# “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. Replacing the obsolete kymograph entails changing all of that, though our usual stories are focussed on progress associated with better measurements with fewer complications, not complications themselves. Such interconnectedness between progress and demise raises uncomfortable challenges for laboratory pedagogy, and for museum practice: what is laboratory education really about, and what kinds of heritage should museums, libraries and archives preserve to document it?

**Keywords.** kymograph; history of education; laboratories; obsolescence; scientific instruments

The rabbit lay sleeping at Table No. 8. A stretched rubber membrane, connected by tube to her carotid artery, moved with every heartbeat. As the membrane pulsed, a lever multiplied the subtle motions into glorious sweeps of a sharp point that scratched a thin white trace onto a soot-coated drum. The five-student team watched as the rabbit graphed her own heartbeat, and they did it again after cutting her vagus nerve, and then again while electrically stimulating the nerve’s cut end. The scene played out over the course of about an hour on that mid-March afternoon in 1942 using apparatus and processes rarely seen in undergraduate teaching today. What happened in that context, that does not happen now? 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?

Back in 1942, the students’ central apparatus — a smoked-drum kymograph (see Figure 1) — was *the* device for visualising the pulse, breathing, muscle action, nervous activity and other physiological actions. Present in research and teaching alike, the kymograph involved multiple processes: 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, and that involved a budget line that would today prompt questions about fiscal restraint. Re-introducing the kymograph would prompt such questions, too, for it required supplies, staff, equipment and space to store, operate and maintain.

Along with a torrent of physiological, psychological and anthropological research, the kymograph inspired numerous complaints and design improvements showing that it was never quite ideal. Its difficulties have been almost completely eliminated by electronic loggers and sensors that do away with the mechanical labours, and most of the electrical, and often do not necessitate opening or even anaesthetising the animal. Out of concerns for logistics, cruelty and relevance, even the animals have been widely replaced: today, undergraduates stick mass-produced, disposable, self-adhesive electrodes to themselves and each other, easing the demands on experimental technique, 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 risk and mess of benzene-filled smoke and sticky fixatives, and have eliminated large storage demands, if not a technician's salary or two. The kymograph was troublesome, as ripe for replacement as it was for innovation. But what of all those complications lost? Has their passing 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?

We can find insights into how the kymograph interacted with and often defined its own millieu in student laboratory reports preserved at the University of Adelaide, including the report written for that rabbit on that day in mid-March, 1942, and in period kymographs that might well include the instrument used at Table No. 8. By closely reading these material remnants of that day in the lab, we can reconstruct something of how pedagogy, curriculum and context change when scientific teaching apparatus evolves, degrades and disappears, and on how that loss is carried through to the ways in which we historicise science and in what we choose to preserve in museums and archives.

This microhistory centres on one of Moore's laboratory reports, treating it as the focal trace of a chronotope whose meaning can be further recovered through other proximate sources: period textbooks, other archival documentation, and the kymographs.[1]

# 1 "Experiment 2 ... 18 March, 1942"

Blue-black ink, laid down by a stiff nib in a tense, controlled hand, records events in a similarly dispassionate tone. The paper is the familiar cheap grade for school exercise books, large post quarto size ($8'' \times 10''$), lined, no watermark. Today, the pages are preserved in a manila archive folder but there are holes punched in the left margin, slightly stretched into the page by something curvaceous, about five millimetres wide, that sometimes ripped tiny tears in the same direction — signs that the page once resided in a ring- or post-binder. Paginations hand-written in the upper outside corners mark their order. We learn from the report's footer that its author was named H.R. Moore. This report is one of Moore's shortest, with pages a–d (page d is blank), and appendix pages i–vii. Every lab report in the set is foliated independently, telling that each stood on its own. The activities did take place in a particular order, however, recorded by the date: 18 March, 1942. The experiments do have numbers and titles — this is Experiment 2, 'Recording of carotid blood pressure & of the effect of vagus stimulation', but the number sequence is erratic. This was the second experiment of the

1. My reading draws on Bakhtin's notion of the chronotype (M.M. BAKHTIN, *The Dialogic Imagination*, trans. C. Emerson and M. Holquist, Austin, TX: University of Texas Press, 1981), applied here to the laboratory experience represented by a flawless report of a problem-free experiment, a sample of research and teaching publications, and a handful of related textbooks and other documents that, taken together, represent an overlay of not only of authors and readers, but also of epistemes and subcultures (David CLARKE, "Culture as a system of subsystems" in: *Interpreting Objects and Collections* London: Routledge 1994 (44–47)), on reaching to context to account for unexpected knowledge revealed by detailed reconstruction efforts (see e.g. Otto SIBUM, "Rewording the mechanical value of heat", *Studies in History and Philosophy of Science* vol. 26, 1995, no. 1 (73–106)), and on the ways in which knowledge inheres in and can, at least in principle, be read from (as opposed to 'into' or 'onto') scientific objects (Davis BAIRD, *Thing Knowledge*, Berkeley, CA: University of California Press, 2004).

term but the first that Moore did, for, as he recorded elsewhere in his laboratory notes, he was absent in the first week.[2]

Other institutional records state that Moore was a medical student, at this point in the third of his six years, taking his second physiology course. The first physiology laboratory course, which he took in 1941, 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 the year. The students hence came to the advanced physiology class already knowing something of kymograph technique, though they had not yet done any physiology work on animals. Animal anatomy was, however, covered in the zoology course, and Moore was engaged enough to borrow Buchanan's *Elements of animal morphology* from the library four times in 1940, noting on the back of one of the borrowing slips that it was "useful for practical work on the frog, dogfish & rabbit".[3]

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 Fitzpatrick. Each time the group convened, their roles changed, presumably to allow everyone an opportunity to learn the full spectrum of skills. Apart from writing his name in the corner and everyone else's name the table of roles, Moore mentions himself and the others only by their roles.

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2. 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 Robinson MOORE, *Medical student records*, University of Adelaide Archives, Series 1553, 1937–1945.
3. MOORE, *Records*, Item 6.

## 2 “Anaethetist and Recorder administered 3.6 cc paraldehyde”

At 11:30 that morning, reads the report, the Anaesthetist and Recorder administered 3.6 cc of paraldehyde. Paraldehyde depresses the central nervous system to induce relaxation and sleepiness without greatly affecting respiration. It is sometimes still given to human children to relieve epileptic fits; in the past, psychiatric patients were commonly injected with it as a combined punishment and sleeping aid.[4]

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), delivered by gavage, i.e. by tube into the stomach. Administration requires two people: “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.”[5]

Anaesthetisation was something of a specialty at Adelaide, where it was valued as a learning experience. Physiologist and nutritionist Cedric Stanton Hicks recalls how, in his early years as a lecturer there, he and colleagues developed — via “much trial and error” — a safe and reliable method, good for teaching. Administering paraldehyde 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

4. Francisco LÓPEZ-MUÑOZ, Ronaldo UCHA-UDABE, and Cecilio ALAMO, “The history of barbiturates a century a er their clinical introduction” *Neuropsychiatric Disease and Treatment* vol. 1, 2005, no. 4 (329–343); Kate DIESFELD, “Apology in New Zealand’s mental health law context: An enigmatic juxtaposition?” *Waikato Law Review: Taumauri* vol. 20, 2012, (50–66).
5. Charles Wallis EDMUNDS and Arthur Robertson 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.

for which he was known, and in the end students learned the 'feel' of the catheter as it was inserted."[6] 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: "If through carelessness of the anaesthetist the animal is killed, he must pay for another."[7]

Following anaesthetisation, there is a seventy-minute gap before the next entry. Given the time of day, the students may have eaten lunch. And they, or someone else, must have readied the rabbit and kymograph.

