineering. After the Second World War, certain disciplines at Toronto physics, notably electromagnetic geophysics and particle physics, included engineering physicists working out of electronics workshops in collaboration with engineers at the Department of Electrical Engineering to design and construct electrical equipment.[69]

Alongside the practicality and robustness of its design, the use of the Tinsley instrument in this context points to the continued relationship of physics and engineering at the university, surrounding electrical metrology's application to and use in the production and testing of other instruments. This, seen in the context of the North American manufacture of the instrument explicitly for the practical contexts of government laboratories, highlights the industrialization of scientific technology, across the 20th century.

The Leeds & Northrup Type R

Our final instrument is a Leeds & Northrup model mirror galvanometer we refer to as the "Type R" (figures 6). This instrument exemplifies the dominance of American precision instruments within the field of electrical metrology, as well as the growing standardization and modularity of instruments into the middle of the 20th century. At least one University of Toronto laboratory standardized on Leeds & Northrup equipment early in the century. A photograph of the Faculty of Engineering's galvanometer lab dated approximately to 1908 shows a facility with students working at a row of identical wall-mounted (Type P) Leeds & Northrup mirror galvanometers.[70]

In the same way, the Department of Physics collection includes several examples and versions of the Type R instrument, representing a period from about 1920 to about 1970.[71] Instruments of this maker and type are also well represented within other collections, a testament to their frequent use in teaching and experimental work during this period.[72] If galvanometers may be considered instrumental infrastructure within the university, these Leeds & Northrup instruments represented an important element of that infrastructure over much of the 20th century.

There are evident reasons for this ubiquity. First, American companies dominated the enormous North American electrical market from the end of the 19th century, with some, like Leeds & Northrup (founded 1899), specialising in precision instruments for industrial and laboratory use.[73] This made Leeds & Northrup instruments, and American-made instruments more generally, accessible, affordable and desirable in training settings, as students were likely to encounter such instruments in their jobs.

Second, the "Type R" chassis was more a platform than a particular instrument. The basic chassis was sold in several models with numerous sub-variants. While all

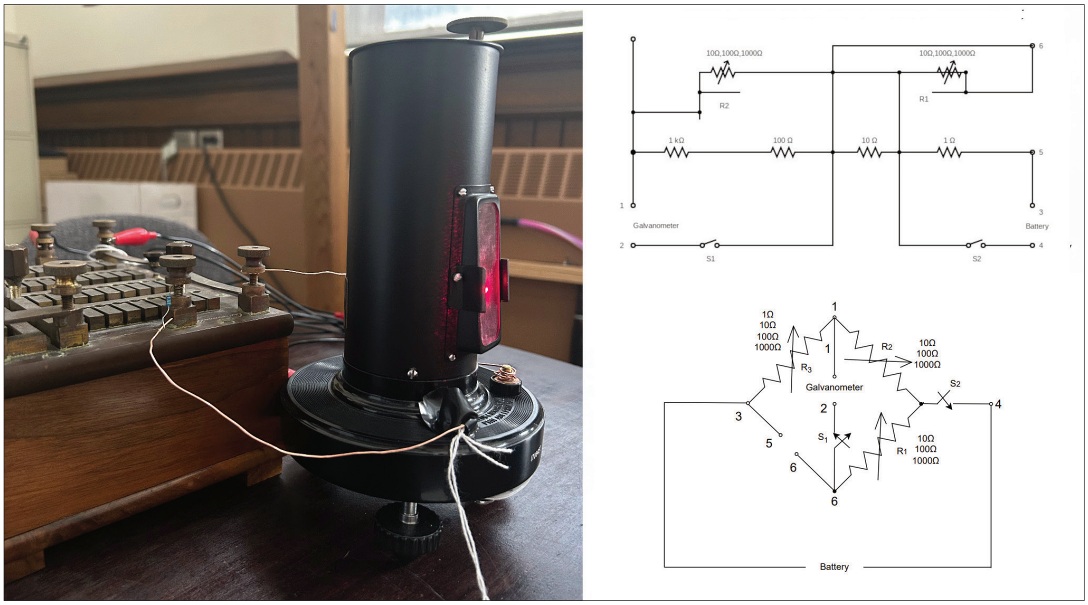


Figure 6: *(Left) The Leeds & Northrup galvanometer connected to the Carpentier Wheatstone Bridge. The laser point is visible in the galvanometer mirror. (Right) Circuit diagrams for the Carpentier Bridge and the Wheatstone Bridge circuit. [Circuit diagrams by Ava Spurr]*

were moving coil galvanometers, they included a variety of suspensions, mirror sizes, and modifications for specialized applications. This customizability made it possible to purchase configurations not listed in the catalogue.[74] Likewise, an existing instrument, purchased for a particular purpose, could be reconfigured.

The Type R instruments were sold with a variety of apparatus including mountings, transformers, lenses, telescopes, lamps, scales, and replacement parts. As with the Tinsley instrument, this modularity was increasingly a feature of teaching instruments in the early decades of the 20th century, as a new generation of utilitarian instruments replaced the classical instruments of the previous century. Whereas some earlier manufacturers had produced lengthy catalogues including older, redundant instruments, the Leeds & Northrup catalogues featured permutations of a few base models.[75]

Another reason for its ubiquity in surviving collections is longevity. The rounded, table-top form factor of the Type R emerged around 1909 and lasted into the last quarter of the 20th century. Given the relative prominence within the American market, it is likely that Leeds & Northrup electrical instruments became an early standard in applications such as testing and calibration within American industry. The longevity of production would have permitted the accumulation of independent metrological data leading to measurement confidence.[76] This may have encouraged the adoption of standardized testing procedures based on particular instruments.

