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The Logic of Noise Reduction

Throughout the history of sound reproduction, efforts to prevent, reduce, or eliminate all of the noise and distortion produced by sound media were a major concern for inventors, engineers, and developers; and the myth of perfect fidelity, based on the ideal of the vanishing mediator, retained a strong appeal. From the standpoint of noise reduction practices, noise and distortion are inherently negative and disruptive. As the conceptual genealogy provided in the previous chapter makes clear, however, the fight against noise and distortion ultimately amounts to an interminable game of cat and mouse. First come innovations in sound definition. It then emerges, however, that the new technologies affect the sounds they reproduce, often in unforeseen ways, which in turn demand new measures for preventing, reducing, or otherwise eliminating these effects.

If only for the fact that its reduction has been a driving force in the history of technical sound media, this struggle suggests that noise is not incidental or epiphenomenal to sound reproduction, but structural and fundamental. This chapter sets out to explore this structural role of noise and distortion and come to terms with how the myth of perfect fidelity disguises, denies, and misrecognizes the inherence of noise in sound media. It does this by taking another, closer look at two technologies that were introduced in the previous chapter. The first is the *suppression* of noise by analog dual-ended noise reduction systems; the second is the *addition* of noise through the practice of dithering in digital sound technology. Together, the analyses of these technologies work to dispel the myth of perfect fidelity by focusing on the conceptual framework supporting it. In short, they reveal how the ideal of clear and pure reproduction is always already undermined by the observation, grounded in information theory, that all signals are affected by the transmission channels that carry them from a to b. Furthermore, toward the end of this chapter, I introduce the concept of the *noise resonance of sound media.* This concept accounts for the inherent presence of noise in a way that does not assume its reducibility (and thus reinforce the myth of perfect fidelity), but actually acknowledges its importance for how technologically reproduced sound appeals to listeners.

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The subject of the first case study, Dolby Noise Reduction, compresses parts of the sound during recording and expands it at playback, thereby covering tape noise with the recorded signal and replacing quiet sounds with silence. The technology is marketed as a neutral procedure, which generates "exceptionally pure" and "remarkably clear" recordings.[1] Nonetheless, as we shall see, its operations are based on idealized notions of noise and signal that developed in the context of communication engineering in the 1930s and information theory in the 1940s. Dolby's systems claim to cleanly separate what is considered "information" from what is considered "noise." They only do so, however, by actively defining "noise" in contrast to "signal" as everything that can—and will—be reduced. The analysis of noise-reduction systems that follows will problematize this basic logic of concealing noise and revealing signals, focusing on the circular reasoning that follows from the idealized principles underpinning their technological operation. In this logic, the system reduces all noise, which it defines as everything that is reduced. Instead of reinforcing and fulfilling this logic—which I will call the *conceptual logic of noise reduction*—my assessment shows that noise reduction is an interminable, inherently partial project. It thereby sheds light on how, despite attempts to reduce its influence, the unavoidable presence of noise poses structural *limitations* to technological sound reproduction.

Because the separation of (analog) noise from (digital) signal is a fundamental principle of digitization, it might initially seem that digital sound processing radically escalates this fundamental logic of noise reduction. However, the implementation of digital principles in the hardware of technical media is never without error, distortion, and noise either. What is more, my second example shows that attempts to alleviate such errors cause noise to reappear in an unexpected way, as a small quantity of random "dither" noise is deliberately added to the digitized signal. This dither both decorrelates quantization errors (preventing harmonic distortion) and adds a minimum amount of energy to low amplitude signals, thereby pushing them above the threshold of registerability (increasing the perceived dynamic range). Accordingly, after my analysis of analog noise-reduction technologies, which problematizes the conceptual logic of noise reduction and confirms the inevitability of noise, my study of dither will show how noise is actually a *productive force*, which allows technologically (re)produced sounds to take shape and meaningfully relate to listeners.

1 "Dolby SR," 1, 5.

Rethinking Noise and Information

In *The Audible Past*, his detailed history of early technical sound media, Jonathan Sterne dispels the myth of perfect fidelity by analyzing the idealistic tendencies underpinning the concept of fidelity itself.[2] From very early on, discourses on sound reproduction were premised on the idea that a reproduction should always be true to its original, presupposing an intrinsic connection between recorded original and reproduced copy. Within this framework, noise and distortion might be regarded as unavoidable side effects of the reproduction process, but they are always understood as external to the reproduced sound. This idealistic framework continued to justify efforts to reduce and eliminate noise, even after electrical recording technologies and the transduction of sound waves into electrical signal had enabled technologically verifiable standards for measuring sound definition. Instead of being replaced entirely by measurable sound definition, subjective, social, and aesthetic ideals of fidelity are still often conflated, along with more objective notions of technological accuracy, such that the terms "hi-fidelity" and "hi-definition" sometimes seem interchangeable in everyday usage.[3]

Hence, despite the fact that increased technical precision in terms of sound definition does not necessarily imply greater fidelity to a source, the quest for higher definition that played out between the 1940s and 1960s remained at least partly motivated by the idealistic goal of eliminating all sonic differences between original and copy. Magnetic tape recording, vinyl records, stereo sound, transistor amplifiers, and Dolby Noise Reduction were each variously conceived as moving toward the vaunted "vanishing medium."

On the one hand, creative explorations of sound recording technology's musical potential really took off in the 1940s and 1950s, both in the avant-garde circles at the newly founded studios for electronic and electroacoustic music in Paris and Cologne, and in the domains of jazz and popular music recording. On the other, new technologies were still being developed in the name of technological progress and the quest for a vanishing mediator. True, long striven-for ways of reproducing the standardized range of human hearing and a dynamic range of 60 dB were sold as achievements in terms of measurable definition and technological accuracy. Still, such "high definition" was also explicitly marketed as stepping stone toward the complete eradication of the difference between copy and original, or toward "perfect" fidelity.[4] This

[2] Sterne, *Audible Past*, 216–221.

[3] Chion, *Audio-Vision*, 98.

[4] Mark Katz describes a famous example of the longevity of the myth of perfect fidelity, somewhat reminiscent of the tone tests of the acoustic era. I am referring to the marketing slogan "Is it live, or is it Memorex?" accompanying advertisements in the 1970s and '80s, which demonstrated "how the recorded

means that technical specifications and psychoacoustical standards (such as the standardized hearing range, standard threshold of hearing, and signal-to-noise-ratio) became more than just engineering benchmarks for recording definition. By extension, they were also taken as indicators for the supposed accuracy of copies as compared with so-called originals.

