File opened: April 14, 2025
Completed draft: May 21, 2025
Rev. June19, 2025

Chapter 9

Experience Generalized

1. Introduction

The goal of small-e empiricism is to provide an updated version of empiricism that is well-adapted to the present character of science. Empiricism privileges experience as a way of being informed about the world because experience gives us a physically continuous connection with those aspects of the world of interest to us. In empiricist writing since the seventeenth century, human sensory experience has been taken to be *the* way that this continuous connection is realized. It has become apparent through the practices of modern science that this privileging of human sensory experience must be rethought.

What matters is the continuity of the connection. The authority of experience derives from it and not from the participation of human sensory organs in the connection. Historically, human sensory organs played an essential role in establishing that connection. They were the best instruments fit for the purpose. We now find that sophisticated scientific instrumentation is quite capable of establishing this connection without human sensory organs playing any essential role. In many cases, these instruments perform far better than does the human sensory system; and in many cases they perform where human sensory experience could not.

Empiricist writing in philosophy of science has been slow to acknowledge this transformation. This may result in part from van Fraassen's controlling influence on the conception of empiricism in recent philosophy of science. His empiricism insisted upon a conception of experience that employed the narrowest form of human sensation. In rejecting this narrowing, I follow Nora Boyd (2018) whose empiricism is based on a recognition that experience as human sensation no longer suffices for an empiricism adequate to modern science. She wrote (p. 404):

> In the hope of replacing observations with something more suitable to science in practice, we might consider the more generic 'empirical results', where 'results' may be understood to include observations and other sensings but also the results of technology-aided detections and measurements, and 'empirical' may be understood in contrast with 'virtual' and 'imagined' and could be cashed out by appeal to a causal story connecting the target of interest to the generation of that result.

Small-e empiricism seeks to maintain the core empiricist doctrine of the authority of experience as a mode of being informed about the world. Thus, the adaptation to modern science requires a generalization of the notion of experience. Since its authority derives from the continuity of the connection to the world, not from any special role of human sense organs, the generalized notion of experience characterizes as experience any process that connects continuously to the aspect of the world of interest to us. The generalized notion includes familiar processes essentially dependent on human sensory organs. It adds many more that are now routinely used in the sciences.

The term "experience" will continue to be used, even though some may find the term incongruous. This usage maintains continuity with the empiricist tradition and its privileging of experience. It is justified since, in my view, the authority of experience never could be justified simply by the participation of human sensory organs. That authority always derived from the physical continuity of the connection, even if this was not apparent in empiricist writings. That continuity can now be secured without human sensory organs.

This chapter articulates and defends this generalized conception. Section 2 below will recall the imperfections of human sensory experience. Hacking, it will say, used the wrong standard when he asked provocatively "Do we see through a microscope?" Human sight is a poor standard since it is prone to illusions. Microscopes serve empiricism well in so far as they realize processes that connect with the systems of interest. The examples of ptychography and radar show that such processes serve well, even if they do not deliver familiar pictorial representations.

Subsequent sections will track how modern scientific instrumentation evolved to enhance and replace processes of human sensory experience. This evolution is pervasive in science. It can be illustrated only with a few examples. Section 3 will recount how nineteenth century analytic chemistry developed chemicals tests for the analysis of samples in which human sensory experience played a major role. It was essential that the chemist see some specific chemical change or smell some characteristic odor. In the course of the twentieth century, these tests were replaced almost entirely by automated analyzers in which human sensory experience played no essential role. They served the same purpose of determining the chemical nature of a sample, but now do it without the chemists' eyes and noses.

Instrumentation has also replaced an integral part of human sensory perception. We humans do not just perceive an excitation of sensory neurons. Our nervous systems translate the excitations of our sensory organs into mental states that reflect the character of the source of excitation. These are "impressions" to use Hume's expression. Some of the processing is so automatic that it is seamless. We then deepen the interpretation with some cognitive processing. Galileo, for example, saw three or four stars through his telescope in the vicinity of Jupiter that he instantly recognized as lying in straight line. After a few moments' reflection, he realized that the line coincided with the plane of the ecliptic. Subsequent observation led him to affirm that the stars were orbiting Jupiter as its moons.

Section 4 traces this development in astronomy in the discovery of new celestial objects. It recalls discoveries by Brahe and Kepler of novas; of the moons of Jupiter by Galileo; and the dwarf planet Pluto by Tombaugh. All these processes have been replaced by observational data of luminous celestial objects collected and processed automatically. Where we might once have thought that human scrutiny was needed, a computer algorithm now sifts through many instances of the brief dimming of the brightness of star to identify those cases in which the dimming results from the transit of an exoplanet.

Section 5 traces a similar development in the replacing of human sensory processing. Genetic material in living cells were first identified by human visual sensing through optical microscopes. Subsequently X-ray diffraction images were recognized as arising from a helical structure. Human genome sequencing, however, was successfully achieved entirely by computer algorithms piecing together the fragments of human DNA into the long strands of human's 23 chromosomes.

Section 6 recounts what is likely the most esoteric replacement for human sensory experience. Where Tycho Brahe and Johannes Kepler saw the blazing light of new stars, the massive interferometers of the LIGO project observe black hole coalescences through a medium quite inaccessible to human sensory organs, pulses of gravitational waves produced by these coalescences.

The discussion in these sections reports only a few examples of how scientific instrumentation has replaced human sensory organs. This replacement has become so pervasive in modern scientific practice that no synoptic survey can do it justice in a single chapter. With apologies to those whose favorite examples of automated scientific instrumentation have been neglected, my selection of examples is haphazard. They are instances that I happened upon that turn out to illustrate the instrumental supplanting of the various phases of human sensory processes sketched above.

2. We Do Not Need to *See* Through a Microscope

2.1 Hacking and the Microscope

Ian Hacking's celebrated (1981) "Do We See Through a Microscope" was one of many expressions of discomfort with van Fraassen's extremely limited view of the reach of experience. Van Fraassen (1981, p. 214) had sought to answer negatively the questions (among several) "Can we observe through an electron microscope? Through an optical microscope?" Hacking's response was both successful and unsuccessful. It was successful in his dissatisfaction with the paucity of understanding of the actual science of microscopy in the philosophy literature. He lamented quite correctly (p. 305):

> … the modern microscopist has far more amazing tricks than the most imaginative of armchair students of perception. What we require in philosophy is better awareness of the truths that are stranger than fictions.

His paper proceeded with a rather unfocussed account (on my reading) of the historical development of modern microscopy from its seventeenth century origins in van Leeuwenhoek's work. Throughout the narrative, Hacking examined how well the evolving instruments could produce images comparable to those familiar to naked eye vision. To deliver such images, microscopists had to compensate for many visual infidelities. They begin with aberrations in lenses, such as spherical and chromatic; and become increasingly complicated as the design of microscopes become increasingly sophisticated. After many complications, Hacking did decide (p. 321) that "we *are* convinced" of the reality of structures seen through microscopes; and I think he intends that we *should* be convinced, even though he italicized the "are."

Where was Hacking's paper unsuccessful? It was in his answer to the question of whether "see" through a microscope. He sought the extent to which the instrument could yield an image comparable those of ordinary visual experience. This betrays a needless reverence for ordinary visual experience. In my view, in an empiricism well-adapted to science, all that matters is whether the physical processes in the microscope connect with the system of interest in such a way that we can infer the system's properties. In his analysis of polarizing microscopes, Hacking does momentarily admit something in the direction of abandoning the standard of ordinary vision. Since we cannot perceive polarization directly, he avers in italics (p. 313):

> *We could use any property of light that interacts with a specimen in order to study the structure of the specimen.* Indeed we could use any property of any kind of wave at all.

This promising remark, however, proved not to be a first step to disavowing the necessity of images akin to ordinary visual perception.

Why disavow the need for images akin to those of ordinary visual perception? There are two reasons. Briefly stated, first, ordinary visual perception is just not good enough to serve as an ultimate standard for the faithful representation of systems of interest. Second, what matters is being informed about the system of interest; and we can do that with any physical process that accesses it, as long as the process delivers something that can be usefully interpreted.

2.2 Visual Illusions

First, we learn from ordinary visual illusions that human vision is imperfect. It is a mistake is to think that our visual perception is like a static photograph, each of whose elements correspond faithfully to some element of reality. Time and again what we perceive visually is a combination of the reality and our brain's best, faltering attempt to interpret it. For example, Figure 1 below is a completely static image that seems to many viewers as beset with rolling wavelike motions.

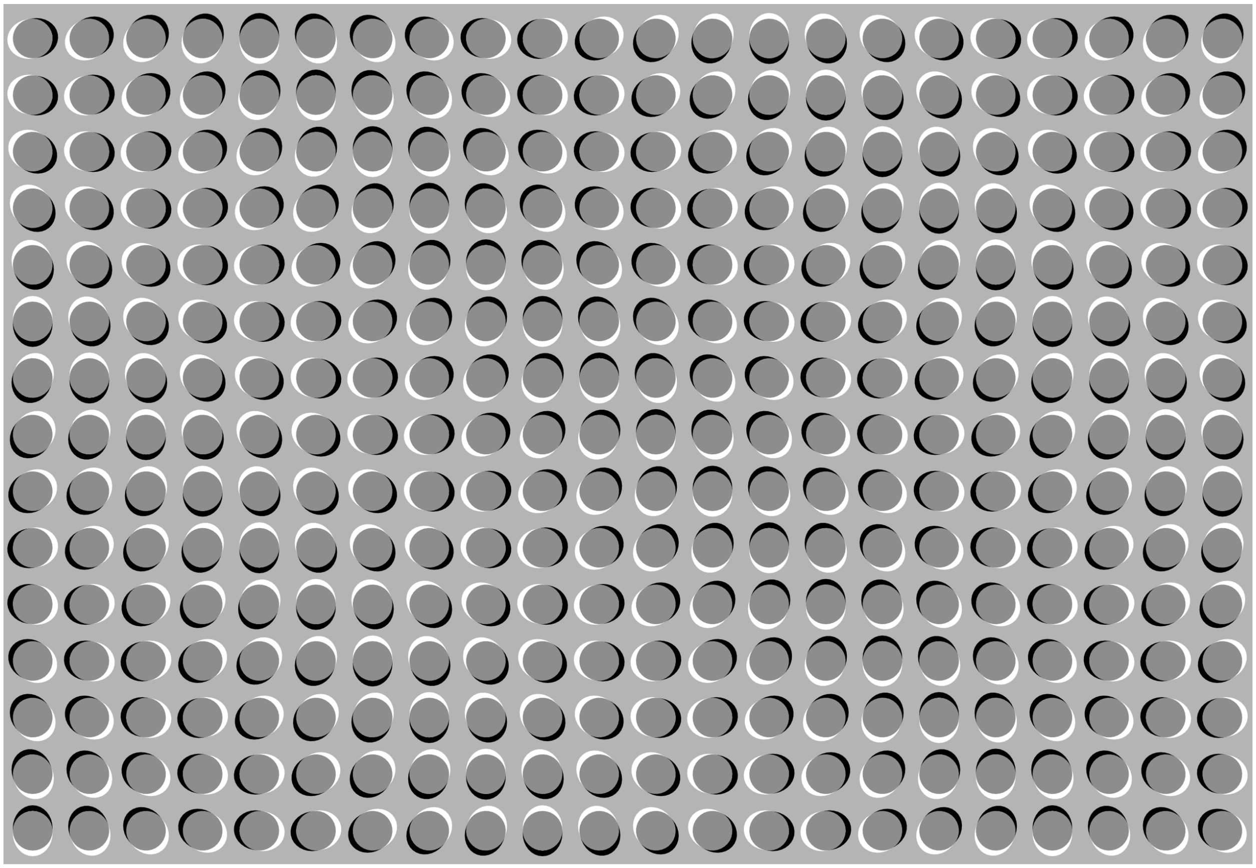

Figure 1. Motion optical illusion[1]

Our vision can also give us the illusion of reality with vivid images of objects that cannot possibly exist, such as in Figure 2.