## 3 "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 King's College, London physiologist William Rutherford called them "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."[8]

Rutherford captures two especially important points: the imprecision and ephemerality of previous techniques, and the record's permanence. An obvious shortcoming with feeling the pulse or shooting blood from an artery is that, once the signal has been

6. Cedric Stanton 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.
7. 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).
8. William RUTHERFORD, "Introductory lecture to the course of physiology in King's College, London, 1869" *The Lancet* vol. 94, 1869, (533–535).

measured, it is gone: there is no way to check for variation or to examine the form of that pulse more closely. Kymographic tracing transforms the temporal domain into a spatial one; preserving the trace freezes 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 especially common, and typically the referent for any researcher advancing improvements or adaptations.[9] Harvard kymographs comprised a clockwork base, the spring wound by a pawl-and-ratchet crank, 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 — swathed in typical lathe marks — were then turned smooth. Porter specified the circumference, rather than radius or diameter, reflecting the instrument’s intended use, viz. to carry paper of a particular length.[10]

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. For biology students, Fraser continues, laboratory work “teaches how to interpret the relationship between structure and function.” She explicitly commits to both “experiment” and “demonstration” as essential complements to theoretical study

9. For the kymograph’s early history, see e.g. H. E. HOFF and L. A. GEDDES, “Graphic registration before Ludwig; the antecedents of the kymograph” *Isis* vol. 50, 1959, no. 159 (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 (345–362); Osman FAROOQ and 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 (219–224); John R. BROBECK, Orr E. REYNOLDS and 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 (293–321).

10. Porter described an early model, however, as having been “cast in one piece”: W. T. PORTER, “An improved kymograph” in: *Proceedings of the American Physiological Society, Sixteenth annual meeting* Philadelphia, PA: American Physiological Society, 1903 (xxxix–xli).

because, “in a highly practical science like medicine, theoretical knowledge by itself is valueless and without meaning.” But it is hard to find a clear statement from the instructors as to what, exactly, hands-on laboratory work teaches that a textbook or lecture does not. The preface to Busch’s *Laboratory manual* states dryly that “one of the main benefits to be obtained from laboratory work is the training in methods of exact observation which the students receive.” It sounds like Busch had also other benefits in mind, but he refrains from saying exactly what they are.

Although similarly elusive about laboratory work’s purpose, William Porter, physiology instructor at Harvard and father of the kymograph-manufacturing Harvard Apparatus Company, left many good lines to read between. Urging reform to physiology education 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 in particular 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 inherently is: “Deal so far as possible with the phenomena themselves, and not with the descriptions of them.”[11]

A simple kymograph setup, indicative of the overall principle, is shown in Figure 1.

11. Lois McPhedran FRASER et al., *A laboratory manual of experimental physiology (including general physiology)*, Toronto: University of Toronto Press 1922, pp. 3–6; Frederick Carl BUSCH, *Laboratory manual of physiology*, New York: William Wood and Company, 1905, p. iii; William Townsend PORTER, “The laboratory teaching of physiology”, *Science* vol. 14, 1901, no. 354, pp. 567–570.

The kymograph proper is just the drum and its engine; in this case it is a spring-driven Harvard model. Alongside the kymograph are two generic clamp stands, each supporting a writing-lever. The upper writing-lever is driven by a frog's aorta, tied to the lever by a silk thread while clips hold the creature down on the frogboard. (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 setup for the frog's leg muscle is not much different — the muscle pulls the lever down, while a spring above balances the force. The frog could be tied to the same side of the fulcrum as the stylus, or on the other side, to determine whether muscle contraction registered as downward movement, or upward. The lower lever traces out a time signal, driven by a clock at the end of the coiled wires (some textbooks recommend installing the clock and other circuitry within easy reach under the laboratory bench). The clock's signal energises the clamped electromagnet, which flicks the short writing-lever periodically up and down to mark time on the trace. Clocks came in various speeds, ranging from geared clockwork for the slower speeds, to tuning forks for the fastest, and vibrating leaf springs for speeds in-between.

For responsiveness to such weak, small movements, the levers had to be rigid and light. Judging from period manuals, sales catalogues and research literature, a wide range of materials worked: bamboo slivers, 'straw' that may have been thin reeds or drinking straws, stiff piano wire, aluminium. Though it was possible to buy straw for kymographs — bundles of hollow, reed-like straw accompany the kymographs at Groningen's University Museum, and also the University of Sydney's Macleay Museum – it was apparently common to make the levers locally from whatever convenient materials served the purpose. Such improvisation from cheap materials renders devices ephemeral, and survivors, especially broken ones, become indistinguishable from scraps and packing materials when detached from their contexts. A fragment of one endures at Adelaide, identity intact: most of it was broken away, but a short length of flattened grass stem remains bound by thread to a metal kymograph lever-hinge.

The scratchy writing-point, if it was not just the tip of the lever arm, was readily 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’.”[12] The do-it-yourself attitude is 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 the continent’s great distance from cutting-edge technocultures. At Adelaide specifically, a handful of plastic writing-points survive, most of them still connected to electromagnetic signal writers, and one to a hefty rod — this latter presumably to trace a fixed reference line, or perhaps for handwriting. The Adelaide writing-points are cut from at least three kinds of thin plastic sheet and may include the cellulose points originally shipped with the Palmer-made signal writers (Figure 3).

## 4 “A real challenge to the uninitiated”

Novices found the kymograph complicated: as Alvah McLaughlin, who taught pharmacology at Michigan State College, reflected in 1928, “Most instructors, who

12. PORTER, “ e 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 and 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, pp. 23, 71, 72; W. 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 and A. J. LUKER, *Laboratory exercises in zoology*, 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. 05. 2016].
An especially beautiful Kagenaar kymograph (object bk0040_01.dc) in the Cushing-Whitney Medical Historical Library has levers of light metal foil that taper down to writing-points now rippled with bending and re-bending over the instrument’s working life.

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."[13] Even for a doctoral student in the 1970s, mastering the kymograph 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 speculated 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."[14]

The first step was to wrap paper around the drum; several laboratory manuals tell us how it was done. 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 drawn up and pulled taut over the drum. The paper is then held firmly in place while the drum is rolled 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* of about a decade later cautions that the paper has to be wrapped in the right direction so that the writing-point does not catch on the overlapped edge.[15]

The reason for laying the shiny side downwards is that its glazed surface must face outwards from the drum to present a low-friction surface to the writing-point. It is not immediately clear how the paper was glazed; Palmer's apparatus catalogue calls it simply a "special surface for smoking". The coating may reasonably have been the same gelatin sizing with which paper has been coated for centuries to limit the

13. Alvah R. MCLAUGHLIN, "A weight-driven kymograph" *Science* vol. 68, 1928, no. 1751 p. 62 (62–64).
14. 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).
15. 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.

bleeding of ink. Polishing could have been done by calendering, i.e. pressing between hot, smooth rollers (calenders) which, like gelatin sizing, was already a well-established practice and matches the paper's dense, fine texture.[16] By the time the paper arrives at the laboratory, however, the paper manufacturing processes are long since done, and it had been cut to size, and gummed. Physiologists did not have to worry about any of this: kymograph paper simply simply came that way.[17]

In nineteenth-century Australia, however, 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 some of the local newspapers were printed on smooth paper that just might work. In a moment of self-help liberation, he asked a printer for the end of a roll to try on his kymograph and found it "to be the best I had ever seen for the purpose."[18]

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 brushed a stripe of liquid latex onto each end of the paper rectangle, on opposite sides. Sheets could be prepared en masse and stored for months, he found, without degrading. 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 undone for removal. Importantly, Pratt explained, pre-brushing with latex "not only saves time for the student, but contributes distinctly to neatness in technique."[19]

Once the drum is covered, the next step is to smoke the paper. A steady gas flame is needed, and the paper is held in the bright yellow part where combustion is not yet

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16. Dard HUNTER, *Papermaking through eighteen centuries*, New York, NY: W.E. Rudge 1930, p. 140.
17. E.g. ARTHUR H. THOMAS CO., *Laboratory apparatus and reagents selected for laboratories of chemistry and biology*, Philadelphia: Arthur H. Thomas Co. 1921, pp. 55, 475; C.H. STOELTING COMPANY, *The great catalog of the C.H. Stoelting Company, 1039–1937* s.l: 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, pp. 14, 29, 138.
18. 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).
19. F.H. PRATT, "Use of latex dry adhesive for kymograph paper" *Science* vol. 89, 1939, no. 2321, (590).

complete. Cannon's directions are notable for their 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."[20]

"A light chocolate color" is preferred, explains Fraser, "because there is less danger of burning the paper".[21] 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.[22] Soot on the writing-point mattered because it made the line thicker and thicker.