The early 20th century witnessed a drive toward standardization of metrology and certifiable (traceable to a standard) products. An example of this is the establishment in 1919 of the Canadian Engineering Standards Association by Sir John Kennedy.[77] Electrical instruments could be certified as conforming to certain internationally recognized measurement standards for accuracy and repeatability. Instruments would be certified as a serially numbered product of a certain type. Tamper-proof seals were attached. Certifying authorities, in most cases government agencies in metrology, maintained logbooks of these certified instruments. Most organizations like University of Toronto had one such certified instrument, which they used to internally certify the instruments of that type used in their labs.

As the Cold War advanced, and priorities shifted towards the space race, nuclear research, and the defence of North American airspace, Canadian industry and academia became increasingly enmeshed in American networks in research and defence. Agreements such as the 1965 Canada-United States Auto Pact furthered the integration of industry.[78] That Leeds & Northrup made numerous standardized instruments for both military and commercial testing applications undoubtedly reflects the company's importance to North American metrology infrastructure in the post-war period.

The multiple examples of Leeds & Northrup galvanometers, connected to issues of standardization, modularity and industrial dominance, continue the narrative begun with the Tinsley galvanometer. While we cannot trace the individual use of any of our Type R examples, this anonymity highlights a key feature of this instrument. In contrast to the Carpentier ballistic and Cambridge Scientific Instrument Paschen galvanometers, which were highly specialised, and likely unique with a department, the Type R or other Leeds & Northrup instruments became in many universities the standard classroom instrument. While the Type R did offer precision, it also represents how, by the second half of the 20th century, instruments with modular, standardized parts dominated the market in both engineering and physics as part of a broader orientation of electrical makers towards industrial settings and standardization in metrology.The ubiquity of the Type R galvanometer makes it a good subject for understanding the nature of electrical training on galvanometers in Canadian universities. Its longevity means that it was used within living memory—indeed, we drew on the memories of one of our authors, Patrick Finnigan, for both sections of this paper. Furthermore, the many examples of the Leeds & Northrup Type R in the collection made this design suitable for replicating historical experiments without risking a unique artifact.

The following section describes our efforts to retrace the ways these instruments were used to teach meteorological skills and principles to many students in engineering and physics over the first half of the 20th century.

Teaching Electrical Science and Technology

In this part of our examination, we study galvanometer use within the teaching of electrical metrology at the University of Toronto. In these educational settings, galvanometers served as components of a variety of experiments designed for pedagogical purposes. Our objective is a clearer understanding of the challenges and tactile skills and the tacit and gestural knowledge involved in operating these fundamental measuring instruments.

Two academic programs—physics and electrical engineering—constituted the centres of teaching about galvanometers at the university. As noted, James Loudon built an undergraduate physics teaching laboratory in 1878 at University College in Toronto, which offered electrical training to both physics and engineering students until the turn of the century. The School of Practical Science, later renamed the Faculty of Applied Science and Engineering, began to offer an Electrical Engineering program in 1891,[79] which was formalised into a separate department in 1909.[80]

This was a period in which the establishment and growth of telegraphy and electrical power networks across North America drove demand for skilled workers familiar with electrical instrumentation.[81] The University of Toronto's electrical laboratories became primary engineering training sites for Ontario's rising electrical industry. Galvanometers entered the university's pedagogical settings under these circumstances.

University course calendars permit us to track the nature of technical teaching across these evolving institutions throughout this period, and the material context surrounding the teaching and learning of this metrological tool. Images and floor plans of the SPS galvanometer lab established in 1896 show a variety of galvanometers installed on brick pillars—an arrangement meant to reduce vibrations by decoupling the instruments from the floor (see Figure 2).[82] Around 1908, standardized wall-mounted Leeds & Northrup galvanometers were integrated with telescopes at a set distance to permit students to read the reflection of a scale in the galvanometer mirror.[83]

Archival records provide further information about teaching practices. The fonds of three former undergraduate students from the UTARMS showcase the prevalence of galvanometers in physics and engineering education. Henry John Cunningham Ireton majored in physics in 1912-17. Richard Hilton Lloyd majored in electrical engineering in 1911-15. Charles Stewart Phelps majored in electrical engineering in 1930-34. They left printed handouts, notebooks, and experimental records for the lab courses on electricity and magnetism or introduction to electrical engineering they took at the University of Toronto in the early 20th century.

These documents situate the galvanometer as an essential general-purpose apparatus within experiments associated with various pedagogical aims. These aims included familiarizing with the procedures of instrumental operations, calibrating metrology, demonstrating general principles, measuring the internal parameters of electric devices, and determining other physical quantities. This variety highlights the galvanometer's role as a multipurpose electrical instrument throughout this period, reflecting the contents of textbooks of the era which include significant discussion of technical features of individual galvanometers and their effects on questions like internal resistance, and the calibration of galvanometers and similar instruments such as ammeters.[84] The basic circuits and fundamental equipment in these experiments were building blocks for more complex applications and research. Below we summarize the didactic experiments that we uncovered from the sources, highlighting slightly more details in the first three types for their relevance to our replication work:

> **Familiarization with Instrumental Operations:** The process of learning to operate a galvanometer typically involved connecting a galvanometer to a variable current source— usually a battery and a variable resistor—in order to record galvanometer readings as the current changed. Its mirror's deflection was measured by the traversing distance of a light spot reflected from the mirror and projected onto a wall as the mirror moved.

