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Hidden in Plain Sight: Discerning Signal from Noise in the Expanded Laboratory Environment

ABSTRACT

What happens when disturbances in precision measurement instruments are indecipherable to physicists despite extensive review of the instruments and their outputs? How do physicists parse instrument outputs to discern sought-after signals from noise that originates from the surrounding natural and built environments, either masking or mimicking these desired signals? I argue that given the extreme sensitivity of the laser interferometers used by the Laser Interferometer Gravitational-Wave Observatory (LIGO) to detect minute length deformations caused by gravitational waves, physicists reconceptualized their traditional laboratory spaces to include the surrounding natural and built environments. Discerning signal from noise in instruments operating close to their low noise floors necessitate an epistemic shift that combines the laboratory with the surrounding natural and built environments beyond its walls through the epistemic space of the "expanded laboratory environment."

KEY WORDS: gravitational waves, laboratory, environment, disturbance, noise, stillness, expanded laboratory environment

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The following abbreviations are used: Caltech, California Institute of Technology; CERN, Conseil Européen pour la Recherche Nucléaire; EHT, Event Horizon Telescope; LIGO, Laser Interferometer Gravitational-Wave Observatory; LSST-DA, Legacy Survey of Space and Time Discovery Alliance; LSU, Louisiana State University; MIT, Massachusetts Institute of Technology; RadLab, The Radiation Laboratory; RWDC, Personal Archive of Rainer Weiss, Massachusetts Institute of Technology Distinctive Collections, MC517; TEM, transmission electron microscope.

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"We need ways to distinguish a real signal from a 'bump in the night' caused by uninteresting noise."[1]

—Peter Saulson, LIGO Physicist

In 2001, physicist Rainer Weiss, a co-founder of the Laser Interferometer Gravitational-Wave Observatory (LIGO), and his colleagues at the location in Livingston, Louisiana, were perplexed about the cause of a regularly occurring disturbance in the output of their instrument—a laser interferometer. This instrument is a type of ultra-sensitive measuring device capable of detecting deformations in spacetime—the literal stretching and squeezing of the very fabric of our universe—caused by gravitational waves. Gravitational waves detectable here on Earth are produced by the most cataclysmic events occurring in our universe—for example, the collision of black holes. To detect gravitational waves, physicists bounce light between nearly free-floating mirrors suspended as elaborate pendulums located inside a vacuum system and spaced many kilometers apart. This design improves the instrument's susceptibility to noise, but gravitational wave scientists still seek enhancements that bring the instrument's sensitivity closer to the noise floor of the conceptual design. The physicists refer to noise whose source is easily derived and modeled as the noise floor, noise whose source is unknown as "anomalous noise," and noise that is known but has yet to be addressed as "excessive noise."[2] Operation in such a state is accompanied by a "lack of robustness" and interference in signal analysis because *any* noise is "easily detectable" by the interferometers, especially disturbances near the noise floor.[3]

The perplexing 2001 disturbance was both anomalous and well above the noise floor at lower frequencies, "which made it so troublesome."[4] It caused the mirrors to vibrate—similar to gravitational waves. Both gravitational waves and noise can cause the distance between the mirrors to increase and decrease in an oscillating rhythm as waves propagate through the instrument. The only

1. Peter Saulson, *Fundamentals of Interferometric Gravitational Wave Detectors* (Hackensack, NJ: World Science Publishing, 2017), 238.

2. B. K. Berger, J. S. Areeda, J. D. Barker, et al., "Searching for the Causes of Anomalous Advanced LIGO Noise," *Applied Physics Letters* 122, no. 184101 (2023): 2–3; Stanley Whitcomb, e-mail correspondence with author, 30 Dec. 2023. Weiss identified many of the potential types of noise sources of concern for a large-scale interferometer, including the noise floors, in a 1972 report. Rainer Weiss et al., "Gravitational Research," *MIT Quarterly Progress Report* 105 (Cambridge, MA: MIT Research Laboratory of Electronics, 1972), 17–76.

3. Berger et al., "Searching for the Causes" (n.2), 2–3.

4. Whitcomb correspondence (n.2).

difference is that length deformations between the mirrors originating from an earthly source are caused by vibrations and those caused by gravitational waves are the result of their warping of spacetime. This measurement phenomenon prevents the physicists from merely eliminating noise through modeling and redesign utilizing methods available to prior detectors such as shielding.[5] According to Beverly Berger, LIGO physicist and noise specialist, "You can't shield gravity."[6] Instead, physicists must reduce the length deformations caused by these earthly disturbances to levels lower than those caused by the gravitational waves, lessen the unwanted noise to levels within the sensitivity ranges of sensors so that the physicists can identify and remove their imprint from the signals, or eliminate the effect of the noise altogether from the instrument—the preferred method. This is particularly challenging because noise generated from the surrounding environment is not static due to evolving environments, populations, industrial activities, and climate change.

To better understand the 2001 disturbance, Weiss and his colleagues placed seismometers—devices measuring ground motion—throughout the town and parish of Livingston, but the source's identity still eluded them. The control rooms at the LIGO sites—one in Livingston, Louisiana, and the other in Hanford, Washington—are also covered with numerous screens, showing the environmental conditions collected by these instruments and additional sensors placed around the interferometer. The data displayed in the control room, numerous real-time data analysis pipelines, and monitoring channels assist the physicists in identifying unwanted noise that can either mask or mimic the much sought-after gravitational wave signals. Although the readouts provided the frequency, amplitude, timing, and duration of these disturbances, their sources often remain a mystery. The noise is hidden in plain sight. "The sensors don't care whether the noise is inside or outside"; it is up to the physicists to track down their origin.[7]

Noise appearing in LIGO's interferometers is continuously in flux. New noise often appears during observation runs—a specific state during which the interferometers are prepared to detect gravitational waves. LIGO physicists often decide not to address such noise until the observation run ends because

5. "Prior detectors" refers to the neutrino detectors of Trevor Pinch's scholarship. See, e.g., Trevor Pinch, *Confronting Nature: The Sociology of Solar Neutrino Detection* (Dordrecht: Springer-Science+Business Media, B.V., 1986). The resonant bar detectors, developed by Joseph Weber, also lacked shielding.

6. Beverly Berger, interview by author, Princeton, New Jersey, 23 May 2023.

7. Ibid.

repairs can "have a negative impact on searches of the data for [gravitational wave] signals and determining the properties of such signals have the highest priority."[8] Thus, to detect and understand gravitational waves produced from distant violent events in space and time, LIGO physicists must possess a nearly encyclopedic understanding of the minute and detailed features of the environments surrounding their instruments and facilities. Only then can the physicists identify the origins of anomalous noise—especially noise near the noise floor—with an origin other than from gravitational waves.

So, what was the 2001 disturbance? Trains passing? Giant pipes falling on the ground in warehouses? The flow of substances through the pipelines under the site? Planes flying overhead? Wind pushing on the instrument's housing? Given the extreme sensitivity of this instrument, the space the physicists had to account and control for expanded well beyond the area inside the laboratory.

The alleged truth-producing features of the laboratory—seemingly two identical detectors equipped with sensors and seismic isolation systems—signaled to the physicists that the aberrations—i.e., anomalous noises—were real.[9] Indeed, the LIGO physicists' requirement of coincident signals between the two widely spaced detectors is the truth-producing feature of the experiment. What did Livingston have that Hanford, Washington, the second twin site, did not? There were two additional clues: (1) this particular disturbance appeared only within a certain frequency range at Livingston, and (2) it did not appear at night.

On November 8, 2001, Weiss solved the mystery.[10] He was working at the LIGO Livingston location, along the laser beam tube outside of its concrete housing and saw trees going down. He ran into the control room to see if this event had the same signal profile as the unidentified disturbance—it did.[11] When Weiss saw the familiar profile of the mystery signal, he left the control room and the laboratory building to continue his investigation outside, where he witnessed the source—the typical activities used in the timber industry of pruning and cutting with chainsaws and mechanized tree cutters of the pine

8. Berger et al., "Searching for the Causes" (n.2), on 8.

9. On the placeness of laboratories and their truth-producing capabilities: Thomas F. Gieryn, *Truth Spots: How Places Make People Believe* (Chicago: University of Chicago Press, 2018).