Cannon (figure 4) shows a fish-tail burner used for smoking, with the characteristic broad flame. Apparatus catalogues often list these as being for glassworking, so laboratories might have had them ready for repurposing. As Cannon's instructions demonstrate, smoking a kymograph was quite a craft. Craft takes practice, practice takes time, and time is usually in short supply. That problem was sidestepped by innovation. The novices' blotchy coverage, for example, could be mollified by a wide burner with a line of multiple jets, or a burner that oscillated back and forth, while a stand held the drum at just the correct height. Eliminating blotchiness eliminated also a second problem: faced with their poor product, novices commonly corrected blotchiness with extra smoking, ultimately making the soot too thick.[23] Problems and innovation also arose from reasons other than skill. Unstable flames could be calmed by surrounding them with draft-blocking skirts. Peugnet's skirts purportedly gave a flame so good that a higher quality of paper was needed to do it justice.[24] If

20. CANNON, *Laboratory course*, p. 9.
21. FRASER et al., *Laboratory manual*, p. 12.
22. Hubert B. PEUGNET, "An improved gas burner for smoking kymograph paper" *Science* vol. 93, 1941, no. 2426, p. 626 (625–626).
23. Shepherd Ivory FRANZ and Thomas A WATSON, "Apparatus for smoking kymograph drum papers" *Journal of General Psychology* vol. 2, 1929, no. 4, p. 509 (509–515)
24. PEUGNET, "An improved gas burner".

clean-burning gas produced insufficient smoke, it could be bubbled through benzene or benzol before combustion.[25] If gas was unavailable or inconvenient, an experimenter could use a hand-held burner for kerosene with a wide strip of wick.[26]

Smoke got everywhere. “Both the experimenter and the instructor is 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 the University of Rochester’s Psychology Department. He designed a cheap fume hood to enclose the smoking apparatus, with a second-hand vacuum cleaner bolted to the top and ducted outdoors through a window. Reconditioned vacuum cleaners were plentiful as the middle class developed its liking for the newest trends, and the used vacuum cleaner dealer, promised the frugal Williams, would “also furnish, usually without extra charge, any reasonable length of hose.”[27] Within two years, Edgar Jones at Akron shaved the price down another dollar 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 no hose was needed: “Great was our satisfaction to find that the sweeper’s sack would retain all carbon, even if benzene were used!”[28]

To eliminate the flames completely, the soot could be sprayed on. One researchers 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 cost concerns that saw Williams and Jones price-checking second-hand vacuum cleaners, a low-grade naphtha sold cheap 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 application process was to spray, from a

25. FRANZ and WATSON, “Apparatus for smoking kymograph papers”, pp. 509–513 See also figure 4.
26. PAULITSCH, Psychological instruments, p. 25; C.F. PALMER (LONDON) LTD, Research and students’ apparatus, pp. 29, 135.
27. Griffith W. WILLIAMS, “Simplified equipment of smoking kymograph drums” *Science* vol. 81, 1935, no. 2106 (465–466).
28. Edgar P. JONES, “A portable hood for smoking kymograph drums”, *Science* vol. 85, 1937, no. 2208 (412).

distance of a foot or two, onto a rapidly spinning drum.[29] It is hard to imagine how the soot made any less mess this way.

Smoking could alternatively be outsourced. Pre-smoked paper came in small strips (for small drums), coiled in cans, with handling instructions to minimise damage to the soot.[30]

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 burners as shown in figure 5. Three of these survive in Adelaide's collections, in two sizes. The burners could be held in one hand, or mounted on a stand beneath the rotating drum. The students had seventy minutes to do the smoking, and may have had to wait their turn at a limited number of smoking stations shared by the whole class.

Once smoked, the 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 also 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.

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29. W. F. WICHART, C. H. THIENES, and M. B. VISSCHER, "Two improvements in the technique of kymograph recording" *Science* vol. 73, 1931, no. 1882 (99–100).
30. 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 examples, see YONKMAN, "Improved kymograph recording"; Ralph GERBRANDS and John VOLKMANN, "A wax-paper kymograph" *American Journal of Psychology* vol. 48, 1936, no. 3 (498–501); K.U. SMITH and Samuel FERNBERGER, "Glass-capillary ink-writing markers for use in kymograph recording" *Journal of Experimental Psychology* 23, 1938, no. 4 (434–438).
    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 A. FORD and John B. WATSON, "Recording apparatus: the electro-kymograph" *Journal of Experimental Psychology* vol. 7, 1924, no. 2 (1924), (157–163); George L. MAISON and 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 (200–209).

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. For slower phenomena, a slower clock is needed.

Two kinds of slow clock are still present in the Adelaide collections: the 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 controls how much of the reed is free to swing, and hence how quickly it moves — for the same mechanical reasons that shorter tuning forks ring with a higher pitch. The oscillation rate of the reed at Adelaide can be varied between 2 and 20 per second. Each time the circuit closes, the electromagnetic signal writer (figure 3) is engaged, and the attached writing point makes a swift sideways move against the drum.

The direct-writing electrical clocks offer markings every $\frac{1}{10}$, 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.

# 5 “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.[31] Back in those days, itinerant 'rabbitoes,' as Australians call them, trapped rabbits in the countryside to sell in town, stereotypically carried in a hessian sack slung over one shoulder, skinned fresh under intense feline scrutiny at the moment of sale. They were already dead for the kitchen, of course — of no use for learning physiology, and perhaps too riddled with parasites and pathology even for anatomy. For live rabbits, however, the University's financial accounts from the 1920s briefly mention rabbit supply and a caretaker who offered to breed them 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 in 1929 in association with discussions about saving money. By the 1940s, the rabbit supply vanishes from discussion, even in the wake of resource constraints imposed by the War.

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 when they measuring their own metabolic rates in introductory physiology classes a year earlier. For that work, Moore recorded his own height and weight as $5'4''$, 141 lb, and his fellow student Fitzpatrick's $6'2\frac{1}{4}''$, 159 lb. Moore normally maintains a clinical objectivity in the reports with one exception, several weeks later: "Rabbit obviously frightened."

"The rabbit was prepared according to instructions," Moore wrote down. The instructions are no longer available but we can surmise that the students learnt how to open and navigate within a rabbit during earlier biology courses and, judging from a selection of period laboratory manuals in Adelaide's library and elsewhere, the process seems to have been reasonably standard.[32]

31. Thorburn Brailsford ROBERTSON and Walter H. BAGOT, *An account of the Darling Building of the University of Adelaide*, Adelaide: University of Adelaide Council 1922, pp. 5, 11, 15, 106.