This distance was proportional to the input current. By plotting several values, students were tasked with determining this linear relationship and the proportional coefficient known as the "galvanometer constant." This constant provided the basis for galvanometer measurement.[85]

Measuring Other Electrical Quantities: Students were also taught to use galvanometers in measuring other electrical quantities. The most common design was to measure an unknown resistance with a galvanometer and an electric bridge circuit, often a Wheatstone bridge. This was a quadrilateral circuit, where each edge was connected with an electrical component. The bridge connected the unknown resistor R1 on one edge and three known resistors R2, R3, and R4 on the other three; a galvanometer was connected across the diagonal of the quadrilateral circuit. When the bridge was "in balance," no current flowed through the galvanometer and the four resistances satisfied $R1 = R3R4/R2$. Measuring R1 thus involved tuning R2, R3, and R4 until the galvanometer gave null deflection.[86] Another exercise was to measure the "absolute value" of the magnetic field from an electromagnet.[87]

Instrument Calibration and Determining Internal Parameters: An important part of laboratory instruction involved calibrating galvanometers or using them to determine their own or other electrical devices' internal parameters. Students were taught, for example, to test whether a battery was under an unfavourable "polarized" condition when hydrogen was released at the cathode.[88] Moreover, a galvanometer was used to measure a battery's or even its own internal resistance. Here, the bridge circuit for resistance measurement became an immediate resource. Since the measurable device served as the power source (battery) or the indicator (galvanometer), the original bridge circuit had to be modified. To measure the resistance of the galvanometer, it was placed in one arm of the bridge while the original galvanometer terminals were connected with a switch. In balance, no matter whether the switch was on or off, the galvanometer's deflection should remain the same. The galvanometer resistance was calculated via $R1 = R3R4/R2$.[89] Making a similar arrangement with the battery could determine the battery resistance.[90]

Demonstrating Fundamental Principles: Certain experiments demonstrated fundamental principles of electricity. One example was a verification of Kirchhoff's law of voltage (the sum of voltages across terminals along a closed loop was zero) and that of current (the sum of currents flowing out of any point was zero). Here, the galvanometer was used to obtain the relevant voltages or currents in a circuit. The sums of these values were then compared against the predictions from Kirchhoff's laws.[91]

Determining Material Properties: Students learned to measure certain material properties with a galvanometer. An experiment measured the hysteresis of an iron core, the variation of the material's induced magnetization with the imposed magnetic field.[92] Another experiment measured the temperature coefficient of a resistor, which was obtained from its resistance measurement at varying temperature.[93]

Practical Electrical Engineering: Certain experiments demonstrated the galvanometer's use as a tool for practical engineering. A session was dedicated to the "Murray's loop test" for locating a fault along a telephone or telegraphic line.[94]

The fact that these fundamental principles and operations were taught using galvanometers contributes to our understanding of them as fundamental instruments. Through this, we can observe that students were expected to combine exploration of theoretical electrical concepts in applied settings, with the practical knowledge of operating a galvanometer.

Knowledge, Skills, and Replication

The final dimension of our investigation explores the operation of the galvanometer by replicating two basic teaching experiments. As discussed above, replication has a well-established history in the history of science. However, unlike many replications (e.g., Otto Sibum), our efforts do not explore a prominent experiment in the history of science, but rather focus on a common experimental rite of passage for physics and engineering students in the early 20th century.[95] Throughout this process, we were assisted by an experienced guide: engineer Patrick Finnigan (among this article's authors) who had much experience operating and repairing galvanometers as lab demonstrator in the Department of Physics at York University in the 1960s and 1970s.

In the following account, we provide an accessible overview of our efforts that is focused on the material insights obtained from our experiments. Those interested can consult a technically oriented account of these experiments on UTSIC's website.[96]

We replicated two experiments from the electrical laboratory courses at the University of Toronto. One measured the linear relationship between the electric current and mirror deflection and thus demonstrated the galvanometer's ability to measure current (item 1 in the previous subsection). The other measured a galvanometer's internal resistance using a Wheatstone bridge (item 3). Both were basic electrical procedures meant to provide a foundation for further, more complicated, experiments. By following the settings and procedures described on the lab handouts, we sought to understand the challenges to obtaining reasonable results.

We selected a Leeds & Northrup "Type R" mirror galvanometer for this project.[97] As noted, this highly evolved and standardized instrument was an excellent example of mid-20th century galvanometers used for precision work in teaching. Among several surviving examples of this instrument within the University of Toronto collection, we were fortunate to find one in working order.

First, we tested it to ensure that it had an ordinary response to input current. We built an auxiliary apparatus for the trial: a homemade stand mounting a laser pointer whose beam was reflected off the galvanometer mirror onto the opposite wall marked with taped scale increments. Measuring electric current with a galvanometer required fixing and stabilizing the instrument, orienting the beam to the mirror, and handling carefully the thin thread inside.

Initial operation of the galvanometer proved unexpectedly challenging and time consuming, due largely to the inherent sensitivity of the suspended coil mechanism. Our space, a third-floor office, was far less adapted to galvanometer operation than the galvanometer laboratories, seen in archival photos, with instruments set on sturdy isolated pillars in basement rooms. Walking nearby or touching the table during measurement caused drastic movements of the light spot. The galvanometer also had to be carefully levelled using its three adjustable feet to permit the suspended coil to move freely within its narrow housing.

We discovered that the instrument was sensitive to being overloaded with current. The specification from historical catalogues indicated the minimum current a galvanometer could measure, but not the maximum current it could tolerate—an example of tacit knowledge. Overloading a galvanometer not only caused an overshoot deflection but made the subsequent measurements unstable: after overshooting, the light spot no longer returned back to its original position. Through repetitive tests, we figured out that the maximum permissible input current to our galvanometer was around 800 nA, or 0.8 µA.

The second experiment, to determine the galvanometer's internal resistance, required a Wheatstone bridge. As mentioned, it was used to determine electrical resistance through balancing. We first chose an example from the Department of Physics Collection manufactured by Carpentier in the 1880s or 1890s.[98] This bridge had built-in resistances R2, R3, and R4, each of which comprised an array of incrementally calibrated resistor blocks so that resistance values could be adjusted by inserting metal pegs into sockets.