[1] The illusion arises if we move our gaze over the surface of the figure. Based on https://en.wikipedia.org/wiki/File:Anomalous_motion_illusion1.svg "This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license."

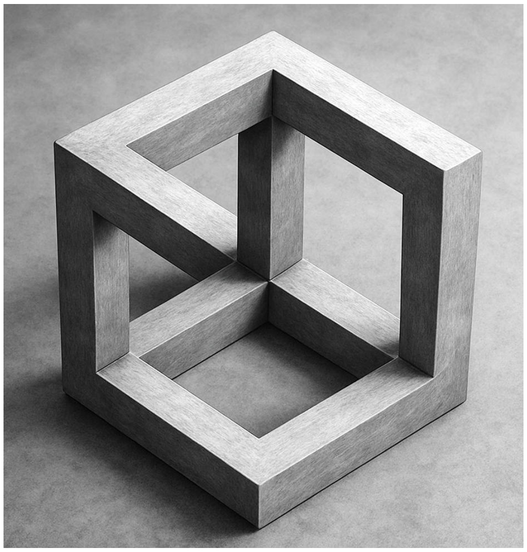

Figure 2. An impossible object[2]

Given the fallibility of human vision, when are we justified in accepting the images in our vision as veridical? It is when we can affirm that the images arise through a process that connects with a system of interest in the world; it does so by a process that faithfully reflects its properties; and we are able to distinguish those real properties from artifacts of our perception. That condition, of course, can be realized by processes that only incidentally involve human sensory organs and need not produce ordinary visual images.

2.3 We Can Do Better Instrumentally

This last point is the second reason for disavowing the images of human vision as the standard. We can often do better without them. An example arises in microscopy. In "ptychography," many microscopic images of some object are taken, each slightly displaced. The resulting set of images is somewhat uninformative to ordinary visual examination. However, the optics of the imaging has been so set up that the images contain phase information, not directly interpretable on visual inspection, but that can be synthesized by a computerized algorithm to deliver a visually informative image. Figure 3 is an example.

[2] Created by chatgpt from prompt "create a hyperrealistic image of an impossible object greyscale" https://chatgpt.com/c/6806fe74-689c-8000-b07a-b2d6c90ac734

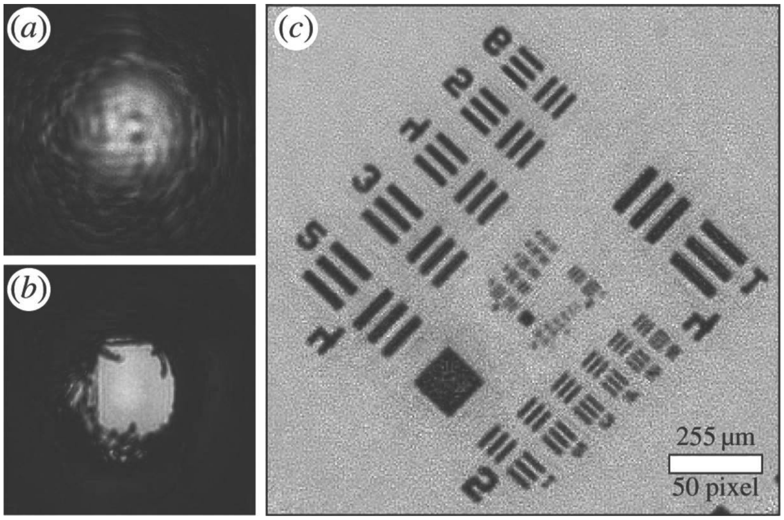

Figure 3. Real and constructed images in pytchography[3]

The actual images taken look like those on the left at (a). They are an unhelpful blur.[4] After a computer has synthesized them, it generates an informative image on the right at (c). There is no sense in which "see" this last image through the microscope. It is a synthetic creation of the computer algorithm, but one that informs us well of the object examined.

A handbook article on ptychography notes the deviation from familiar practices in microscopy (Rodenburg and Maiden, 2019, p. 821):

> Unlike the immediacy of a conventional microscope, ptychography puts a huge obstruction between the microscopist and the image. First, we must wait while at least the two interference patterns are recorded; the experiment takes time. Second, we have to rely on the computer to reconstruct the image from the data. The data usually look nothing at all like the object of interest; we must wholly trust a

---

[3] Image from https://commons.wikimedia.org/wiki/File:Ptychography_experiment_with_visible_light_in_a_laboratory.jpg "This file is licensed under the Creative Commons Attribution-Share Alike 4.0 International license."

[4] Figure 3 is a greyscale rendering of the original color image, where color differences encode phase differences, but are not much more informative to visual inspection.

computer algorithm to deliver our results, something that unnerves quite a lot of scientists.

It then notes how this method improves on conventional microscopy. For example, it can work with images produced by poor lenses or even no lenses at all.

2.4 Non-Pictorial Imagery

In ptychography, the results are eventually delivered in the form of an image such as we imagine we would see if were shrunk down to the microscopic size of the object. It is convenient for we humans to have results delivered to us in such a familiar form. Such presentations are likely to be comprehended more easily and quickly than others. That mode adapts to the results to our human idiosyncrasies. There may be nothing intrinsic to the results that requires this adaptation to the pictorial form familiar to us. What matters is whether the instrument gives us some representation that enables us to infer properties of the system of interest. Such a representation may even be better than a pictorial representation.

Hacking briefly discussed radar. The early history of radar, not mentioned by Hacking, is an example of how imaging can usefully tell us about a system of interest without producing the sorts of pictorial images of ordinary vision. Figure 4 shows radar displays from early, mid 1940s radar sets, as described in Navy Department (1946, pp. 13-14). The screen on the right is the display now familiar to us. It gives something that looks like an overhead view of the surroundings, such as we imagine we might see visually if were to observe the surroundings from an overhead position. A rotating radial line, corresponding to the direction of the radar beam, leaves bright spots corresponding to the locations to the objects reflecting the beam. Another early screen type is shown on the left. There is no sense that it mimics the familiar pictorial images of ordinary vision. In the "L-type scope," the distance vertically in the display of the "blip" indicates the distance to the object reflecting the beam. The direction to the object is determined independently by noting the direction in which the radar antenna is pointing.

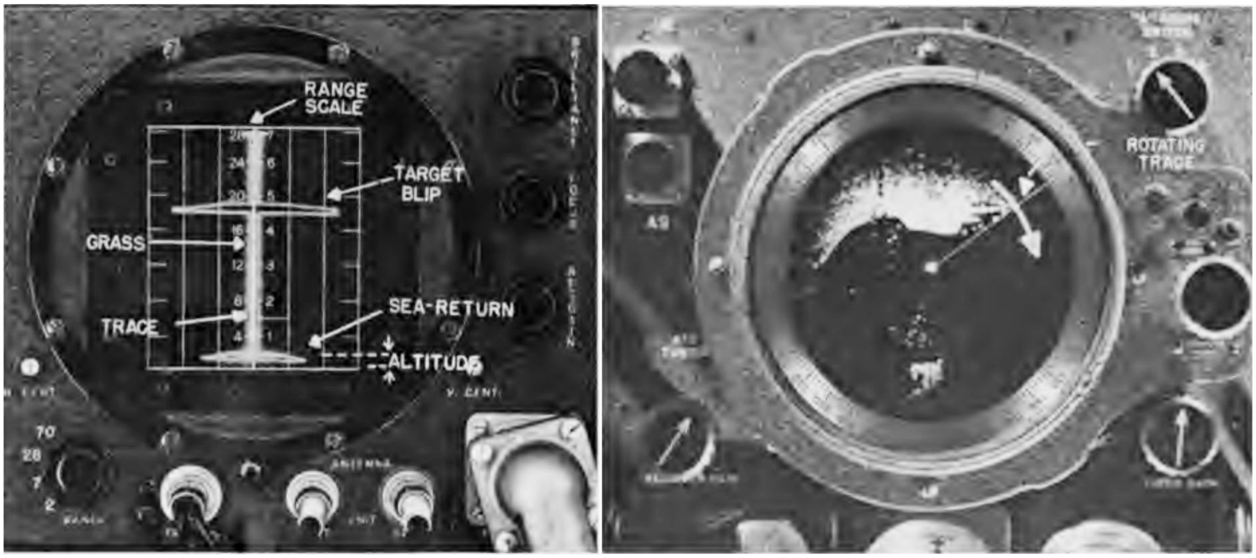

Figure 4. “L-type scope” and “PPI-type scan” in early radar sets[5]

The non-visual presentation of the L-type scope gives quite serviceable information on the distances to the echoing objects. It may even provide better information than the more familiar display since the L-type scope isolates the echoes from a specific direction and can give a more detailed display of the magnitude of the echo.

3. Instruments Replace Human Sensory Organs: Analytic Chemistry

In traditional human sensory experience, the first stage of the process is the excitation of sensory organs as a way of registering the result of a process that connects with the system of interest. Throughout the sciences, human sensory organs have been replaced by instrumentation. This transition is illustrated in this section by the transition in the methods of analytic chemistry over the last century from the well-trained eyes and noses of analytic chemists to the automation of analytic instruments.