At this point in the development of sound reproduction, the technological quantification, analysis, prediction, and ultimately control of many of its noises and distortions was successfully achieved. This was thanks to a diverse set of methodological approaches that had emerged in psychoacoustics, information theory, and communication engineering over the course of the twentieth century. In his book *MP3: The Meaning of a Format*, Sterne describes how noise was reconceptualized between the 1910s and 1960s—that is, roughly, between the development of the telephone and the introduction of hi-definition equipment. No longer just an external threat, noise could now be "masked and put in its place"—rendered either useful or irrelevant.[5] As a result of this process, which Sterne calls the "domestication of noise," noise was no longer considered a real problem among psychoacousticians, computer scientists, and communication engineers.[6] Rather, it was a structural nuisance that could be "tamed" using sophisticated technology designed by skilled engineers.

Once it has ceased to be a problem for engineers, noise came to be considered theoretically unimportant, uninteresting, and even trivial. Still, this only reaffirms the deeply rooted discursive assumption that it is an external intrusion or unwanted addition that must (and thus can) be eradicated, prevented, or indeed "tamed." This discourse goes all the way back to the gradual expansion of the definition of noise beyond "random interferences" through the 1920s and 1930s and, further still, to Tainter's separation of internal and external sounds in the 1880s. In both of these cases, changing conceptions of noise were inspired by the practical concerns of communication engineers. Indeed, it was in grappling practically with telephone engineering at Bell Labs that Claude Shannon developed his seminal and highly influential *Mathematical Theory of Communication*, which redefined the concepts of information and noise altogether.[7]

voice of jazz great Ella Fitzgerald could shatter a wine glass—as recorded on Memorex brand cassette tapes." Katz, *Capturing Sound*, 2.

5 Jonathan Sterne, *MP3: The Meaning of a Format* (Durham: Duke University Press, 2012), 94–95.
6 Sterne, *MP3*, 94.
7 Mills, "Deafening," 136; Schwartz, "Improving," 18; Shannon and Weaver, *Mathematical Theory*.

Published in 1948, Shannon's book consists of a series of mathematical articles that appeared the previous year, accompanied by a commentary by Warren Weaver. Most importantly for the postwar development of strategies for dealing with noise, Shannon and Weaver's model, reproduced as Figure 2.1, conceives noise as not external disturbance, but rather something internal to any system of communication. On the one hand, by conceptually including noise in the communication system, Shannon could show how one can calculate the amount of noise that accumulates over the course of a given transmission. This, in turn, allowed for more effective ways of confronting noise accumulation and diminishing its influence. On the other hand, however, Shannon's information theory had more disquieting consequences for noise reduction. Indeed, in presenting noise as not ulterior but inherent to communication systems, it shows that completely eradicating noise is fundamentally impossible.

At the root of this new approach to noise is Shannon's statistical redefinition of both noise and information. For Shannon, the amount of "information" is defined—counterintuitively perhaps—as the improbability of a given message. In other words, as the extent to which the content of the message is to be expected or not. Compared to a very simple message ("I am here"), a very complicated message ("my second cousin's best friend from Brazil will arrive at Amsterdam central station tomorrow, accompanied by my brother's wife

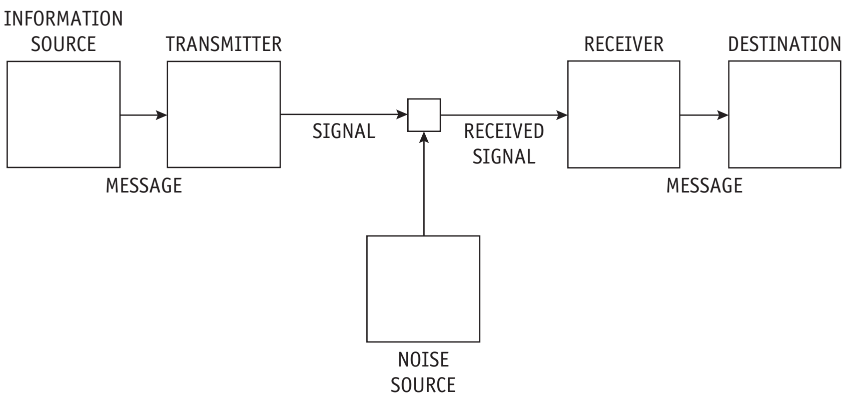

Figure 2.1 Schematic Diagram of a General Communication System. Note the "noise source" that appears in-between "transmitter" and "receiver," separating the (transmitted) "signal" from the "received signal." (From: Claude Shannon, "A Mathematical Theory of Communication," *Bell System Technical Journal* 27 (1948), reprint, accessed November 6, 2019, http://www.math.harvard.edu/~ctm/home/text/others/shannon/entropy/entropy.pdf).

and three Entlebucher mountain dogs") is less likely to occur and relatively hard to predict. In view of this, the amount of information contained in a message is statistically defined by its probability. Much like the use of "entropy" in thermodynamics—where it designates the level of molecular disorder in a system—Shannon calls a message's improbability its entropy rate. In short, the less likely it is that the content of a message will occur, the more improbable and harder to predict it is. This means that its entropy rate is higher, and it contains more information. Conversely, the part of a message that is more likely to occur, more probable, and thus easier to predict, contains less information and is more redundant. For this reason, it is called the redundancy rate. A high redundancy rate equals a low entropy rate and vice versa. Me saying "I am here" is a largely redundant because entirely self-evident statement that conveys very little information. Conversely, my more complicated statement regarding the very specific whereabouts of my second cousin's best friend contains a lot of new information.

As the analogy between Shannon's concept of entropy and its definition in thermodynamics indicates, messages with a high entropy rate and information level are more complex, less organized, and thus more random. This makes very good sense, for (in everyday life as in information theory) repetitive or periodic occurrences are much less eventful and easier to predict than something entirely unexpected or random. The observation that the sun rises in the morning is not especially interesting. The prospect of a comet crashing to earth three blocks away, however, is eminently newsworthy. Crucially for our understanding of noise, this statistical definition of information as the more random, more unpredictable, and more complex part of a message equates closely with the physical definition of random noise. Indeed, if the highest amount of information—the highest entropy level—statistically equals the highest level of unpredictability, then random noise, which by definition is entirely uncorrelated and highly unpredictable, is potentially rich with information.