We discovered that the Carpentier bridge malfunctioned at some resistance values, most likely due to metal corrosion. Consequently, we replaced it with a more modern bridge made by UK company Croydon Precision Instruments circa 1950. This later bridge was likely contemporary with the galvanometer in use.

While the archival notebooks rarely indicated a specific type of instrument used, our misadventure with the Carpentier bridge produced some insight. When an old-style Wheatstone bridge with built-in resistors was used with a galvanometer to measure an unknown resistor, the precision of the results was largely influenced by the precision of the bridge's built-in resistor blocks. Calibration of these resistors during manufacturing was difficult, and defects (e.g., rust on the built-in resistors) could not be easily fixed. Given these shortcomings of the old-style bridges, the electrical teaching laboratories at the University of Toronto likely adopted bridges with external resistors (like our Croydon example) in the early 20th century.

Using a bridge-galvanometer set to determine the galvanometer's resistance, referred to as R1 required the specification of the three parameters R2, R3, and R4 (see the previous subsection). We approached this by fixing two parameters and adjusting one until balance was reached. This required a rough estimate of the unknown resistance R1. Only after knowing the crude range of R_1, could we determine the scaling factor R4/R2, tune R3 toward balance, and obtain R1 from R3R4/R2. Estimating the numerical scale of the unknown quantity was thus an important step before actually measuring it, as we have learned from this replication.

In one notable episode, we obtained results inconsistent with theoretical predictions. Upon investigating, we attributed this inconsistency to the galvanometer's mirror locking mechanism. From our measurement using both a multimeter and an electronic multi-function tester, the galvanometer's "unlocked" (or normal) resistance was 500Ω. When locked, it was 50Ω. Once we incorporated this result, the inconsistency was resolved. We did not discover this factor from archival documents, but through hands-on experiment. This is therefore a clear demonstration of new experiential knowledge gained through this project.

Ultimately, we found the two galvanometric experiments to be reliably replicable, as might be expected for teaching experiments. We obtained a linear relationship between the mirror deflection and input current. Our measurement of the instrument's internal resistance (500Ω) was confirmed with the result from a modern electronic multi-function tester. Yet, the unexpected difficulties encountered provided insight into the complexities of these precise and delicate instruments. Our experience was in line with those of our colleague, Patrick Finnigan, who instructed undergraduate students in using galvanometers.

Conclusion

University collections are richly endowed with instruments purchased for teaching and research purposes. These artifacts present an opportunity to investigate the history of science and instruction in a university setting from a material perspective, exploring features of the practice of science that may otherwise not have been recorded, and answering questions about local experiences and techniques that can help shed light on "on the broader picture of precision instruments and the contexts in which they were used..

Through this investigation, we sought to better understand a foundational instrument in electrical measurement throughout the latter part of the 19th and much of the 20th centuries. This was of particular significance for our local context since this period corresponded to the establishment and flourishing of science and engineering at the University of Toronto.

The ubiquity and diversity of galvanometers permits us to survey this development through a close study of representative instruments. These artifacts reflect and embody important themes: the process and prestige of attaining early instruments; the emergence of sophisticated local independent research; the development of local instrument manufacture; standardization of metrological instruments across multinational industries. Such exercises demonstrate the value of artifacts as primary sources within the history of science, especially their value in exploring local instances of broader historical themes in science and technology.

In replicating fundamental teaching experiments, we sought a detailed account of the instrument's place within the education of students in electrical engineering and physics. We obtained such insight, both within the archival texts prepared by students, and through a process that replicated the more basic galvanometer-based exercises found within those texts. In the latter exercise, we pursued details not recorded in text, but implicit within a broad community of users. The maximum current relative to a given instrument's sensitivity or the perturbing effect of the mirror locking mechanism on measurement of the instrument's internal resistance would, no doubt, have been common knowledge among the engineers and laboratory workers who used such instruments regularly.

Ultimately, our understanding of apparently familiar laboratory instruments will be limited if we do not study real and specific examples, with their characteristics and individual biographies. By following the footsteps of students through the teaching laboratory, we uncover practices, material factors and metrological technologies that were foundational—but perhaps not well recorded—to advanced electrical and electronic research and industrial development.

Victoria Fisher (victoria.fisher@utoronto.ca) was awarded her PhD in the History of Science in March 2023 and is Historian in Residence at the Department of Astronomy & Astrophysics at the University of Toronto.

Erich Weidenhammer (erich.weidenhammer@utoronto.ca) received his PhD from the University of Toronto in 2014. He is curator of the University of Toronto Scienctifc Instruments Collection and adjunct curator at Ingenium: Canada's Museums of Science & Innovation.

Chen-Pang Yeang (chenpang.yeang@utoronto.ca) received his PhD and ScD from MIT. He is a professor at the Institute for the History and Philosophy of Science and Technology, University of Toronto.

Patrick Finnigan (Patrick_Finnigan@ieee.org) is a Professional Engineer in Ontario. He holds a M.Math degree from the University of Waterloo, and is Life Senior member of IEEE.

Ava Spurr (ava.spurr@mail.utoronto.ca) is an undergraduate student at the University of Toronto majoring in History and Philosophy of Science and minoring in Astronomy and Astrophysics, Material Culture and Semiotics, and Science, Technology, and Society.

Endnotes

1 Geoffrey Bowker and Stephen Slota, "How infrastructures matter," in *The Handbook of Science and Technology Studies*, eds. Ulrike Felt, Rayvon Fouché, Clark A. Miller, and Laurel Smith-Doerr (Cambridge, MA: MIT Press, 2017), 529-554; Susan Leigh Star and Geoffrey Bowker, "How to infrastructure," in *Handbook of New Media: Social Shaping and Social Consequences of ICTs*, eds. Leah Lievrouw and Sonia Livingstone (New York: Sage, 2010), 230-245.