It is a transition I experienced on a compressed timescale. As a teenager fascinated by chemistry, I pored over old chemistry texts for interesting effects that I could recreate in my parents’ garage. I routinely prepared many gases that I learned to identify by their smell. Some were easy, such as hydrogen sulphide (“rotten egg gas”), ammonia and chlorine. Might a red-hot

[5] Images from Navy Department (1946, pp. 13-14) is a US government publication and thus in the public domain.

copper wire immersed in methyl alcohol vapor produce formaldehyde in a self-perpetuating catalytic reaction? I tried and yes, it does, copiously; and I thereby learned to identify formaldehyde by its distinctive smell. (This was an earlier age in which little heed was paid to the question of which substances might be carcinogenic.)

A few years later, as a junior chemical engineer in an oil refinery, the means of identifying gases no longer needed my sense of smell. I would draw a gas sample from a process line with a thick rubber bladder and ride it over to the laboratory. There an analyst would pass it through a gas chromatograph and provide a quantitative breakdown of the composition of the gas sample. It far transcended what my risky sniff test could have revealed. We were testing for hydrogen, which is odorless. It had to be completely purged from our high temperature pressure vessels before oxygen could be introduced, lest the entire unit explode.

3.1 The March Test

James Marsh's (1836) sensitive test for arsenic was a celebrated triumph of nineteenth century analytic chemistry. Arsenic trioxide was freely available in the nineteenth century as, for example, rat poison. It is also poisonous to humans. It is a white powder, resembling flour, and its presence in food is not readily detectible by casual consumers. The symptoms of arsenic poisoning resemble the gastric symptoms of cholera, a common illness in the nineteenth century, so that poisoning by arsenic trioxide may not be correctly identified. As a result, arsenic trioxide had become the favored medium for murder by poisoning. Marsh's test was a celebrated addition to forensic science, since it made it possible to detect arsenic poisoning, even from trace quantities of arsenic. A footnote in Marsh's (1936, p. 229) paper notes that "The Large Gold Medal of the Society of Arts of London, was presented to Mr Marsh for the above valuable communication…"[6]

Marsh's test was not the first analytic test for arsenic. Rather its value lay in its greatly improved sensitivity. It would be applied to arsenic containing fluids, such as suspect food or drink, or the stomach contents of its poisoning victims. The test employed a sulfuric acid solution into which some pieces of zinc have been added. This is the standard method of producing hydrogen gas. If the sample is added to this solution, arsenic in it will be converted by

[6] See Hempel (2013) for further details of the historical context.

the hydrogen gas to arsine gas, or “arsenuretted hydrogen,” as Marsh called it. The arsine gas was allowed to escape through a jet and, if ignited, burns in the air.

The trained senses of the analyst were essential to the test. Marsh (1836, p. 232) noted the presence of arsenic is already evident in the color of the flame, compared with that of the burning of the pure hydrogen: “If no arsenic be present, then the jet of the flame as it issues has a very different appearance…” A later treatment (ICS, 1900, p. 49) elaborates “If arsenic should be present, the flame of hydrogen burning at the end of the tube will, often in a few seconds, change its color, becoming whitish…” The flame is directed towards a cold surface. Marsh (p. 230) suggested a pane of window glass. Then, a distinctively visible layer of metallic arsenic is deposited. If the flame is directed into a glass tube, the analyst’s sense of smell can complete the analysis. Marsh noted: (p. 230)

> In this case, if the tube, while still warm, be held to the nose, that peculiar odour, somewhat resembling garlic, which is one of the characteristic tests of arsenic, will be perceived. Arsenuretted hydrogen itself has precisely the same colour [as hydrogen?], but considerable caution should be used in smelling it, as every cubic inch contains about a quarter of a grain of arsenic.

Figure 5 shows the simpler apparatus Marsh (1836) proposed on the left and, on the right, a later, more elaborate apparatus described in ICS (1900, p. 49). It is called “Marsh’s apparatus” and has added components to filter out possible contaminants in the arsine gas stream.

Figure 5. Apparatus for the Marsh test

3.2 Nineteenth Century Analytic Methods

The Marsh test illustrates two characteristics of nineteenth century analytic chemistry. First, the test depends narrowly on the specific chemistry of arsenic. It could not be used to detect other metals or metalloids in the sample.[7] Second, trained human sensory capacities comprise an essential step in the analysis. The analyst should recognize the difference between a hydrogen flame and an arsine flame, how a metallic deposit on the cooled surface looks and the distinctive garlic-like smell of arsine.

We see these same characteristics in the huge range of different analytic tests devised by nineteenth century chemists. Muter (1898) is a massive catalog of chemical reactions and related physical properties that can be used to determine the chemical composition of a sample. It is divided into two parts: the first covers qualitative analysis; and the second covers quantitative analysis. No simple summary is possible since the text just consists of a massive compilation of distinct methods. They are given is a terse form to facilitate quick consultation by practicing

---

[7] Antinomy was an exception, as noted in ICS (1900, p. 16). Antinomy deposits can be distinguished from arsenic, the source notes, since they are less volatile and not removed by a solution of chlorinated lime.

chemical analysts. An example, chosen quite arbitrarily, concerns the detection of Manganese compounds and gives an indication of the methods: (p. 21)

> NH_4HS *in the presence of* NH_4Cl *and* NH_4HO (*group reagent*) precipitates a flesh-coloured manganous sulphide—MnS—soluble in dilute and cold hydrochloric acid (distinction from the sulphides of Ni and Co). It is also soluble in acetic acid (distinction from zinc sulphide). This precipitate forms sometimes very slowly and only after gently warming. If a good excess of NH_4Cl has not been added, or if, after adding the excess of ammonium hydrate, the solution be exposed to the air, a portion of the manganese will sometimes precipitate spontaneously, as manganic dioxyhydrate—$Mn_2O_3(HO)_2$— and be found with the iron, etc., in the first division of the third group. In this case its presence will be easily made manifest during the fusion for chromium by the residue being green. It is therefore evident that small quantities of manganese cannot be perfectly separated from large quantities of iron by NH_4Cl and $NH_4H\grave{O}$ only.

Later, the means of detecting hydrochloric acid are listed: (p. 30)

> Hydrochloric Acid—HCl—may be recognised—
>
> 1. By its acidity and its giving off Cl_2 when heated with MnO_2.
> 2. By producing dense white fumes when a rod dipped in ammonium hydrate is held over the mouth of the bottle.[8]
> 3. By giving a curdy white precipitate of argentic chloride with argentic nitrate, instantly soluble in ammonium hydrate.

In these, and many, many more paragraphs like them, we see that the analyst is actively engaged in selecting and undertaking a sequence of tests that would enable the discrimination among many possible substances. The results require observation by a skilled analyst who has no trouble discerning just what is meant by a "flesh-coloured" precipitate, how it differs visually from the sulphide precipitates of cobalt, nickel and zinc, by a "curdy white precipitate" and that a pungent-smelling gas given off is chlorine gas (Cl_2).

---

[8] As a teenager, I was greatly amused by this acid's ability to produce these dense white clouds of ammonium chloride when exposed to vapors of a strong ammonia solution.

3.3 Instrumental Methods

In the course of the twentieth century, analytic methods were transformed. The new methods no longer focused on the chemical properties of the substances to be analyzed. Instead, they worked on the physical properties, such as the masses of the individual atoms or molecular fragments, the different rates at which they might diffuse in media and the characteristic frequencies of radiation that may emit or absorb. The transformation in analytic chemistry has been massive. The older "wet" methods, such as developed in the nineteenth century, have been replaced almost entirely by automatic instrumentation. Crucially for our purposes, human sensory organs no longer play a central role in analysis. Rather the presence of atomic or molecular species in the sample is read, for example, from the location of peaks in a graph produced by the instrument. An operator no longer needs a trained nose to distinguish benzene from acetone. Which is present and to which extent is read from the location and magnitude of peaks in a graph produced by the instrument.

A recent textbook (Robinson et al., 2021) surveys the range of analytic instrumentation according to the physical principles implemented in each. The survey is divided into sections according to the physical principles employed. The methods are:

Spectroscopy: divided into visible and ultraviolet molecular spectroscopy; infrared, near-infrared, and Raman spectroscopy; magnetic resonance spectroscopy; atomic absorption spectrometry; atomic emission spectroscopy; x-ray spectroscopy; mass spectrometry.

Chromatography: divided into gas chromatography; chromatography with liquid mobile phases; electroanalytical chemistry.

Thermal Analysis

In X-ray dispersal spectroscopy, a sample is irradiated by X-rays that induce the emission of secondary X-rays. The emission occurs when electrons in the irradiated atoms jump to higher energy states; and then, on returning to their lower energy states, reradiate the energy acquired during their irradiation. For each element irradiated, the energy of the X-ray quanta carried by the emitted radiation can take on only a small set of values, according to the characteristic energy differences between the energy states allowed for the atom's electron. The energies of this emitted radiation are so distinctive of each chemical element that they can serve as a fingerprint that identifies the presence of that element.

Figure 6 shows an example of X-ray dispersion spectroscopy. The sample is a mineral crust on the vent shrimp *Rimicaris exoculate*. The plot in the figure shows the intensities of the emitted radiation, separated out according to their energies. Each peak can then be associated with a definite chemical element: C, carbon; O, oxygen; Fe, iron; Mg, magnesium; Si, silicon; P phosphorus; and so on.

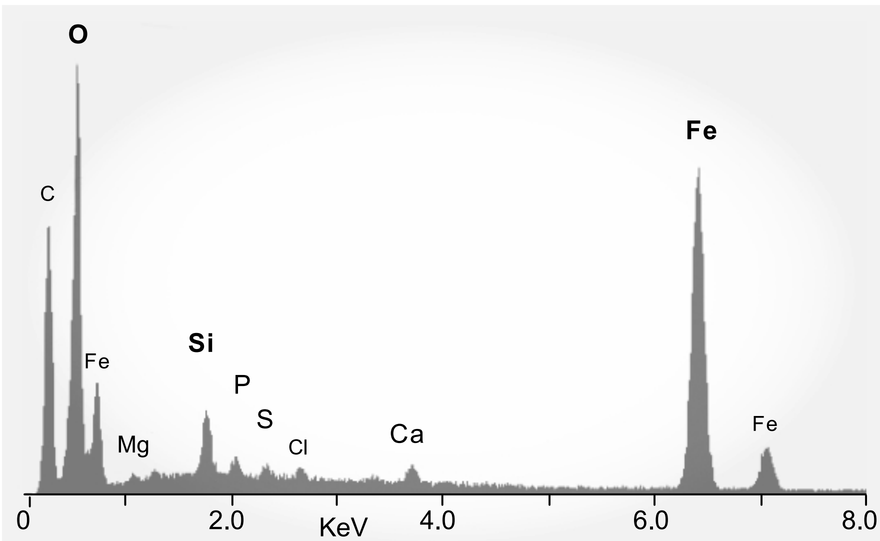

Figure 6. Energy Dispersal X-ray Spectrum (EDS)[9]

The method allows detection of the range of elements present in one analytic process. This replaces the multiple tests that nineteenth century methods required; and it dispenses with the need for chemists trained to distinguish the pungent odor of Chlorine (Cl) from that of hydrogen chloride (HCl).

