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"DO NOT KILL GUINEA PIG BEFORE SETTING UP APPARATUS": THE KYMOGRAPH'S LOST EDUCATIONAL CONTEXT

Abstract: *The objects of science education are transformed, degraded and disappeared for many reasons, and sometimes take other things with them when they go. This close reading of an undergraduate physiology laboratory report demonstrates how the kymograph was never a stand-alone instrument, but intertwined with conceptual frameworks and technical skills, laboratory amenities, materials, animal supply, technicians, much of this costly or otherwise undesirable. Over the decades, improvers sought to eliminate many of these complications. But what else did they implicitly give up? The unwanted complications contributed to their own laboratory culture, and to a range of teaching and learning activities that no longer happen. They contributed to a hands-on and mechanically legible concept of "experiment" and "data" that contrasts markedly against the invisible mechanisms of electronic instrumentation. The reciprocity between progress and demise raises uncomfortable challenges for laboratory pedagogy, and also for curatorial practice: what is laboratory education really about, and what kinds of heritage should be preserved to document it?*

Keywords: *kymograph; history of education; teaching laboratories; laboratory pedagogy; obsolescence; historical scientific instruments*

„Dbejte, abyste morče nezabili ještě před seřízením aparátu!" Ztracený výukový kontext kymografu

Abstrakt: *Předměty, které jsou využívány ve˝výuce věd, podléhají transformacím, degradacím či celkovému ústupu z mnoha různých důvodů. Stává se také, že s sebou cestou strhávají i své okolí. Níže předkládaná analýza zápisů z vysokoškolské laboratoře fyziologie činí zjevným, že kymograf nikdy nebyl samostatně funkčním instrumentem, nýbrž že byl vetkán do sítě konceptuálních rámců, technické zručnosti, širšího laboratorního vybavení, potřebných materiálů, pokusných zvířat či také technických pracovníků. Mnohé z těchto věcí jsou nákladné či jinak problematické, a tak vylepšení, kterých se kymografu během několika desetiletí dostávalo, směřovala právě k odstranění původních komplikací. Co dalšího bylo ale s nimi potichu opuštěno? Odstraňované komplikace se ve skutečnosti podílely na vytváření svébytné laboratorní kultury, kdy na sebe vázaly celou řadu později opouštěných výukových aktivit. Spoluvytvářely koncept bezprostředního a hmatatelného „experimentu" a přímo zakoušených „dat", tedy něco zcela odlišného od později preferovaných neviditelných mechanismů elektronické instrumentace. Nejednoznačnost vztahu mezi pokrokem a překonáváním stárnoucího klade laboratorní pedagogice stejně jako kurátorské praxi nepříjemné otázky: co výuka laboratorních prací ve skutečnosti obnáší a jaký typ vědeckého archivu by měl být pěstován, aby bylo svědectví o této praxi zachováno?*

Klíčová slova: *kymograf; historie vzdělávání; cvičné laboratoře; pedagogika laboratorních prací; zastarávání; historické vědecké nástroje*

ALISTAIR KWAN
Centre for Learning and Research in Higher Education
Faculty of Education and Social Work, The University of Auckland
Private Bag 92601, Symonds Street /// Auckland 1150
email / alistair.kwan@auckland.ac.nz

Charting the Leporine Pulse

The rabbit lay sleeping at Table number 8. The pulses of her heartbeat travelled, via a tube connected into her carotid artery, to a stretched rubber membrane. As the membrane undulated, almost imperceptibly, with the rabbit's pulse, a lever multiplied that subtle wobble into glorious sweeps of a sharp point that scratched a thin white trace onto paper blackened by soot. The five-student team stood by as the rabbit graphed her own heartbeat, and they watched again after cutting her vagus nerve, and still again while stimulating the nerve's cut end. What can we learn about the nature and practice of laboratory education by revisiting the hours that these students spent entraining a rabbit's heart to trace its own beat in 1942?

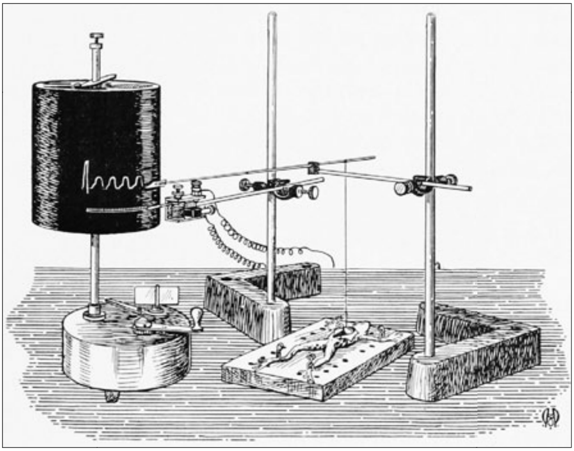


Figure 1: A kymograph driven by a frog's aorta (upper lever) and a clock (lower lever). From Dennis E. JACKSON, *Experimental Pharmacology*. St Louis, MO: C. V. Mosby 1917, p. 67. The kymograph shown is of the Harvard kind. The lever with a knob is for winding the spring, and the rectangular vane spins to engage with the surrounding air, limiting the spring-driven drum's speed. At the top of the axle, the knob allows the drum axle to be quickly engaged with, and disengaged from, the drive. When disengaged, it rotates freely for turning into position, or spinning by hand for rapid traces. The angled spring clip at the top of the drum holds the drum onto the axle. Pressing it down with a thumb while the fingers grip the spokes allows for single-handed adjustment of the drum's height on the axle, to set or re-set the base heights of the traces.

The students' central apparatus – a smoked-drum kymograph (see Figure 1) – was *the* device for visualising pulse, breathing, muscle action, nervous activity and other physiological actions. In research and teaching alike, the kymograph called for several tasks: preparing and connecting the animal, smoking the drum, balancing the mechanical parts and synchronising their activations to get a good trace, and then fixing the trace for interpretation. The animals came had to be bred, fed and supplied, necessitating a budget line that would today prompt questions about fiscal restraint. The kymograph itself required supplies, staff, storage space.

As the lynchpin of a network of scientists, students, technicians and scientific supply houses, the kymograph enabled a torrent of physiological, psychological and anthropological research, but it was never quite ideal. From the outset, researchers devised ever more ways to improve it. Its difficulties have been almost completely eliminated by electronic loggers and sensors that do away with the mechanical labours, and most of the electrical needs. Even the animals have been widely replaced: today's undergraduates stick disposable electrodes to themselves and each other, easing the demands on experimental technique, and re-situating students to where rabbits once slept. They no longer need the mechanical and surgical nous to set up, operate and maintain specimens and kymographs, nor the complications of benzene, smoke and varnish. But what of all those complications eliminated? Has improvement also transformed the concept of "laboratory work", for example, now that manual kymograph technique no longer needs perfecting? And how about the laboratory itself, now that the kymograph's logistical needs are gone?

This microhistory focusses on one of Moore's laboratory reports which reads, on the surface, as a straightforward report of a straightforward task. It can alternatively be read as a Bakhtinian chronotope overlaying not only multiple authors and readers, but also epistemes and subcultures.[1] The chronotopic richness will be uncovered through supporting materials: period textbooks and journal articles revealing teacherly intention, struggles, and the relationship between teaching and research. Such sources offer ways to seek out knowledge both within the local context and beyond it.[2] And, by including extant kymographs and their accessories among our primary

[1] Mikhail M. BAKHTIN, *The Dialogic Imagination*. Austin, TX: University of Texas Press 1981; David CLARKE, "Culture as a System of Subsystems." In: PEARCE, S. M. (ed.), *Interpreting Objects and Collections*. London: Routledge 1994, pp. 44–47.

[2] See e.g. Otto SIBUM, "Rewording the Mechanical Value of Heat." *Studies in History and Philosophy of Science*, vol. 26, 1995, no. 1, pp. 73–106.

sources, we can recover knowledge that inheres in the physicality of scientific instrumentation, including information absent from written texts.[3]

"Experiment 2 ... 18 March, 1942"

Blue-black ink, laid down by a stiff nib in a tense, controlled hand, passionlessly documents the student's laboratory work. The lined, large post quarto (8 in × 10 in) pages bear no watermark; they are a cheap exercise-book paper for only ephemeral intent. They are preserved now in a manila archive folder but worn, stretched holes in the left margin signal that the pages once resided in a ring- or post-binder. The author, H.R. Moore, wrote his name in the footers. This report is one of Moore's shortest, with hand-written paginations running from *a* to *d* (page *d* is blank), and appendix pages *i–vii*. Every lab report in the set is paginated independently, and the experiments also have numbers and titles – this is Experiment 2, "Recording of carotid blood pressure & of the effect of vagus stimulation". The number sequence, however, is erratic. Dates – in this case, 18 March, 1942 – signal that this was the second experiment of the term. Moore had missed the first experiment, having been absent in the first week.