2 Edward L. Nichols, *The Galvanometer: A Series of Lectures* (New York: McIlroy & Emmet, 1894), 68.

3 Olivier Darrigol, *Electrodynamics from Ampère to Einstein* (Oxford: Oxford University Press, 2000), 6-7; Frederic Holmes and Kathryn Olesko, "The images of precision: Helmholtz and the graphic method," in *The Values of Precision*, ed. Norton Wise (Princeton: Princeton University Press, 1995), 198-221.

4 Crosbie Smith and Norton Wise, *Energy and Empire: A Biographical Study of Lord Kelvin* (Cambridge: Cambridge University Press, 1989), 649–683.

5 Nichols, *The Galvanometer*, 54–55 .

6 James Swinburne, *Practical Electrical Measurement* (London: H. Alabaster, Gatehouse & Co., 1888), iii–iv.

7 Graeme Gooday, "Precision measurement and the genesis of physics teaching laboratories in Victorian Britain," *British Journal of the History of Science* 23 (1990): 1–39.

8 James Swinburne, *Practical Electrical Measurement* (H. Alabaster, 1888); Ernst Julius Berg, Walter Lyman Upson, *Electrical Engineering: First Course* (McGraw-Hill Book Company Inc., 1916); Albert Campbell, Ernest C. Childs, *The Measurement of Inductance, Capacitance, and Frequency* (D. Van Nostrand, 1935).

9 Gooday, "Precision measurement," 1–39.

10 Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins University Press, 1983), 140–174.

11 Michelle Hoffman, "Constructing School Science: Physics, Biology, and Chemistry Education in Ontario High Schools, 1880-1940," (PhD Dissertation, University of Toronto, 2013); Danielle Ouellet, "L'Emergence de deux disciplines scientifiques à l'Université Laval entre 1920 et 1950 - La chimie et la physique," (PhD Dissertation, Université Laval, April 1991); Victoria Fisher, "Getting Down to Brass & Wax: The Material Culture of Physics at Canadian Universities, 1890-1939," (PhD Thesis, University of Toronto, 2023).

12 Yves Gingras, *Physics and the Rise of Scientific Research in Canada* (McGill-Queen's University Press, 1991), 14–15; Fisher "Getting Down to Brass & Wax," 278–297.

13 Charlotte Connelly and Hasok Chang, "Galvanometers and the many lives of scientific instruments," in *The Whipple Museum of the History of Science*, eds. Joshua Nall, Liba Taub, and Frances Willmoth (Cambridge: Cambridge University Press, 2019), 159–186.

14 Paolo Brenni, "The evolution of teaching instruments and their use between 1800 and 1930," *Science and Education* 21 (2012): 191–226.

15 Jean-François Gauvin, "Playing with Quantum Toys: Julian Schwiner's Measurement Algebra and the Material Culture of Quantum Mechanics Pedagogy at Harvard in the 1960s," *Physics Perspective* 20 (2018): 8–42.

16 The University of Toronto Scientific Instruments Collection (UTSIC) https://utsic.utoronto.ca/

17 For examples of these methods, see: Katharine Anderson, Mélanie Frappier, Elizabeth Neswald, and Henry Trim, "Reading instruments: Objects, texts and museums," *Science and Education* 22 (2013): 1167–1189; David Pantalony, "Biography of an Artifact: The Theratron Junior and Canada's Atomic Age," *Scientia Canadensis: Canadian Journal of the History of Science, Technology and Medicine* 34 No. 1 (2011): 51–63.

18 Hjalmar Fors, Lawrence Principe, and Otto Sibum, "From the library to the laboratory and back again: Experiment as a tool for historians of science," *Ambix* 63, 2 (2016): 85-97.

19 Pamela Smith, *From Lived Experience to the Written Word: Reconstructing Practical Knowledge in the Early Modern World* (Chicago: University of Chicago Press), 2022. For an explanation of a historical scientific controversy explored through experimental reenactment, see Alberto Martinez, "Replication of Coulomb's torsion balance experiment," *Archive for the History of Exact Sciences* 60, 6 (2006): 517-563. For a reevaluation of received scientific knowledge through experiment, see Hasok Chang, "How historical experiments can improve scientific knowledge and science education: The case of boiling water and electrochemistry," *Science and Education* 220 (2-11): 317-341. For an exploration of contradictory scientific effects, see Jed Buchwald, Chen-Pang Yeang, Noah Stemeroff, Jenifer Barton, and Quinn Harrington, "What Heinrich Hertz discovered about electric waves in 1887" *Archives for the History of Exact Sciences*, 75:2 (2021): 173-218.

20 H. Otto Sibum, "Reworking the mechanical value of heat: Instruments of precision and gestures of accuracy in early Victorian England," *Studies in the History and Philosophy of Science* 26 (1995): 73–106.

21 Rob Yates, "Sandford Fleming Ravaged by Fire," *Toike Oike* Extra Vol. 80, No. 7 (1977): 1-4. https://exhibits.library.utoronto.ca/exhibits/show/recollections/the-blaze

22 William J. Loudon and John C McLennan, *A Laboratory Course in Experimental Physics*, (New York, London: Macmillan, 1895), 224-225.

23 Jules Carpentier, "Ballistic Mirror Galvanometer" (c.1896) University of Toronto Scientific Instrument Collection (UTSIC), artifact no. 2009.uc.14 (https://utsic.utoronto.ca/wpm_instrument/2009-uc-14/).

24 David Pantalony, *Altered Sensations: Rudolph Koenig's Acoustical Workshop in Nineteenth-Century Paris* (Dordrecht: Springer, 2009), xxvi – xxvii.

25 Carpentier "Ballistic Mirror Galvanometer." At some point in the more recent past, an acrylic cover was constructed to protect it from dust and reveal the inner mechanism.

26 Nichols, *The Galvanometer*, 52- 53.

27 Nichols, *The Galvanometer*, 24; James Loudon, "Evolution of the Physical Laboratory," *The University Monthly* 8 (1908): 44-45.