Mass spectrometry employs a physical principle already well understood in the nineteenth century. A beam of charged particles, atoms or molecular fragments in an evacuated chamber, can be deflected by electric and magnetic fields. The magnitude of the deflection is fixed by the mass to charge ratio of the charged species and by the strengths of the deflecting fields. This process was employed, famously, by J J Thomson (1897) on cathode rays, which he believed to consist of charged particles, later known to us as electrons. His belief in the particle

[9] Source: Corbari et al. (2008), Figure 6. "This work is distributed under the Creative Commons Attribution 3.0 License."

character of the beam was affirmed when varying the deflecting fields allowed him to determine a unique mass to charge ratio for its constituent particles.

A few decades later, A. J. Dempster and F. W. Aston employed the same technique for chemical analysis. It can be applied to any sample that can be vaporized and ionized, so that the sample can form an electrically charged beam of ions. The ions can then be sorted according to their mass to charge ratios. The sorting is carried out by varying the strength of the deflecting fields. Figure 7 shows a schematic of Dempster's (1918) original apparatus.

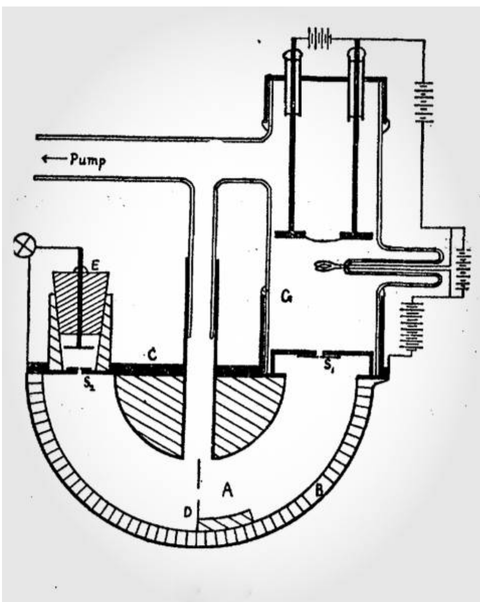

Figure 7. Dempster's mass spectrometer[10]

The beam of charged ions is generated at the left. It is then deflected in a semi-circular arc through the semi-circular channel in the bottom half of the figure to the detector at the right. Only charged ions with just the right mass to charge ratio can fully traverse the channel. Changing the strength of the deflecting field, allows a separation of the charged ions according to their mass to charge ratios to complete the analysis.

Marsh's test for arsenic remained the favored test well into the twentieth century. Mass spectrometry proved to be a better option. Tanaka et al. (1996) showed the effectiveness of the method for forensic purposed for detecting arsenic in blood and stomach contents. In a single

[10] Image source: Dempster (1918), Fig. 1, p. 317.

test, their mass spectrum allowed them to determine the presence and extent of many elements, including potassium, calcium, iron, zinc, copper and arsenic, without the need to detect the garlic-like scent of arsine.

4. Intelligent Instruments: Astronomical Detection of New Stars

The replacing of human sensory organs by instrumentation is only a small part of the transition in the empirical foundations of science. Another part of human sensory experience happens automatically. We do not just recognize that one or other sensory receptor has been stimulated. We recognize that, through the smoky glass at a solar eclipse, we are seeing the sun's disk with a moon shaped piece occluded; or that we just heard the distinctive squeal of an ignited hydrogen/oxygen mixture; or that we are smelling roasted coffee[11] and not cocoa or onions. The recognition is immediate and separating it from the mere fact of stimulation is artificial. Consider the photograph below in Figure 8. It is not perceived as a pattern of various shades of grey. It is instantly recognized as an image of the Egyptian Sphinx. Only a few moments of subsequent reflection tells us that the image is likely quite old and comes from the first excavations of the artifact.

[11] Coffee tasting has long been the province of human experts. Gabrieli et al. (2022) report success in creating what they call an "AI-assisted electronic tongue" that could discriminate among 21 varieties of coffee.

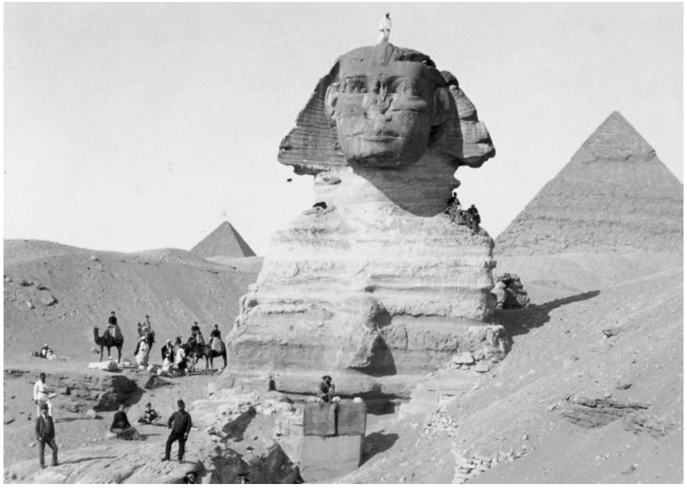

Figure 8. The Egyptian Sphinx[12]

Across the sciences, instrumentation is replacing this automatic faculty of human sensory processes; and often in a way that far exceeds human capacities. The example to be explored in this section is the development of automatic techniques in astronomy for detecting and characterizing new celestial objects. The following Section 5 describes how the detection and characterization of genetic material has been automated.

4.1 Naked-Eye Astronomy

Simple observation of the night sky has, for millennia, sufficed for the identification of comets and other bright novelties. Two have a special place in sixteenth and seventeenth century astronomy. Their appearance was useful evidence that, contrary to ancient Greek thought, the heavens were not immutable. In November 1572, Tycho Brahe observed a new star in the constellation Cassiopeia. Figure 9 is his representation of it in his Brahe (1573). The "new star" (*nova stella* in Latin) is marked *I*:

[12] Photograph by Beniamino Facchinelli (1839-1895). Source https://gallica.bnf.fr/ark:/12148/btv1b10508565d/f1.item#

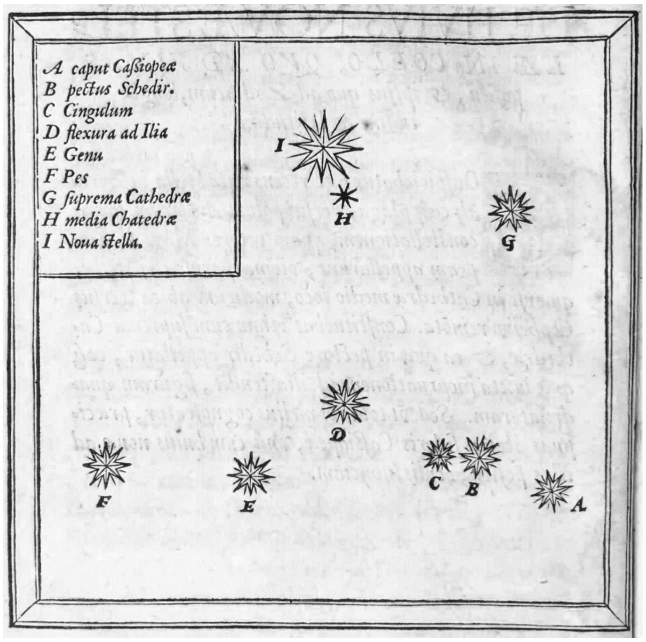

Figure 9. Tycho Brahe's *Nova Stella*

Johannes Kepler (1606) then recorded his observations of a second new star appearing in 1604 in the constellation *Ophioukhos* (*Serpentarius*, in the title of Kepler (1606)).

4.2 The Telescope

Famously, the first step beyond naked-eye astronomy towards observations through mediating instruments came within a few years. Galileo commenced his observations of the heavens using the new instrumentation of the telescope. In January 1610, he began nightly observations of the stars around the planet Jupiter. He saw three and then four stars arranged in a straight line that was parallel to the plane of the ecliptic. Over subsequent nights in January through to March, he carefully noted how these stars rearranged their positions. As a result, Galileo could identify them as moons, orbiting Jupiter. He called them the "Medicean planets" in deference to his patron, Cosmo II de' Medici. In his (1610) *Sidereus Nuncius*, Galileo printed images of 63 of his nightly observations. The first seven only are show in in Figure 10.

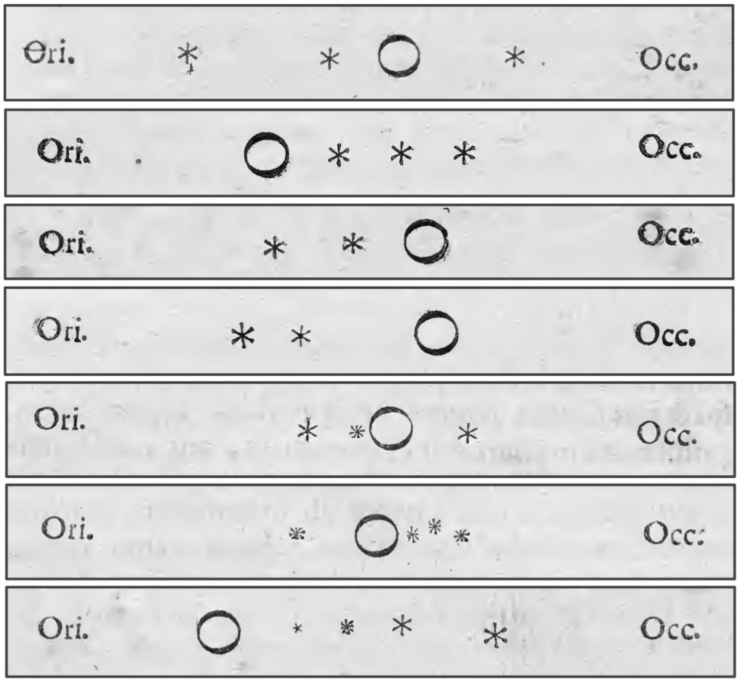

Figure 10. Galileo's first seven images of Jupiter and its surrounding moons on successive nights[13]

Once he had identified the stars as moons, Galileo immediately pointed out how this deflated an objection to the new Copernican, heliocentric planetary system. It seemed anomalous that our Earth's moon should be the exceptional body that did not directly orbit the sun. Galileo could now report other moons orbiting another planet. The Earth's moon was not a lone exception.