32. For a list of basic dissection exercises that should be mastered before pursuing experimental physiology, see, for example, Edward Albert SHARPEY-SCHÄFER, *Experimental physiology*, London; New York: Longmans, Green, and Co. 1918, p. 1. 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.

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."[33] Photographs of Adelaide students at work survive from 1929 and 1938, in one of the two downstairs laboratories in the Darling Building (Figure 2). 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 small white benches crammed into the downstairs laboratories. The 1929 photograph shows the animal, outstretched, at one end of the table and, on the shelf below, the pile of white hair just shaved.[34]

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

As a supplement to the textbook instructions, we could look for local process insights from another Adelaide medical student, Roy Muerke who recorded it in his notes some thirteen years earlier, though it turns out that he does not depart from the textbook accounts, beyond adding some finer details.[35]

First, our multiple sources instruct, the surgeon must isolate the right carotid artery and left vagus nerve and insert a tracheal cannula. This is used to convey ether fumes directly to the lungs — the technique had clearly developed since 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 of the air goes direct. The anaesthetist can adjust the blend of fresh and etherised air, controlling dosage more than is possible by dripping ether onto a muslin mask.

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33. CANNON, *Laboratory course*, p. 91.
34. HICKS, *Papers*; ROBERTSON and BAGOT, *Account of the Darling Building*, p. 7.
35. Muerke's notes are included in HICKS, *Papers*, Series 13. Hicks was the instructor when Muerke took the course.

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 apparatus the students used — whether they bought and maintained their own dissection kits, or whether the laboratory provided these tools. At the least, they needed scissors, scalpels, dissectors, needles both sharp and blunt (the hefty, blunt aneurysm needles were for slipping ligatures around arteries, nerves and trachea), forceps. Occasionally the textbooks mention adding other items, too, like 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.[36]

The cannula then needed to be joined to the kymograph. This was done by hydraulics. The celebrated seminal configuration that Ludwig published in 1847 used rubber tubes to convey the arterial pressure, via the sodium carbonate solution, to a mercury manometer.[37] A float rode on the mercury surface, while a long vertical rod emerging from its top scraped 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

36. 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).

37. Carl LUDWIG, "Beiträge zur Kenntniss des Einflusses der Respirations-bewegungen auf den Blutlauf in Aortensystem" *Archiv für Anatomie, Physiologie und wissenschaftliche Medicin*, 1847 (242–302). The same configuration was recommended by some twentieth century textbooks, e.g. F. A. BAINBRIDGE, James Acworth MENZIES, and Hamilton HARTRIDGE, *Essentials of physiology*, London: Longmans, Green 1931, p. 138.

mercury worked its way up. Contrivances to hold the writing-point against the drum introduced asymmetries, increasing the chances of the mercury jamming the float. Various things could be done, such as better float designs, and better ways to guide the writing-point.[38]

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 set particular levels for tracing as horizontal lines on the kymograph as fiduciary referents 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[39] — the students would have first wound the spring, then released the brake after activating the clock signal. With all 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.[40]

38. STUART, "Improvements".
39. ROBERTSON and BAGOT, *Account of the Darling Building*.
40. BUSCH, Laboratory manual of physiology; G. BACHMANN, "An automatic spinning device for the Harvard kymograph", *Journal of the American Medical Association* vol. 66, 1916, no. 3 (188–188); W.A. HIESTAND, "A commutator for the Harvard kymograph" *Science* vol. 81, 1935, no. 2103 (382–383); N.W. ROOME, "Simple synchronous motor for the Harvard kymograph" *Science* vol. 84, 1936, no. 2169 (91–92); Hugh B. MCGLADE, "Improvements in the Harvard spring kymograph" *Science* vol. 91, 1940, no. 2365 (412).

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 pressure source, and the mouth is closed with a rubber membrane. Rubber unavoidably hardens and cracks so is lost, over the decades, to its own natural decay, but a few tambours (see Figure 6) survive in the Adelaide collections with remants of rubber still attached. Some catalogues offer clip-on and screw caps for holding the membranes down; at Adelaide, they were tied down with thread.

As the pressure inside the tambour rises and falls, the membrane swells and recedes. As with the mercury manometer, the tambour movement less than that of the blood itself, attenuating the motion both by surface area and by the membrane's elasticity — the larger the tambour and the tighter the membrane, the greater the change. The membrane's motion is transmitted via a light cork or metal strut, riding atop the membrane, to a lever, at the end of which the writing-point moves 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 multiplies, giving the experimenters two controls over how far the heartbeat sweeps across the drum.[41]

# 6 "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.[42] In this particular case, it had been established in 1845 that cutting the vagus nerve results in a faster pulse, and

41. 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. J.J. PUTNAM, "On the reliability of Marey's tambour in experiments requiring accurate notations of time" *Journal of Physiology* vol. 2, 1879, no. 3 (209–13); H. SEWALL, "The tympanic kymograph: a new pulse and blood-pressure registering apparatus" *Journal of Physiology* vol. 8, 1887, no. 6 (349–353); D. F. MOORHEAD and H. W. NEILD, "A simple method for Increasing the amplification of the Marey tambour" *Science* vol. 80, 1934, no. 2062 (18); L. GURR, "A pneumatic nest-recording device" *Ibis* vol. 97, 1955, (584–586).
42. See, e.g. CANNON, *Laboratory course*, p. 80, and also the refinements in ROY, "Form of the pulse-wave"

stimulating it slows the heart down.[43] The students could have read up in advance, but Moore's library records show no signs that he did so. They might have been told about it in lectures but no lecture notes survive to tell us.

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 rabbit's natural blood 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, without further detail), refill with sodium (bi)carbonate and re-connect the tube. Fraser offers a few more hints: the cannula should be slightly oiled, and a sodium citrate solution used to prevent clotting.[44] 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 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 mechanical tapping, effected by dripping mercury onto the nerve, and electrical. Electrical stimulation took many forms — one-off voltage pulses, and various ways of producing waves. For the vagus stimulation experiment, applying a "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 causes tetanus, i.e. sustained contraction without relaxation. Tetanus was achieved by alternating the current with a frequency between 50 and 200 Hz, or between 5 and 10 Hz, depending on whether the nerves had been removed.

43. William Dobinson HALLIBURTON, *Handbook of physiology*, London: John Murray 1924, p. 242.
44. CANNON, *Laboratory course*, p. 93; FRASER et al., *Laboratory manual*, 87 ff.

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 is a long, straight leaf spring, mounted horizontally on a clamp stand, and kept in vibration with an electromagnet. When the reed swings down, its end dips into a mercury cup 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.[45]

Signal strength could be controlled with 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 from the second coil. As mentioned, Adelaide had acquired twenty-five of these when fitting out the Darling laboratories.

When blood pressure fell, 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 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 1 cc of atropine solution. Atropine (extracted from nightshade or henbane) is well known among historians of medicine for its ability to dilate the pupils as a cosmetic benefit.

45. C.F. PALMER (LONDON) LTD, *Research and students' apparatus*, pp. 122–123.

For these twentieth-century students, however, it renders the vagus nerve ineffectual. When the students applied the electrical stimulus after injecting atropine, it had no effect. This Moore attributed to “paralysis of the vagal nerve by atropine.”

Moore’s report is written with 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. Throughout the report, Moore’s claims are dryly factual, even detached, and backed up by reference to the kymograph tracings. We do not have the original traces for this experiment (but we do have 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 re-positioned 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 representation. And, 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, all it takes is to press the thumb down on the Harvard drum’s spring clip to release it from the axle while the fingers hold the spokes, and the drum can be slid up or down to a new position.