The University records that Moore was a medical student, at this point in the third of his six years, taking his second physiology course.[4] The first physiology laboratory course, which he took a year earlier, had been designed around the students observing themselves and each other, sometimes connected to kymographs, making small traces only a few inches tall and not much longer. Many of these are pasted into Moore's laboratory notes for that year. Moore hence came to the advanced physiology class already knowing the basics of kymograph technique, plus animal anatomy from the zoology course, for which he had borrowed Buchanan's *Elements of Animal Morphology* four times in 1940 – a book "useful", he noted on the borrowing slip, "for practical work on the frog, dogfish & rabbit".[5]

On the report's first page, a table of "Staff" tells that Moore was the "Anaethetist" (sic) at Table No. 8, with four other students: Surgeon Howard, Assistent (sic) Surgeon Cocks, Mechanic Hamilton and Recorder Fitzpat-

[3] Davis BAIRD, *Thing Knowledge*. Berkeley, CA: University of California Press 2004.
[4] Harold Robinson Moore matriculated in 1939, graduated Bachelor of Medicine and Bachelor of Surgery in 1945, and became an allergist at the Royal Adelaide Hospital. A substantial collection of Moore's student work survives at the University of Adelaide: Harold R. MOORE, *Medical Student Records*. University of Adelaide Archives, Series 1553, 1937–1945.
[5] MOORE, *Records*, Item 6.

rick. Different reports show the group in different roles, presumably to allow everyone an opportunity to learn the full spectrum of skills.

"Anaethetist and Recorder administered 3.6 cc paraldehyde"

At 11:30 that morning, the Anaesthetist and Recorder administered 3.6 cc of paraldehyde, a drug that depresses the central nervous system to induce relaxation and sleepiness without greatly affecting respiration.[6]

The University of Michigan *Laboratory Guide* by Edmunds and Cushney directs 1.7 cc paraldehyde per kilogram of body weight (slightly less than the students administered) by gavage, i.e. by tube into the stomach. It is a job for two: "While your assistant holds up the animal by all four legs and head, place a gag in the mouth and pass a stomach tube through the opening in the gag, being very careful not to pass it into the lungs. Draw the paraldehyde into a pipette and place the point of the pipette in the opening of the stomach tube and blow the drug into the stomach, and then withdraw the tube."[7]

At Adelaide, anaesthetisation was valued as a learning experience. Physiologist and nutritionist Cedric Stanton Hicks recalls how, in his early years teaching there, he and colleagues developed – via "much trial and error" – a safe and reliable method, good for teaching. It could be done by just one student, with the rabbit secured in a holding-box and with a wooden guide in its mouth to prevent it from chewing the gavage tube. It took skill to slide the tube in the right direction, and, for this, students needed guidance. The laboratory technician, Ernest "Eldridge watched over this stage with all the native skill for which he was known, and in the end students learned the "feel" of the catheter as it was inserted."[8] After that, the anaesthetist kept watch over the rabbit's body, applying ether to the muslin face-mask as needed. Cannon's *Laboratory Course* directs the anaesthetist to watch the eyes and abdomen in particular, and has the student shoulder responsibility:

[6] Francisco LÓPEZ-MUÑOZ – Ronaldo UCHA-UDABE – Cecilio ALAMO, "The History of Barbiturates a Century after Their Clinical Introduction." *Neuropsychiatric Disease and Treatment*, vol. 1, 2005, no. 4, pp. 329–343.

[7] Charles W. EDMUNDS – Arthur R. CUSHNY, *Laboratory Guide in Experimental Pharmacology: Directions for the Course Given in the University of Michigan*. Ann Arbor, MI: G. Wahr 1905, pp. 11–12.

[8] Cedric S. HICKS, *Sir Cedric Stanton Hicks Papers*. University of Adelaide Special Collections, MS 572.9942, Item 9, p. 6. The implementation of these procedures is attested by laboratory records by student Roy Muerke, dated 1929, kept with the Hicks papers.

"If through carelessness of the anaesthetist the animal is killed, he must pay for another."[9]

Following anaesthetisation, there is a seventy-minute gap before the next entry.[10] Perhaps the students ate lunch. And they, or someone, must have readied the rabbit and kymograph.

Time	Event	Trace
11:30	Paraldehyde administered.	
12:40	Neck incision.	
1:00	Tracheal ligature.	
1:10	Left common carotid ligature.	
1:26	Right vagus ligature.	
1:28	Right external jugular vein cannula.	
1:37	Left common carotid artery cannula.	
1:40	Normal tracing.	1
1:42	Vagus cut.	2
1:44	Blockage of cannula.	3
1:46	Stimulus to vagus – central end.	4
1:47	Weak stimulus to vagus – distal end.	5
1:48	Strong stimulus to vagus – distal end.	6
1:50	Very strong stimulus to vagus – distal end.	7
2:00	0.5 cc 1 : 10,000 adrenalin, then saline.	8
2:02	Stimulus to vagus as in trace 7.	9
2:15	Normal tracing.	10
2:16	1 cc 1 : 1,000 atropin.	11
2:17	Stimulus to vagus as in trace 7.	12

Table 1: Experiment chronology recorded by the student. MOORE, *Records*, laboratory report for Physiology II, Experiment 2.

[9] Walter B. CANNON, *A Laboratory Course in Physiology.* 2nd ed., Cambridge, MA: Harvard University Press 1913, p. 90. Cannon's experiments are predominantly on frogs rather than mammals; this was due to ill-informed influence from Boston's anti-vivisection lobby, according to Yandell HENDERSON, "A Laboratory Course in Physiology [Review]." *Science*, vol. 35, 1912, no. 900, p. 504 (504–505).
[10] See the Table 1 for timings.

"Instruments of precision"

By the time Moore did this experiment in 1942, kymographs were long established in education. They performed the same roles as in 1869, when London physiologist William Rutherford championed the pedagogical progress afforded by these "instruments of precision," explaining to his introductory physiology class that "we no longer estimate the force of the heart's action by merely feeling the pulse, or by observing the distance to which blood is projected from a divided artery [...] movements are recorded on revolving cylinders or flat surfaces, so that a tracing, or writing, indicating the character and extent of the motion, may be preserved."[11] Kymographic tracing represents the temporal domain in a spatial one, freezing the motion for closer, thoughtful examination of "character and extent", i.e. of shape, duration, rate and strength.

Over the years, kymographs had undergone considerable development, though the sort produced since the 1890s by the Harvard Apparatus Company was typically the referent for any researcher advancing improvements or adaptations.[12] Harvard kymographs comprised a crank-wound clockwork base, and a set of four air-stirring vanes to control the rotation rate. The drums are aluminium. A glance inside reveals that they were cast initially as rough sheet, then curled and welded into cylinders whose exteriors were then turned smooth.[13] Since the beginning, sellers and researchers have specified the drums by circumference to reflect the instrument's intended use, viz.

[11] William RUTHERFORD, "Introductory Lecture to the Course of Physiology in King's College, London, 1869." *The Lancet*, vol. 94, 1869, no. 2407, pp. 533–535.

[12] For the kymograph's early history, see e.g. Hebbel E. HOFF – L. A. GEDDES, "Graphic Registration before Ludwig; The Antecedents of the Kymograph." *Isis*, vol. 50, 1959, no. 159, pp. 5–21; Angela de LEO, "The Origin of Graphic Recording of Psycho-Physiological Phenomena in Germany." *Physis: Rivista internazionale di storia della scienza*, vol. 43, 2006, no. 1–2, pp. 345–362; Osman FAROOQ – Edward J. FINE, "An American Physician-Physiologist Who Had Profound Impacts on Physiology and Medical Education in the United States." *Journal of the History of the Neurosciences*, vol. 22, 2013, no. 2, pp. 219–224; John R. BROBECK – Orr E. REYNOLDS – Toby A. APPEL (eds.), *History of the American Physiological Society: The First Century, 1887–1987*. New York: Springer 1987, pp. 42–43; Merriley BORELL, "Instruments and an Independent Physiology: The Harvard Physiological Laboratory, 1871–1906." In: GEISON, G. L. (ed.), *Physiology in the American Context, 1850–1940*. New York: Springer 1987, pp. 293–321.

[13] Porter described an early model as having been "cast in one piece" as if the drum would have no seam: William T. PORTER, "An Improved Kymograph." In: *Proceedings of the American Physiological Society, Sixteenth Annual Meeting*. Philadelphia, PA: American Physiological Society 1903, pp. xxxix–xli.

to carry paper for traces of a particular length, in contrast to specifying the diameters that matter during manufacturing.

Students used kymographs for much the same activities as researchers did – tracing phenomena like pulses, muscle movements and breathing patterns, though with pedagogical rather than expert goals. For medical students, "the physiological laboratory serves as the portal to the clinic," explains Fraser's textbook preface. It "teaches how to interpret the relationship between structure and function." She explicitly commits to both "experiment" and "demonstration" as essential complements to theoretical study because, "in a highly practical science like medicine, theoretical knowledge by itself is valueless and without meaning." But educators are coy about exactly what meaning hands-on laboratory work teaches that a textbook or lecture does not. The preface to Busch's *Laboratory Manual* asserts that "one of the main benefits to be obtained from laboratory work is the training in methods of exact observation which the students receive." As for the other main benefits, Busch says no more.