4.3 The Blink Comparator

The introduction of astrophotography altered the methods used for detecting new celestial bodies. Instead of painstakingly scrutinizing the heavens night upon night for new objects, astronomers could take multiple photographic plates over many nights as records of the state of some small patch of the heavens. The search for new celestial objects now reverted to a painstaking comparison of these plates, tiny region by tiny region. The tedium was relieved by the introduction of the blink comparator. Two plates of images of the same part of the night sky were loaded into the comparator for inspection by the user. The comparator would flip back and forth at roughly one second intervals between some portion of the first plate and the

[13] Ori. = Oriens, East. Occi. = Occidens, West.

corresponding portion of the second plate. Any difference between the two plates would appear dynamically.

The most celebrated use of the blink comparator was Clyde Tombaugh's January 1930 discovery of a long-suspected planet outside the orbit of Uranus. This was the "trans-Neptunian" planet long sought by Percival Lowell (1915). It was named "Pluto," with the first letters "PL" matching Lowell's initials, and only 76 years later demoted to the ignominy of a "dwarf planet." Figure 11 shows a pair of images taken by Clyde Tombaugh in January 1930 in which the position of what will be identified as Pluto changes as marked.

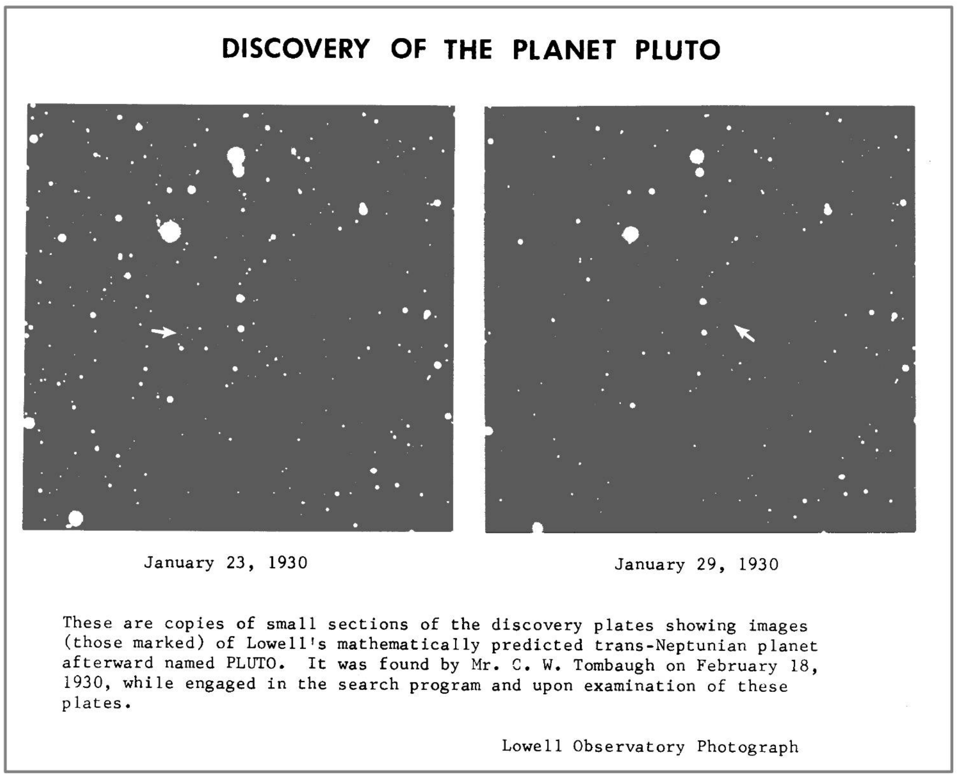

Figure 11. Clyde Tombaugh's images in which Pluto was found[14]

[14] Image source: Lowell Observatory archives, https://collectionslowellobservatory.omeka.net/items/show/1247 The image is used under the provisions of fair use. The photos enter the public domain in January 2026, which is 95 years after their creation.

Popular accounts reduce Tombaugh's discovery merely to noticing a moving celestial object in a part of the sky. For example, the noted astronomer H. N. Russell (1930), in his July 1930 *Scientific American* article described the discovery as follows: (p. 21)

> Photographs of moderate exposure covering the whole region of the heavens around the predicted position were obtained and on one of them, taken on January 21, 1930, Mr. Tombaugh of the observatory staff found "a very promising object." It was identified from its motion past the numerous fixed stars as revealed on plates of the same star field while being compared under the blink comparator. This showed that one faint star among many thousands had shifted its place by a certain expected order of distance, in the interval between the taking of the two plates.

This report, no doubt abbreviated for a popular audience, understates the amount of interpretation needed. Tombaugh had to do more than merely see something moving in a suitable part of the sky. He had to determine that it was not a spurious sighting of something other than a new planet. In a later recollection, Tombaugh (1946) recounted how he precluded the possibility that his sighting was of an asteroid or other "suspicious object." (pp. 76-77)

> Much time, effort and expense may be lost in running down planet-suspects that turn out to be only asteroids near their apparent stationary points where they imitate the slow motion of a more distant planet. The simple expedient was to photograph each region near its "opposition point" (180° from the Sun), where the apparent retrograde motion is a maximum for all planets outside the Earth's orbit, and the daily shift in position against the star background is roughly inversely proportional to the distance of the object. As a consequence, the asteroids, on the average, moved about 7 millimeters per day on the plates, and exhibited short trails during the hour's time of exposure, whereas Pluto moved only 1/2 millimeter per day. This criterion was useful in estimating at sight the distance of any suspicious object, and extremely convenient in computing a rough ephemeris when it was necessary to re-photograph a region later in running down a promising planet suspect. The known asteroids number a few thousand and are widely scattered between the orbits of Mars and Jupiter.

Even this apparently quite mechanical observation required considerable intelligent interpretation.

4.4 The Discovery of Exoplanets

Both Galileo and Tombaugh applied human insight to complete their identification of novel celestial bodies. The need to preclude spurious sightings persists in the modern search for new celestial bodies. Because of the large number of candidate objects delivered by modern telescopes, the sort of insights Galileo and Tombaugh provided had to be automated. There are just too many candidate objects for practical human scrutiny.

This automation has been a central part of the recent discovery of thousands of "exoplanets." They are planets that orbit stars in our galaxy outside our solar system. The search for these exoplanets was furthered decisively by the masses of new data supplied by the Kepler space telescope mission. It was launched in 2009 and decommissioned in 2018. There are several methods of detecting exoplanets. One involves a detection of the dimming of the light from a star when an exoplanet passes in front of it. Figure 12 shows the dip in brightness due to an exoplanet transit for the Kepler mission's first five exoplanet discoveries.

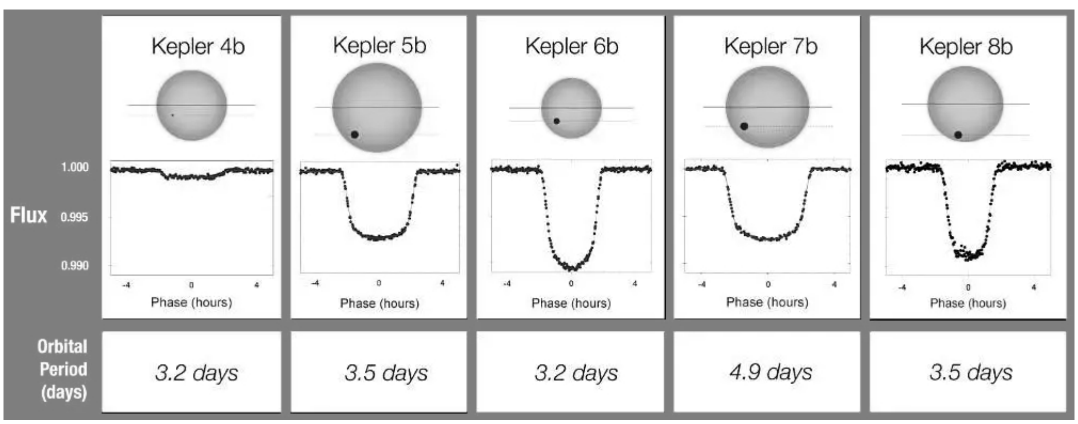

Figure 12. Brightness dip from exoplanet transit[15]

The age-old difficulty arises with this detection method. These sorts of dimmings can come about in other ways. For example, they may result from a binary star when the alignment of the pair of stars is such that one eclipsed the other; or they may arise from some other chance alignments. The challenge was to discriminate these so-called "false positives" from the genuine

[15] Source: https://www.nasa.gov/image-article/light-curves-of-keplers-first-5-discoveries/ Public domain image from US Governement website.

detection of an exoplanet. The huge number of candidate "Kepler objects of interest" precluded easy human scanning. Morton et al. (2016) reported the successful result of an automated search of Kepler's database of survey results by means of the "VESPA" procedure.[16] To use it, they fitted a trapezoidal shape to the curve of the light dimming in the signals from the Kepler survey. The procedure then applied a simple Bayesian model to distinguish which of the modeled signals were most likely to result from an exoplanet as opposed to another source. Among 7056 Kepler "objects of interest," they found 1935 that were most likely exoplanets. That is, there was a less than 0.1% posterior probability that they were false positives. For our purposes, what matters is that this search was not conducted by humans, scanning case after case. It was fully automated. "This work," Morton et al (2016, p.2) were proud to report, "presents results from applying VESPA *en masse* to the entire Kepler catalog."

The program of discovery of exoplanets has continued to advance since the time of these earlier studies. In a 2024 account of the different methods of exoplanet detection, Kaushik *et al.* (2025) report a new tally of over 5500 exoplanet discoveries; and the number continues to grow. As Morton *et al.* (2023) report, the VESPA procedure has been recommended for retirement. The detection of false positives is now implemented successfully by machine learning algorithms, such as reported in Armstrong *et al.* (2021).