10. Laser Interferometer Gravitational-Wave Observatory (LIGO), "Weekly Report for Week Ending November 8, 2001." https://labcit.ligo.caltech.edu/~weekly/pastreports/weekly2001/011108.htm

11. Rainer Weiss, interview by author, Cambridge, MA, 22 Nov 2016; Rainer Weiss, e-mail correspondence with author, 13 Aug 2021.

trees at the edge of the forest abutting the laboratory facility. This caused Weiss to incorporate this activity within his expanded conceptual understanding of the LIGO Livingston laboratory. With this reconceptualization of laboratory, he achieved a fuller accounting of noise appearing in the interferometer and its origin.

Only when Weiss considered what was beyond the laboratory facility during his investigation of the surrounding environment—an integral activity throughout LIGO's planning, design, and operation—was he able to identify and treat the disturbance that plagued the instrument and hindered its sensitivity to detect gravitational waves. This has been and continues to be LIGO's reality due to the need to operate the interferometers "close to their noise floor."[12]

In the following sections, I provide the scope and justification for the expanded laboratory environment framework, a history of the LIGO gravitational wave physicists' exploration and understanding of the expanded laboratory environment as an epistemic space. I demonstrate that physicists of ultra-sensitive experiments formed new epistemologies of laboratory boundaries from their processes of searching for noise origins. In turn, I show how the physicists navigated the inner confines of their laboratories while accounting for and traversing the boundary between the laboratory and the surrounding natural and built environments.

As the physicists' instruments increased in size from a prototype with 1.5-meter-long arms to a large-scale interferometer with 4-kilometer-long arms, the scope of the surrounding environment expanded from the laboratory and surrounding rooms to geographic areas extending well beyond the traditional laboratory space. I begin in the early 1980s at MIT and Caltech where physicists developed prototype instruments to demonstrate how they could potentially overcome environmental noise by gaining insights into how noise would affect their future large-scale experiment and their attempt to control the surrounding environment of a few city blocks around the university laboratory. When scaling up from the prototypes to the large-scale instruments, I reveal how the physicists interpreted the vibrations on the facility sites of Livingston and Hanford prior to the installation of the large-scale interferometers. Further, I elucidate how the physicists were unable to translate how vibrational noise would affect the future interferometers from a commissioned seismic assessment of the two locations without the instruments in place. Once the

12. Berger et al., "Searching for the Causes" (n.2.), on 2.

interferometers were in operation, I show how the physicists overcame natural and anthropogenic noise issues manifesting in the instruments at Livingston and Hanford through investigations of their surrounding environments. This requirement illustrates the need to expand their concept of laboratory to encompass the hosting surrounding landscape. This history illuminates the environmental and vibrational epistemologies of LIGO physicists and shows that the scope of the laboratory environment and the physicists' understanding of their minute features increased with the growing scale and sensitivity of the interferometers and vice versa.

THE EXPANDED LABORATORY ENVIRONMENT

The laboratory is indeed an environment.[13] In the case of LIGO, the natural and built environments have become the laboratory. I situate this transformation in the relationship between environment and laboratory in the historical evolution of astronomy and astrophysics observatories. Observatories as places have historically been "set apart" to facilitate direct or instrument-mediated astrophysical observations. Evolving from sites designated for the practice of observation to specialized buildings with laboratory features, observatories now allow for precision imaging of the universe and astronomical phenomena.[14]

Along with the extreme sensitivities of LIGO's detectors, the interferometers, LIGO's focus on changes in spacetime are what differentiates its facilities apart from prior and current detectors and observatories, and those telescopes, which observe across the electromagnetic spectrum.[15] Although LIGO physicists can control what vibrations originate from within their traditional laboratory space, they do not have such control over those emanating from the surrounding natural and built environments. The scope of LIGO's environment is determined by what its interferometers are sensitive to—whether the heat produced from the lasers, inherent material properties of the mirrors and their suspensions, vibrations of vehicles driving by the facilities, or

13. Robert E. Kohler and Jeremy Vetter, "The Field," in *A Companion to the History of Science*, ed. Bernard Lightman, 282–95 (Hoboken, NJ: John Wiley & Sons, Ltd., 2016), 283–84; Catherine Jackson, "The Laboratory," in *A Companion to the History of Science*, ed. Bernard Lightman, 298–309 (Hoboken, NJ: John Wiley & Sons, Ltd., 2016), 297.

14. Robert Smith, "The Observatory," in *A Companion to the History of Science*, ed. Bernard Lightman, 282–95 (Hoboken, NJ: John Wiley & Sons, Ltd., 2016), 196–209.

15. Keep in mind that the sensitivity of telescopes and neutrino detectors, for example, are difficult to compare as each is designed to detect a specific messenger.

pulsations in the earth's magnetic fields.[16] This phenomenon necessitates that LIGO physicists often traverse the laboratory-observatory/field boundary, ultimately collapsing the laboratory and its surrounding environments into a single epistemic space—the expanded laboratory environment.[17] I define this epistemic space as the ecosystem—the land, dirt, and the physical and social atmosphere and landscape—surrounding the laboratory buildings and structures that become embedded in the output signals of the instruments therein, becoming anomalous noise and affect the instruments' achievable noise floors. By expanding the concept of the laboratory to and encompass the surrounding natural and built environments, I build upon histories of noise, laboratory space, and the spatial and geographic locations of science by showing how physicists identify, understand, and address what signatures of the epistemic space of the expanded laboratory environment appear in the output signals produced by their highly sensitive instruments.[18] Only in this epistemic space can physicists discern gravitational waves from environmental noise, especially noise that is considered anomalous.

Signals have been typically defined as an effect on an instrument that is "distinct from the background of the field" where background is noise.[19] The handling of such background noise is a "constitutive" component of the

16. Providing a subset of noise LIGO must grapple with: B. P. Abbott et al. "A Guide to LIGO-Virgo Detector Noise and Extraction of Transient Gravitational-Wave Signals," *Classical and Quantum Gravity* 37, 055002 (2020): 1–54.

17. Latour explores expanding practices of the laboratory to a space beyond its walls, where I instead focus on those instances when scientists cannot control outside occurrences and characteristics that seep through the walls and invade the laboratory. Bruno Latour, "Give Me a Laboratory and I Will Raise the World," in *Science Observed: Perspectives on the Social Study of Science*, ed. Karin Knorr Cetina and Michael Mulkay, 141–70 (London: Sage Publications, Ltd., 1983), 150–52, 155, 166.

18. See, e.g., Peter Galison and Emily Thompson, eds., *The Architecture of Science* (Cambridge, MA: MIT Press, 1999); Christopher R. Henke and Thomas F. Gieryn, "Sites of Science Practice: The Enduring Important of Place," in *The Handbook of Science and Technology Studies*, ed. Edward J. Hackett et al. (Cambridge, MA: MIT Press, 2007): 353–76; Robert Kohler, *Landscapes and Labscapes: Exploring the Lab-Field Border in Biology* (Chicago: University of Chicago Press, 2002); Kohler and Vetter, "The Field" (n.13); Jackson, "The Laboratory" (n.13); Steve Shapin, "The House of Experiment in Seventeenth-Century England," *Isis* 79, no. 3 (1988): 373–404; Emily Thompson, "Dead Rooms and Live Wires: Harvard, Hollywood, and the Deconstruction of Architectural Acoustics, 1900–1930," *Isis* 88, no. 4 (1997): 597–626.

19. Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts* (Princeton, NJ: Princeton University Press, 1986), 127; Harry Collins, *Gravity's Shadow: The Search for Gravitational Waves* (Chicago: University of Chicago Press, 2004), 50.

experimenter's craft.[20] For high-energy physics, that entails showing that "traces of nature" appearing in the detectors are "not noise, but data."[21] As for nanoscale experiments, material scientists must not only eliminate ambient sounds from within the traditional laboratory, they must also utilize those sounds as an "experimental cue."[22] For astronomers, this means placing their observatories at high enough altitudes and limiting their observation times to account for weather and atmospheric conditions.[23] However, such straightforward solutions are not available to LIGO physicists given the function and sensitivity of its interferometers.

Much is revealed when considering the influences of sound aberrations and auditory practice originating from laboratories and their host buildings. Through such revelations physicists and material scientists have developed methods of addressing noise using methods ranging from modeling, shielding, reduction, filtering, subtraction, collection of larger data samples, automation, relocation, and apparatus design.[24] However, these activities and their study by historians of science have been confined to those interventions physicists detected and performed *inside* the laboratory.

Given the sensitivity of LIGO's interferometers and the resulting physical effects of gravitational waves, a more nuanced understanding of noise is

20. Peter Galison, *How Experiments End* (Chicago: University of Chicago, 1987), 71.

21. Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists* (Cambridge, MA: Harvard University Press, 1988), 159. Galison has claimed that the elimination of background shifted away from machinery and "toward the reduction of data." Galison, *How Experiments End* (n.20), 72. A call for more focus on the history of noise, see Chen-Pang Yeang and Joan Lisa Bromberg, "Understanding Noise in Twentieth-Century Physics and Engineering," *Perspectives on Science* 24, no. 1 (2016): 1–6. For a history of epistemologies of noise across engineering and physics from 1900–1955, see Chen-Pang Yeang, *Transforming Noise: A History of Its Science and Technology from Disturbing Sounds to Informational Errors, 1900–1955* (Oxford: Oxford University Press, 2023).

22. Cyrus C. M. Mody, "The Sounds of Science Listening to Laboratory Practice," *Science, Technology, and Human Values* 30, no. 2 (2005): 175–98.

23. Smith, "The Observatory" (n.14).

24. David Cahan, *An Institute for an Empire: The Physikalisch-Technische Reichsanstalt 1871–1918* (Cambridge: Cambridge University Press, 1989); Jimena Canales, *A Tenth of a Second: A History* (Chicago: University of Chicago Press, 2009); Allan Franklin, *Shifting Standards: Experiments in Particle Physics in the Twentieth Century* (Pittsburgh: University of Pittsburgh Press, 2013); Allen Franklin, *What Makes a Good Experiment?: Reasons & Roles in Science* (Pittsburgh: University of Pittsburgh Press, 2016); Galison, *How Experiments End* (n.20); Edward J. Gillan, "Tremoring transits: railways, the Royal Observatory and the capitalist challenge to Victorian astronomical science," *British Journal for the History of Science*, 53, no. 1 (2020): 1–4; Mody, "Sounds of Science" (n.22); and Pinch's *Confronting Nature* (n.5).

required—one that considers space beyond the laboratory. For LIGO, noise is any and all phenomena that cause the arm lengths between the mirrors of the interferometers to change. These disturbances are quite vast—spanning quantum, local, and cosmic scales—and often mask, and/or mimic the effects gravitational waves have on the instrument. Such noise is recognizable to the physicists through its effect on the instrument, but its origin is often unknown. In most instances, gravitational wave signals are buried within the noise.[25] As a result, LIGO physicists cannot always control and disaggregate the background from the signal.

Although Karin Knorr-Cetina has argued that the senses have shifted to a secondary role in laboratory sciences, that is not the case for LIGO.[26] LIGO physicists must develop a nuanced and detailed understanding of how the surrounding built and natural environments generate these vibrations and how these disturbances manifest in the interferometers. This activity necessitates direct use of the physicists' senses and embodiment within the surrounding environment in addition to what they can discern from the instruments' operation and sensor data. The physicists must then convert the individual environmental disturbances to their respective frequency domain signatures and map the noise to the effect detected in the interferometer. This connection allows physicists in some instances to modify the instrument and data analysis techniques to eliminate the effects of noise on their and in some instances reduce noise through negotiation with the environmental actors who produce the noise. Only then can the physicists apply methods of determining signal from noise through calculating statistical noise distributions, applying gravitational waveform templates to length deformation data, or detecting signals occurring far above the noise.[27] Thus, LIGO physicists cannot merely alter

25. Steve Gubser and Frans Pretorius, *The Little Book of Black Holes* (Princeton, NJ: Princeton University Press, 2017), 134.

26. Knorr Cetina, *Epistemic Cultures: How the Sciences Make Knowledge* (Cambridge, MA: Harvard University Press, 1999), 94–95. Knorr Cetina defines laboratory as a place where objects are detached from their natural environment and "objects as they occur in nature" are "rarely" worked upon in a laboratory. Karin Knorr Cetina, "The Couch, the Cathedral, and the Laboratory: On the Relationship between Experiment and Laboratory in Science," in *Science as Practice*, ed. Andrew Pickering (Chicago: University of Chicago Press, 1992), 116–17. LIGO physicists cannot manipulate the objects of study, LIGO instruments merely "listen" for gravitational waves much like an astronomy observatory, which Knorr Cetina expressly excludes from the definition of laboratory.

27. On the technical account of the data analysis techniques used by the LIGO Scientific Collaboration, see Abbott et al. "Guide to LIGO-Virgo Detector Noise" (n.16). For a participant

characteristics of the laboratory alone as done for prior and less sensitive instruments. Instead, LIGO physicists must often physically exit their laboratory, investigate the surrounding natural and built environments, and negotiate for mitigation or elimination of disturbances with the constituents of that surrounding environment.

Gravitational wave physicists must construct stillness to achieve low noise levels that allows them to detect the faint jostling of gravitational waves reporting on the events of our universe. I define constructing stillness as the assemblage of practices including theorizing experimental design to account for noise and how much noise the experiment can tolerate, finding facility locations that are as still as possible, understanding noise and modifying the instrument to achieve higher sensitivities, data analysis methods to remove noise or statistically interpret its occurrence, and negotiating with non-laboratory/extra-laboratory actors to understand and/or abate noise.[28] Turning gaze toward scientists' attempts to tame this enlarged laboratory space reveals how the natural and built environments hosting these laboratory facilities profoundly influence the LIGO experiment and experiments also operating close to their own low noise floors.[29]

By shifting focus from prior methods of analyzing laboratory spaces, I ask additional questions, including: How are laboratory sites found? How do laboratory scientists understand their surrounding environment? What happens when the surrounding environment becomes embedded in the experimental apparatuses and their outputs? These questions are captured in the overarching inquiry of, what happens when the landscape disturbs the experiment? Through the lens of the expanded laboratory environment tuned to how physicists identify and understand noise, I show that the laboratory is not separate from, but instead entangled with, its surrounding natural and built environments, especially for ultra-sensitive instruments. This shift in how the physicists defined laboratory allowed them to develop bespoke solutions to

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history of the initial efforts to develop LIGO templates, see Daniel Kennefick, "The Wagers of Science," in *Einstein Was Right: The Science and History of Gravitational Waves*, ed. Jed Buchwald, 63–75 (Princeton, NJ: Princeton University Press, 2020).

28. Tiffany Nichols, "Constructing Stillness: Theorization, Discovery, Interrogation, and Negotiation of the Expanded Laboratory of the Laser Interferometer Gravitational-Wave Observatory" (PhD Dissertation, Harvard University, 2022).

29. To understand how physicists conceptualize and interact with this space, I draw from the institutional archives of LIGO and host universities, site proposals, scientific publications, dissertations, internal studies, oral histories, site visits, and the LIGO Laboratory activity log, which is a running record of the state and health of the instruments.

address the disturbances originating from beyond the laboratory walls and account for this phenomenon as an act of constructing stillness within the expanded laboratory environment. These solutions, in turn, leave their mark on how "true" signals are registered. Through these practices, the correction for the environment is in turn embedded in the instrument and analysis of data.