## 7 “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 drew the knife along the join, the other had to hold the drum steady, with the thumb on the paper so it did not fall off. At this state, 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."[46]

"Great care should be taken not to scratch the soft surface of the drum" when cutting, cautions Mitchell and Taylor's *Laboratory manual.*[47] A heavy touch could easily drive the knife into the drum where it would leave long cuts, compromising 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 8). Such cuts could be smoothed off on a lathe, but the problem could also be addressed by eliminating the cutting risk altogether. Mitchell and Taylor suggest capturing a thread under the paper when attaching it, so that pulling on its overhanging ends would later to cut the paper. A more durable fix involves cutting a narrow groove along the drum, 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.[48] 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.[49]

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

46. MAISON and HATERIUS, "Application of electrical methods", p. 200.
47. P.H. MITCHELL and I.R. TAYLOR, *Laboratory manual of general physiology*, New York and London: McGraw-Hill Book Company, Inc 1938, p. 8.
48. A.N. SOLBERG, "A further improvement in the Harvard kymograph" *Science* vol. 96, 1942, no. 2504 (590).
49. Several kymograph drums in the University of Sydney's Macleay Museum are also cut like the Adelaide cases, and one drum does have a groove cut down one side, marked by an arrow stamped into the top. There is no apparent attachment for a wire, however.

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 thin layer like this, we could anticipate (and can confirm with shellac today) that only a few minutes are needed for drying.

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.[50] 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 the slower-drying solution and a softer, more pliable result.[51] The Palmer apparatus catalogue suggests a quicker way to attain the same outcome: add a touch of castor oil.[52] Shellac in ethanol was not the only option: Fraser's textbook specifies a solution of rosin at a concentration of 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."[53]

After dipping, the trace must be hung to dry. One way to do this is shown in figure 7, where a space has been dedicated to this function alone. As the drawing shows, there was specialised varnishing trough. When the pedal is released, the trough tilts upwards so the varnish flows down into the closed reservoir where it is protected from evaporating away.[54] A varnishing trough almost exactly like this survives at Adelaide,

50. W.T. PORTER, *An Introduction to Physiology*, Cambridge, MA: Harvard University Press 1901, p. 53
51. Jan W. GOOCH, *Encyclopedic Dictionary of Polymers*, New York; London: Springer 2010, p. 658.
52. C.F. PALMER (LONDON) LTD, Research and students' apparatus, p. 30.
53. 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 (874).
54. Cf. the similar tank, re-shaped to be stable in both the dipping and storage orientations without need for weight or springs, in ibid.

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. Mounting from above would agree with the back-weights hanging on a chain approximately 30 cm long. The varnishing 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 inside of the trough part is lined with a thick deposit of dried shellac, as would be expected. The outside is likewise coated, with drips running down to the metal loop beneath. Varnishing would appear to have been a messy process.

Next, the sticky paper has to be hung to dry. Figure 7 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 an impression, but only a light and gingerly impression — to avoid adding blood to the mix. 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. Moore's hand-drawn traces are in fact of special interest, for they document the post-processing that took place. He included seven pages of them for this particular experiment.

# 8 “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 and what they represent.

First, the time marks. Zoethout illustrates clear sinusoids from a tuning fork, but textbook descriptions of electrically-inscribed timing systems are generally not accompanied by photographs or drawings showing what to expect. Circuit diagrams suggest a square wave, at least as a likely ideal. The short timing lines on Moore’s ink-traces waver slightly off a straight baseline, and they are not quite parallel, and 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.[55] Still, the key point for our immediate purposes is that a perfect comb-shaped trace is not necessarily to be expected. 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.

Second, the trace of horizontal segments immediately beneath the time marks in Figure 10(b). This appears to have been inscribed by a lever set between two positions. It would be easy to arrange this by using an electromagnetic signal writer connected via a manual switch. The line level changes at moments corresponding to the beginnings and ends of tracing phases. Notice the wavering and bleeding at the end of each line segment. An electrical system as simple as described seems much less likely to

55. 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.

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.

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 if traced automatically. 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, it is not easy to say how these inked traces were produced. They 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 accurate 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.

Whatever the process, the marker gave his evaluation of the entire report in a single pencilled word: ”Good.”

# 9 The kymograph's lost educational context

A 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: the Adelaide ones each stood on a small laboratory workbench, adjacent to clamp stands holding levers whose sharp tips scraped against their surfaces, while five undergraduate students clustered around. The kymograph took a mostly passive function, acted upon by the writing-points that were driven by a combination of electrical devices and, via hydraulic and mechanical intermediaries, a rabbit. There were specialised burners for smoking the drum, hoods for confining the smoke, and a specialised trough for varnishing the traces. There was at least one rack for hanging those traces up to dry.

The kymograph required skills of several kinds. Some of these 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 cannula, and to maintain the anaesthesia underpinning its unconscious contributions while making the experimental changes that the students were there to study.

There were 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 at least know the kymograph manufacturers, even if not the middle-men who brokered the deals, and the manufacturers or traders might also have been the suppliers of consumable paper, shellac, benzol, gum and alcohol.

There were storage demands. The kymographs needed shelves or cupboards when they were not in use, and their presence on moveable benches crowded into the Darling Building's laboratories shows that the space for using them was improvised. Wherever we find liquids and smoke, there are messes to clean, and someone to clean them. The smoke and liquids were apparently confined to specific areas. This brings a benefit in confining the mess, but also two logistical bottlenecks where students had to queue for their turn.

Frugality 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 used for research.

Such complications are not especially unusual of teaching apparatus, and can be motivating for reformers looking to improve both the running of the laboratory and the learning. Simpler apparatus allows students to focus on the physiology rather than the manual skills of making the machinery run. Eliminating the liquids and smoke eliminates the time and effort needed to clean them. Replacing one-off paper traces by digital logs replaces manual duplication with easy print runs.

All three of those changes have been effected by the transition to electronic logging. These days, educational apparatus suppliers such as Pasco and Vernier sell pre-amplifiers and logging systems for use with standard disposable EKG electrodes mass-produced for medical use, and medical-style blood pressure sensors. Students stick these electrodes onto each other and do little experiments like subjecting themselves to various minor stresses — exercise, holding the breath — to see how their EKG traces change. There are no bottlenecks at the smoking or varnishing stations; laser printouts emerge so quickly that only minor chokes happen, largely due to students not being able to identify which graph is whose. Students do not accidentally lose their traces by rubbing them off the paper, or by bumping the clamp stands and the delicately balanced levers. Cleanup is limited to the the little pieces of waxed paper peeled off the adhesive electrodes. It is easy to see why electronic options are valued.

The kymograph's mechanical complexity, however, is not merely complication. It is a whole practice, a conceptual framework in which the entire registration process is completely legible. Earlier, I described the rabbit as having plotted her own pulse. The reason for that phrasing is to contrast against the new electronic systems in which the arterial pressure variations is understood to be detected, then encoded in an electronic signal, then the signal passed through a pre-amplifier that, in addition to amplifying, also filters and re-shapes the pulse into something amenable to further processing. The trace is delivered in the last step: a desktop or tablet computer reads that signal and makes a plot as if connected directly to the rabbit's heart. What happens, and how, is not easy for a novice to see — it all takes place inside the invisible enclosures of circuits in black boxes.

The students, while relieved of messy manual labour, are also transplanted to a new conceptualisation of what it means to do an experiment. Where once it was a delicate process of carefully ensuring that signals passed from link to visible link along the mechanical chain, with opportunities to adjust every one of those links for optimal outcomes (and at least to make sure that every one of them worked), now it is a matter of inserting a few plugs into the right sockets and clicking a mouse button. The student has not only been relieved from messy labour, but excluded from it. Does it still mean the same thing, "to do an experiment?" Does "experimental work" mean coaxing data from finicky natural systems, 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 learning, yet it was still important, indeed a guardian of competence, in postgraduate research. Nor do the progressives address how the undergraduate's understanding of experimentation — in particular, the experimenter's knowledge of and control over the information stream — might be changed by transferring functions and agency to a new genre of black-boxed apparatus.