For Shannon's information theory, then, the definitions of information and noise represent two sides of the same coin. It follows that noise and information—or, in engineering terms, noise and signals—cannot be unequivocally separated. From the perspective of the receiver, Weaver points out, all disturbances that occur during the transmission of a message simply increase its complexity and, potentially, information level.[8] In consequence, noise can no longer be defined on the basis of predetermined physical

[8] Shannon and Weaver, *Mathematical Theory*, 18–19. "Certain things," Weaver writes, "are added to the signal which were not intended by the information source. These unwanted additions may be distortions of sound (in telephony, for example) or static (in radio), or distortions in shape or shading of picture (television), or errors in transmission (telegraphy or facsimile), etc. All of these changes in the transmitted signal are called noise." Shannon and Weaver, *Mathematical Theory*, 8.

characteristics, such as levels of randomness or nonperiodicity. Noise is identified instead with only those parts of a message that were not intended by the sender. This means that everything that changes the message, and increases its entropy during transmission, constitutes noise.[9] Noise is defined as the difference between what was sent and what was received—the difference, that is, between input and output. This renders it essentially relative to the context of transmission. Crucially, information theory thereby defines noise as "that which disturbs a transmission," which means that everything can potentially be classified as noise.

On one level, Shannon's communicational concept of noise originated in the concrete practice of communication engineers at Bell Labs, dealing with random interferences on telephone lines. In optimizing telephone lines, his model of communication served clear economic interests. In this context, the desire for optimal signal quality is often secondary to the efficiency of transmission lines. At the same time, the statistical analyses put forward in information theory distinguishes this new concept of noise significantly from the practical concerns of communication engineers and their more straightforward, physical definition of noise as random physical disturbance. Shannon's statistical approach renders noise and information entirely relative to the content of a message and conditions of its transmission. Accordingly, his concept of noise is no longer restricted to phenomena that showcase the nonperiodic or random characteristics of sonic or physical noise. Instead, what is considered noise and what information is framed entirely by the statistical logic of information theory itself.

Notwithstanding its recognition of noise's inherence as an unavoidable part of the system, in the final analysis, information theory still considers noise a disturbing factor that limits clean and efficient signal transmission. True, it clearly complicates the noise/signal- and noise/information-binaries. What is more, information theory proves that getting rid of noise entirely is practically impossible. Nevertheless, this does not detract from its ultimate technical and socioeconomic goal: to reduce noise as much as possible and minimize its influence.[10] In fact, sociologist Urs Stäheli argues that information theory, precisely because it only defines noise from the perspective of the sender,

[9] Abraham Moles explains the primacy of the sender in information theory: "there is no absolute structural difference between noise and signal [in information theory]. They are of the same nature. The only difference which can be logically established between them is based exclusively on intent on the part of the transmitter: a noise is a signal that the sender does not want to transmit." Abraham Moles, *Information Theory and Esthetic Perception*, trans. Joel E. Cohen (Urbana: University of Illinois Press, 1966), 78–79.

[10] Martin Donner, "Fouriers Beitrag zur Geschichte der Neuen Medien," 2006, accessed March 6, 2018, https://www.musikundmedien.hu-berlin.de/de/medienwissenschaft/medientheorien/hausarbeiten_essays/pdfs/fourier-neue-medien-web.pdf, 25.

"always already knows where to locate noise."[11] Indeed, the noise that was rendered harmless or useful in the "domestication of noise" was first defined as noise by the statistical analyses of information theory, which identifies and problematizes its presence so as to reduce its influence as much as possible. By deciding what counts as noise and what escapes the net, the information theoretical framework forms a key part of the process of noise reduction.

The discursive framing and justification of Ray Dolby's noise reduction system, which first hit the market in 1964, exemplify this logic of information theory. The conceptual and technological preconditions for Dolby's dual-ended system were created, first, by the development of electrical signal processing and noise filtering technologies after World War I. These enabled the measurement of signal and noise levels, application of technical standards such as the signal-to-noise ratio, and early noise-reduction technologies. Then, in the decades following World War II, magnetic tape offered a more flexible material basis with which earlier dual-ended pre-emphasis/de-emphasis-systems could be applied. Lastly, the mathematical language of information theory provided the conceptual framework used by Dolby's "companding" procedure.

Noise Reduction Reconsidered

At the start of every sound reproduction chain is a singer or instrumentalist. The sounds produced by vocal cords; vibrating strings; vibrating reeds and columns of air; percussive blows; resonating plates; or ringing bells are captured by microphones, or picked up by an electrical element, and fed into an amplifier. After traveling through many intermittent channels, these sounds are stored on a record, tape, hard drive, or some other medium. At the other end of the chain, they are transduced back into sound waves and played through loudspeakers or headphones. Here they reach their destination: a listener. Along the way, each link in the chain has affected the signal. Each device, each cable, each acoustic space, each plug, each instrument, and each electrical circuit adds specific characteristics to the sound. Some of these are clearly audible, others only very minute and hardly noticeable. They either change the spectral and temporal contours of the signal itself or appear as entirely new sonic objects, which only come into sonic existence at the output of

[11] Urs Stäheli, "Financial Noises: Inclusion and the Promise of Meaning," *Soziale Systeme* 9, no. 2 (2003): 246.

the chain. Such additions are called “sonic artifacts.”[12] Sonic results of physical processes of signal transmission, they are brought forth entirely by the recording and reproduction chain itself.

In the instruction manual for the Dolby B, C, and S systems used on commercial cassette players, Dolby Laboratories describes artifacts that are produced in the companding process applied by their noise reduction system.[13] If tapes that were recorded with Noise Reduction turned on, the manual reminds users, are subsequently played back with Noise Reduction turned off, they will “sound brighter.” This is because the compressed high frequencies will not be restored to their original amplitude and thus remain louder.[14] When you hear these higher, overbright frequencies, the brochure adds, “you are hearing the encoded sound, not the original.”[15] What Dolby calls “the original,” however, is not the input signal prior to recording, but an output signal that has already been processed twice: encoded or compressed upon recording, and decoded and decompressed upon playback. This “original” only appears when the signal is recorded and played back with Dolby Noise Reduction. If noise reduction were not used at all, this logic goes, the output signal will suffer from noise artifacts; whereas if reduction is only used upon recording, but not upon playback, the artifact will be brightness caused by compression. In this way, the act of switching noise reduction on and off indicates the operational logic that defines dual-ended noise reduction systems: concealing noise and revealing signals.

If noise reduction is turned on during both recording and playback, the listener hears what Dolby Laboratories calls “the original.” When it is turned on only during recording, and not during playback, a compressed, encoded, brighter version of the signal is revealed: an artifact of the noise reduction process itself. The very existence of this artifact (the encoded version of the signal) retroactively changes our understanding of the so-called original (the encoded and decoded version of the signal). Switching noise reduction on during playback conceals all tape hiss and other background noises, thereby revealing the “original.” This shows that this “original” is produced by the noise reduction system itself. What Dolby considers original is neither the unrecorded and uncompressed signal that sounded prior to recording, nor the

[12] This use of the term “artifact” is analogous to its use in the natural sciences, where it designates experimental results that are produced by the measuring apparatus or test procedure itself.