THE EXPANDED LABORATORY ENVIRONMENT OF THE PROTOTYPE SCALE

Weiss's experience with the loggers at the Livingston site was not his first encounter with the expanded laboratory environment. Over fifteen years earlier, his team at the Massachusetts Institute of Technology (MIT) conducted the first observational run of their prototype, a precursor of the interferometers at Livingston and Hanford, from June 3–10, 1985. Building 20—the former location of the Radiation Laboratory (RadLab)—ran along Vassar Street, at the then-edge of the MIT campus in a bustling area of Cambridge, Massachusetts. Just below the surface of Building 20, a busy portion of the Boston Area subway system traversed the path between two major stops—Central and Kendall Squares—in Cambridge. To add to the cacophony of vibrations and noise, a train line also ran throughout the day along this part of campus to service the manufacturing area of the city, just a few blocks over.[30]

The 1.5-meter prototype's susceptibility to these vibrations provided a glimpse into the future environmental disturbances that perturb the present-day large-scale LIGO interferometers. Weiss and his laboratory group members, Jeffrey Livas, Daniel Dewey, and David Shoemaker, had to continually consider these vibrations from beyond Building 20 that housed the prototype under vacuum. They turned to methods of damping, avoidance, and extraction from the data stream as they developed a robust understanding of their laboratory that expanded from the vacuum enclosure of the 1.5-meter prototype to the laboratory room it occupied, and eventually to the very scale of Cambridge. Any decrease in the decibel level of noise would result in an increase in order of precision when measuring the distance between the

30. During the period, the Commonwealth of Massachusetts considered building a highway along Building 20. MIT scientists opposed this project due to potential effects on their experiments. See Hilary Moss, Yinan Zhang, and Andy Anderson, "Assessing the Impact of the Inner Belt: MIT, Highways, and Housing in Cambridge, Massachusetts," *Journal of Urban History* 40, no. 6 (2014): 1054–78.

mirrors. This would later translate to an expansion in the range of the universe the LIGO interferometers would be able to listen for gravitational wave signals.

To understand the disturbances that would allow the team to develop methods and systems to keep the mirrors of the prototype as still as possible, they set up microphones, shut the doors to the closet housing their brand-new VAX 730 next to the laboratory room, and designed circuits to amplify recordings of the disturbances to human-audible levels to assist in identification of their origin.[31] They also meticulously tracked the temperature of the room, discovering that the weather outside triggered the air conditioner during both the summer and the winter—because Building 20, meant to only serve the RadLab for World War II, had rudimentary installation and temperature controls to mediate the extreme temperature fluctuations between the New England summers and winters. These temperature swings caused the prototype's housing to expand and contract as the weather wavered, altering the length of the optical path.[32] To tame the effect, Dewey developed a servo system to control and reduce the temperature swings caused by the built-in thermostat of the window air conditioner. He, along with Livas, also developed a servo control system for the balloon floats on which the giant granite table that supported the prototype sat. It, too, fluctuated with the microclimates of the room and the Boston Area, altering the prototype and its operation.[33]

The team at the California Institute of Technology (Caltech) in Pasadena, California, under the leadership of physicists Ronald Drever and Kip Thorne, co-founders of LIGO with Weiss, also built a prototype. More sensitive, with forty-meter-long arms, the Caltech team's prototype was also susceptible to its environment. On the first day of the 1983 Caltech observation run, then

31. Physicist Robert Forward engaged in similar techniques on an earlier interferometer. For his setup, he used his ear to discern and identify the noise. Robert Forward, "Wideband Laser-Interferometer Gravitational Radiation Experiment," *Physical Review D* 17, no. 2 (1978): 379–90, on 388.

32. Compare with Mody's example of turning the air conditioner off when constructing micrographs to capture a sharper image with transmission electron microscopes (TEM). Mody, "Sounds of Science" (n.22), 179, 185.

33. Collective laboratory notebook, Gravity I, Personal Archive of Rainer Weiss, Massachusetts Institute of Technology Distinctive Collections (RWDC), MC517, Box 95, Folder Gravity I 1983 July 2 to December 4; Dewey interview by author, Cambridge, MA, November 5, 2021; personal Journal of Daniel Dewey, personal documents of Daniel Dewey. Note the collective laboratory notebook. In Weiss's laboratory, each member kept their own laboratory notebooks, and each project had a collective laboratory group notebook that was a running log of the work on the prototype's operation. This eventually became the LIGO Activity Log.

graduate student Mark Hereld, observed that "the temperature in the laboratory was particularly stable because of the prevailing overcast weather." He believed this led to the air conditioning running more efficiently than normal "because of the small load on the chilled water supply" for the laser. But to handle the temperature swings from day to night that were common in the San Gabriel Valley, Hereld inserted himself into the feedback loop rather than rely on servo control systems as the MIT team had done. "I periodically adjusted the thermostats in each arm of the detector to compensate for the effectively low 'loop gain' of the air conditioning system." Hereld made "occasional adjustments to the optics to compensate for drifts (chiefly induced by temperature changes)."[34]

When the MIT team was ready for their observation run in 1985, using servo equipment to control for the surrounding laboratory room and building did not result in the baseline stillness that the experiment required. Weiss, Livas, and Dewey thus had to expand their conceptions of the boundaries of their laboratory space and noise awareness to the scale of the city for the observation run. To avoid noise from the urban landscape, they ran their experiment during the most "seismically and acoustically quietest times" after the "Cambridge subway ceased operation [at] 1:30 am."[35] Livas also recalled, "There was a change in slope of the road (a 'bump') immediately outside the lab that caused trouble because cars and especially trucks would bounce over this bump."[36] Such timing adjustments were made to keep the mirrors inside the arm cavities still or minimize movement in the mirrors suspended as pendulums. If the mirrors wiggled sufficiently, the laser light would diffract spuriously in all directions rather than travel back down the arm toward a photodetector, which measured whether the distance between the mirrors had changed through detecting phase shifts in the laser light.

However, moving the time of the observations to the predawn hours of the night was not enough. The team would eventually pull community members into the experiment. For example, they petitioned the City of Cambridge via the MIT police to close Vassar Street to traffic and the parking lot adjacent

34. Mark Hereld, "A Search for Gravitational Radiation from PSR 1937+214" (PhD Thesis, California Institute of Technology, 1984), 48–49.

35. Jeffrey C. Livas, "Upper Limits for Gravitational Radiation from Some Astrophysical Sources" (PhD Thesis, Massachusetts Institute of Technology, 1987), 76. Compare this example with the material scientists of Mody's study who performed TEM runs at night. Mody, "Sounds of Science" (n.22), 180.

36. Jeffrey Livas, e-mail correspondence with author, 2 Sep 2021.

FIGURE 1. Sign used during the first observation run of the prototype to inform people that the parking lot next to Building 20 (right side) was closed. *Source:* Presentation, "Some of the Lives of Richard Benford on his retirement from MIT and the Kavli Institute for Astrophysics and Space Research," presented at the MIT Kavli Institute for Astrophysics and Space Research, Cambridge, Massachusetts, 13 Oct 2006.

to their laboratory space for two nights over the weekend to increase the stillness of the site and in turn increase the sensitivity of the prototype.[37] Although they could not block off Vassar Street, the physicists did the next best thing and reduced traffic around the laboratory itself by restricting access to the adjacent MIT parking lot during the portion of the observation run (figure 1).[38]

Constructing stillness for the prototypes not only entailed expertise of the instrument and the laboratory space defined by the walls of the laboratories but also required detailed and encyclopedic knowledge of the idiosyncratic noise profiles of the climate and surrounding environments, as captured in Livas's statement contemporaneous to the experiment, "Previous experience had indicated that the seismically and acoustically quietest times in the laboratory

37. Livas, "Upper Limits" (n.35), 76; Daniel Dewey, "A Search for Astronomical Gravitational Radiation with an Interferometric Broad Band Antenna" (PhD Thesis, Massachusetts Institute of Technology, 1986), 66; Rainer Weiss, interview by author, Cambridge, MA, 12 Apr 2019; Richard Benford, interview by author, Cambridge, MA, 24 Sep 2020.