The on-going search for exoplanets is just one of the programs of astronomical investigation in which the search for celestial objects has become automated. Another example is the All-Sky Automated Survey for Supernovae (ASAS-SN). It was initiated in the later 2010s in order to search for supernovae and other similar objects. Its scope has since expanded to include the search for a wider range of variable stars. The number of variables recovered is so enormous that automated techniques are essential. A 2021 report (Jayasinghe, T. *et al.*, 2021) noted that the survey had then already cataloged over 60 million sources in which about 426,000 variable sources were located by machine learning methods, of which about 219,000 were new discoveries.

4.5 The Event Horizon Telescope

In astronomy, there are many more important instances of the use of instrumentally mediated observations. A most striking example has been provided by the Event Horizon

[16] "Virtual European Solar and Planetary Access"

Telescope Collaboration. On April 10, 2019, the Collaboration published its first image (Figure 13) of the black hole at the center of the galaxy M("Messier")87.

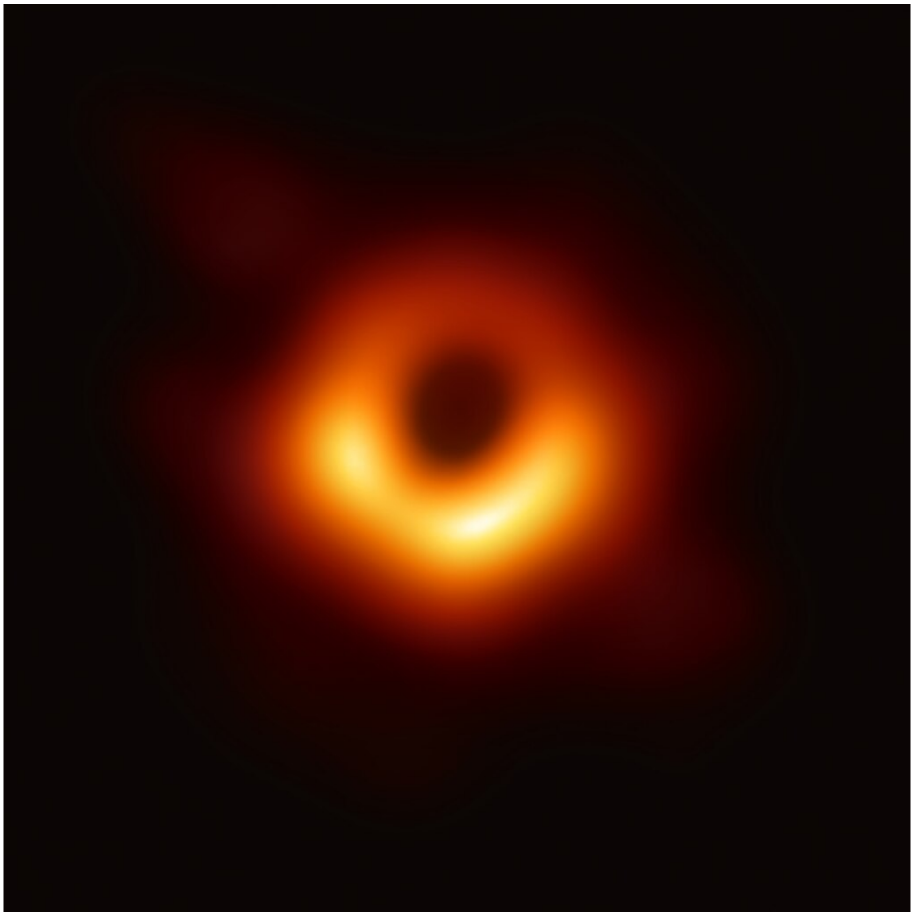

Figure 13. Event Horizon Telescope image of the black hole in galaxy M87[17]

The announcement was greeted with enthusiasm in the press. On the day of the Collaboration's announcement, The *New York Times* published a celebratory report (Overbye, 2019) with the full headline: "Darkness Visible, Finally: Astronomers Capture First Ever Image of a Black Hole: Astronomers at last have captured a picture of one of the most secretive entities in the cosmos." Casual readers of the headline would be forgiven for imagining an astronomer, peering through the eyepiece of some immense device—the new "event horizon telescope"—

---

[17] Image source: https://en.wikipedia.org/wiki/File:Black_hole_-_Messier_87_crop_max_res.jpg "This file is licensed under the Creative Commons Attribution 4.0 International license."

and, in astonishment, seeing something most extraordinary. In great excitement, a camera shutter clicks and an image is captured for us all to see of the most elusive beast in the astronomical menagerie.

The reality of the production of the image is much different. The famous image was never seen by some eager astronomer, hovering over the eyepiece of a fancy new telescope. To begin, the image is from electromagnetic radiation in the gigahertz frequency range used by radio telescopes. It is far from the terahertz frequencies of visible light. The black hole shadow captured is far too small an object in the sky to be resolved by any single radio telescope. A device with an aperture the size of the earth itself is needed to resolve it. The Collaboration managed to simulate such a device by collecting huge amounts of data from many radio telescopes, spread across the surface of the earth. Collecting that data was just a first step. What followed was massive processing over two years of the data by multiple teams in parallel. The celebrated image was produced as a consensus of their work. See Ochigame et al. (manuscript) for a careful analysis with attention to epistemological details of the production of the image.

In 1610, in his *Siderius Nuncius* (1610, pp. 8-11), Galileo published his hand-drawn images of the surface of the moon derived on his telescopic observations. The changing patterns of light and dark over time in those images provided observational evidence of high mountains and low seas. It was the beginning of a new, instrumentally mediated tradition of observation in astronomy. Four centuries later, images of light and dark, derived from radio telescopes, provide observational evidence of a black hole's event horizon.

5. Identification of Genetic Material in Cells

5.1 Flemming's Chromatin

In the nineteenth century, genetic material in cell nuclei was identified using optical microscopes. Walther Flemming (1882) saw rounded clumps containing coiled threads in the cell nuclei. He called them (p. 130) "chromatin," because of their special affinity in taking up dyes, which made them more easily visible under optical microscopes. (We now recognize chromatin as consisting of coiled DNA and associated proteins.) Figure 14 is Flemming's (1882, p. 319) representation of the cell division of cells of a green algae, spirogyra. It shows the fission of the chromatin into two and the formation of two cell nuclei. Flemming (1882, p. 376) later called the division "mitosis."

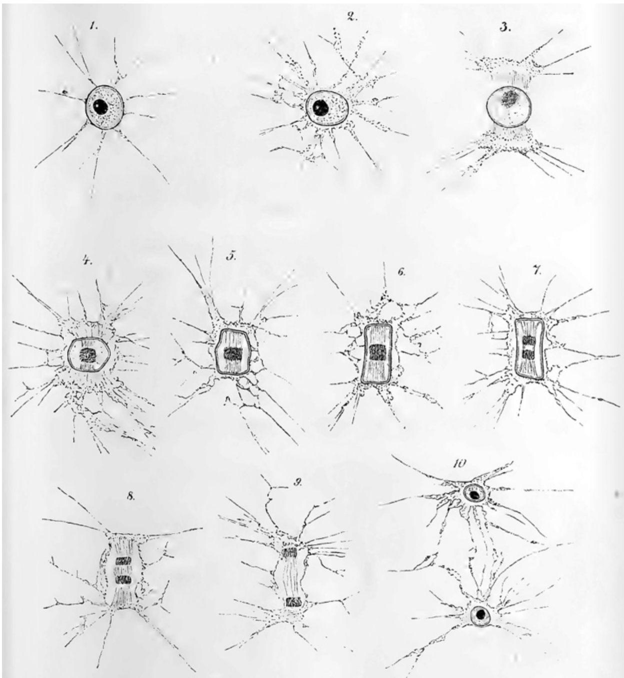

Figure 14. Flemming's depiction of cell division

This image in unusual because Flemming gives some details of its creation. It was by traditional optical instruments. He wrote (p. 319) "Images 1–9 were taken with a camera clara [an old form of a *camera obscura*], all at the same magnification (photographically reduced)." The images are not photographs, but, apparently, hand drawn from them. He wrote (p. 401): "The text images [in this volume] … are drawn directly from the specimens."

5.2 X-ray Diffraction Imagery

Flemming's investigations dealt with images visible through an optical microscope. They were accessible to ordinary visual experience. The identification of rounded clumps and threads was automatic since the microscopic images give familiar, pictorial representation of their subjects. In the mid twentieth century, the further investigation of chromatin employed X-rays. They no longer provided pictorial images that could be interpreted automatically with normal human vision. They were the next stage in the replacing of human experience by instrumentation.

X-ray diffraction imagery play a major part in the famous story of Crick and Watson's Nobel Prize winning identification of the double helix structure of DNA. In the April 1953 issue of *Nature*, Watson and Crick (1953) published their still tentative structure for the DNA molecule.[18] Behind their announcement lay an energetic competition to be the first to determine the molecular structure of DNA. In their 1953 note, Watson and Crick disputed their chief competitor, the triple chain model of Linus Pauling and others.

An important component of Crick and Watson's evidence for the double helix lay in X-ray diffraction images of crystalline DNA. When X-rays diffract off the regular lattice of a crystal, they produce patterns that are captured photographically. The images of chromatin that Flemming saw through his microscope were pictorially akin to their source. A clump looks like a clump. A thread looks like a thread. X-ray diffraction photographs, however, as shown in Figure 15 below, were not pictorial. They consisted of streaks and spots; and it requires expertise in X-ray crystallography to decode the crystal structure that produced them.

This interpretive step was then still carried out by human cognition. Such a step is recounted by Watson in his autobiographical account of the discovery. Rosalind Franklin and her student Raymond Gosling had prepared painstakingly some of the best X-ray diffraction images of DNA. They included a "B" form of DNA that arises when the molecule is surrounded by large amounts of water. In January 1953, Watson visited Franklin's laboratory at King's College, London. During the visit, Franklin's colleague, Maurice Wilkins, without Franklin's knowledge and possibly improperly, showed Watson one of Franklin's X-ray images of the B form of DNA. Watson (1968, Ch. 23) recalled the moment as one of high personal drama:

> The instant I saw the picture my mouth fell open and my pulse began to race. The pattern was unbelievably simpler than those obtained previously ("A" form). Moreover, the black cross of reflections which dominated the picture could arise only from a helical structure. With the A form, the argument for a helix was never straightforward and considerable ambiguity existed as to exactly which type of helical symmetry was present. With the B form, however, mere inspection of its X-ray picture gave several of the vital helical parameters. Conceivably, after only a few minutes' calculations, the number of chains in the molecule could be fixed.

---

[18] "So far as we can tell, [the structure proposed] is roughly compatible with the experimental data, but it must be regarded as unproved until it has been checked against more exact results." (p. 737)

Figure 15 shows the difference between the X-ray diffraction patterns of the A and B forms.