[13] Kadis describes how the “improper adjustment” of equipment “will result in artifacts created by the noise reduction systems.” Kadis, *Science*, 131. Rumsey and McCormick warn against wrongly aligning the settings used for compression and expansion, writing that the recording will “sound [. . .] overbright and with fluctuations in HF [high frequency, MK] level” if the settings do not match up. Rumsey and McCormick, *Sound and Recording*, 192.

[14] “Dolby B, C, and S.”

[15] “Dolby B, C, and S.”

compressed signal created prior to playback: only the encoded and decoded signal is "original." Produced by the noise reduction process itself, the "original" is not some neutral sound unaffected by reproduction technology. Rather, it is an artifact of (correctly applied) noise reduction, produced by concealing noise and revealing silence. In this way, Dolby's compansion process complicates the status of the input and output (noises and signals) of its filtering operation.

Long before advanced technological noise reduction filters became available, Tainter relied on listeners' corrective abilities in separating internal sounds on a graphophone recording from external noises produced by the graphophone.[16] Almost a century later, by the 1960s, listeners were well trained in applying their own, internalized noise reduction—a cognitive filter for listening through instead of to noise.[17] Given the ubiquity of these personal filtering habits, listeners did not necessarily experience sound recordings as inherently noisy or distorted. Indeed, far from cleaning or clearing up a pre-existing, noisy sonic environment, advances in noise reduction actually introduced a new, more silent and less noisy sonic environment that had never existed before. Michel Chion describes how, when Dolby Noise Reduction was applied to cinema soundtracks in the early 1970s, listeners initially recognized the new silence it introduced—or rather they noticed the absence of the background noise that had always been there, but which they had routinely filtered out.[18] Once they had grown accustomed to the newly created silence of technological noise reduction, however, it ceased to signify this absence of noise and just signified the presence of silence. Generic background noise thus turned into generic background silence.

A similar silence features in Mack Hagood's analysis of the "Bose QuietComfort Acoustic Noise Cancelling Headphones," which is equipped with "tiny microphones and signal processing to produce an out-of-phase copy of the aural environment in an attempt to negate its phenomenological existence."[19] In his reading of this technology, Hagood stresses that these

[16] Stan Link, too, writes that: "Listeners learned to 'hear through' noise. The dust and nicks on vinyl recordings, amplifier hum, or speed inaccuracies of tape mechanisms produced types of noise that were basically as predictable as potholes on a familiar road." Stan Link, "The Work of Reproduction in the Mechanical Aging of an Art: Listening to Noise," *Computer Music Journal* 25, no. 1 (2001): 36.

[17] Greg Hainge, "Of Glitch and Men: The Place of the Human in the Successful Integration of Failure and Noise in the Digital Realm," *Communication Theory* 17, no. 1 (2007): 37. This idea of what could be called a cognitive noise filter actually predates the introduction of technical sound media. Helmholtz, for instance, writes that "those who listen to music make themselves deaf to these noises [of musical instruments, MJK] by purposely withdrawing attention from them, but a slight amount of attention generally makes them very evident for all tones produced by blowing or rubbing." Helmholtz, *Sensation*, 109.

[18] Michel Chion, "Silence in the Loudspeakers: Or—Why, with Dolby Sound in Films, It Is the Film Which Is Listening to Us," *Framework: The Journal of Cinema and Media* 40 (April 1999): 108.

[19] Mack Hagood, *Hush: Media and Sonic Self-Control* (Durham: Duke University Press, 2019), 178.

headphones allow a listening subject to turn the environment on and off, essentially tuning in and out of their societal relations and controlling what enters their personal space. The difference between signal and noise thus becomes an issue of power. In considering everything that enters the users' aural environment an unwanted intrusion or nuisance to be cancelled and covered over, the headphones regulate the difference between self and others. By recording background noise and cancelling it out with an out-of-phase copy (a mirror image of the noisy waveform), noise-cancelling headphones actively silence everything that intrudes on the sonic space of the listener. Technologically, they insert silence where noise abounds. Hagood quotes Bose's founder and inventor Amar Gopal Bose, who stresses how the headphones separate "things that you don't want from things that you want."[20] In this sense, they not only shut ears off from the outside world but actively "mediatize it in order to cancel it out."[21]

Not unlike switching Dolby Noise Reduction on and off, "the power button" offered by noise-cancelling headphones, Hagood expands, "offers an (imperfect) on/off interface with the soundscape" that can produce an idealized, noiseless sonic environment.[22] It thereby solidifies the logic of Shannon's information theory—which presupposes the ideal separation of, and control over, noises and signals—into media hardware. In the case of Bose's headphones and Dolby's dual-ended technology, the on/off-gesture provides silence with an active agency: this silence is created by these technologies. It is not the result of their doing nothing, the absence or suspension of action. Instead, it is carefully constructed and maintained through the active technological masking or cancelling out of background noise. This silence obtains only so long as the device remains on. When the device is switched off, silence disappears, and noise reappears. As a product of active mediation, it is an equally significant part of the output signal as the reproduced sounds themselves. Silence essentially becomes information.[23]

This twofold operation of concealing and revealing noise and silence resonates with Martin Heidegger's famous notion of "enframing" (*Ge-stell*), with which he describes technology's "challenging forth into the frenziedness of ordering" the world.[24] This process of technological ordering is possible,

[20] Bose in Hagood, *Hush*, 177.
[21] Hagood, *Hush*, 195, emphasis in original.
[22] Hagood, *Hush*, 180.
[23] John Mowitt talks of "a systematic logic that produces information out of suppressed noise." John Mowitt, "The Sound of Music in the Era of Its Electronic Reproducibility," In *Music and Society: The Politics of Composition, Performance and Reception*, eds. Richard Leppert and Susan McClary (New York: Cambridge University Press, 1987), 194.
[24] Martin Heidegger, "The Question Concerning Technology," in *The Question Concerning Technology and Other Essays*, trans. William Lovitt (London: Harper & Row Publishers, 1977), 33.

Heidegger argues, where nature is grasped as "standing-reserve" (*Bestand*), that is, as readily available resources or stock, available for transformation and use in the service of technological progress.[25] For the world to show up as standing-reserve, the sciences must unravel its mysteries to make it "orderable as a system of information."[26] In tracing these interconnections among technology, nature, and science, Heidegger shows not how technology is "based" on the laws of nature, but, conversely, how the laws of nature, as formulated by science, serve technology's "challenging forth" of existence into standing reserve.[27] Science recasts nature, facilitating technological progress and control by turning the world into manageable and coherent sets of information, or data.[28] This logic can be seen in how noise-cancelling headphones digitally process the laws of acoustics according to information theoretical principles in ways that give the user control over their environment and, by extension, the people in it.