38. Jeffrey Livas, e-mail correspondence with author, 2 Sep 2021.

occurred in the early morning."[39] Thus, knowing the operational characteristics of the prototypes entailed developing a sufficient understanding of the local surrounding environment.

DIFFICULTY IN UNDERSTANDING THE ENVIRONMENTAL IMPACTS WITHOUT OPERABLE LARGE-SCALE INSTRUCMENTS

In 1996, with the large-scale interferometer design set and the two LIGO sites chosen and acquired, but prior to the construction of the large-scale interferometers, the LIGO physicists ordered seismic studies of both the Hanford and Livingston sites to better understand their baseline noise levels.[40] With the interferometer design in place, Alan Rohay, a geophysicist for Pacific Northwest Laboratories, known for its geotechnical work at Hanford, studied a diverse array of environmental characteristics of the two LIGO locations relevant to understanding their role as hosts of the future LIGO interferometers. He concluded that the Livingston location had "low frequency (less than 5 Hz) noise consistently higher than both the LIGO design spectrum and the measured Hanford noise spectrum." He also observed "train traffic" "twice daily" at the south end of the projected site that increased noise by "nearly a factor of 10." Around 10 Hz, the ambient noise stayed within design limits "except when acoustic noise from aircraft [was] transmitted into the ground."[41] Further, the traces of the seismometer showed an "oil pipeline passing beneath the west arm" that "generate[d] a significant portion of the ambient noise." In addition to the seismic and wind measurements, Rohay interrogated the environment through techniques including digital recordings, playback and analysis software, and using infrasound microphones able to detect low-frequency noise, paralleling techniques of knowing the environment from the earlier prototype period.[42]

During Rohay's observation period at Livingston, the microphones were flooded by rainwater, and heavy showers affected the function of the

39. Livas, "Upper Limits" (n.35) 76; The display of the prototype at The MIT Museum is based on this aspect of my dissertation research. The material scientists of Cyrus Mody's scholarship were not required to seek assistance from the community and block access to space beyond their laboratory. Mody, "Sounds of Science" (n.22).

40. For an extensive history of LIGO's site selection: Nichols, "Constructing Stillness" (n.28)

41. Alan Rohay, "Ambient Ground Vibration Measurements at the Livingston, Louisiana LIGO Site," 2 May 1996, LIGO Document Collection, LIGO-C96-1022-00-O: 1.

42. Ibid., 6.

seismometers. As much as the environment foiled his attempts to characterize it, he did observe planes flying overhead, "hunters with dogs (after dark) and hunters hunting for lost dogs (during the day)," and "groups of cows at all measurement locations." Most notable: "On several occasions chainsaws were audible from the forest."[43] Rohay's parallel study at the Hanford site reported only vehicular traffic at certain times correlated with the shifts of workers flowing into and out of the Hanford nuclear reservation.[44] This is not entirely surprising given Hanford's nuclear legacy and the resulting need to ensure environmental stability—a requirement that conveniently maps onto the needs of LIGO.

Without the large-scale interferometers on site, the physicists did not understand the ways that the vibrations would manifest in the interferometers and affect their experiment. Indeed, they remember Rohay's seismic studies as uninterpretable without the laboratory instruments and the sensors constructed and installed. "We didn't really understand what needed to be tailored to the sites particularly," explained physicist Stanley Whitcomb, who served as the Detector Group Leader of LIGO during this period. He continued, "What we were beginning to understand was that seismic noise at much lower frequencies could couple nonlinearly and create noise in our observational frequency band." This is when the limitations of using knowledge gained from the prototypes to interpret Rohay's studies became clear. Any disturbance in the prototypes' laboratories happened in the same environment—actually, the same building—because the mirrors were separated by only 1.5 meters at MIT and forty meters at Caltech. However, given the diversity of expanded laboratory environments of the large-scale interferometers with arms four kilometers in length, the environments at the vertex and each end station "move differently because they are more than (about) one seismic wavelength apart."[45] That is, when the physicists accounted for expanded laboratory environment of LIGO, components of the instruments responded to the environment differently. The over 2,000-fold difference between the

43. Ibid., 10. LIGO physicists would have to later account for each of these factors, including errant bullets targeting the Livingston site. Nichols, "Constructing Stillness" (n.28).

44. Alan Rohay, "Ambient Ground Vibration Measurements at the Hanford, Washington LIGO Site," 2 May 1996, LIGO Document Collection, LIGO-C95-0572-02-O: 1, 14–18. LIGO physicists would later discover excess noise during shift changes caused increased traffic near one of the Hanford end stations. Beverly K. Berger, "Identification and Mitigation of Advanced LIGO Noise Sources," *Journal of Physics: Conference Series* 957, no. 012004 (2018): 1–6, on 3.

45. Whitcomb correspondence (n.2)

large-scale interferometer and the MIT 1.5-meter prototype and the 100-fold difference with the forty-meter Caltech prototype resulted in expanded laboratory environments of drastically different scale. Whitcomb admitted, "We didn't have adequate modeling tools. We hadn't really dealt with that on campus. So, it was something that we basically discovered in real time as we were building and assembling the detectors."[46]

Showing the importance of understanding the intricate details of the expanded laboratory environment surrounding and along the interferometers' arms—and comparable instruments—and constructing stillness, Whitcomb explained, "To the extent that we eventually got that stuff right, it was done after the fact, when we discovered what problems we had. And what didn't work, we set out to fix them." One such investigation and solution circled around the whir of the chainsaws Rohay observed at Livingston. However, according to Weiss, "It was too late" when the physicists realized the significance of Rohay's findings for the instruments had already been constructed and begun operating.[47] To rectify the situation, the physicists had to expand their conception of the laboratory environment from the prototype-scale, the vacuum housing of the instrument, and their control rooms with their mediating devices to the natural and built environments surrounding their instruments. Even with this expansion in scope, the physicists could gain a comprehensive understanding of the expanded laboratory environment only through analyzing it directly and comprehending how the noise it produced manifested in the instrument.

CONSTRUCTING STILLNESS IN THE EXPANDED LABORATORY ENVIRONMENT

The Livingston Example

Returning to Weiss's quest to identify the source of the anomalous disturbance in the large-scale interferometer at the LIGO Livingston site in 2001, he had seen the profile of the persistent signal aberration many times before November 8, 2001, and it coincided with periods when the interferometer was incapable of maintaining a locked state—that is, being held in a fixed position in such that the numerous cascading servo control systems can maintain the

46. Ibid.; Stanley Whitcomb, interview by author, Cambridge, MA, 5 Jan 2022.
47. Ibid.

instrument in a null state. It is only in this locked state that the interferometer can observe for gravitational waves.

After carefully inspecting the instrument, Weiss turned outward to determine the source of the disturbance through the clues offered by the power spectra of length deformations[48] of the interferometer across frequencies and the data the sensors reported. First, he considered the pipelines that ran under the LIGO structure. A four-foot-diameter line running beneath the site is used to transport "viscous fluids" from St. John the Baptist Parish to "just outside of Chicago." The pipeline had "pumping stations every 50 miles with a control center for the line in Metairie, Louisiana, near the New Orleans Airport" used to maintain the flow the fluids. When Weiss went to investigate, he learned that the "pipeline owners were very worried about causing turbulence in the line" but "were very happy for LIGO to help them avoid the turbulence which would have caused excess vibrations" under the Livingston site. It turned out that the pipeline was not a "serious source of seismic noise."[49]

During the summer of 2001, Weiss continued investigating the expanded laboratory environment to find the origin of the aberration. He, along with visiting MIT students, placed seismometers on roads and at factories near the site and along the train route that ran at the edge of Livingston. They formulated guesses of the source of the noise based on the mediated experience of analyzing the numerous readings displayed on the screens of the control room.[50] The physicists used their sight when viewing the numerous outputs projected on the screens and their ears to listen to the recordings picked up by the various microphones placed around the site. Although Weiss and his team gained a more nuanced understanding of the expanded laboratory environment, the identity of the source continued to evade them.