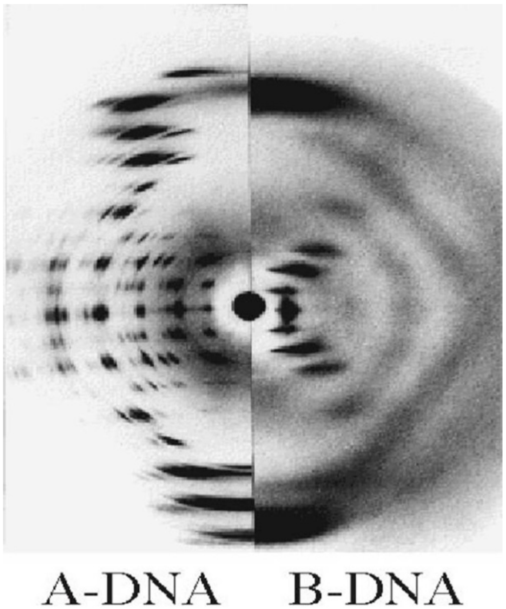

Figure 15. X-ray diffraction patterns for two forms of DNA[19]

We should read the narrative details of this moment with a little caution. It is part of a self-aggrandizing narrative that is also unconscionably dismissive of Franklin. For our purposes the main point is likely secure. Watson had become quite adept at understanding the sorts of X-ray diffraction patterns that would be produced by helical structures. Visual inspection of Franklin's X-ray image was sufficient for him to recognize its source as a helical structure. "Mere inspection," Franklin noted, sufficed.

[19] Image source: https://commons.wikimedia.org/wiki/File:ABDNAxrgpj.jpg "Physical Chemistry of Foods, vol.2, van Nostrand Reinhold: New York, 1994." "This work is free and may be used by anyone for any purpose. … The Wikimedia Foundation has received an e-mail confirming that the copyright holder has approved publication under the terms mentioned on this page." "This file is licensed under the Creative Commons Attribution-Share Alike 3.0 Unported license."

5.3 Human Genome Sequencing

In the late nineteenth century, Flemming began research into the genetic material in a cell nucleus through his visual, microscopic examination of chromatin. The modern development of this program is the sequencing of genomes in the DNA of different organisms. That is, a genome is sequenced when we have a full map of order of the bases A, G, C, T (adenine, guanine, cytosine, thymine) in each strand of the organism's DNA. One of the foremost achievements of this development was the sequencing of the human genome. It was carried out by a massive collaboration, the International Human Genome Sequencing Consortium, from 1990 to 2003.[20] The final stage of the sequencing is yet another instance in which the recognition of the structure to be learned is no longer possible for human cognition. It must be carried out by computers.

In overall concept, the final stage of the sequencing of the human genome is akin to solving a jigsaw puzzle. Human cognition suffices to solve such a recreational puzzle. When two puzzle pieces match along their edges, they likely belong together in solved puzzle. A solver scrutinizes the various puzzle pieces for what the solver identifies as matching patterns at the edges. These matches enable a painstakingly assembly of the complete puzzle. A large and challenging puzzle may have as many as 1,000 pieces.

In DNA sequencing, the individual puzzle pieces are fragments of DNA of sufficient size that overlaps between their parts makes it likely that the two fragments belong together in the final sequence. The corresponding puzzle addressed in human genome sequencing is vastly larger than a recreational jigsaw puzzle. Human DNA consists of 23 chromosomes that contain approximately 3.1 *billion* base pairs. The assembly of the DNA fragments into a completed sequence could only be done by computers. The consortium (IHGSC, 2001, pp. 863-64) reported two related approaches: the "hierarchical shotgun sequencing" approach was implemented by the consortium; and the "whole-genome shotgun approach" was implemented by a biotechnology company, Celera Genomics. Agreement between the results of the two approaches affirmed the correctness of the final sequencing. Figure 16 shows how one of the "front-line participants" conceived of the shotgun approach.

---

[20] For reports on the completion of the sequencing, see IHGSC (2001, 2003).

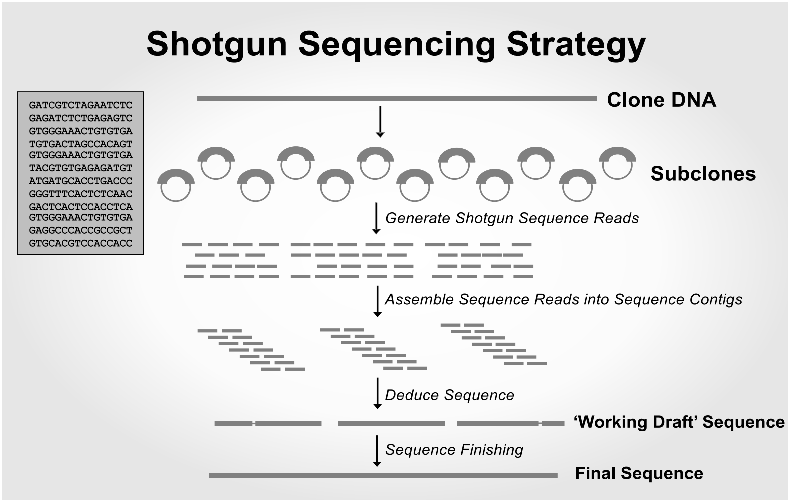

Figure 16. The shotgun approach as presented in a Human Genome Project Powerpoint slide[21]

6. LIGO: Laser Interferometer Gravitational Wave Observatory

Experience derives its authority from its realization as a physical process that connects with the object of interest. It is the presence of that process that matters. That human sensory organs may be involved is incidental. Any suitably interpretable physical process can serve as experience in this generalized notion of experience, no matter how esoteric the process may be. Perhaps the most esoteric of these processes is supplied by LIGO.

Essentially all[22] astronomical investigations, since the earliest moments, have employed electromagnetic radiation. They were initially limited to visible light; that is, the small frequency band to which human eyes are sensitive. Recent developments, such as X-ray astronomy, have opened the usable band considerably. A most significant advance came with the 2015 success of the LIGO Scientific Collaboration and Virgo Collaboration. It employed a new channel for observation. In place of electromagnetic radiation, it employed gravitational waves.

---

[21] Based on a slide from Powerpoint, Eric Green, "The Story of The Human Genome Project (HGP)…as Told by a Front-Line Participant" 9_1_Human_Genome_Project.pptx. Downloaded from website, The Human Genome Project, https://www.genome.gov/human-genome-project link at "Human Genome Project Overview Slides." Since the image is drawn from a US Government website, there is a presumption of public domain.

[22] The few exceptions include the examination of meteorites and, more recently, cosmic rays.

That there are waves propagating in a gravitational field was long supposed. It is a default expectation of any relativistic theory of gravity. Since special relativity is usually understood to prohibit effects propagating at faster than the speed of light, it seemed inevitable that a change in gravitational masses in some distant place must produce an effect that propagates towards us at no more than the speed of light. This expectation was realized theoretically in the 1910s with Einstein's discovery of the general theory of relativity. It is still our best theory of gravity and entails the existence of gravitational waves. Nevertheless, gravitational waves remained a troubled, theoretical speculation. For a while, Einstein even doubted their existence. Matters worsened with Joseph Weber's failed experimental efforts in the 1960s to detect gravitational waves.[23]

The formidable obstacle in detecting gravitational waves is that those likely accessible to us are extremely weak. Local detection is all but precluded since their effects are of the order magnitude of the thermal noise in even the best shielded detector. Their successful detection in 2015 by LIGO resulted from an extraordinary technological achievement. LIGO employs interferometers of enormous size. Each consists of two, four kilometer long evacuated tubes that are oriented perpendicularly. It follows from general relativity that a gravitational wave slightly alters the spatial geometries of bodies. When a gravitational wave passes through the interferometers, one arm contracts slightly and the other expands; and then the reverse; and so on. To detect these changes, the lengths of the arms are monitored by reflected laser beams. In spite of the huge size of the interferometers, the length changes that must be measured to detect gravitational waves are minuscule. Length changes of as small as 1/1,000th[24] the width of a proton are measurable by the LIGO interferometer. These minuscule perturbations have to be distinguished from background noise. That was achieved in 2015, with the first successful detection, by comparing the readings on two widely separated interferometers. One is in Hanford, Washington State; the other in Livingston, Louisiana, some 3,000 kilometers away. A gravitational wave would be judged as detected only when the changes in lengths ("strain")

---

[23] For a survey of the historical tribulations of gravitational waves, see Kennefick (2007).

[24] The LIGO website in 2025 expects this factor to be reduced to 1/10,000th. https://www.ligo.caltech.edu/page/facts

measured in both interferometers were well correlated. For it is unlikely that local noise at the two distant locations could be so correlated.

The Collaboration reported that their gravitational wave interferometer had detected a binary black hole merger in Abbott et al. (2016). The plots of the strain measurements against time in the two locations are given in a figure in Abbott *et al.* (2016). A section of the figure that shows the strains measured at each detection is given here as Figure 17.[25]

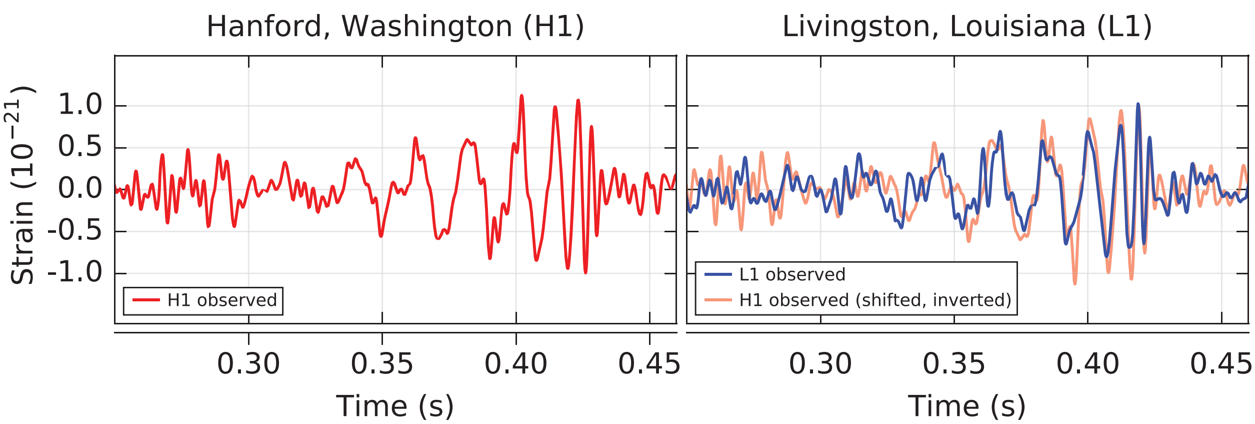

Figure 17. Strain measurements for LIGO event GW150914

That the event detected results from a distant black hole merger is determined by comparing the shape of the detected curve with a library of template curves computed numerically for such events on the basis of the general theory of relativity.