Although similarly elusive, William Porter, physiology instructor at Harvard and founder of the kymograph-manufacturing Harvard Apparatus Company, left many rousing lines to read between. In 1901, he endorsed the "just contempt for men who profess to have learned disease without practical observation of the sick [...] but the public is ready to applaud, and even to compel by law the study of the same organs in their normal state by reading or hearing a description at second hand of what some third person saw." Porter's discomfort with that double standard originated in his deeper commitment to the nature of scientific knowledge and the inadequacy of language for fully representing concepts. Porter conceptualised physiology as dealing "with phenomena, not with words. Many of these phenomena, for example the heart-sounds, cannot be described; others can be pictured dimly, but only to those who know related phenomena from having actually seen or otherwise sensed them; in no case can lectures properly instruct unless the fundamental facts or closely related facts have first been learned by actual observation in the laboratory." Actual observation, then, is Porter's reason for laboratory study because actual observation is what physiology is: "Deal so far as possible with the phenomena themselves, and not with the descriptions of them."[14]

[14] Lois M. FRASER et al., *A Laboratory Manual of Experimental Physiology (including General Physiology)*. Toronto: University of Toronto Press 1922, pp. 3–6; Frederick C. BUSCH, *Laboratory Manual of Physiology*. New York: William Wood and Company 1905, p. iii; William T. PORTER, "The Laboratory Teaching of Physiology." *Science*, vol. 14, 1901, no. 354, pp. 567–570.

A simple kymograph setup, indicative of the overall principle, is shown in Figure 1. The kymograph proper is just the drum and its engine; in this case a spring-driven Harvard model. Generic clamp stands each support a writing-lever. The upper writing-lever is driven by a frog's aorta, to which it is tied by a silk thread while clips hold the creature down on the frog-board. (Chances are that the frog had been etherised and pithed, i.e. its brain scrambled using a needle inserted under the back of the skull.) Tugged by the frog's heart, the stylus traces out the shape and rhythm of the pulse. The lower lever traces a time signal, driven by a clock at the end of the coiled wires. The clock's signal energises the clamped electromagnet, which flicks the short writing-lever regularly up and down to mark time on the trace.

For responsiveness to such weak movements, the levers had to be rigid and light. Judging from period manuals, sales catalogues and research literature, a wide range of materials served well: bamboo slivers, "straw" that may have been thin reeds or drinking straws, stiff piano wire, aluminium. Though it was possible to buy straw prepared specially for kymographs, it was apparently common to make the levers locally from whatever convenient materials served the purpose. Such improvisation from cheap, perishable materials renders devices ephemeral, and survivors, especially broken ones, soon become indistinguishable from scraps and packing materials. A fragment of one endures at Adelaide, identity intact: a short length of flattened grass stem remains bound by thread to a metal kymograph lever-hinge.[15]

A scratchy writing-point, if it was not just the tip of the lever arm, was improvised and stuck on with wax or glue: writers variously mention an elongated pentagon or triangle of stiff parchment, waxed paper or photographic film, a steel phonograph needle, a glass filament, a strip of tinsel. Zoethout's *Laboratory Experiments* says that parchment is especially good because "it does not have a tendency to 'fuzz'."[16] The do-it-yourself attitude is

[15] Commercially prepared bundles of hollow, reed-like straw accompany the kymographs at Groningen's University Museum, and at the University of Sydney's Macleay Museum.

[16] PORTER, "The Laboratory Teaching of Physiology," p. 56; CANNON, *Laboratory Course*, p. 10; Grosvenor HOTCHKISS, "Electrosensitive Recording Paper for Facsimile Telegraph Apparatus and Graphic Chart Instruments." *Western Union Technical Review*, vol. 3, 1949, no. 1, p. 15 (6–15); Fredrick F. YONKMAN, "Improved Kymograph Recording." *Science*, vol. 77, 1933, no. 1989, p. 172 (172); C. V. HUDGINS – E. H. STETSON, "A Unit for Kymograph Recording." *Science*, vol. 76, 1932, no. 1959, p. 52 (59–60); Christian PAULITSCH, *Psychological Instruments*. Münster: Monsenstein und Vannerdat 2011, p. 23, 71, 72; William D. ZOETHOUT, *Laboratory Experiments in Physiology*. St Louis, MO: C. V. Mosby 1934, p. 26. A more recent high school textbook suggests cutting a writing-point "from the plastic top of a coffee or baby food tin": H. S. LUKER – A. J. LUKER, *Laboratory Exercises in Zoology*.

clear, and it brings us to Australia where, in addition to the instrumentation imported from Britain, Europe and the United States, impromptu improvisations were perhaps more usual owing to inconvenient supply lines. As for what the Moore might have used at Adelaide: a handful of plastic writing-points survive, cut from at least three kinds of thin plastic sheet, perhaps including the cellulose points originally shipped with the Palmer-made signal writers (Figure 2).

Figure 2: A signal writer with a plastic writing-point, University of Adelaide Heritage Collections. A current through the electromagnet moves the lever. This particular signal writer has two independent electromagnets, allowing two independent traces.

London: Butterworth 1971, p. 197. The Museum of Victoria describes a 1960s research kymograph in its collection as having a "straw of glass fibre": MUSEUM OF VICTORIA, Item HT 2788: kymograph [online]. Available at: <http://collections.museumvictoria.com.au/items/288347> [cit. 24. 5. 2016].
An especially beautiful Kagenaar kymograph (object bk0040_01.dc) in the Cushing-Whitney Medical Historical Library has levers of metal foil that taper down to writing-points now rippled with bending and re-bending over the instrument's working life.

"A real challenge to the uninitiated"

Novices found the kymograph complicated, and it could be daunting to teach: Alvah McLaughlin, who taught pharmacology at Michigan State College, reflected in 1928, "Most instructors, who have tried to explain to the student in the laboratory [...] how to arrange the writing-points of the signal-magnet and of the muscle-lever in the same vertical line, open the switch, pluck the tuning fork and spin the drum a single revolution only, have been struck by the look of dismay upon the student's face."[17] Even for a doctoral student in the 1970s, mastering kymographs was no minor feat: studying at Buffalo, physiologist Gordon Bolger found that kymograph technique "posed a real challenge to the uninitiated. [...] I always felt that I should have received, along with my colleagues, a merit award for our successes in using it." Bolger surmised that his advisor used the instrument also to measure competence, for "failure to negotiate the smoked drum kymograph meant you did not get to stay in his laboratory."[18]

The first step was to wrap paper around the drum. Cannon's *Laboratory Course*, a 1910 compilation of the laboratory pamphlets that he taught from at the Harvard Medical School, says to lay the rectangle of glazed paper flat on the table, shiny side down, and to place the kymograph cylinder across it in the middle. The ungummed end is pulled taut over the drum. That end is held firmly in place while rolling the drum forwards onto the other end. If the alignment is good and the paper still taut, the gummed edge is moistened and the overlap sealed. Fraser's *Laboratory Manual* cautions that the paper has to be wrapped in the right direction so that the writing-point does not catch on the overlapped edge.[19]

The glazed surface must face outwards to provide the writing-point with a low-friction surface. Palmer's apparatus catalogue calls it a "special surface for smoking". It could have been prepared by gelatin sizing and calendaring, i.e. pressing between hot, smooth rollers (calenders), two long established practices that match the surviving paper's dense, fine texture.[20]

17 Alvah R. MCLAUGHLIN, "A Weight-Driven Kymograph." *Science*, vol. 68, 1928, no. 1751 p. 62 (62–64).

18 Gordon T. BOLGER, "From B.Sc. To Ph.D., My Shuffle off to Buffalo." *Biochemical Pharmacology*, vol. 98, 2015, no. 2, p. 285 (283–291).

19 CANNON, *Laboratory Course*, p. 9; FRASER et al., *Laboratory Manual*, p. 12. Cannon remained in circulation through to the time of our student Moore, reaching its tenth edition in 1942.

20 Dard HUNTER, *Papermaking through Eighteen Centuries*. New York, NY: W. E. Rudge 1930, p. 140.

Well-provisioned physiologists did not, however, have to worry about any of this: kymograph paper simply came that way.[21]

In nineteenth-century Australia, glazed paper had been hard to source. "In Europe I suppose one would have no difficulty in procuring a better article," grumbled Sydney physiologist T. P. Stuart, prefacing his realisation that local newspapers were printed on smooth paper that just might work. In a moment of self-help liberation, he asked a printer for a remnant to try on the kymograph and found it "to be the best I had ever seen for the purpose."[22]

Speed and deftness concerned Boston University Medical School physiologist F. H. Pratt who thought to eliminate the need to wet the paper's gummed end. Inspired by self-adhesive envelope flaps, he pre-brushed a stripe of liquid latex onto each end of the paper rectangle, on opposite sides. It could be done months in advance, easing prep time in the laboratory. The two latex stripes stick as soon as they are brought into contact. The latex seal stood up to handling and smoking, and was easily peeled apart for removal. Importantly, Pratt explained, pre-brushing with latex "not only saves time for the student, but contributes distinctly to neatness in technique."[23]

Once the drum is covered, the next step is to smoke the paper. A steady flame is needed, spread out into a flat sheet (Figure 3), and the paper is held in the yellow part where combustion is not yet complete. Cannon's directions ring with kinaesthetic timbre: "Support the rod [i.e. the drum axle] by the first two fingers of each hand with the tips of the fingers pointed downward toward the body. Let the rod roll down the fingers and be caught each time before it is in danger of rolling off. [...] Lower the drum into the upper edge of the flame and rotate it slowly and evenly until the glazed surface is covered with a chocolate-colored film of smoke."[24]

[21] E.g. ARTHUR H. THOMAS CO., *Laboratory Apparatus and Reagents Selected for Laboratories of Chemistry and Biology*. Philadelphia: Arthur H. Thomas Co. 1921, p. 55, 475; C. H. STOELTING CO., *The Great Catalog of the C. H. Stoelting Company, 1039–1937*. C. H. Stoelting Company 1930, p. 106; C. F. PALMER (LONDON) LTD, *Research and Students' Apparatus for Physiology, Pharmacology, Psychology, Bacteriology, Phonetics, Botany, Etc.* London: C. F. Palmer 1934, p. 14, 29, 138.