Weiss contemporaneously recorded the events leading to the identification of the source in the LIGO Weekly Report—an ongoing record of the health and operation of the instruments to allow the members of the collaboration to stay abreast on the LIGO remote facilities—for the week ending on November 8, 2001. The continuous data stream showed that the unidentified aberration took a break on the weekends and at night. Focusing on the expanded laboratory environment including the land, its features, and occupants—here, the

48. Expressed as gravitational wave strain, which is the ratio of the length deformations between the interferometer's arms.

49. Rainer Weiss, interview by author, Cambridge, MA, 22 Nov 2016.

50. Rainer Weiss, e-mail correspondence with author, 13 Aug 2021.

trees and the local logging industry of Livingston—reveals their nuanced presence in the archival record. Weiss wrote in the activity log:

> We have begun a systematic study of what happens to the recombined interferometer when the seismic noise starts at about 6 AM. It is now trivial to lock the recombined system by 5:30 AM and wait for the world to wake up. With this strategy it is still possible to watch the lock drop out and acquire and watch again until 6:30 [PM] when currently moderately close logging activities begin. The data from these lock loss events is still being analyzed, however, it is clear that the primary symptom that leads to the breakdown are antisymmetric angular motions (one cavity beam goes left the other right or one goes up the other down).

Weiss compared the profile of the disturbance with other candidates to be sure his identification was correct. This is because there were numerous noise sources near the site. Was it instead the active train line that ran not too far from the site? No, although the train left other forms of noise signatures on the instrument's outputs. Livingston was also known as a place for manufacturing large pipes and gravel pits. Weiss thought the pipes and gravel caused this particular vibration when they fell to the ground. However, upon interrogating the data, these were found not to be the source. They also checked the flight logs and found nothing at the times the mysterious noise appeared.[51]

On November 8, 2001, when Weiss, was working outside along one of the beam tubes, he saw trees falling in the forest. He quickly ran inside to verify that this was the troubling disturbance that had been appearing on the control room screens. The signature of the falling trees matched that of the mystery aberration. So, he immediately walked out the door to investigate further.[52] He did not just leave the control room; he left the laboratory building altogether to return to the site where he witnessed the source of the noise. As he made this transition from building to the surrounding environment, he expanded his conception of LIGO's laboratory space. Being outside the facility, but still in the expanded laboratory environment, allowed Weiss to identify and understand the source of the offending noise. There was a correlation between what he saw, what was recorded on the seismometers, and the aberration in the interferometer. He saw and heard using no instruments beyond his own eyes and ears loggers chopping branches from the trees abutting

51. LIGO, "Weekly Report" (n.10).

52. Rainer Weiss, interview by author, Cambridge, MA, 22 Nov 2016; Rainer Weiss, e-mail correspondence with author, 13 Aug 2021.

LIGO's facility. As they cut, the limbs and trunks fell to the ground. This disturbance was particularly troubling because, according to Weiss, "Broadly, logging at 1km from the y end station provides seismic motions as large as the trains but with an even more ragged statistic between rms and peak to peak motions."[53]

The source had been hidden in plain sight the entire time. It was the very logging industry that allowed for such a large, continuous, and remote parcel of land to exist and meet the scientific criteria for LIGO. Weiss recalled his thinking upon realization, "The key mistake made was to assume a commercial forest like the one we had built LIGO in is farmed not only once every forty years (a tree lifetime) but continuously in small patches. I was horrified."[54] This was because the vibrations caused by chopped trees falling to the ground were akin to having localized earthquakes right next to the interferometer. To secure the duration of lock periods achieved at night, Weiss calculated that "the closest logging activity" would have to be "further than 225km away."[55] Such disturbances would not only prevent the interferometer from gaining a locked state but also could cause the mirrors to wiggle enough "to overwhelm the displacement produced by gravitational waves."[56] When the servo systems tried to respond to low-frequency noise caused by the falling trees, they generated additional noise in the instrument at higher frequencies—a factor contributing to the difficulty in identifying the source of the noise through the instrument's response. Such a cascade of noise could mask gravitational waves and reduce the overall sensitivity of the instruments to detect them.

Weiss also had to revisit the original assumptions about the frequency of logging activity provided in the Livingston site proposal, as this new information caused him to realize that the logging activity was an ongoing and continuous occurrence in the ecosystem that hosted the LIGO laboratory. He explained: "In a visit with the Weyerhauser chief logger in the Livingston area" "he informed me that it is guaranteed that there is some logging activity within a 10km radius of LIGO at any time in the year."[57] This differed from the

53. Rainer Weiss, interview by author, Cambridge, MA, 22 Nov 2016.

54. Rainer Weiss, e-mail correspondence with author, 13 Aug 2021. Weiss is unusual in that he was accustomed to being outside of the laboratory environment. Much of his earlier work was with cosmic background radiation balloons that he and his team would need to retrieve from random sites throughout the United States.

55. LIGO, "Weekly Report" (n.10).

56. Whitcomb correspondence (n.2).

57. Ibid.

assumed frequency of activity occurring in the assumed once every twenty-five years that was indicated in the original proposal for the Livingston site.[58] The logger provided Weiss with a more nuanced understanding of this expanded laboratory environment. Weiss's recorded recollection: "It happens that the fall is most intensive since the weather is cooler, there is less rain and Christmas funds are empty. . . . One of the nuisances with the logging is that though they harvest once every 20 years, they have small patches not large tracts and they come into the patches three times in twenty years. The first visit is to thin out the growth, the second to remove lower branches and then, finally the third, to harvest the wood."[59]

Given how fast pine trees grow, the loggers engaged in unwanted noise-producing activity, working through small patches around the instrument, on a *continual* basis. How could LIGO physicists preserve the potential ability to detect gravitational waves? Weiss continued modeling based on his newfound understanding: "[The chief logger] told me of their cutting schedule around the planned [the seventh experimental] run when they intend to cut well within 3km of LIGO near the [laser and vacuum equipment area] and then along the y arm. He explained that Weyerhauser is also in the business of selling land. The value is about $3K/acre so a 10km radius area would cost about $230M." The $230 million price tag to buy all of the land within a 10-kilometer radius of the site was "ill-advised" because "there were other noise sources to deal with even through it now seems that logging is the source of the bulk of the noise."[60] The LIGO team opted to explore reconfiguring the instruments to lessen the effects of the surrounding environment.

To construct stillness to prevent unwanted movement in the mirrors despite this inherent disturbance, the physicists had to reconfigure their instrument. They adopted a feed-forward seismic isolation system, developed by physicist Daniel Debra. This system eliminates the generation of excess high-frequency noise caused by the feedback control of low-frequency noise by applying a control signal to stabilize high-frequency noise when disturbances at low

58. "Proposal for a Louisiana LIGO site," Office of the Chancellor Records, University Archives, Hill Memorial Library, LSU, Box 82, Folder Laser Interferometer Gravitational-Wave Observatory (LIGO) Project 1991–1995.

59. LIGO, "Weekly Report" (n.10). Weyerhauser acquired the land from Cavenham in 1996.

60. Ibid. Further, Weyerhauser was not in the business of selling land. Nichols, "Constructing Stillness" (n.28). Recall that the Reichsanstalt purchased land around its facility to buffer itself from noise. Cahan points out that this was insufficient to abate the effects of noise on the experiments. Cahan, *An Institute for an Empire* (n.24), 168–75.

frequencies are controlled for. As part of the upgrades of Advanced LIGO, which became operational much later in 2015, LIGO physicists also replaced the simple pendulum suspension for mirrors with a multi-staged one developed at the University of Glasgow to better isolate the mirrors from the natural and anthropogenic noise of the surrounding environment. All modifications that arose from the improved understanding of environmental noise resulted in increased sensitivity levels that allowed for the first direct detection of gravitational waves.