28 James Loudon, "The Universities in Relation to Research," *Science* 15, 391 (1902): 1003–04; Fisher "Brass & Wax," 263-267.

29 Martin Friedland, *The University of Toronto: A History* (Toronto: University of Toronto Press, 2002), 78 – 81.

30 James Loudon, "The evolution of the physical laboratory," *University of Toronto Monthly*, 8 (1907): 44–45; University of Toronto, *The Calendar of the University of Toronto… for the year 1895-96* (Rowsell & Hutchinson, 1895), 30.

31 David Pantalony, *Altered Sensations*, 119-121; Letter from R. Koenig to J. Loudon, October 10, 1895; Letter from Agent of J. Carpentier to R. Koenig, October 12, 1895; Letter from R. Koenig to J. Loudon, October 13, 1895, B1972-0031-004(11), University of Toronto Archives (UTARMS).

32 Anon., "The Galvanometer of D'Arsonval and Deprez," *Nature* 31 (Nov. 1884): 86-88.

33 School of Practical Science, *Calendar of the School of Practical Science, Province of Ontario, 1892-1893* (Warwick & Sons, 1892), 27, 34. https://archive.org/details/spscalendar1888/page/n247/mode/2up (accessed September 10, 2023.)

34 School of Practical Science, *Prospectus of the School of Practical Science, Province of Ontario, 1887-1888* (Warwick & Sons, 1887), 38. https://archive.org/details/spscalendar1887/page/38/mode/2up (accessed September 10, 2023.)

35 Loudon and Mclennan, *A Laboratory Course*, 212-227.

36 Gingras, *Physics*, 20-21.

37 Fisher, "Brass & Wax," 300.

38 J. Carpentier, "Ampere-Metre" (c.1885) UTSIC Artifact no. 2009.uc.15 (https://utsic.utoronto.ca/wpm_instrument/ampere-meter/).

39 Fisher "Brass & Wax," 269-270.

40 Gingras, *Physics,* 14-15; Fisher "Brass & Wax," 286-297, 387-396.

41 E.g. School of Practical Science, *Calendar of the School of Practical Science, Province of Ontario, 1895-1896* (Warwick Bros. & Rutter, 1895), 75-82; For other schools, Gingras, *Physics*, 32; A.S. Eve, "Macdonald Physics Building McGill University Report for the Session 1919-1920."

42 School of Practical Science, *Prospectus of the School of Practical Science, Province of Ontario, 1888-1889* (Warwick & Sons, 1888), 11. https://archive.org/details/spscalendar1887/page/38/mode/2up (accessed June 6, 2024.)

43 School of Practical Science, *Calendar of the School of Practical Science of the Province of Ontario, 1896-1897* (Warwick Bros. & Rutter, 1896), 7, 59.

44 School of Practical Science, *Calendar of the Ontario School of Practical Science, 1905-1906* (Warwick Bros. & Rutter, 1905), 14-15.

45 Letter from J.C. McLennan to J. Loudon, September 4, 1898, B1972-0031 Box 004 File 44, UTARMS.

46 Cambridge Scientific Instruments Ltd., "Paschen Galvanometer (Cambridge Scientific Instruments)" UTSIC, artifact no. 2009.ph.228 (https://utsic.utoronto.ca/wpm_instrument/paschen-galvanometer-cambridge/)

47 Nichols, "The Galvanometer," 81.

48 H. A. Daynes, "The Sensitivity of the Paschen Galvanometer (I) The Moving System," *Journal of Scientific Instruments* 3, 7 (1925): 12.

49 Nichols, "The Galvanometer," 81.

50 Robert Craig Brown, "The Life of Sir John Cunningham McLennan Ph.D., F.R.S., O.B.E., K.B.E. (1867 -1935)," *Physics in Canada* 56, 1 (2000): 93. https://pic-pac.cap.ca/index.php/Issues/view_issue/268

51 John C. McLennan and Raymond C Dearle, "On the Infra-Red Emission Spectrum of the Mercury Arc," *Proceedings and Transactions of the Royal Society of Canada* 9 (1915) Section III: 181-186.

52 Raymond C. Dearle, "Lines in the Infra-red Spectrum of the Mercury Arc" (MA Thesis, University of Toronto, March 1916), see Fig. 4, Arrangement of Apparatus, A07-032-001, Western University Archives, London, Canada.

53 Brown "Sir John Cunningham McLennan," 92-93.

54 Fisher "Brass & Wax," 433.

55 Ibid, 377, 433; J. Satterly, Mechanics and Heat Laboratory – New Apparatus & Supplies (Ledger, 1912-1934), UTARMS (unaccessioned).

56 M.J.G. Cattermole, A.F. Wolfe, *Horace Darwin's Shop: A History of the Cambridge Scientific Instrument Company 1878 to 1968* (Adam Hilger, 1987), 38.

57 The employment of former graduates was listed in the faculty's yearly calendars. See, for instance School of Practical Science, *Calendar of the School of Practical Science, Province of Ontario, 1895-1896* (Warwick Bros. & Rutter, 1895), 75-82.

58 School of Practical Science, *Calendar of the Ontario School of Practical Science, 1905-1906* (Warwick Bros. & Rutter, 1905), 66–69, 78–79

59 University of Toronto, *The Calendar of the University of Toronto Faculty of Applied Science and Engineering, 1910-1911* (Toronto University Press, 1910), 90.