[22] T. P. STUART, "On Some Improvements in the Method of Graphically Recording the Variations in the Level of a Surface of Mercury, e.g. In the Kymograph of Ludwig." *Journal of Physiology*, vol. 12, 1891, no. 2, p. 156 (154–192).

[23] F. H. PRATT, "Use of Latex Dry Adhesive for Kymograph Paper." *Science*, vol. 89, 1939, no. 2321 (590).

[24] CANNON, *Laboratory Course*, p. 9.

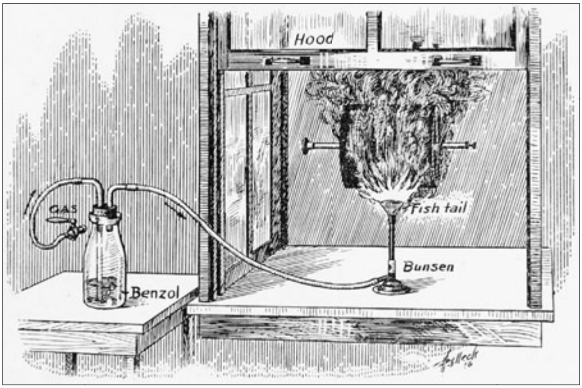


Figure 3: Smoking a kymograph drum over a fish-tail burner. The gas is bubbled through benzol in a one-pint milk bottle to increase the smokiness. The experimenter's hands are not shown here. JACKSON, *Experimental Pharmacology*, p. 61. Fishtail burners were widely advertised for glassblowing, so laboratories may have re-purposed existing stock instead of needing to buy a special one just for smoking kymograph drums.

"A light chocolate color" is preferred, explains Fraser, "because there is less danger of burning the paper."[25] Washington University physiologist Hubert Peugnet added that a cooler flame made for a thinner, less clingy film of soot that could be scraped with much less writing-point pressure, and did not pile up on the writing-point so quickly.[26] Soot blobs on the writing-point mattered because the made the line progressively thicker as plotting progressed.

As Cannon's instructions demonstrate, smoking a kymograph was quite a craft. Craft takes practice, practice takes time, and time is scarce. That scarcity was sidestepped by innovation. Blotchy coverage, for example, could be mollified by a wide burner with a row of many small flames, or by a single flame that oscillated automatically back and forth while a stand held the drum at exactly the right height. That eliminated also a second problem: novices commonly corrected blotchiness with extra smoking, ultimately

25 FRASER et al., *Laboratory Manual*, p. 12.
26 Hubert B. PEUGNET, "An Improved Gas Burner for Smoking Kymograph Paper." *Science*, vol. 93, 1941, no. 2426, p. 626 (625–626).

making the soot too thick.[27] Innovation also addressed problems other than poor skill. Flame-fluttering drafts could be blocked by metal skirts. Peugnet deemed his skirts so good that a higher quality of paper was needed to do the flame justice.[28] If the gas burned too cleanly, it could be bubbled through benzene or benzol to produce more smoke.[29] If gas was inconvenient, an experimenter could use a kerosene burner with a wide strip of wick.[30]

Smoke got everywhere. "Both the experimenter and the instructor [are] confronted with the necessity of smearing the paint[work] and equipment of the laboratory as well as the clothing of the students with the excess soot," complained Griffith Williams at Rochester's Psychology Department. He responded by designing a cheap fume hood to enclose the smoking apparatus, using a second-hand vacuum cleaner to suck the fumes out through a window. Reconditioned vacuum cleaners were plentiful as the middle class pursued the latest domestic trends, and the used vacuum cleaner dealer, promised Williams, would "also furnish, usually without extra charge, any reasonable length of hose."[31] Within two years, Edgar Jones at Akron shaved another dollar off the price by recycling a packing-crate (which made the smoker portable), and choosing a particular Hoover model available for only $6 reconditioned. Choosing a Hoover meant that neither window nor hose was needed: "Great was our satisfaction to find that the sweeper's sack would retain all carbon, even if benzene were used!"[32]

To eliminate the flames completely, soot could be sprayed on. One researcher recommended suspending 16 g of vegetable black per litre of volatile carrier, ideally carbon tetrachloride for its quick evaporation and well-matched density though, citing the same monetary concerns that saw Williams and Jones price-checking second-hand vacuum cleaners, they conceded that cheap naphtha, formulated for cleaning, would do. The mixture was to be shaken hard, then strained through a fine cloth into household preserving jars that screwed onto a common spray gun. The suspension was

[27] Shepherd I. FRANZ – Thomas A. WATSON, "Apparatus for Smoking Kymograph Drum Papers." *Journal of General Psychology*, vol. 2, 1929, no. 4, p. 509 (509–515).
[28] PEUGNET, "An Improved Gas Burner."
[29] FRANZ – WATSON, "Apparatus for Smoking Kymograph Papers," pp. 509–513. See also Figure 4.
[30] PAULITSCH, *Psychological Instruments*, p. 25; C. F. PALMER (LONDON) LTD, *Research and Students' Apparatus*, p. 29, 135.
[31] Griffith W. WILLIAMS, "Simplified Equipment of Smoking Kymograph Drums." *Science*, vol. 81, 1935, no. 2106, pp. 465–466.
[32] Edgar P. JONES, "A Portable Hood for Smoking Kymograph Drums." *Science*, vol. 85, 1937, no. 2208, p. 412.

sprayed, from a distance of a foot or two, onto a rapidly spinning drum.[33] It is hard to imagine how the soot made any less mess this way.

Figure 4: Smoking burner at Adelaide, made by Palmer (London). There are three of these in the Adelaide Heritage Collections: this one 22 cm wide, and two others 15 cm wide. The holes of all three are 1 mm in diameter, centres spaced 2 mm apart. The lower end is a capsule for benzol.

[33] W. F. WICHART – C. H. THIENES – M. B. VISSCHER, "Two Improvements in the Technique of Kymograph Recording." *Science*, vol. 73, 1931, no. 1882, pp. 99–100.

The cleanest solution was undoubtedly to outsource the smoking altogether. Pre-smoked kymograph paper could be bought coiled in cans, with instructions on how to unpack and unfurl the strips without harming their precious coating.[34]

The Adelaide students' traces are much darker than a light chocolate brown, and our best guess for their smoking method is that they were blackened over gas burners as shown in Figure 4. Three of these survive in Adelaide's collections, in two sizes. The burners could be hand-held or mounted on a stand beneath the rotating drum. With only a few burners available, students may have had to wait to take turns.

Once smoked, paper had to be trimmed flush with the drum. This was done with a knife, Cannon explains, run along the drum's edge so that the drum and the blade act together like a pair of scissors. In the era of mass-produced kymograph paper, however, this step may not have been necessary. The Adelaide drums include many with rounded edges, unsuited to scissor action, and a band of soot extends about 2 cm in from each end. There are no cuts or scrapes into the drum edge as would be expected from running the knife in too hard, too fast or at the wrong angle. It appears that, at Adelaide, the paper was narrower than the drums, and already of the right width.

The students needed also a timing signal. There are various ways to scratch a timing trace onto the drum, the most direct being to use a writing-point attached to a tuning fork. As the fork vibrates, it inscribes a wave into the soot film. Obviously, a tuning fork will lose its energy, so it receives a magnetic pulse on each vibration to re-energise its hum. A fork is also very fast, so it is good only for very fast phenomena. To time a heartbeat requires

[34] PAULITSCH, *Psychological Instruments*, p. 27. Some others avoided smoking altogether by devising writing-points that deposited ink onto cellophane or paper. These writing points could be drawn from glass tubing, or flexible steel pen nibs. For example, see YONKMAN, "Improved Kymograph Recording"; Ralph GERBRANDS – John VOLKMANN, "A Wax-Paper Kymograph." *American Journal of Psychology*, vol. 48, 1936, no. 3, pp. 498–501; K. U. SMITH – Samuel FERNBERGER, "Glass-Capillary Ink-Writing Markers for Use in Kymograph Recording." *Journal of Experimental Psychology*, vol. 23, 1938, no. 4, pp. 434–438. A few ink-pens, improvised from rubber tubing and fine metal tubes (perhaps hypodermic needles), survive in Sydney's Macleay collections.
Electrical writing was also devised to do away with both smoke and ink, both by sparks burning holes into paper (the sparking frequency could double as a timing reference), or on paper that turns black when a voltage is applied across it – see Adelbert FORD – John B. WATSON, "Recording Apparatus: The Electro-Kymograph." *Journal of Experimental Psychology*, vol. 7, 1924, no. 2, pp. 157–163; George L. MAISON – Hans O. HATERIUS, "The Application of Electrical Recording Methods to the Student Laboratory for Physiology and Pharmacology." *Journal of the Association of American Medical Colleges*, vol. 22, 1947, no. 4, pp. 200–209.

a slower clock. At Adelaide, there may have been some choice: the heritage collections there contain an adjustable vibrating reed, and several models of electrical signal clocks.