Unlike Brahe and Kepler's observations of novas, human sensory organs played no essential role in the detection and analysis of the merger. The initial detection was announced by an alert issued by computers engaged in real time monitoring of the data streams from the two interferometers. What followed was an elaborate reanalysis and interpretation of the detection, again all carried out by computers. The extent of these data processing operations is extraordinary. A paper devoted merely to these processes, Abbott et al. (2020), has over 150 authors.

The first and obvious achievement of the Collaborative was the empirical affirmation of a result predicted by general relativity, the existence of gravitational waves. The more significant

[25] From Figure 1 in Abbott (2016, p. 061102-2). "Published by the American Physical Society under the terms of the Creative Commons Attribution 3.0 License."

achievement for future work was heralded in an early publication by the LIGO Consortium. The title of Abbott et al. (2016a) talked of “the Era of First Discovery” and the abstract described the first discovery as “launching the era of gravitational-wave astronomy.” That this was their ambition from the outset was heralded by their naming of the Consortium: “Laser Interferometer Gravitational Wave *Observatory*.”

Rigorously skeptical empiricists may want to dispute whether processes as esoteric and hard to detect as gravitational waves can serve as a medium of observation. The scientists of LIGO clearly harbored no such reservations; and I think they are right. LIGO is an observatory in the sense that matters to empiricism. It employs physical processes, gravitational waves, that connect directly to objects of interest, black hole mergers and other massive gravitational events.

A decade later, it had become clear that LIGO’s ambitions to be an observatory had been realized. In a March 2025 press release (Burtnyk, 2025), the LIGO Collaborative announced the 200th gravitational wave detection in the then ongoing observational run; and the 290th detection in the overall life of the Consortium. These amount to the detection of many massive gravitational events. Most are black hole mergers, but also include neutron star mergers and neutron star-black hole mergers.

7. Conclusion

Empiricism has long privileged human sensory experience as the final arbiter of scientific fact. Might there really be egg-laying mammals with a duck bill in the new antipodean colony of New South Wales? Even eyewitness reports of platypuses published in 1802 did not convince all anatomists in the distant Northern hemisphere.[26] A sample that could be examined by them helped, but even then fears of a hoax specimen had to be allayed. It was a dispute that had to be settled by the eyewitness testimony of experts.

Such was the long-standing tradition of empiricism. Modern science has overturned this tradition. The ambitions of modern science now reach far beyond what eyewitness testimony can supply. There are no human sensory organs that can see, hear or smell the cataclysmic merger of two black holes. No human has the time and patience to scrutinize by eye the vast number of celestial objects now detected telescopically in a search for variable stars and exoplanets. Even

[26] See Hall (1999) for a recounting of this historical episode.

the most adept of human puzzle solvers are completely defeated by the challenge of assembling vast numbers of DNA fragments to reconstruct the human genome. All these discoveries are now made and interpreted automatically by instruments. They are the new authority that replaces the human eyewitness in an empiricism adapted to modern science.

References

Abbott, B. P. *et al.* (2016) "Observation of Gravitational Waves from a Binary Black Hole Merger," *Physical Review Letters*, 116, 061102, 1-16. DOI: 10.1103/PhysRevLett.116.061102

Abbott , B. P. *et al.* (2016a) "GW150914: The Advanced LIGO Detectors in the Era of First Discoveries," *Physical Review Letters*, 116, 131103 (2016).

Abbott, B. P. *et al* (2020) "A guide to LIGO–Virgo detector noise and extraction of transient gravitational-wave signals," *Classical and Quantum*, Gravity **37**, 055002

Armstrong, David J.; Gamper, Jevgenij; and Damoulas, Theodoros (2021) "Exoplanet validation with machine learning: 50 new validated Kepler planets," Monthly Notices of the Royal Astronomical Society, **504**, pp. 5327–5344. doi:10.1093/mnras/staa2498

Boyd, Nora Mills (2018) "Evidence Enriched," *Philosophy of Science*, **85**, pp. 403–421.

Brahe, Tychonis (Dani) (1573) *De nova et nullius aevi memoria prius visa stella, iam pridem anno a nato Christo 1572*. Hafniae [Copenhagen]: Impressit Laurentius.

Burtnyk, Kimberly (2025) "LIGO-Virgo-KAGRA Announce the 200th Gravitational Wave Detection of O4!" News Release • March 20, 2025 https://www.ligo.caltech.edu/WA/news/ligo20250320

Corbari, Laure *et al.* (2008). "Iron oxide deposits associated with the ectosymbiotic bacteria in the hydrothermal vent shrimp *Rimicaris exoculate,*" *Biogeosciences*, **5**, pp.1295–1310.

Dempster, Arthur J. (1918) "A New Method of Positive Ray Analysis," *Physical Review*, **11,** pp. 316–325.

Flemming, Walther (1882) *Zellsubstanz, Kern und Zelltheilung*. Leipzig: Verlag von F.C.W. Vogel.

Fraassen, Bas C. van (1981) *The Scientific Image*. Oxford: Clarendon Press.

Gabrieli, Gianmarco (2022) "Accelerated estimation of coffee sensory profiles using an AI-assisted electronic tongue," *Innovative Food Science and Emerging Technologies*, **82**, 103205, pp. 1-11.

Galilei, Galileo (1610) *Sidereus Nuncius*. Venice: Tommaso Baglioni.

Hacking, Ian (1981) "Do We See Through a Microscope?" *Pacific Philosophical Quarterly*, **62** pp. 305-322.

Hall, Brian K. (1999) "The Paradoxical Platypus," *Bioscience*, **49**, pp. 211-218.

Hempel, Sandra (2013) "James Marsh and the poison panic," *The Lancet*, **381**, pp. 2247-48.

International Correspondence Schools (ICS) (1900) *A Treatise on Chemistry and Chemical Analysis*. Volume II. *Inorganic Chemistry*. Scranton: the Colliery Engineer Co.

International Human Genome Sequencing Consortium, IHGSC (2001) "Initial sequencing and analysis of the human genome," *Nature*, **409**, pp. 860-921.

International Human Genome Sequencing Consortium, IHGSC (2003) "Finishing the euchromatic sequence of the human genome," *Nature*, **431**, pp. 931-45.

Jayasinghe, T. *et al.* (2021) "The ASAS-SN catalogue of variable stars IX: The spectroscopic properties of Galactic variable stars," *Monthly Notices of the Royal Astronomical Society*, **503**, pp. 200–235, https://doi.org/10.1093/mnras/stab114

Kaushik, Mahima; Mattoo, Aditee; Rastogi, Ritesh; and Mayank Deep Khare (2025) "Exoplanet Detection: A Detailed Analysis" pp. 138-153 in S. Sachdeva, Y. Watanobe and S. Bhalla, eds.,*Big Data Analytics in Astronomy, Science, and Engineering: 12th International Conference on Big Data Analytics, BDA 2024, Aizu, Japan, November 26–28, 2024, Proceedings*. Springer.

Kennefick, Daniel (2007) *Traveling at the Speed of Thought: Einstein and the Quest for Gravitational Waves*. Princeton: Princeton University Press.

Kepleri, Joannis [Kepler, Johannes] (1606) *De stella nova in pede Serpentarii*. Prague: Pauli Sessii.

Lowell, Percival (1915) "Memoir on a Trans-Neptunian Planet," Memoirs of the Lowell Observatory, Vol. 1, No. 1. Lynn, Mass; Thos. P. Nichols and Son, Co.

Marsh, James (1836) "Account of a method of separating small quantities of arsenic from substances with which it may be mixed,". *Edinburgh New Philosophical Journal*, **XXI**, pp. 229-36.

Morton, Timothy D. (2016) “False Positive Probabilities for all Kepler Objects of Interest: 1284 Newly Validated Planets and 428 Likely False Positives,” *The Astrophysical Journal*, **822**:86, pp. 1-15.

Morton, Timothy D.; Giacalone, Steven; and Bryson, Steve (2023) “A Recommendation to Retire VESPA for Exoplanet Validation,” *Research Notes of the American Astronomical* Society, **7**, 107, pp. 1-3.

Muter, John (1898) *A Short Manual of Analytic Chemistry*. 8th British ed. 2nd American ed. Philadelphia: P. Blakiston, sons & Co.

Navy Department (1946) *Radar Bulletin No.2. The Tactical Use of Radar in Aircraft*. Washington: United States Government Printing Office. Declassified.

Ochigame, Rodrigo; Skulberg, Emilie; Van Dongen, Jeroen (manuscript) “Coloring Black Holes: Epistemic and Aesthetic Choices in Astronomical Imaging”

Overbye, Dennis (2019) “Darkness Visible, Finally: Astronomers Capture First Ever Image of a Black Hole,” *New York Times*. Online, April 10, 2019; print, April 11, 2019, p. A1.

Robinson, James W., Skelly Frame, Eileen M. and Frame II, George W. (2021) *Instrumental Analytical Chemistry: An Introduction*. Boca Raton: CRC Press: Taylor and Francis Group.

Rodenburg, John and Maiden, Andrew (2019) “Ptychography,” Ch. 17 in P.W. Hawkes, J.C.H. Spence (Eds.), *Springer Handbook of Microscopy*, Springer Handbooks.

Russell, Henry Norris (1930) “Planet X,” *Scientific American.* July 1930, pp. 20-22.

Tanaka, Toshiko et al. (1996) “Determination of arsenic in blood and stomach contents by inductively coupled plasma/mass spectrometry (ICPI MS),” *Forensic Science International,* **81**, pp. 43-50.

Thomson, Joseph J. (1897) “Cathode Rays,” *Philosophical Magazine,* **44**, pp. 293–316.

Tombaugh, Clyde W. (1946) “The Search for the Ninth Planet, Pluto,” *Astronomical Society of the Pacific Leaflets*, Vol. 5, No. 209, pp.73-80.

Watson, James D. (1968) *The Double Helix: A Personal Account of the Discovery of the Structure of DNA*. 3rd. ed. 1976. New York: Scribner Classics.

Watson, James D. and Crick, Francis H. C. (1953) “Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid,” *Nature*, **171**, pp. 737-38.