Museum catalogues likewise make little mention of these complications: kymographs are normally described kymographs without much reference to their context. Occasionally, a note says that a particular was "used for" physiological, anthropological or some other sort of recording, or that it came from the laboratory or office of a particular researcher. The complex of skills, people, spatial contexts and supply lines, however, is generally not recorded. The photographs seldom include drums gashed by heavy-handed paper removal and with blackened rims, scarred and sooty with real-life rigours like the drum in Figure 8; these are often not prized, either. While pristine specimens are not bad things, they represent ideal practice and conceptual design, not what learners did in the laboratories. Did learners in different institutions gash their drums differently, reflecting local variations in technique? Did skilful but hurried researchers 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 – battle-scarred specimens are needed for that, in multiple instances to show both that we are not looking at idiosyncratic singletons and also to characterise the range of variations. In the case of the kymograph, the instrument on its own is inherently incomplete. As a reading of Moore's laboratory report shows us, it did not function as a stand-alone device, and indeed couldn't — it was never intended to be a single instrument, but was rather a specialised module at the end of a chain that began with the physiological and electrical drivers. Even the manufacturers' catalogues show this via the vast range of accessories sold à-la-carte, modular and interchangeable for any local context. Preserving the kymograph's historical meaning hence requires more than the kymograph alone — just as more is required for x-ray cameras without film, particle accelerators without pico-ammeters, slide rules without numbers to multiply and divide. Their full scientific meaning resides not in what they were designed to do, but in what they *did* do, impossible without the other instruments and spaces in which they did it, pointless without the particular problems that went to them instead of to other apparatus, and often via adaptations and compromises that allowed the science to get done.

Moore's laboratory report has directed us towards a great deal, but it remains at the same time obscure through the absence of the laboratory instructions that Moore and his fellow students had. We saw what a few published manuals had to say, and that their instructions left many details tacit. Perhaps these details were expected from students' prior studies, or perhaps they were taught in the laboratory by demonstrators and technicians. There were also various in-house productions, such as those that

Cannon conveyed to press. Northwestern University still has a copy of its in-house manuals, apparently mimeographed or spirit-duplicated from the typescript in black ink. It is substantially annotated by the medical student in whose papers it survives, hinting at how the student interacted with the instructions. On one page, the student added a note that captures the risk of making serious mistakes by acting without all of the consequences in mind. For us, that note can double as metaphor, cautioning against all else that vanishes when scientific instruments are, for good reasons, deemed obsolete: "Do not kill guinea-pig before setting up apparatus."[56]


## Acknowledgements

I am grateful to several individuals for collection access and associated assistance: Mirna Heruc, Anna Rivkin and Elizabeth Pascale in University Collections at the University of Adelaide; Cheryl Hoskin, Marie Larsen and Lee Hayes in the University of Adelaide Special Collections; Andrew Cook in the University of Adelaide Archives; Jan Huisman at the Universitetsmuseum Groningen; Jan Brazier at the University of Sydney's Macleay Museum.


56. Laboratory instructions for "General Principles of Pharmacology" in: Harold Clifford MORRIS, *Papers*, Northwestern University Archives, Box 1, Folder 6, p. 35.

# List of Figures

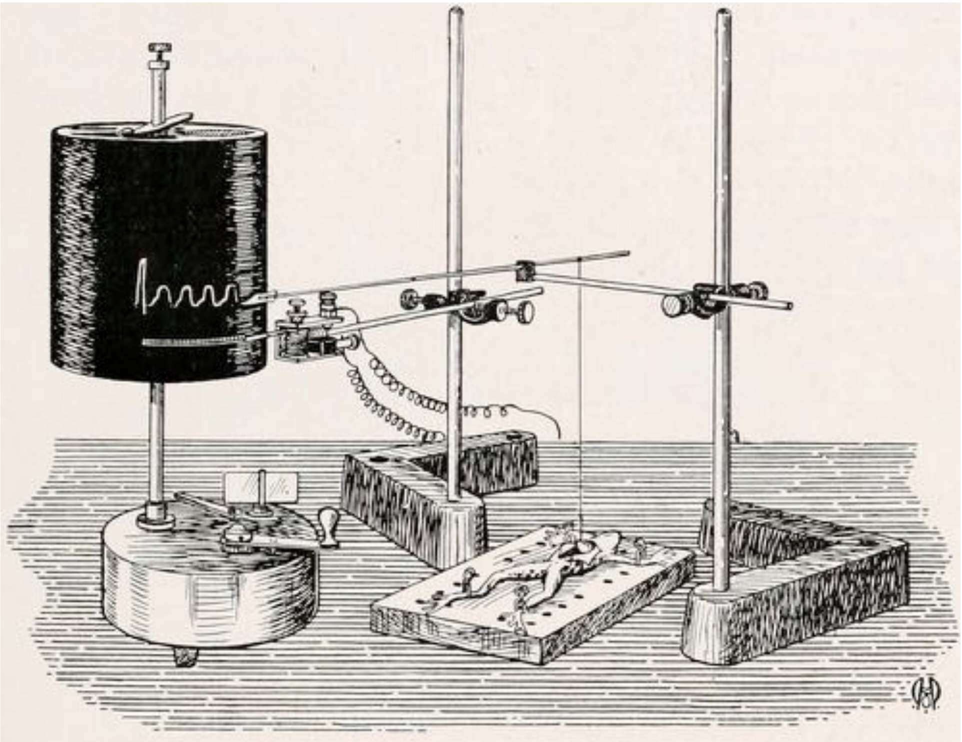


**Figure 1:** A kymograph driven by a frog's aorta (upper lever) and a clock (lower lever). From D.E. JACKSON, *Experimental Pharmacology*, St Louis, MO: C.V. Mosby 1917, p. 67. The kymograph shown is of the Harvard kind. The lever with a knob is for winding the spring, and the rectangular vane spins 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.

**Figure 2:** Students working in the Darling Building, University of Adelaide, 1929. The kymographs are adapted from the original Harvard instruments. In HICKS, *Papers*.

**Figure 3:** 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.

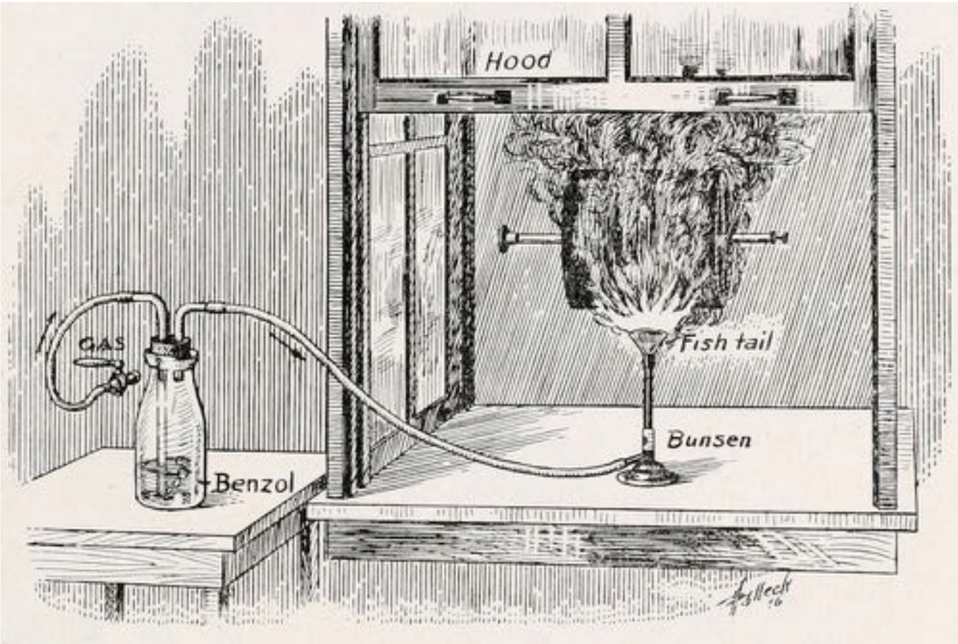



**Figure 4:** Smoking a kymograph drum over a fish-tail burner. The gas is bubbled through benzol in a one-pint milk bottle to increase the smokiness. The experimenter's hands are not shown here. JACKSON, *Experimental Pharmacology*, p. 61.