The adjustable reed is a long, flat leaf spring with a weighted end. It wobbles up and down, and a spike through the weight enters a pool of mercury on each down-stroke, completing an electrical circuit through the reed itself. The oscillation frequency can be varied by sliding a clamp that limits how much of the reed is free to swing, and hence how quickly it moves – for the same mechanical reasons that shorter pendula swing faster. The Adelaide reed can be varied between 2 and 20 oscillations per second. Whenever the circuit closes, the electromagnetic signal writer (Figure 2) is engaged, and the attached writing point jerks sideways against the drum.

The direct-writing electrical clocks offer markings every 1/10, 1, 5, 10, 30, 60 seconds. These devices depend on the frequency of the AC mains supply to power the motors (so the frequency has to be advised when ordering), which are geared down to the required rates. Some of the clocks energise signal-writer electromagnets; others have a small stem of their own, on which to attach a lever arm with a writing point.

"Neck incision 12.40 p.m."

It is not clear where the rabbit came from. Records for the Darling Building, where the medical school held its laboratory classes, record amenities for breeding mice and frogs, and incubating chicken eggs, but not for rabbits.[35] The University's financial accounts from the 1920s briefly mention rabbit supply and a caretaker who offered to breed rabbits for Physiology in his free time. Professor Robertson suggested in 1924 that they be bred at the Waite Agricultural Research Institute, established by the University in that same year, but the issue recurs, apparently unresolved, in 1929 in association with discussions about saving money. By the 1940s, the rabbit supply vanishes from discussion, even in the wake of wartime resource constraints.

Wherever the rabbit came from, its weight was noted as part of the anaesthetisation procedure. Though they never seem to make use of the information, the students record also the rabbit's sex. This one was a doe. They did similarly for other specimens, too, including their own a year earlier. When measuring his own metabolic rate, Moore methodically logged his

[35] Thorburn B. ROBERTSON – Walter H. BAGOT, *An Account of the Darling Building of the University of Adelaide*. Adelaide: University of Adelaide Council 1922, p. 5, 11, 15, 106.

own height and weight as 5 ft 4 in, 141 lb, and those of his towering partner Fitzpatrick's as 6 ft 2¼ in, 159 lb. The clinical objectivity is broken only once in the two years' records: "Rabbit obviously frightened."

"The rabbit was prepared according to instructions," Moore wrote down. We no longer have those instructions but can surmise that the students learnt how to open and navigate within a rabbit during earlier biology courses. Judging from a selection of period laboratory manuals in Adelaide's library and elsewhere, the process seems to have been reasonably standard.[36]

Cannon explains how to get started. First, the rabbit is laid on its back and its head and limbs secured to anchor points on a purpose-made board. Then the neck must be shorn: "make a series of snippings as the scissors are moved forward close to the skin. Gather the cut hair from the blades and deposit it in a pan. Repeat the procedure until only short hairs cover the surface."[37] Photographs of Adelaide students at work survive from 1929 and 1938, in one of the two downstairs laboratories in the Darling Building (Figure 5). Those two rooms had distinctive wedge-shaped benches around the outside of the room, shaped so that students sitting side-by-side would not cast shadows on each others' microscopes. Though an advanced physiology laboratory space had been planned upstairs, the students were clearly not working there, but rather at narrow white benches crammed into the microscopy rooms downstairs. The 1929 photograph shows the outstretched animal at one end of the table and, on the shelf below, the pile of white hair just shaved.[38]

The first cut was made at 12:40, seventy minutes after anaesthesia began.

As a supplement to the textbook instructions, we could look to the notebook of another Adelaide medical student, Roy Muerke. Thirteen years earlier, Muerke documented the process with finer details than the textbooks provide.[39] First, the surgeon must isolate the right carotid artery and left vagus nerve, and insert a tracheal cannula. The cannula conveys ether fumes directly to the lungs – the technique had clearly advanced since

[36] For a list of basic dissection exercises that should be mastered before pursuing experimental physiology, see, for example, Edward A. SHARPEY-SCHÄFER, *Experimental Physiology*. London: Longmans, Green and Co. 1918, pp. 1–2. The prescribed rabbit dissection exercises include a study of the nerves and blood vessels in the neck and around the thorax, providing opportunity to learn which of the many structures are the carotid artery and vagus nerve.
[37] CANNON, *Laboratory Course*, p. 91.
[38] HICKS, *Papers*; ROBERTSON – BAGOT, *Account of the Darling Building*, p. 7.
[39] Muerke's notes are included in HICKS, *Papers*, Series 13. Hicks was the instructor when Muerke took the course.

the muslin face-mask of only a few years earlier. Some of the air flowing into the cannula passes over ether in a bottle, while the rest goes directly. The anaesthetist can adjust the blend of fresh and etherised air, controlling dosage more than is possible by dripping ether onto a muslin mask.

Figure 5: Students working in the Darling Building, University of Adelaide, 1929. The kymographs are adapted from the original Harvard instruments. In HICKS, *Papers*.

Ligatures are passed under the trachea and key nerves and arteries to mark them out from surrounding structures and to provide handles by which to lift them up and close them off later. Moore records the tracheal ligation at 1:00 pm, twenty minutes after the first incision, a ligature on the left carotid at 1:10, vagus ligature at 1:26. The rabbit remained open throughout, of course, and the surgeons had to keep its innards from drying out by applying a saline solution whenever needed.

We do not know much about what dissection apparatus the students used – whether they bought and maintained their own kits, or whether the laboratory provided these tools. At the least, they needed scissors, scalpels, dissectors, needles both sharp and blunt, forceps. Occasionally the textbooks mention improvising other items, too, like using bits of paper as signal-flags that make the heartbeats more visible.

The students cannulated the jugular and carotid at 1:28 and 1:37. This involved stemming the flow by tightening one of the ligatures around each artery, cutting a flap in its wall, slipping the cannula in, tying a second ligature to seal the cannula in place, and filling the cannula with a solution of sodium carbonate or bicarbonate (depending on which textbook one follows). It was a job for two – which explains the need for both a surgeon and an assistant surgeon in Moore's team rosters.[40]

The cannula then needed to be joined to the kymograph. This was done hydraulically. The celebrated seminal configuration that Ludwig published in 1847 used rubber tubes to convey the arterial pressure, via sodium carbonate solution, to a mercury manometer.[41] Atop the mercury rode a float, from which a long vertical rod extended upwards to scrape the trace onto the revolving drum. This method was not quite perfect – the trace was small, and the float often became stuck in the manometer as mercury worked its way up around it. Contrivances to hold the writing-point against the drum introduced asymmetries, increasing the chances of the mercury jamming the float. Various improvements were proposed such as better float designs, and guides for the struts and writing-points.[42]

Having the bicarbonate solution reservoir on the side allowed for calibration. Raising or lowering the reservoir adjusted the reference pressure in the manometer, raising or lowering the float to a useful height. This could be done to trace horizontal reference lines on the kymograph for quantifying the pulse pressure later.

From their first cut, the students took forty minutes to connect the sleeping rabbit with the kymograph.

Had they been using the University's original Harvard kymographs – twenty-five had been bought when fitting out the Darling Laboratories in the 1920s, along with twenty-five Harvard inductoria for attenuating and transmitting electrical signals[43] – the students would have first wound the spring, then released the brake after activating the clock signal. With all

[40] CANNON, *Laboratory Course*, p. 92; Charles S. ROY, "The Form of the Pulse-Wave: As Studied in the Carotid of the Rabbit." *Journal of Physiology*, vol. 2, 1879, no. 1, p. 71 (66–81).
[41] Carl LUDWIG, "Beiträge zur Kenntniss des Einflusses der Respirations-bewegungen auf den Blutlauf in Aortensystem." *Archiv für Anatomie, Physiologie und wissenschaftliche Medicin*, vol. 13, 1847, pp. 242–302. The same configuration was recommended by some twentieth century textbooks, e.g. Francis A. BAINBRIDGE – James A. MENZIES – Hamilton HARTRIDGE, *Essentials of Physiology*. London: Longmans, Green and Co. 1931, p. 138.
[42] STUART, "Improvements."
[43] ROBERTSON – BAGOT, *Account of the Darling Building.*

these steps in addition to the detailed set-up of levers and connections, it is no wonder that Harvard kymographs inspired so much self-help literature. Researchers and educators strove to adapt the device, making small changes for better ergonomics and workflow (the winding lever could be bent to prevent the knob from catching during tracing runs, for example, and the drum's spring catch modified for better tension control), and also much larger adaptations such as axle-mounted activators for triggering stimuli, or swapping the clockwork for an electric motor.[44]

By 1942, it is possible that students were using the new electric kymographs and tambours bought from Palmer. Tambours are little metal funnels; the narrow end connects to the cannula or another hydraulic pressure source, and the mouth is closed with a rubber membrane. Over the decades, rubber is lost to its own natural decay, but a few tambours (see Figure 6) survive in the Adelaide collections with red rubber remnants still attached. Some manufacturers offered clip-on and screw caps for holding the membranes in place; at Adelaide, they were tied on with thread.

Figure 6: A tambour, made by Palmer, in the University of Adelaide Heritage Collections. Some fragments of the rubber membrane have survived natural degradation, as has the binding of thread that held it in place.