In the case of Dolby Noise Reduction, Heidegger's concept of technological "enframing" helps us understand the principle of concealing noise and revealing silence, which maximizes information by increasing the signal-to-noise ratio. Instead of drawing attention to (the absence of) "things that you don't want," the active process of noise reduction continuously reveals "things that you want": signals, sounds, silence. Useful information. With its twofold operation of compression and expansion, noise reduction conceals what, following the logic of information theory, is deemed outside information (noise), and reveals what an original, unfiltered, unprocessed recording should sound like. Prior to any actual technological filtering, the operation therefore presupposes a conceptual filter that already defines "what you want" and "what you don't want." This conceptual filter is the basis of the logic of noise reduction: it negatively defines noise in contrast to everything that is not reduced (and thus by definition belongs to the signal) as everything that can and will be reduced.

Bernhard Siegert gives an earlier example of this logic of noise reduction in an article from 2007, in which he describes the "on-going exclusion of noise" that occurred in German radio plays in the 1950s.[29] By excluding as much noise as possible, the directors of these plays maximized the

[25] Heidegger, "Question," 23; Hans Ruin, "Ge-stell: Enframing as the Essence of Technology," in *Martin Heidegger: Key Concepts*, ed. Bret W. Davis (Durham: Acumen Publishing, 2010), 192.

[26] Heidegger, "Question," 23.

[27] Heidegger, "Question," 23.

[28] Ruin, "Ge-stell," 186, 191.

[29] Bernhard Siegert, "Die Geburt der Literatur aus dem Rauschen der Kanäle: Zur Poetik der Phatischen Funktion," in *Electric Laokoon: Zeichen und Medien, von der Lochkarte zur Grammatologie*, eds. Michael Franz, Wolfgang Schäffner, Bernhard Siegert and Robert Stockhammer (Berlin: Akademie Verlag, 2007), 32.

signal-to-noise-ratio to turn the resulting silence, as Siegert puts it, into "the expression of an absolute interiority."[30] As in the cinema soundtracks of the 1970s, silence gained greater significance in the absence of noise. The resulting "meaningful silence," in turn, also relates to the inwardness of the Romantic reading subject, which Kittler identifies as the paradigm of literary reading in the pretechnological era.[31] Based on discrete alphabetic signs, silent writing and reading filters out everything that does not slot into the symbolic framework of the written word. This reduction of external disturbances ensured fixed, lucid, and comprehensible meanings. Contrary to this supposedly clean transmission of information through discrete symbolic signs, technological signal processing relies on physical signal. Over the course of their transmission, something always sticks to these signals or, as Kittler has it, something "ceases not to write itself."[32] These are the artifacts of the transmission channel itself: what information theory calls 'noise.'

As in Siegert's example of 1950s German radio plays, and the symbolically integrated world of nineteenth-century literature, the conceptual logic of noise reduction presupposes the possibility of entirely clear output signals, transmitting unambiguous information, framed by meaningful silence. Because noise reduction technologies rely on electronic signal processing, however, their physical operations are not as perfect as this ideal suggests: their output is inevitably shaped by their own operations as well. This is the gap between the conceptual logic of noise reduction—according to which noise can always be found and put in its place—and its implementation in the physical hardware of technological media. Acknowledging this gap's significance and ultimate intractability gives rise to a different understanding of noise.

Michel Serres conceptualizes the gap between ideal and physical transmission—between absolute noise reduction and physical channels' inevitable influence—through the metaphor of two mythical ships carrying two Greek heroes: Odysseus and Orpheus.[33] Although they have both sailed safely past the deadly Sirens, whose singing has lured many a sailor to their death, the two heroes' accounts of their journeys indicate very different attitudes toward the Sirens' dangerous song, which represents noise in Serres's metaphor. By clogging the ears of his men with wax and having himself tied to the mast, Odysseus pretended that its malicious influence did not in the least threaten

[30] Siegert, "Geburt," 34.
[31] Friedrich Kittler, *Discourse Networks, 1800/1900*, trans. Michael Metteer and Chris Cullens (Stanford: Stanford University Press, 1990), 161.
[32] Friedrich Kittler, *Gramophone, Film, Typewriter*, trans. Geoffrey Winthrop-Young and Michael Wutz (Stanford: Stanford University Press, 1999), 3.
[33] Michel Serres, *The Five Senses*, trans. Margaret Sankey and Peter Cowley (London: Continuum, 2008), 126.

his safe passage through the channel. Orpheus, however, guided his fellow travelers through the channel by drowning out the Siren's song with his own singing, in the full knowledge that he could temporarily cover the noise, but not make it disappear.[34]

Odysseus was a man of reason and logic, the great teller of tales, who used a clever ruse to elude the sirens. Always looking for practical solutions and unambiguous answers, he blocks out the Siren's noise to ensure the safe and steady passage of his ship—the signal's clean transmission through the noisy channel. With less noise, signals are more likely to reach their destination. It is therefore "hardly surprising," writes Serres, "that his messages are heard."[35] History, of course, is told by the victors. Accordingly, having safely sailed his ship through the channel, Odysseus could tell his story as if the Sirens had not got through to him and his noise-reduction strategy had worked perfectly.[36] Orpheus's strategy was different: he drowned out the noise with music and signing, masking but not eliminating it. This makes his victory more precarious. Indeed, Serres writes that Orpheus remains "open to the risk of collapsing into noise"—were he to stops singing, even momentarily, the noise would get through.[37] A far cry from Odysseus's pretense of complete noise reduction, Orpheus's strategy is self-consciously relative and temporary: reduction is never complete and noise can crop up again at any time.

For Serres, the story as told by Odysseus, presented as if no noise had come through, exemplifies a rationalist, scientific worldview that always "presupposes a world without noise"—a world with clear solutions, perfect signals, and pure information.[38] This worldview is best encapsulated, Serres argues, by Leibniz's eighteenth-century law of continuity, as represented by

[34] Hagood also uses the metaphor of Orpheus's singing drowning out the siren noise in describing what he calls "orphic media," that is, devices that "promise to help users [. . .] remain unaffected in changeable, stressful, and distracting environments, sonically fabricating microspaces of freedom for the pursuit of happiness." Hagood, *Hush*, 3.

[35] Serres, *Senses*, 126.