60 Loudon and Mclennan, *A Laboratory Course*, 212-227.

61 H. Tinsley & Co. Ltd, "Mirror Galvanometer (H. Tinsley & Co.) UTSIC, artifact no. 2009.ph.180 (https://utsic.utoronto.ca/wpm_instrument/mirror-galvanometer-tinsley/

62 Cattermole and Wolfe, *Horace Darwin's Shop*, 38.

63 The comparison between enclosed suspension galvanometers and Weston-type instruments is discussed in Leeds & Northrup trade literature that notes the resistance to fall damage of a particular enclosed galvanometer relative to "pivot and jewel" instruments. See Leeds & Northrup Company, *Moving-Coil Galvanometers: Catalogue 20* (Philadelphia, PA, 1913), 24.

64 Leeds & Northrup Company, *Galvanometers: Catalog 20* (Leeds & Northrup Company, 1927), 39.

65 See, for instance, University of Toronto Department of Physics, "Twelve-Channel Seismic Refraction Recorder,"(c. 1970s) University of Toronto Scientific Instrument Collection (UTSIC), artifact no. 2019.ph.851 (https://utsic.utoronto.ca/wpm_instrument/twelve-channel-seismic-refraction-recorder/); Evans Elecroselenium Ltd., "Prothrombin Meter (Evans Elecroselenium Ltd.)," (c. 1960s – early 1970s) University of Toronto Scientific Instrument Collection (UTSIC), artifact no. 2022.MTS.2 (https://utsic.utoronto.ca/wpm_instrument/prothrombin-meter-evans-elecroselenium-ltd/); Cambridge Instrument co., "Portable Electrocardiograph (Cambridge Instrument)," (c. 1950s) University of Toronto Scientific Instrument Collection (UTSIC), artifact no. 2019.ihpst.105 (https://utsic.utoronto.ca/wpm_instrument/portable-electrocardiograph/).

66 Anon., "Bénédiction d'une importante usine à Saint-Jérôme," *L'Avenir du Nord* (May 9, 1952): 1.

67 Jonathan Turner, "The Defence Research Board of Canada, 1947 to 1977," (PhD Thesis, University of Toronto, 2012), 70.

68 Anon., "Bénédiction," 1; Anon., En Attendant la 'Verte'." L'Avenir du Nord (September 26, 1957): 7; Anon., "Smiths Falls," *Ottawa Citizen* (December 3, 1957), 34.

69 Gordon West et al., "John Tuzo Wilson: A Man Who Moved Mountains," *Canadian Journal of Earth Sciences* 51, 3 (2014): xxiv. U of T electrical engineering professor Shashi B. Dewan and collaborators designed power supplies for various equipment for the TRIUMF and CERN accelerator laboratories. They also designed the high power transmitter for the MOSES undersea EM system in the U of T collection, see University of Toronto Department of Physics "MOSES Receiver" UTSIC artifact no.2024.ph.885 (https://utsic.utoronto.ca/wpm_instrument/moses-receiver/).

70 Unknown, "Engineering Building – Group of Students in Galv. Lab," Photograph Digitized from glass plate negative (c. 1908), Department of University Extension and Publicity fonds, 2010-22-3MS/A1965-0004/[6.36], UTARMS.

71 We use "Type R" as a shorthand for several models with the same format: a compact, rounded, table-top model that is very common in collections of 20th century instruments. The "Type-R" is the most common variant, with sufficient precision for most research and teaching requirements. However the chassis was also used for a vibration galvanometer, a marine galvanometer, and the Type HS (high sensitivity) galvanometer. See, for instance: Leeds & Northrup Company, *Galvanometers: Catalog 20* (Leeds & Northrup Company, 1927).

72 See, for instance, the following example from the Astronomy collection: Leeds & Northrup, "Moving-coil Galvanometer (Leeds & Northrup)," (c. 1960s) University of Toronto Scientific Instrument Collection (UTSIC), artifact no. 2018.ast.87 (https://utsic.utoronto.ca/wpm_instrument/moving-coil-galvanometer/). In an interview, electrical engineer Patrick Finnigan and coauthor of this paper, noted that Leeds & Northrup was the only manufacturer whose galvanometers he recalls using during his time teaching physics in the 1970s. Patrick Finnigan, P.Eng., Personal Communication, February 14, 2023.

73 I. Melville Stein, "Measuring Instruments," *A Measure of Progress Leeds & Northrup Company* (The Newcomen Society, 1958), 5.

74 Leeds & Northrup Company, *Electrical Measuring Instrument for Research, Teaching and Testing, Catalog E 1946* (Philadelphia, PA: Leeds & Northrup Company, 1946), 3.

75 Brenni, "The evolution of teaching instruments," 116, 221.

76 Barry E. Jones, "Measurement: Past, Present and Future: Part 1 Measurement History and Fundamentals," *Measurement and Control* 46, 4 (2013): 108-114.

77 Stuart B. McKenzie, "Canadian Engineering Standards Association," *The Annals of the American Academy of Political and Social Science* 137, 1 (1928): 17-24.

78 Turner, "The Defence Research Board," 122, 231.

79 In this year, Electrical Engineering was advertised as part of, but now equal to, the Mechanical Engineering program, *School of Practical Science Calendar of the School of Practical Science, 1891-92* (Warwick & Sons, 1891), 11.

80 University of Toronto, *The Calendar of the University of Toronto Faculty of Applied Science and Engineering, 1909-1910* (Toronto University Press, 1909), 38.

81 These academic programs were established during the period when, across Ontario, Western Union from the US and Canadian Pacific and Grand Trunk (later Canadian National) railway expanded their telegraph conglomerates, Bell Telephone Company of Canada laid its networks, and numerous hydroelectric suppliers appeared after Edison lights were introduced to the province's large cities. See Ian M. Drummond, *Progress without planning: the economic history of Ontario from Confederation to the Second World War* (Toronto: University of Toronto Press, 1987), 134-146.