[44] BUSCH, *Laboratory Manual of Physiology*; George BACHMANN, "An Automatic Spinning Device for the Harvard Kymograph." *Journal of the American Medical Association*, vol. 66, 1916, no. 3, pp. 188–188; W. A. HIESTAND, "A Commutator for the Harvard Kymograph." *Science*, vol. 81, 1935, no. 2103, pp. 382–383; N. W. ROOME, "Simple Synchronous Motor for the Harvard Kymograph." *Science*, vol. 84, 1936, no. 2169, pp. 91–92; Hugh B. MCGLADE, "Improvements in the Harvard Spring Kymograph." *Science*, vol. 91, 1940, no. 2365, p. 412.

As the tambour pressure rises and falls, the membrane swells and recedes. Like the mercury manometer, the tambour movement attenuated the motion, in this case by all three of spreading it over a wide area, the compressibility of air, and by resistance from the membrane's elasticity – the larger the tambour and the firmer the membrane, the greater the attenuation. Via a light cork or metal strut, the pulsing membrane pushes a lever, whose sweeping end carries the writing-point up and down with the physiological signal. In our students' case, this whole process is driven by the rabbit's pulse which the tambour diminishes, and the lever then multiplies, giving experimenters two controls over how far the heartbeat sweeps across the drum.[45]

"A normal carotid tracing was made..."

By 1:42, the students had embarked on a classic experiment, re-enacting a decades-old research investigation with well-known outcomes.[46] It had been established in 1845 that cutting the vagus nerve results in a faster pulse, and stimulating it slows the heart down.[47]

A complication arose at 1:44, when the cannula was blocked. This was likely a clot, a standard inconvenience to be expected owing to having disturbed the blood's natural flow. At that point, the students had to undo the rubber tube at the cannula end, wipe the clot out (Cannon says to use a feather), refill with sodium (bi)carbonate and re-connect the tube. Fraser offers a few more hints: the cannula should be lightly oiled, and a sodium citrate solution used to prevent clotting.[48] If the clot caused the students any serious inconvenience, Moore does not say. All we know is that, merely two minutes later, they were back to capturing the rabbit's tracings.

Moore's report expands only briefly on the tracings. The first was "a normal carotid tracing" of the rabbit's arterial pressure with no further

[45] There was widespread dissatisfaction with the Marey tambour, and it was improved in various ways, but was clearly good enough to remain in use nonetheless. See e.g. James J. PUTNAM, "On the Reliability of Marey's Tambour in Experiments Requiring Accurate Notations of Time." *Journal of Physiology*, vol. 2, 1879, no. 3, pp. 209–213; Henry SEWALL, "The Tympanic Kymograph: A New Pulse and Blood-Pressure Registering Apparatus." *Journal of Physiology*, vol. 8, 1887, no. 6, pp. 349–353; D. F. MOORHEAD – H. W. NEILD, "A Simple Method for Increasing the Amplification of the Marey Tambour." *Science*, vol. 80, 1934, no. 2062, p. 18; L. GURR, "A Pneumatic Nest-Recording Device." *Ibis*, vol. 97, 1955, no. 3, pp. 584–586.
[46] See e.g. CANNON, *Laboratory Course*, p. 80; and also the refinements in ROY, "Form of the Pulse-Wave."
[47] William D. HALLIBURTON, *Handbook of Physiology*. London: John Murray 1924, p. 242.
[48] CANNON, *Laboratory Course*, p. 93; FRASER et al., *Laboratory Manual*, pp. 87–88.

interventions. They then ligated and cut the vagus nerve, and took a second tracing which showed no difference from the first. Stimulating the nerve's two cut ends produced no difference in one case, and a decline in blood pressure in the other.

The means of stimulation is something that Moore does not record. The textbooks mention various ways to do it; the main ones are mechanically tapping by dripping mercury onto the nerve, and an electrical signal. For the vagus stimulation experiment, and electrical "tetanising current" was the norm. Though applied to the nerve, tetanising current was defined in terms of muscle response: a non-tetanising current causes the muscle to repeatedly twitch and relax; a tetanising current alternates quickly enough to cause tetanus, i.e. sustained contraction without a moment for relaxation. That requires a current alternating at 50 to 200 Hz, or, if the nerves have been pulled aside onto an adjacent board for easier access, between 5 and 10 Hz.

Palmer's catalogue lists an extensive range of electrical devices, several of which are represented in the Adelaide collections. The vibrating reed mentioned earlier as a clock can also stimulate the animal rather than just the writing-lever, and in fact there is a purpose-designed "tetanus set" that does exactly that job. The tetanus set comprises a long, straight leaf spring, mounted horizontally on a clamp stand, kept in vibration with an electromagnet. When the reed swings down, its end dips into a mercury pool to close the electrical loop, just as with the adjustable vibrating reed. There was also a pendulum-based "variable interrupter" whose period could be adjusted from 4 to 100 cycles per second. This, too, explains the catalogue, could provide a tetanising current.[49]

Signal strength could be controlled using inductoria. These are essentially transformers comprising two coils, one of which slides loosely within the other. The generated signal is applied to one coil; adjusting the coils' overlap controls how strong the output will be. As mentioned, Adelaide had acquired twenty-five of them when fitting out the Darling laboratories.

When blood pressure fell under these circumstances, Moore gave a standard textbook explanation, attributing it to "the inhibitor effect of the vagus on the heart." Eventually, the heart responded with a ventricular escape beat, i.e. a contraction that follows a long interruption to the heart's usual rhythm.

At this point, we learn what the venous cannula was for: the students used it to inject a dose of adrenalin. The tracing showed them "an increase

[49] C. F. PALMER (LONDON) LTD, *Research and Students' Apparatus*, pp. 122–123.

in blood pressure which then remained high for a considerable time but eventually dropped back to normal." After that, they stimulated the vagus again and noticed that it took much less stimulation time to provoke the same ventricular escape that they had provoked before.

After waiting again for the blood pressure to normalise, they gave the rabbit atropine. Atropine (extracted from nightshade or henbane) is well known among historians of medicine for its ability to dilate the pupils. For these twentieth-century students, however, it renders the vagus nerve ineffectual. The electrical stimulus hence lost effect due to "paralysis of the vagal nerve by atropine," concluded Moore.

Moore's report shows only one minor mistake betrayed by a subtle amendment: the word "very" in smaller script, squeezed into the space between the words around it. It looks as though Moore had already worked out his report and subsequently made a good copy, to hand in, from notes or a draft that have not survived. He did not include the original traces for this experiment (but instead gave representations to which we will return later). Looking at Moore's tracings for other experiments, however, we can see that the students took a series of traces sequentially, along a single height of the drum. Each trace is a few inches long and followed immediately by the next. There was not space for all of them at a single height; the students repositioned the drum for a second run. There are various ways to do this: were the rabbit connected via a mercury manometer, the plot could be moved also be raising or lowering the sodium carbonate reservoir, at the cost of linear proportionality in the graph. For any device involving generic laboratory clamp stands (as shown in Figure 1), the whole lever system can be moved up or down. Most likely, though, because it is easy by design, a thumbpress on the Harvard drum's spring clip releases it from the axle while the fingers hold the spokes, and the drum can be slid up or down to a new position.

"With a sharp knife cut through the overlap ..."

One last phase remained before interpreting the trace. It had to be removed from the drum, and fixed so the image did not rub off.

Cannon explains how to cut the paper along the overlapping join, passing the blade through only the top layer of paper so as not to damage the drum. While one hand draws the knife along the join, the other holds the drum steady, with the thumb on the paper so it does not fall off. At this point, the trace is fragile: the soot comes off as readily as when the writing-styluses touch it, and "that hard won perfect record," warned Ohio University physiologists Maison and Haterius, could be "wiped off by a fellow student's elbow."[50]

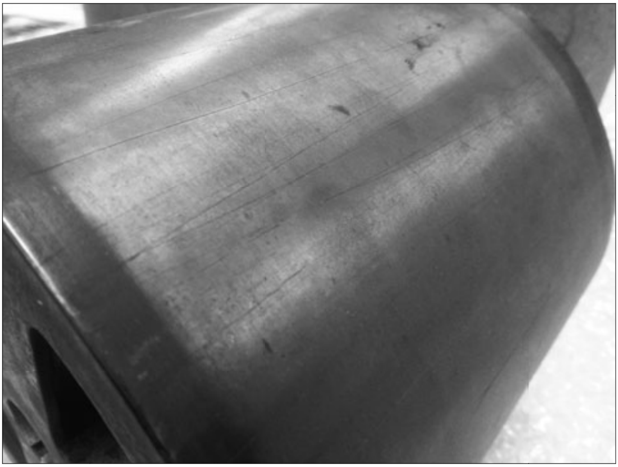


Figure 7: Cuts on a brass kymograph drum in the University of Adelaide's Heritage Collections. Several drums bear numerous cuts like this one, while the others show no such damage. This particular drum is brass, and of a style suggesting that it was part of the many kymographs that Adelaide sourced from London-based manufacturer, C. H. Palmer. Note the rounded edges, and the bands of soot coating each end, extending all the way up the spokes.