[36] In the first volume of *Musik und Mathematik,* Kittler describes how he empirically verified Odysseus's account of his journey past the Sirens, by sailing past the Italian islands Il Gallo Lungo, Casteltuccia, and Rotonda while opera singers were singing at shore. Contrary to what Homer has Odysseus recount, Kittler concludes, the hero cannot have received the Siren song as clearly as he claims. Kittler describes the results of the experiment in the following way: "we heard, clear and pure, ... radiating vowels, but not the slightest trace of consonants. So, no word had reached us." If Odysseus, as Homer describes, really stayed onboard, tied to the mast, the transmission of the Siren song would have failed, because only vowels would have reached his ears. Since Homer nonetheless transcribes the words of the song, Kittler concludes, Odysseus must have lied: he did *not* sail past the island but landed on it. Although Odysseus claimed that the Siren song reached his ears loud and clear, he is betrayed by the noise of consonants, without which the words of the song would not have made any sense and which Kittler "proves" must have been lost in the transmission from island to ship. Hence, Kittler warns that we must "not trust the biggest liar of Greece, but two Sirens." Friedrich Kittler. *Musik und Mathematik*, Volume 1, Part 1 (München: Wilhelm Fink Verlag, 2006), 58.

[37] Serres, *Senses*, 126.

[38] Serres, *Senses*, 126.

his famous dictum that "nature does not make jumps."[39] With the law of continuity, Leibniz described a world in which each part reflects the whole, because there is complete continuity from the smallest element to the largest structure. This conception is reinforced by his theory of the elementary ontological unit, the perfectly self-contained "monad" (an elementary particle of sorts). In a world governed by the law of continuity, ambiguity, inextricability, confusion, and randomness do not exist. In this world, there is no noise. It is the world of Odysseus; the ideal of complete noise reduction, motivating Dolby's technological operation, belongs to it too. By suggesting that every signal gets through the channel completely unaffected, the conceptual logic of noise reduction presupposes that pure, clear, and transparent transmission is always possible.

Regardless of Odysseus's heroic claims, Leibniz's rational system, and Dolby's technical filters, however, Serres insists that "the purest is never pure enough to remain the master forever."[40] Whereas these variations on a noiseless world assume the possibility of complete reduction, Shannon's model of communication confirms that this is ultimately impossible. In fact, the purity claimed by noise reduction is relative and precarious, for noise is internal and inherent to all communication systems. Reduction is never complete, then, for noise reduction systems are themselves also communication channels, that is, technical media subject to the basic rules of signal transmission. As the "brighter" sound of a nondecoded Dolby recording reveals, signals are shaped by passing through the physical channels of the noise-reduction process itself.

Whereas the perfect separation of signal and noise in Odysseus's heroic retrospective account resembles Dolby's "ideal audio device," Orpheus's strategy shows that every noise-reduction filter is applied using specific criteria to a specific context. No signal can pass through a channel without being affected.[41] Despite the claim that Dolby's most advanced SR system is able to "create an infinite number of filters through which the signal must pass before it is recorded," each of these only filters out what the system identifies as noise to begin with.[42] Actual noise-reduction technologies do not use ideal filters, which would effortlessly separate clearly defined signals from precisely located noise, but physical filters, which, like Orpheus's singing, must continuously and precariously mask noise with signal. All through this process,

39 Serres, *Senses*, 126. Gottfried Wilhelm Leibniz, *Philosophical Essays*, eds. Roger Ariew and Daniel Garber, trans. Roger Ariew and Daniel Garber (Indianapolis: Hackett Publishing Company, 1989), 473 (1765).
40 Serres, *Genesis*, 131.
41 "Dolby® SR," 2.
42 "Dolby® SR," 5.

the signal is shaped by the noise-reduction system itself and runs the risk of "collapsing into noise." No ideal passage or perfectly smooth journey, noise reduction is an active, unceasing, and inherently partial procedure.

What is received at one end of the chain is never identical with what went into the other: something always sticks to the signal. This is why noise reduction is not—and can never be—the final word on the role of noise in sound recording. What is more, the concealing and revealing of noise and signals regulated by the on-/off-button of Dolby's compander shows that what comes out as a supposedly noiseless "original" differs from what "originally" went in. In fact, it is produced by the medium itself. To understand the role of noise in sound recording, therefore, we must renounce ideas of a supposedly inherent connection between input and output that are based on the supposedly unambiguous difference between signal and noise. Instead, we should acknowledge the gap between the idealized logic of perfect noise reduction and the physical operations that occur in the filtering channel itself. This entails closely attending to how they continuously conceal and reveal, configure and reconfigure different layers of signals and noise and the relations among them.

Noise, Distortion, Error

In the early 2000s, composer William Basinski decided to digitize a series of ambient loops that he recorded on magnetic tape some two decades earlier. He put them in a digital recorder and let it run. The tapes had laid dormant for many years, however, and slowly began to deteriorate as they ran through the machine. The recorder chipped bits of magnetic coating from the tape, causing more and more music to disappear with each run. Serendipitously, this process resulted in a series of long, (un)winding, ethereal pieces of strangely melancholic music. Each piece consists of the same loop played over and over again. The loop is slightly different on each rotation, however, because it is damaged slightly more each time around.[43] Aside from recognizing the musical potential of this disintegration process, Basinski's only deliberate compositorial act was the addition of a considerable amount of reverb.[44]

The finished pieces, released as *The Disintegration Loops* in four parts between 2002 and 2004, make an interesting case for the complexity of questions

[43] *The Disintegration Loops*, by William Basinski, *2062*, 2002, compact disc.

[44] For a detailed analysis of Basinski's "Disintegration Loops," see Jakko Kemper, "(De)compositions: Time and Technology in William Basinski's *The Disintegration Loops* (2002)," *Intermediality: History and Theory of the Arts, Literature and Technologies* 33 (Spring 2019), accessed November 27, 2019, https://doi.org/10.7202/1065020ar.

regarding noise, noise reduction, and the basic principles of sound reproduction. The eroding tape is what Caleb Kelly calls a "cracked medium"—a faulty, broken, or malfunctioning device. A "crack," here, signifies "a point of rupture or a place of chance occurrence, where unique events take place that are ripe for exploitation toward new creative possibilities."[45] In *The Disintegration Loops*, the imperfect replay of prerecorded sound, which is destroyed in the very process of reproduction, constitutes the musical material in its entirety. It would be fruitless to attempt to determine where the signal ends and noise begins, for the pieces' explicit focus on the "cracked" transmission channel—the medium itself—cuts across this distinction. Whereas noise reduction systems generally diminish the artifacts of material carriers and recording mechanisms, in these pieces the accumulation of such artifacts constitutes a driving musical force. Had the tape been in pristine condition and transferred smoothly to the digital realm, nothing interesting would have happened—Basinski would just have produced an endless loop. The noise and distortion produced by randomly deteriorating tape are what make *The Disintegration Loops* musically compelling: reducing them would destroy the piece itself.

At the same time, it is significant that these random sonic artifacts of analog material decay were transferred to the digital domain. It would have been possible for Basinski to transfer the sound on the disintegrating magnetic tapes to new and unaffected tape. The transition to digital media, however, makes this musical use of the noise of sound media all the more poignant. In the digital age, after all, the conceptual logic of noise reduction has become, as Siegert puts it, "nothing less than systemic."[46] Returning to a representational system based on discrete, coded signs—like the series of signs that make up written language—digital media reinstate the complete symbolic separation between transmission channels and transmitted signals that defined the age of alphabetic writing's primacy.