It was not until Weiss witnessed the polyphony across the potential gravitational signal frequency range, the background noise, and the rhythm of the logging industry—a combination that came together only in the expanded LIGO Livingston laboratory environment—that he and his team were able to understand the epistemic space of their experiment and identify the offending disturbance. Once they knew the identity of its source, the physicists were able to construct stillness by designing systems to reduce its effects, unmasking the signature of gravitational waves. The LIGO physicists have also formed communication channels between themselves and the logging industry whose operational environment spatially, audible, and vibrationally overlaps with LIGO's laboratory. This facilitates coordination between LIGO observation runs and pine tree harvesting, allowing for the coexistence of commodity production and the operations of the expanded laboratory environment in this shared space. This competition for space paired with the need to compromise experimental activities is uncommon in the physical sciences, but quite ubiquitous in disciplines utilizing fieldwork where "the politics of competing uses [are] not an externality, as in labs."[61]

The Hanford Example

Despite being located in a remote nuclear waste storage site, disturbances also plague the Hanford LIGO interferometer. During the summer of 2017, physicists noticed a repetitive disturbance appearing in the output—specifically, the gravitational wave channel—of the Hanford interferometer, but not at the Livingston site.[62] Its presence also greatly puzzled them because the signal appeared to be a gravitational wave, but the instrument was not in observation mode. Whatever it was had resulted in changes in the interferometer's optical

61. Kohler and Vetter, "The Field" (n.13), 284.
62. Berger et al., "Searching for the Causes" (n.2), on 4.

path length and movement in the mirrors, causing light to spuriously reflect and recombine with the main beam path.[63] A resolution was necessary to ensure that the interferometer would be ready for the upcoming listening period, or "observation run." Physicist Robert Schofield of LIGO's noise reduction team had placed microphones around the interferometer's exterior housing, mirroring the practices of his predecessors.[64] They picked up a pecking sound—Ratta tat tat – ratta tat tat—at the same time each day.[65] The disturbance's noise signature revealed that the culprit—or culprits, in this case—were ravens. Thirsty ravens foraged for much-needed water "in a desert environment where water sources are precious." They landed upon the ice that had accumulated on the "liquid nitrogen feed pipe to an ion pump" of the interferometer's vacuum system. After an investigation outside the instrument and its housing, LIGO scientists identified the peck marks on the accumulated ice and observed the behavior in action.[66] To better understand the noise source, LIGO physicist Pep Covas mimicked the ravens' behavior by taking a hammer to the vent line in the pattern revealed on the interferometer's output to determine the degree to which this disturbance would affect the instrument.[67]

LIGO physicist Philippe Nguyen and colleagues explained how the effects of the ravens were propagated: "The Rube Goldberg-like mechanism began in the desert sun at [LIGO Hanford], where ravens pecked at ice accumulations on a cryopump vent tube just outside of an end station building." He described a chain of consequences—"vibrations from pecking," "transmitted through the vent tubes to the cryopump," vibrations "transmitted through the beam tub to a calibration structure located inside of the vacuum," that structure "vibrated slightly with each peck." The resulting effects were amplified by a prior correction the scientists made when they designed the calibration

63. T. J. Massinger, "Characterization: Of Bangs and Buzzes," *LIGO Magazine* 13 (September 2018): 19; S. Mukherjee et al., "Classification of Glitch Waveforms in Gravitational Wave Detector Characterization," *Journal of Physics, Conference Series* 243, no. 1 (2010): 012006, on 1–10.

64. LIGO Logbook, 19 Jul 2017, https://alog.ligo-wa.caltech.edu/aLOG/index.php?callRep=37630; Berger et al., "Searching for the Causes" (n.2), on 4; Grrlscientist, "Thirsty Ravens' Tap-Tap-Tapping Creates Data Glitch At LIGO," *Forbes* (May 15, 2018).

65. L. K. Nuttall, "Characterising Transient Noise in the LIGO Detectors," *Philosophical Transactions of the Royal Society of London Series A: Mathematical, Physical, and Engineering Sciences* 376 (May 28, 2018): 20170286, 1–8, 3–4; Berger et al., "Searching for the Causes" (n.2), on 4.

66. Berger et al., "Searching for the Causes" (n.2), on 4–5.

67. Nuttall, "Characterising" (n.65), 1–8, on 3–4; LIGO Logbook, 19 Jul 2017 (n.63).

structure to prevent scattering light ten meters away from the structure. Fixing one problem had resulted in another. Each peck scattered light off the polished grooves of that very calibration structure in such a way that, according to the physicists, "the varying interference caused fluctuations in the light of the main beam, similar to the fluctuations produced by gravitational waves."[68] With that, the ravens—pecking on the ice for fresh water while on a quest for survival—mimicked the signature of gravitational wave signals, reducing the coincidence sensitivity between the two detectors.

"With each peck, it would get longer and shorter and longer . . . causing the beam to flash the tiniest bit, making the beam a little brighter . . . or a little darker, and that's actually how we detect gravitational waves," explained Schofield, an expert on all environmental noise that appears within LIGO's instruments. This caused a phase change when the light is returned back down the arm to the photodetector "at 1 part in 10^{20}" photons—which is "on the scale of those produced by gravitational waves."[69] "So that's how a raven could in some way imitate a black hole," said Schofield while laughing at the absurdity of the situation.[70]

Absent investigation of local ecologies, the physicists would not have been able to detect cosmic phenomena from the farthest reaches of the universe. The sequence of steps in discovering the origin of the disturbance mirrored what Weiss had done years before when he discovered that pine tree harvesting practice generated noise in the Livingston interferometer. At Hanford, the physicists first became aware of the noise through the myriad of sensors placed around the interferometer. Schofield described the process as imprecise. First a noise "showed up on the gravitational wave channel." This aberration in the channel was something they could sense with their eyes through mediated devices. The noise was flagged for concern because it could potentially mask a frequency range believed to coincide with gravitational waves or, to the physicists' dismay, mimic a gravitational wave signal. Schofield then remembered that his colleagues told him the microphones were "going off at the same time as these strange glitches in the gravitational wave channel." Switching to analyzing the aberration from his eyes to his ears, he recalled, "When they played it for me, I said, 'Oh, that's the crows.' I wasn't sure they were ravens

68. Philippe Nguyen et al., "Environmental Noise in Advanced LIGO Detectors," *Classical and Quantum Gravity* 38, no. 145001 (2021): 1–33, on 20–21.

69. Ibid., 20.

70. Robert Schofield, interview by author, Cambridge, MA, 10 Feb 2022.

then, but it only took a fraction of a second because when I'm driving around between all the buildings and stuff, I noticed the stuff that going on, and I had noticed, but in the past, that there were ravens around the building."[71]

Connecting his observations of sight and sound over time, Schofield said, "I had been inside the building once and heard what they're pecking on when they pecked on stuff and that is what it sounded like." Similar to Weiss's reaction to the trees in Livingston, Schofield responded, "And I was like, what is that weird noise, and I ran outside. The ravens went flying away. And so that's how I knew it was ravens," he recalled.[72] Here, Schofield was able to identify the noise only through combining his historical accounting and sensing of the expanded laboratory environment through observations, including listening to the recordings of the aberration and capturing a sensory understanding of the landscape from his numerous inspections of the site, and from the interferometer's perspective of sensed changes in the optical path length. Only through this multisensory—that is, multiple human senses combined with the sensors around the interferometer—understanding of the aberration could the LIGO physicists identify whether an aberration was of environmental or astronomical origin.

Finding the problem was only the first step in addressing it. As Schofield put it: To discern "how pecking way out here was getting all the way in [to the interferometer] was a tricker process." He frankly explained to me:

> That is the most important part of the process because just by covering up the ice so the ravens couldn't peck on it out here might solve the raven problem. But the problem was indicative of more important problems—anything that vibrated this thing [a baffle] . . . would produce noise. It didn't have to just be ravens; it could be an airplane flying over or wind or any or anything that could vibrate that would also shorten and lengthen that optical path and produce noise. So, figuring out that it was coming from this thing was really the most important part.[73]

To construct stillness, it was not enough just to cover the ice that collected around the cryopump pipes to keep the ravens away; the physicists needed to understand the noise—its source in the surrounding environment, along with the environmental circumstances that created it—and how the noise

71. Ibid.
72. Ibid.
73. Ibid.

manifested in the interferometer to rule out that it was not of astrophysical origin.[74] To know the sound of a gravitational wave is to know the unprocessed disturbances of the natural and built expanded laboratory environment.