"Great care should be taken not to scratch the soft surface of the drum" when cutting, cautions Mitchell and Taylor's *Laboratory Manual.*[51] A heavy touch could easily drive the knife into the drum where it would compromise the smooth finish necessary for a perfect trace. Many of Adelaide's drums have cuts matching such heavy-handedness; their waywardness and wavering suggest an untutored hand (an example is shown in Figure 7). Such cuts could be smoothed off on a lathe, but the problem could also be addressed by eliminating the blade altogether. Mitchell and Taylor suggest capturing

[50] MAISON – HATERIUS, "Application of Electrical Methods," p. 200.
[51] Philip H. MITCHELL – Ivon R. TAYLOR, *Laboratory Manual of General Physiology*. New York: McGraw-Hill Book Company, Inc. 1938, p. 8.

a thread under the paper when attaching it, so that pulling on its overhanging ends would later to cut the paper. A more permanent approach involves cutting a narrow groove across the drum surface, barely deep and wide enough to hold a thin, strong wire, held by a set-screw in the spokes at each end. The paper is joined over the wire and, after tracing, one screw is loosened to release one of the wire's ends. The wire can be pulled through the paper, cutting it, like the thread, without a knife.[52] The wire would presumably fare better during smoking than the loose ends of a thread, but none of the extant Adelaide drums have been modified this way.[53]

The whole drum is lifted up after cutting, says Cannon, and the trace allowed to drape free for removal. It is then laid on the table where annotations can be gingerly scratched in by hand, using something like the blunt end of a dissection needle. On the traces in Moore's reports, our students added "Bench 8", numerals identifying sections of the graph, and a few fingerprints.

The trace then needs to be fixed. It is held with a hand at each end and passed through a trough of thin varnish. One end is held low and sunk into the varnish while the other end is held high, and then the first hand rises while the second hand falls, sliding the whole trace through its sticky bath. The smoky side must be uppermost, instructs Cannon, presumably so it is not damaged by rubbing against the bottom of the trough. For a light dip like this, we could anticipate (and confirm with shellac today) that drying takes, at most, only a few minutes.

Varnish – the manuals typically mention shellac – took some preparation: Porter says to let the shellac scales (the dry form in which shellac is stored and sold) stand in alcohol for at least a month before use.[54] Porter does not explain why, but we can surmise that he is thinking of the degradation that begins as soon as shellac is dissolved. Today, that degradation remains a bane to artisans desiring a hard, quick-drying finish but the kymographer benefits from a more pliable result.[55] The Palmer apparatus catalogue suggests a quicker way to attain the same outcome: add a touch of castor

[52] Archie N. SOLBERG, "A Further Improvement in the Harvard Kymograph." *Science*, vol. 96, 1942, no. 2504, p. 590.

[53] Several kymograph drums in the University of Sydney's Macleay Museum are also marred like the Adelaide cases, and one drum does have a square-sectioned groove milled or sawn precisely down one side, marked by an arrow stamped into the top. There is no apparent attachment for a wire, however.

[54] William T. PORTER, *An Introduction to Physiology*. Cambridge, MA: Harvard University Press 1901, p. 53.

[55] Jan W. GOOCH, *Encyclopedic Dictionary of Polymers*. New York: Springer 2010, p. 658.

oil.[56] Shellac in ethanol was not the only varnish: Fraser's textbook specifies dissolving rosin at 120 g per litre of 95% ethanol; Northwestern University's Medical School used 150 g gum dammar per litre of benzol for "a hard elastic semigloss finish."[57]

Figure 8 shows a space dedicated to varnishing alone. As the drawing shows, there was specialised trough that automatically protects unused varnish from evaporation.[58] A varnishing trough almost exactly like this survives at Adelaide, but with low-hanging makeshift weights instead of a spring, and its metal bracket is positioned above rather than below. The bracket and weights indicate that it must have been hung from the underside of a shelf or cupboard rather than stood on top of one. The trough has been painted dark blue, except for the hidden sides of the mounting brackets and a stripe along one side, suggesting that it was painted while mounted against a wall or a large piece of furniture such as a cabinet or shelf – only where the paintbrush could reach. The trough attests to a messy process: a thick deposit of dried shellac sits inside, and trails dribble down the outside to the metal weight-hanging loop beneath.

Next, the sticky, wet paper has to be hung to dry. Figure 8 shows one way to do it: a wall rack with spiked rods. Something similar seems to have been done with the traces in Moore's notebook. A close look (Figure 9) reveals five tiny holes along one end of the paper, each of them covered and surrounded by a cluster of fingerprints (whereas the other end is relatively untouched). These holes would seem to be where the paper was pressed onto spikes while the varnish was still soft enough for the fingers to leave a light, gingerly impression. A second trace has holes with the same spacings, suggesting use of the same pre-made rack.

Moore did not present the traces for this experiment, but he does include them for some others. The explanation is simple: the kymograph normally produces only one trace, so only one member of the five-student team can have it. The others must copy the original trace by some means, which is what Moore did, by hand. He included seven pages of them for this particular experiment.

[56] C. F. PALMER (LONDON) LTD, *Research and Students' Apparatus*, p. 30.

[57] FRASER et al., *Laboratory Manual*, p. 12; Roy G. HOSKINS, "A Portable Shellacking Device for Kymograph Records." *Journal of the American Medical Association*, vol. 67, 1916, no. 12, p. 874.

[58] Cf. the similar tank, re-shaped to be stable in both the dipping and storage orientations without need for weight or springs, in HOSKINS, *ibid*.

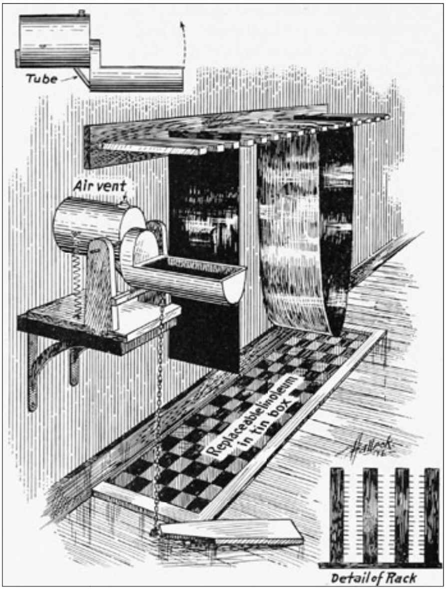


Figure 8: Apparatus for varnishing the trace and hanging it to dry on spiked bars. When not in use, the spring-loaded trough uprights itself to drain into its reservoir, limiting evaporation. The book's next illustration shows a setup for dipping long traces: two stools for the students to stand on, and a trough on the floor between them. JACKSON, *Experimental Pharmacology*, p. 63.

"See tracings 10, 11 & 12."

In lieu of the original kymograph tracings, Moore presented what look like hand-inked representations. By reading these in conjunction with some smoke traces that he did include for another experiment later that same year, we can partially understand how they were produced (to show that they were not machine-inked) and what they represent.

First, the time marks. Zoethout's *Laboratory Experiments* illustrates clear sinusoids from a tuning fork, but textbooks tend not to show the traces expected from electrical timing systems. Circuit diagrams suggest a square wave or spikes, as we find on Moore's ink-traces. His short strokes waver slightly off a straight baseline, and they are not quite parallel. Only rarely are they straight. In fact, it is hard to find any adjacent triplet that are all the same. On the smoke-trace (Figure 9), the time signal is also not very regular. Each stroke is shaped like a script *i*, often, but not always, with a tittle. It is hard to imagine what configuration of the writing point could have produced that pattern so repeatably, and future research may perhaps involve replicating the process to find out.[59] The key point for our immediate purposes is that a perfect comb-tooth trace is not necessarily the norm. Still, the marks on this smoked trace show consistency of form: they are much more similar to each other than those on the inked trace in Figure 10, which curve in both directions and exhibit a wide variety of swelled and angular terminations as if hand-drawn with more haste than skill.

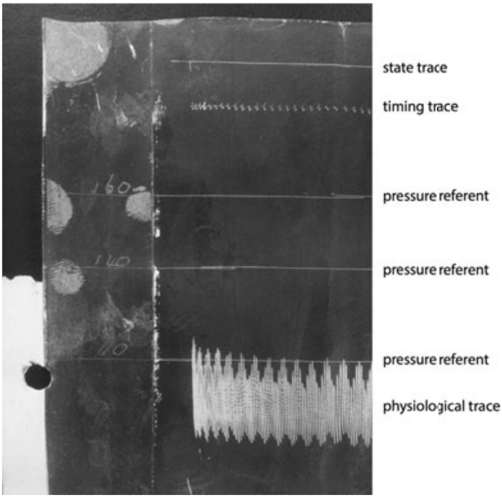
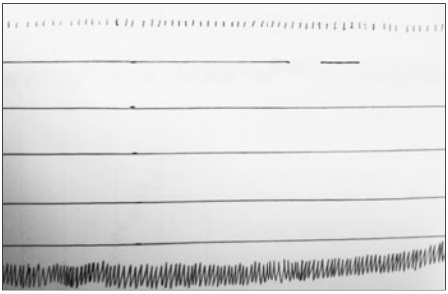


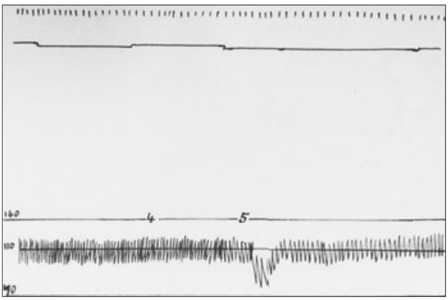
Figure 9: A corner of a smoked drum trace. Light, overlapping fingerprints cover the perforations directly above the 0's of "160" and "110"; note also the *i*-shaped timing strokes, the over-drawn pressure referents and the dashed tracing. Reading top-to-bottom, the lines show experiment state, timing, three pressure referents, then the physiological trace.