With the advent of digital media, the automatization and optimization of this logic of discrete signs enabled the storage, production, reproduction, and transmission of physical signals. In Basinski's pieces, the inevitable influence of the material basis of sound reproduction is brought to the fore—much like The Caretaker's use of the scratches, cracks, and noises on an old recording of Schubert's *Winterreise*. The technical operations of digital sound media, in sharp contrast with this, are premised on the complete separation of this material basis from the signals they reproduce. Because of digital domain's very rigorous separation of all the things that you want from all the things that you

[45] Kelly, *Cracked Media*, 4.
[46] Siegert, *Cultural Techniques*, 30.

do not want, everything that is deliberately not reduced in *The Disintegration Loops* (such as the normally "unwanted" sound of deteriorating tape) must logically be considered part of the "wanted" signal. What would usually be considered the "unwanted" noise of sound media thereby becomes an indispensable part of the musical signal.

The promotional brochure for Dolby's final analog system, released at the dawn of the digital age in 1987, admits that "a typical digital recording provides performance that is better than unassisted analog tape in several obvious ways," not least in that "the noise level is [. . .] much lower than the noise of analog tape."[47] True enough, Dolby's analog noise-reduction systems were commercially threatened by the rapid rise in digital recording studios and the introduction of the CD, which operationalized the separation of noise and signal in a radically new way. Nevertheless, the brochure also warns that "the usable improvement in noise level [of digital systems] is not as great as theory predicts." Indeed, in response to the rise of digital sound technology, the brochure cleverly highlights one of its most obvious drawbacks: the occurrence of quantization errors and the addition of dither.

Like the gap that obtains between the complete separation of noise and signal projected by the conceptual logic of noise reduction, and what the physical operations of technological noise-reduction systems can actually achieve, the addition of dither highlights the distance between the theoretically seamless operations of digitization and their physical implementation in technical hardware. My analysis of dual-ended noise reduction systems problematized the conceptual logic of noise reduction, which defines noise negatively and retroactively as everything that can be ignored, eliminated, or instrumentalized. However, analyzing the more rigorous filtering operations of digital media, and especially the return of noise in the form of dither, allows for a different, altogether more positive reading of the noise of sound media.

Critics of digital sound reproduction often remark that the frequency response of digital recordings is inherently limited. Following the sampling theorem, a digital system can only capture frequencies up to half its sampling rate. Taking into account the need for a slight cut-off slope, a sampling rate of 44.1 kHz cannot reproduce frequencies above approximately 20 kHz. Now, it is possible to increase the sampling rate so as to record higher frequencies, but every sampling rate—whether twice the maximum frequency or even higher—will posit an absolute limit. This limit is inherent to digital reproduction. Analog media might be restricted by physical variables particular to its storage media (wax, tape, vinyl, etc.), so this argument goes, but

[47] "Dolby SR," 7.

not by any fundamental principles underpinning the reproduction procedure as such. "The upper limit of fidelity in an analog system is perfection," write Eric Rothenbuhler and John Durham Peters, "while the upper limit of fidelity in a digital system is the Sony-Phillips [sic] convention."[48] The argument put forward here recalls Zeno's paradox of Achilles and the tortoise, in which Achilles, having given the tortoise a head start in a running contest, fails to beat it, because the distance he must travel to overtake his opponent can be divided in half an infinite number of times. In this way, this argument against digital accuracy assumes that the infinitely discrete might be able to approximate but can never actually attain the status of a continuous signal. Digital reproductions, in other words, are considered "asymptotic" (from the Greek *asumptōtos*, meaning "not falling together"). This is mathematically illustrated with a geometric curve that continuously tends toward the x- or y-axis, but never actually coincides or intersects with it.

This assumption is based on a fallacy. It erroneously represents temporal events as spatial problems, whereas both the race between Achilles and the tortoise and digital sampling of sound waves take place in space and over time.[49] Much as Achilles can never bridge the distance between him and the tortoise, the reduction of digitization to purely spatial terms—according to which the A/D-converter will always miss the "spaces" in between samples—is based on a crucial misunderstanding. A digital signal is often visualized as a series of discrete samples with "nothing" (silence or emptiness) between them, but what comes out of the speakers is an entirely continuous, and in fact analog signal. Just as Achilles can simply speed up to cross the distance between himself and the tortoise, when digital signs are transduced back into electric voltage levels and these voltage levels into sound waves, the Nyquist theorem assures that the discrete discontinuities of the binary representation are turned into entirely continuous signals. This is the very foundation of digital sound processing.

True, the sampling theorem states that a digital system cannot reproduce frequencies above the Nyquist limit of half the sampling rate. Nevertheless, just as the frequency response of digital systems is limited by the sampling theorem, the frequency response of an analog system is restricted too: by the available bandwidth of the medium and by noise, distortion, and other interferences that occur during signal transmission. An analog system with

[48] John Durham Peters and Eric W. Rothenbuhler, "Defining Phonography: An Experiment in Theory," *Musical Quarterly* 81, no. 2 (1997): 235.

[49] For more on (the history of) the epistemological fallacy of reducing temporal phenomena to spatial terms, see Milič Čapek, "Introduction," in *The Concepts of Space and Time: Their Structure and Their Development*, ed. Milič Čapek (Dordrecht: D. Reidel Publishing Company, 1976), xvii–lvii.

an unlimited frequency response is as hypothetical as an infinitely precise sampling procedure. “The upper limit of fidelity in an analog system,” then, is not perfection—whatever that may be anyway—and neither is the upper limit of fidelity in a digital system. In focusing on the limitations of the sampling procedure imposed by the Nyquist theorem, critics of digital sound processing pay rather less attention to the other half of the digitization procedure, namely quantization. This oversight is curious, for quantization much more clearly indicates the preconditions and structural limitations of the digital procedure, which resonate strongly with problems originating in the analog domain.

In Shannon and Weaver’s model of communication, “all [. . .] changes in the transmitted signal,” whether they be the result of random noise, distortion, errors, static, or any other type of interference, are grouped together under the label of “noise.”[50] At the level of the physical characteristics of these phenomena, however, Shannon writes that “noise and distortion may be differentiated on the basis that distortion is a fixed operation applied to the signal, while noise involves statistical and unpredictable perturbations.”[51] In other words, whereas distortions are nonrandom or systemic changes to the signal caused by specific and predictable occurrences, noise remains random and unpredictable. Owing to its “fixed,” predetermined, statistically correlated, and predictable nature, distortion can, “in principle, be corrected by applying the inverse operation”—that is, by applying the exact opposite of the process that caused it in the first place.[52] Random and unpredictable noise, by contrast, “cannot always be removed, since the signal does not always undergo the same change during transmission.”[53] On the physical level of technological operations, in short, both systemic interferences (distortion) and completely random perturbations (physical noise) affect signals. Whereas the first can be retrospectively eliminated, the second can only be prevented, masked, or reduced. On the symbolic level of Shannon and Weaver’s information theory, however, all disturbances (whether random or systemic) are referred to as “noise,” and the changes they cause are called “errors.”