**Figure 5:** Smoking burner at Adelaide, made by Palmer (London). There are three of these: 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 has a capsule for benzol.

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

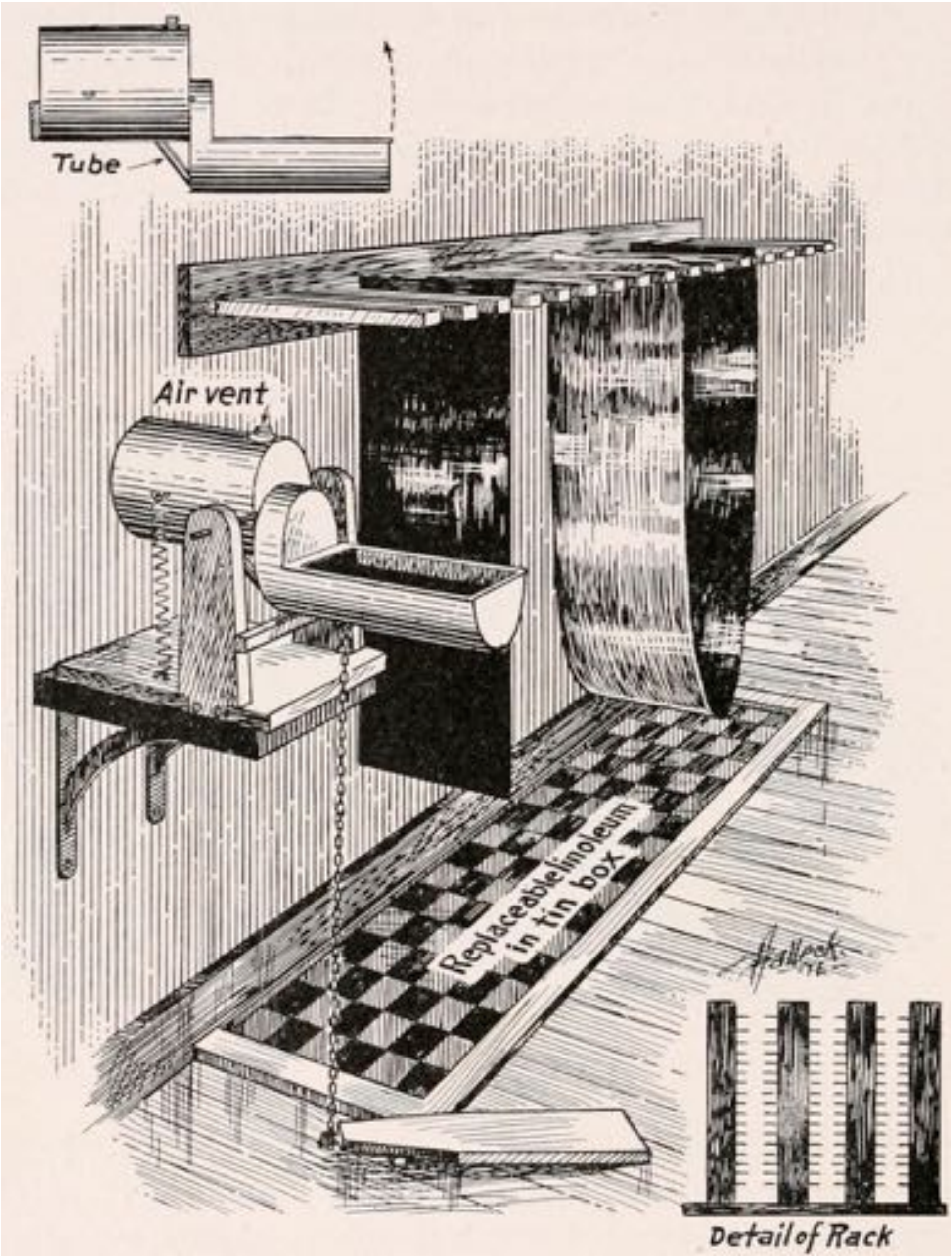



**Figure 7:** Apparatus for varnishing the trace and hanging it to dry on spiked bars. When not in use, the spring-loaded trough uprights itself to drain into its reservoir, limiting evaporation. The book's next illustration shows a setup for dipping long traces: two stools for the students to stand on, and a trough on the floor between them. JACKSON, *Experimental Pharmacology*, p. 63.

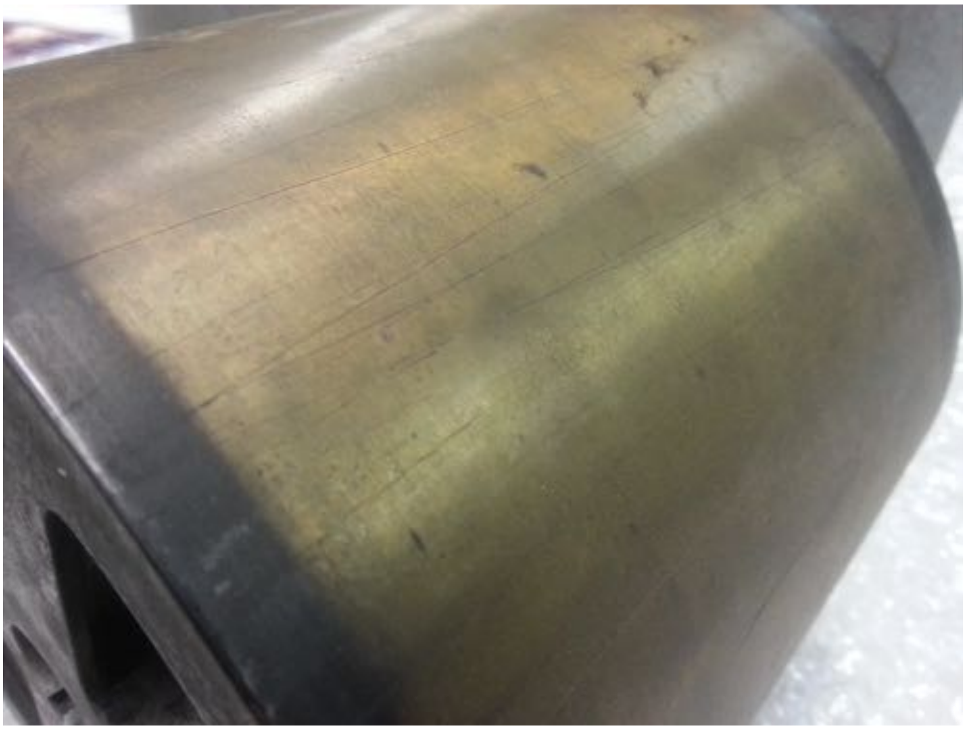


**Figure 8:** Cuts on a brass kymograph drum in the University of Adelaide's heritage collections. Several drums bear numerous cuts like this one, while the others show no such damage. This particular drum is brass, and of a style suggesting that it was part of the many kymographs that Adelaide sourced 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.