[59] Some of Moore's traces from the previous year include time marks that seem explainable as due to the drum and lever axes not being quite parallel, so that the writing-point's motion has a longitudinal element rather than being purely radial as is ideal.

Second, the trace of horizontal segments immediately beneath the time marks in Figure 10(b). This appears to have been inscribed by a lever moving between two possible positions, easily arranged using an electromagnetic signal writer and a simple switch. The line level changes at the beginnings and ends of tracing phases. Notice the wavering and bleeding at the end of each line segment. An electrical system seems much less likely to produce that than the unsure hand of a student, slowing down as it approaches the end of the stroke rather than stopping abruptly between periods of uniform speed as the kymograph drum ought to.



(a)



(b)

Figure 10: Parts of inked traces, showing evidence for hand-drawing: (a) time signal stroke irregularity and dots marking heights for pressure reference lines; (b) gaps left for numbering the traces.

Third, the standard pressure lines. These are at 50, 70, 110, 140 unspecified units (being in mm Hg would correspond to a range typical for rabbits). Curvature and swellings at the ends (especially tracing 9), and, more conspicuously gaps where the tracing number is inserted (tracings marked "4" and "5" on Figure 10(b)), suggest hand-drawing: it would have taken substantial effort to arrange for the writing-point to come completely off the drum during an automatic tracing. In Figure 10(a), a column of very short strokes appears to have marked the line positions before they were ruled in.

There is overlap from re-ruling, but that happens on the smoked traces as well. It may be interpreted as a consequence of the hand-work needed to rotate the drum for these lines, introducing one more opportunity for the equipment to be nudged slightly off-axis: alignments as small as a fifth of a millimetre are easily visible; it takes only a tiny tilt to make that happen. Whether this is characteristic of particular kymograph models rather than operator skill would entail close comparisons of fitting tolerances and wear.

Overall, the inked traces certainly mimic smoked traces for other experiments in general character and great detail but, without the original smoked traces for this experiment, we cannot easily tell how faithful that detail is. The inked traces may be a merely Gestalt representation, perhaps traced with the aid of a camera lucida. That will have to await another investigation.

As for the quality of these representations, the marker summed up his evaluation of the entire report in a single pencilled word: "Good."

The Kymograph's Lost Educational Context

Our close, contextualised reading of Moore's laboratory report shows how the kymograph did not exist alone. It operated, to begin with, in a particular place: standing on a small laboratory workbench, surrounded by clamp stands holding levers whose sharp tips scraped against its paper-wrapped surface while five undergraduates clustered around. The kymograph took care of the paper while the writing-points were driven variously by electrical devices and, via hydraulic and mechanical intermediaries, a rabbit. Somewhere in the vicinity, there were specialised burners for smoking the drum, some way to confine or remove the excess smoke, and a specialised trough for varnishing the traces. There was a rack for hanging those traces up to dry.

From the students' and teachers' standpoint, the kymograph required skills of several kinds. Some were mechanical and electrical, to construct and adjust the leverage and signal-generating systems. Some of them were manual, to cover the drum in paper and smoke, and to remove and varnish the traces. Some were surgical, to anaesthetise the rabbit, open its thorax, connect the cannulae, and to maintain the anaesthesia underpinning its unconscious contributions to the students' medical educations.

From the technicians' standpoint, kymographs linked them into multiple supply chains. We do not know where the rabbit came from, but we do know that there were occasional thoughts about having technical staff breed them. We know the kymographs' manufacturers, even if not the middle-men who sold and shipped them; the manufacturers or traders might also have supplied paper, shellac, benzol, gum and alcohol. In the laboratory, it would have been the technicians who maintained supply levels, dissolved the varnish, and made sure that materials were available when students needed them.

Technicians dealt also with storage. Kymographs are bulky and heavy, needing strong, spacious shelves or cupboards when not in use. At Adelaide, their positioning on moveable benches crowded into a microscopy laboratory speaks of both shortage and adaptation of space. Technicians are almost guaranteed to be the staff who cleaned up spilt vanish and wayward smoke. Those messes were likely localised by their apparatus, which also imposed bottlenecks where students had to queue for their turn.

In teaching and research alike, frugality and innovation featured clearly in the kymograph's use and development. We saw recycled vacuum cleaners, milk bottles, Mason jars and packing crates, and kymograph paper oversupplied from the institutional teaching budget so that the surplus could be re-routed for research. Though centred on a mass-produced apparatus, kymography was a creative, penny-pinching, living art.

Such complications, we saw, motivated reformers looking to improve both the running of the laboratory and the learning. Their complaints have finally been solved by today's educational apparatus suppliers. Electronic pre-amplifiers read signals from medical-style blood pressure cuffs and mass-produced EKG electrodes that students stick onto themselves and each other. There are no bottlenecks at the smoking or varnishing stations; laser printouts emerge so quickly, in multiple copies, and all so similar that chokes are due largely to students not being able to identify which unlabelled graph is whose. There is no fragile soot to accidentally rub off the paper, nor delicately balanced levers to bump. Cleanup can entail little more than sweeping up the little pieces of waxed paper peeled off the adhesive electrodes. It is easy to see why electronic options are valued.

The kymograph's complexity, however, is not merely complication. It is a whole practice and conceptual framework in which the entire process is completely legible. Earlier, I described the rabbit as having plotted her own pulse. Through the kymograph, she did, whereas in an electronic system, her physiological phenomena would be encoded in an electronic signal to be processed and re-processed in mysterious black boxes. The trace does not appear until the last step: a desktop or tablet computer reads that signal and makes a plot as if connected directly to the rabbit's heart. How that happens, in fact whether it really happened at all, is not easy for a novice to see – it all takes place inside the invisible enclosures of electronic black boxes.

The kymograph conveys sensible signals from link to visible link along the mechanical chain, with opportunities to adjust every one of those links for optimal outcomes (and to see immediately which ones did not work). Today, all it takes is to insert a few plugs and click a mouse button. Students are not only relieved from complication, but *excluded* from it. Does it still mean the same thing, "to do an experiment?" Does "experimental work" mean carefully coaxing data from natural systems through delicate contrivances with an entourage of trustworthy technicians keeping watch nearby, or is it analysis of graphs that a computer provided? When educators proposed better methods, they consistently pointed to a better focus on the science itself, and a reduction in wasted time. The kymograph was seen as a distraction in undergraduate coursework, yet those same technical demands made it a guardian of competence in postgraduate research. Something has changed in the undergraduate's exposure to experimentation – in particular, the learners' stewardship over their own information streams – via the transfer of functions and agency to a pre-made, black-boxed apparatus. Without an explicitly causal path back to the rabbit, it is hard to say that laser-printed graphs are not the phenomena themselves, (to recall Porter,) but mere descriptions of them.

Our interpretation of such degradation is limited, of course, by degradation of its record. Student work samples are scarce: most universities keep rich archives of law school dinner speeches, student newspaper critiques and medical school revues, but surprisingly few direct traces of how students learnt, indeed little evidence that students ever studied at all. In the museum collections, instruments tend to have survived much better if associated with a prominent owner, or if pristine. Instruments marred and modified by real use – whether for learning or research – tend to be less celebrated.

Did learners in different institutions gash their drums differently, reflecting local variations in technique? Did skilful but hurried experts also gash their drums or squash their straws or curl their writing-points in the same or different ways? We cannot tell from unblemished exemplars – pristine exemplars document design intentions and manufacturing quality, but it is degradation that records an instrument's active life.

Kymographs, moreover, are inherently incomplete. As our reading of Moore's laboratory report shows us, the kymograph was but just one module at the end of a rabbit-driven chain. Its modularity is shown also by the manufacturers' catalogues selling vast menus of accessories both *prix fixe*, like tetanus sets, and à la carte. Preserving the kymograph's meaning hence requires more than the kymograph alone. The kymograph's full meaning resides not in what it was designed to do, but in what individual instruments *did* do, impossible without the people, auxiliary apparatus, supplies and spaces; generic without the particular problems that went to them instead of to other instruments; impracticable without the adaptations and compromises that betray how charmingly inadequate the kymograph always was.

Moore's laboratory report is similarly incomplete without the instructions that he followed. Some of it, like rabbit anatomy, could have been learnt from lectures or library books. Some things, like the Adelaide anaesthetisation protocol, were taught in-person by laboratory demonstrators and technicians. Instructions could be found in published laboratory manuals derived, like Cannon's, from well-tested in-house productions; there were more such manuals in other universities that never went to press. A copy of Northwestern's in-house manuals was helpfully annotated by the medical student in whose papers it survives. On one page, he pencilled a note suggesting an instructor's attempt to head off a common blunder. For those of us working in pedagogy, history and heritage, that note cautions metaphorically against losing all else that vanishes when scientific instruments are, even for good reasons, deemed obsolete: "Do not kill guinea-pig before setting up apparatus."[60]

[60] Laboratory instructions for "General Principles of Pharmacology." In: Harold C. MORRIS, *Papers*. Northwestern University Archives, Box 1, Folder 6, p. 35.

Acknowledgements

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