Most critical in their attempts to construct stillness across both sites were the practices of noticing the disturbance, identifying the disturbance through extensive monitoring of the expanded laboratory, and correlating the noise profile of the disturbance with the noise that appears in the instrument. Understanding each, individually and collectively, required the physicists to have an encyclopedic understanding of the scope and features of the expanded laboratory environment. The LIGO physicists then used these practices time and time again to identify any mysterious aberrations in the system, quiet them, and construct the stillness needed to detect and discern gravitational waves from the noise that masks and mimics them.

CONCLUSION

Gone are the days when the "sounds of science" were confined to and fixable from within the laboratory.[75] Now the sounds—or more broadly, noise—of science can also originate from beyond the laboratory, such as the surrounding natural and built environments. By traversing the boundary between laboratory and the surrounding natural and built environments, the LIGO physicists were able to identify noise sources that were, until then, hidden in plain sight on the numerous graphs of their control rooms.

The LIGO laboratory environment has evolved over time. Changes in scale and sensitivity of instruments were not the only impetus that caused the physicists to reconceptualize their laboratory environments. The very surrounding natural and built environments where the interferometers were placed, and beyond, also caused the physicists to conceptualize the scope of environment, and thus laboratory, which they had to control and incorporate into their experiment. When the interferometers increased in scale, the range of environmental disturbances and the scope of their origin also increased, as well as the surrounding environment's presence in peer-reviewed articles. This also occurred when the interferometers increased in sensitivity, as evidenced in

74. Noting Berger et al.'s point on "fixing noise." The physicists found the raven noise during an observation run and had to wait until the run ended to address the noise issue. Thus, they had to adjust that data analysis during that observation run to account for the raven noise.

75. Mody, "Sounds of Science" (n.20).

the physicists' understandings of the effect of environment when shifting from scales of measurable length to photon counts. In many instances, efforts to address the noise resulted in an increased sensitivity in the interferometers, which expanded the depths from which the interferometers could detect gravitational waves.

What began as localized environmental noise from within the laboratory (e.g., temperature fluctuations caused by air conditioning systems or the whir of computers) became noise from the local vicinity surrounding the laboratory building (e.g., vehicle traffic or vibrations caused by subway trains). The scope of the environment that generated noise hindering the experiment expanded in scale to the social and natural fabrics of the natural and built environments hosting the facilities. To preserve the ability to detect and distinguish gravitational waves from noise and background, LIGO physicists now have expertise in environmental ecologies and commodities in production cycles occurring near their facilities. The importance of knowledge of background noise and environments that produce such noise is now a mainstay feature in LIGO physicists' epistemologies of experiment, and what is and is not a gravitational wave signal. This is further reflected in the increase of articles focused on noise and environment—once deemed as unworthy of publication in physics and astrophysics during LIGO's early efforts, when observations of astronomical phenomena were the standard bar for publication. The rise in environmental noise specialists at LIGO—and fields such as astronomy, astrophysics, and high-energy physics—also indicates how precision measurements and detection demands knowledge of the environment.

Just as field biologists "cannot avail themselves of" placelessness, I have shown that physicists also cannot conduct their experiments and make universal claims without acknowledging idiosyncrasies of place.[76] The expanded laboratory environment of each location leaves an imprint on the output of instruments—especially in the case of ultra-sensitive detectors. What was outside of the controlled laboratory—but nonetheless affecting the instruments and the experiments—was tucked away in the blind spots of awareness within the laboratory. Such objects and conditions become apparent only through inquiring about their presence, walking the land, or as Kate Brown calls it, "being there" in the surroundings of the physical laboratory building and understanding the ecologies and features of the landscape that compose

76. Kohler, *Landscapes* (n.18), on 9.

the expanded laboratory, as the gravitational wave physicists did.[77] Once the disturbances are known, they often cause a flurry of reconfigurations of the experiment, instrumentation, and data analysis, resulting in an experiment that continuously evolves alongside the evolving knowledge the physicists possess of the environment. Mechanisms for embodied environmental monitoring, such as the techniques utilized by Weiss, Schofield, and their colleagues, are now built into the experiment.

By exploring the LIGO sites through the epistemic space of the expanded laboratory environment, I have shown how the features of the surrounding environment and landscapes are embedded in the act of measuring and the data produced by the instrumentation and prompt reconfigurations in the experiment and experimental design to construct stillness, which in turn, preserves the ability to detect gravitational waves. Such an approach provides new sources of knowledge—namely, the surrounding community—that are required for the instruments to perform their intended purposes and operations of the laboratory to continue. Also illuminated are additional activities, labor practices that experimental physicists must engage in to preserve their ability to "listen" to the universe. This method also makes characteristics of the land that were invisible—in this case, logging and raven activity—visible through considering the sensitivity of the instruments and how physicists understand the metes and bounds of the laboratory environment and identify, understand, and translate signals that appear from the expanded laboratory environment space.

Although these questions and insights apply to the example of the present article, their implications can be broadened to any instrument that is sensitive to background noise beyond the walls of the laboratory—an increasingly common phenomena as instruments and laboratories grow in scale and footprint across the globe, including, for example, the radio quiet zone surrounding the Green Bank Observatory and diverse telescopes, such as the Event Horizon Telescope (EHT) and the in-development Next Generation EHT, which are limited by the time of day and weather conditions and must be placed at unobstructed viewing points. Additional examples include the gamma bursts from neutron star binaries obstructing the ability of the US Vela satellites to detect their intended targets of nuclear weapons testing; the satellites and asteroids that cause streaks in astronomy observations, especially

77. Kate Brown, *Dispatches from Dystopia: Histories of Places Not Yet Forgotten* (Chicago: University of Chicago Press, 2015), on 1–18.

sky surveys such as the Sloan Digital Sky Survey and the upcoming Large Survey of Space and Time; and the necessity of CERN physicists to account for many aspects of its broad environment, including earthquakes, which can cause peak-to-peak relative energy swings; tidal forces; current leakage from by nearby trains; and seasonal fluctuations that wrap the ring's shape, causing beam misalignment.[78] Given these numerous examples, historians of science should revisit conceptualizations of laboratories as controlled spaces, where nature is made malleable, or as locations of exclusive environments where noise can be removed and filtered through activities internal to the laboratory.

Disturbances indicate environmental change, altering how scientists understand their experimental designs, instruments, and laboratory spaces. By default, disturbances are not necessarily bad.[79] Here environmental disturbances allowed physicists to identify and recognize the aberration in their instruments, which led them to constructing stillness by gaining a more nuanced understanding of noise and upgrade, reconfiguring the interferometers when they accounted for the characteristics of the expanded laboratory environment, ultimately leading to the first direct detection of gravitational waves. Their acts of leaving the traditional laboratory to embody the surrounding environment mirrors the dynamic reconfiguration of not only the universe but also the environment that is the laboratory.

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78. With the birth of multi-messenger astronomy started by LIGO's first neutron star merger in 2017, scientists are just now realizing that the spurious gamma ray bursts were likely detecting neutron star mergers rather than terrestrial sources from Earth. On CERN: E. Todesco and J. Wenninger, "Large Hadron Collider Momentum Calibration and Accuracy," *Physical Review Accelerators and Beams* 20, no. 081003 (2017): 1–14, on 6–7; E. Bravin et al., "The Influence of Train Leakage Currents on the LEP Dipole Field," CRN SL/97–47, European Organization for Nuclear Research (Aug. 1997). https://cds.cern.ch/record/334095/files/sl-97-047.pdf

79. Anna Tsing, *Mushroom at the End of the World: On the Possibility of Life in Capitalist Ruins* (Princeton, NJ: Princeton University Press, 2015), 160.

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