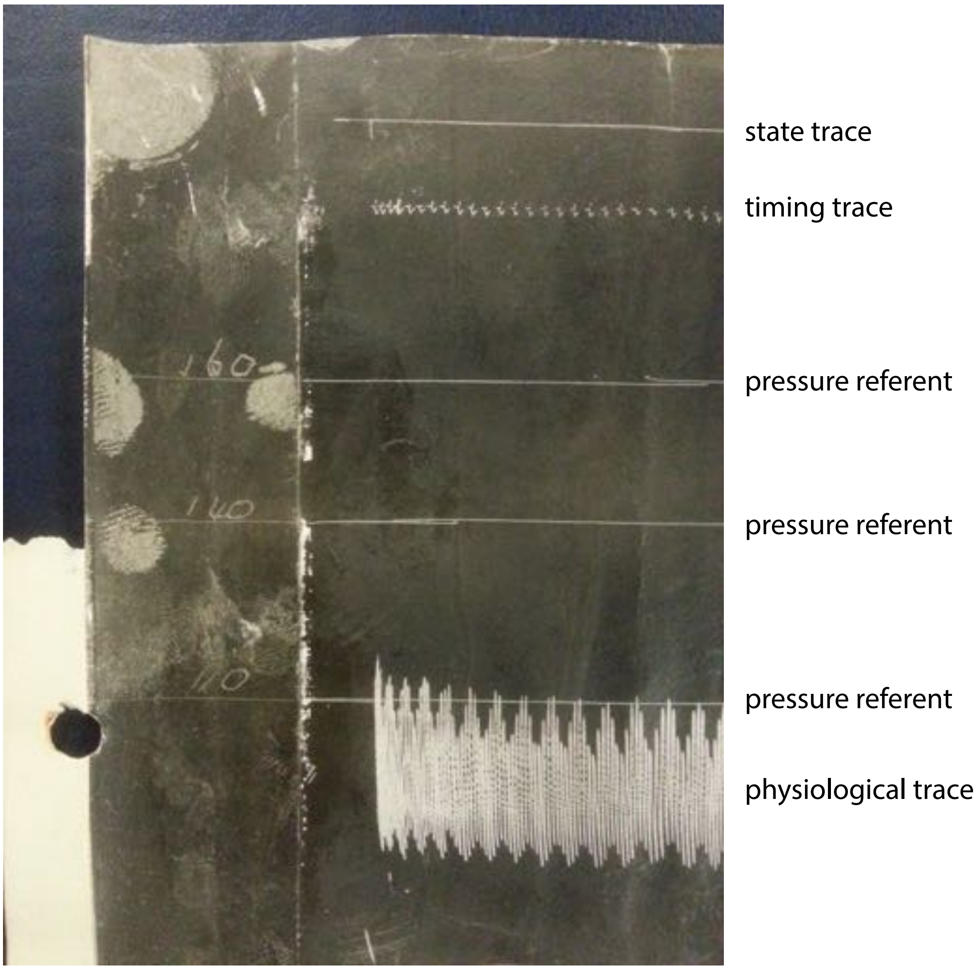
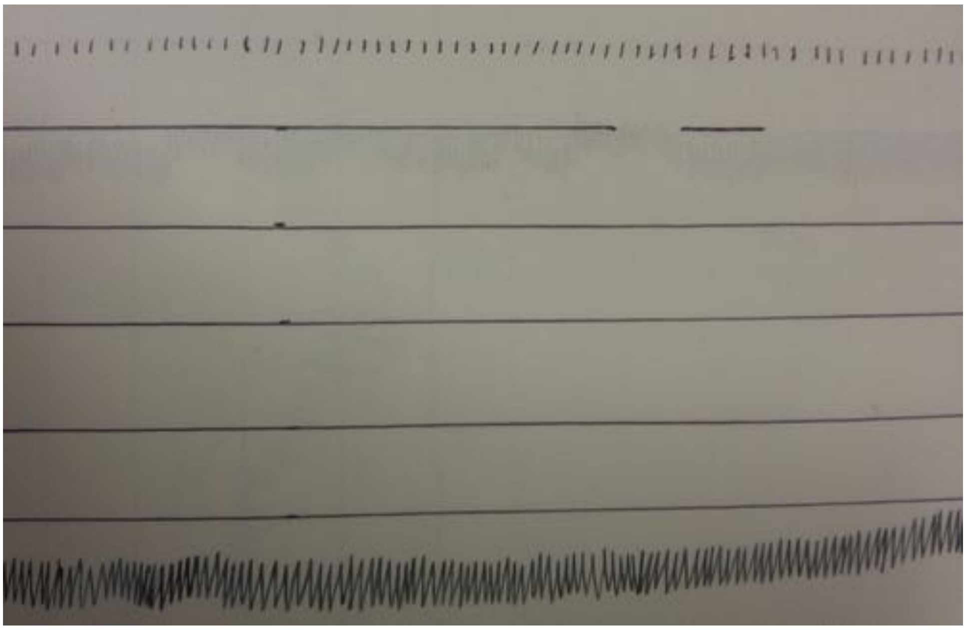
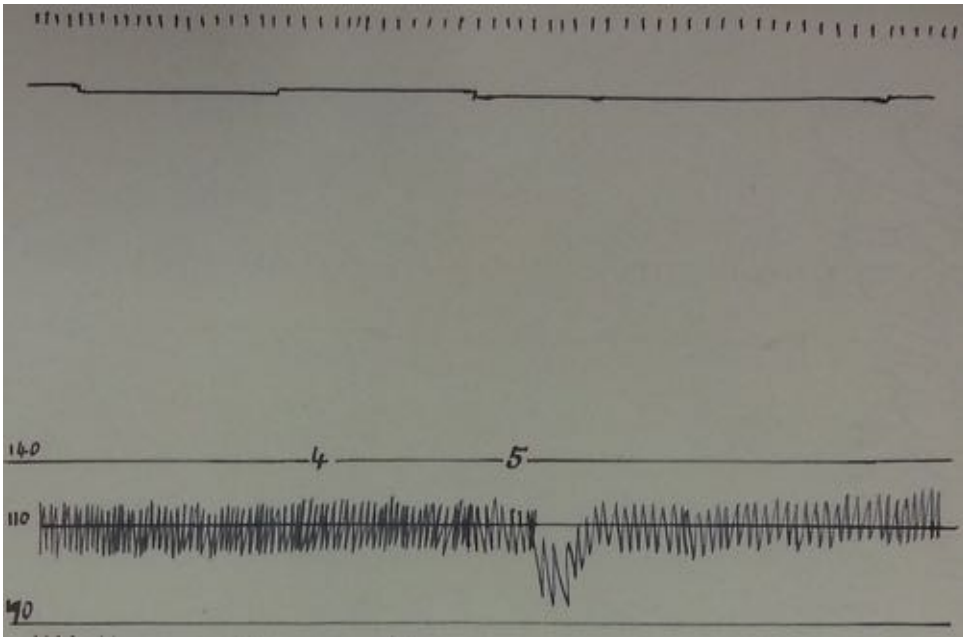



**Figure 9:** A corner of a smoked drum trace. Light, overlapping fingerprints cover the perforations directly above the 0's of '160' and '110'; note also the *i*-shaped timing strokes, the over-drawn pressure referents and the dashed tracing.



(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.

# List of Tables

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

| 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 $\frac{1}{10000}$ adrenalin, then saline. | 8 |
| 2:02 | Stimulus to vagus as in trace 7. | 9 |
| 2:15 | Normal tracing. | 10 |
| 2:16 | 1 cc $\frac{1}{1000}$ atropin. | 11 |
| 2:17 | Stimulus to vagus as in trace 7. | 12 |