82 School of Practical Science, *Calendar of the School of Practical Science of the Province of Ontario, 1896-1897* (Warwick Bros. & Rutter, 1896), 7. University of Toronto, "Prospectus of the School of Practical Science, Province of Ontario, 1888-1889", 5. https://archive.org/details/spscalendar1888/page/n531/mode/2up (accessed September 10, 2023.); Likewise, the 1901-02 Calendar of the Department of Physics first described an "Electrical Laboratory" equipped with galvanometers, electrometers, resistance coils, magnetometers, voltmeters, ammeters, and other instruments. Along with an Acoustical Laboratory and an Optical Room, this Electrical Laboratory was part of the department's Physics Laboratory.

83 See Citation 55.

84 Swinburne, "Practical Electrical Measurement," 25-56; Loudon and Mclennan, *A Laboratory Course*, 212-227.

85 H.J.C. Ireton, “Find the Constant of a Ballistic Galvanometer,” October 29th. 1914, Ireton [0864-0879] B1992-0030_002, UTARMS; Faculty of Applied Science, Electrical Laboratory [Guide Book], c. 1912-1915, Lloyd [1321-1322] UTA 1481/ B1987-0070, UTARMS; Richard Hilton Lloyd, “Experiment- To find the Galvanometer (and Voltmeter) Constants,” [Lab Report], October 31, 1912, Lloyd 1347-1350 [UTA 1481/ B1987-0070], UTARMS.

86 H.J.C. Ireton, “Electricity and Magnetism – Slide Wire Bridge – Galvanometer,” October 7, 1913 (student report), B1992-0030 Box 1 File 20, UTARMS; R.H. Lloyd “Experiment I: To find the resistance of a conductor by the Wheatstone Bridge Method” October 10, 1912 (student report, B1988-0065 Box 2 File 1, UTARMS.

87 H.J.C. Ireton, “Exp’t 2 – Measurement of a Magnetic Field Galvanometer”, October 30, 1914, B1992-0030 Box 2 File 10, UTARMS.

88 Electrical Laboratories – Faculty of Applied Science, University of Toronto, “Second Year – Polarization and Recovery Test of a Cell,” *Department of Electrical Engineering Laboratory Experiments in Electrical Engineering* (University Press, Toronto, n.d.) R.H. Lloyd Fonds, B1988-0065 Box 2 File 1, UTARMS; University of Toronto, Department of Electrical Engineering, “Laboratory Experiments in Electrical Engineering,” Experiment Number 114 – Two methods of calibrating a ballistic galvanometer by a solenoid, and by a condenser (classwork publication, n.d.), C.S. Phelps Fonds B1994-0012 Box 2 File 6, UTARMS.

89 Electrical Laboratories –Faculty of Applied Science, University of Toronto, “Second Year – Galvanometer Resistance” (instructional pamphlet), R.H. Lloyd Fonds B1988-0065 Box 2 File 1, UTARMS; R.H. Lloyd, “Electrical Laboratory Report – Experiment To find Resist. of a Galv. By Thompson’s & Diminished Deflection Methods,” October 17, 1912, B1988-0065, Box 2 File 1, UTARMS; Electrical Laboratories – Faculty of Applied Science, University of Toronto, “Second Year – Battery Resistance,” R.H. Lloyd Fonds, B1988-0065, Box 2 File 1, UTARMS.

90 Electrical Laboratories – Faculty of Applied Science, University of Toronto, “Second Year – Battery Resistance,” R.H. Lloyd Fonds, B1988-0065, Box 2 File 1, UTARMS.

91 Electrical Laboratory – Faculty of Applied Science, University of Toronto “Experiment II- First Year Ohm’s Law,”; Electrical Laboratory – Faculty of Applied Science, University of Toronto “Experiment III, First Year Kirchoff’s Law II,” c. 1911-1915, R.H. Lloyd Fonds, B1988-0065, Box 1 File 4, UTARMS.

92 University of Toronto, Department of Electrical Engineering, “Laboratory Experiments in Electrical Engineering,” Experiment Number 14 – Two methods of calibrating a ballistic galvanometer by a solenoid, and by a condenser (classwork publication, n.d.), B1988-0065/002(08), UTARMS; Charles Stewart Phelps, “Laboratory Experiments in Electrical Engineering – Experiment No. 14,” Lloyd [1390-1393] UTA 1481/ B1987-0070, UTARMS; Charles Stewart Phelps, “Electrical Lab III – Exp. 115-126,” (Class notes) - Experiment 115: Determination of the saturation curve of a sample of iron or steel by the ballistic galvanometer method,” C.S. Phelps Fonds, B1994-0012, Box 2 File 6, UTARMS.

93 Richard Hilton Lloyd, “Electrical Laboratory Report: Experiment – Measurement of Temperature Coefficient of Resistance,” December 12, 1912 [Lab Report] R.H. Lloyd Fonds, B1988-0065, B1988-0065, Box 2 File 1, UTARMS.

94 Faculty of Applied Science, Instructions for Experiment – Murray’s Loop Test for locating a fault in a line. c. 1911-1915, R.H. Lloyd Fonds, B1988-0065, Box 1 File 4, UTARMS.

95 Sibum, ”Mechanical Equivalent,” 73-74.

96 See Ava Spurr, Chen-Pang Yeang, Patrick Finnigan, “Historical Application of Ballistic Galvanometers in Teaching Electrical Science and Technology,” September 26, 2023, UTSIC catalogue website: https://utsic.utoronto.ca/historical-application-of-ballistic-galvanometers-in-teaching-electrical-science-and-technology/

97 Leeds & Northrop Company, “Mirror Galvanometer (Leeds & Northrup),” UTSIC, artifact no. 2009.ph.21.1-4 (https://utsic.utoronto.ca/wpm_instrument/mirror-galvanometer-ph21/)

98 Jules Carpentier, “Wheatstone Bridge,” UTSIC, artifact no. 2017.ph.746 (https://utsic.utoronto.ca/wpm_instrument/wheatstone-bridge/)