The case of quantization errors, however, is more complicated than this technical difference between noise and distortion might suggest. During quantization, *errors* in the digital representation cause harmonic *distortion* that is eliminated by *noise*. This means that digital quantization errors and

[50] Shannon and Weaver, *Mathematical Theory*, 8.
[51] Claude Shannon, “Communication in the Presence of Noise,” *Proceedings of the IEEE* 86, no. 2 (1998): 447.
[52] Shannon, “Communication,” 447.
[53] Shannon, “Communication,” 447.

the resulting harmonic distortion are statistically equivalent to random background noise in the analog scenario: the analog signal-to-*noise* ratio becomes a signal-to-*error* ratio in the digital realm. Furthermore, whereas analog noise reduction masks random noise and other disturbances using a louder nonrandom signal, in the case of dithering, random noise is deliberately added to reduce the effect of nonrandom errors. Dither thereby turns the resulting distortion into a layer of random (or semirandom) noise, which closely resembles an analog noise floor. In terms of their effect on the signal, analog background noise and digital quantization errors are therefore statistically similar. They are not identical though. In fact, the difference between the two ratios exemplifies the difference between analog and digital recording as such.

The analog signal-to-noise ratio, on the one hand, signifies dynamic range (the difference between the minimum noise floor and the maximum amplitude level), thereby indicating the bandwidth of a transmission channel and its capacity to transmit information without error. The digital signal-to-error ratio, on the other hand, only indicates the precision of the measured sample values or "the degree of accuracy that's used to capture a sampled level."[54] Because quantization errors are not random, but statistically correlated to the digitized signal, they technically count as a form of distortion.[55] Still, Shannon's assertion that distortion can "be corrected by applying the inverse operation" does not quite go for quantization errors. With the background noise of analog recordings, the way in which the signal-to-noise-ratio was conceptualized allowed engineers to treat signal and noise as if they were two entirely separate signals. This idealization contributed greatly to the development of sophisticated noise-reduction technologies.[56] Quantization errors, in contrast, cannot be symbolically separated from the signal in quite this way.

As Von Neumann explains, "what [a digital machine] produces when a product is called for is not that product itself, but rather the product plus a small extra term—the roundoff-error."[57] These roundoff-errors occur at the moment of digitization itself, when the digital signal comes into being. Whereas analog noise is caused by the physical materiality of the reproduction medium affecting the signal, quantization errors result from the digital recording and reproduction process itself. They are not physical corruptions of the signal, but misrepresentations of it: quantization errors are misrepresented (parts of) signals. Like the noisy artifacts of analog recording channels, the

[54] Huber and Runstein, *Recording Techniques*, 207.
[55] Pohlmann, *Principles*, Fourth Edition, 36.
[56] Friedrich Kittler, "Signal-to-Noise Ratio," in *The Truth of the Technological World: Essays on the Genealogy of Presence*, trans. Erik Butler (Stanford: Stanford University Press, 2013), 167.
[57] Von Neumann, "Theory," 295.

quantization errors that appear during analog-to-digital conversion—that "small extra term"—emphasize an inherent limitation of digitization: the impossibility of representing infinitesimally precise values with an inherently finite number of signs. This similarity between analog and digital media, and their relation to noise, can be further explained by reference to the discursive origins of both digital and analog technology in the longer history of analytical representation as such.

In *Passage des Digitalen*, his long and imposing genealogy of the idea of the digital from the eleventh to the twentieth century, Bernhard Siegert traces the emergence of the basic principles of digital technology. He situates this development within the larger history of mediatic inscription and representation. The emergence of modern mathematical analysis in the seventeenth and eighteenth centuries, and of technical media in the nineteenth and twentieth centuries, he argues, constitute a decisive "rupture" or "rift" (*ein Riß*) in the classical order of representation, which had been dominant up until the seventeenth century.[58] This classical order of representation had presupposed the possibility of "a complete description of all things" on the basis of writing. [59] Using the discrete signs of the alphanumeric writing system, complete representation was assumed possible. The most concise example of this worldview is Leibniz's fundamental law of continuity, according to which everything, from the smallest element to the largest planetary system, could be counted, described, organized, and represented by words and numbers.[60] Although this Leibnizian law stands as a key paradigm of this representational logic, it is equally true that his invention (alongside Newton) of the infinitesimal calculus set the stage for the demise of this "world without noise" and its logic of seamless and complete representation.[61]

From the development of the calculus in the late sixteenth century, through Leonhard Euler's discontinuous functions in the eighteenth century, to Joseph Fourier's *Analytical Theory of Heat* in the nineteenth century, mathematical analysis introduced functions that were initially considered absurd or nonsensical. Indeed, these functions do not directly represent observable phenomena in the physical world but exist only on paper. Contrary to the rationalist logic of classical analysis, however, modern mathematical analysis does not assume the possibility of complete and exhaustive representation. As such, its emergence triggered what Siegert calls a "drift of the non-representational"

[58] Bernhard Siegert, *Passage des Digitalen: Zeichenpraktiken der Neuzeitlichen Wissenschaften 1500–1900* (Berlin: Brinkmann & Bose Verlag, 2003), 17.
[59] Siegert, *Passage*, 16.
[60] Siegert, *Passage*, 16.
[61] Serres, *Senses*, 126.

from the seventeenth century onward, which would eventually precipitate the "removal of the foundations" of classical representation altogether.[62] In place of a discourse of complete representation (which presupposes the ideal of perfectly self-sufficient, noiseless writing), a different framework emerged, based not on the law of continuity, but on modern mathematical analysis. It was this analytical framework that would ultimately "open up a space for technical media" able to technologically reproduce what analysis cannot fully represent.[63]

The first crack to appear in the representational logic of Leibniz's own law of continuity was his introduction, in the context of the infinitesimal calculus, of a new mathematical conceptualization of infinity. This idea of infinity is best illustrated by Leibniz's metaphor of the noise of the sea, through which he explains his idea that human perception is an aggregate of infinitely many infinitesimally small perceptions (*petites perceptions*).[64] The "roar or noise of the sea that strikes us when we are at the shore," writes Leibniz, may seem inextricably complex. However, this complicated and confused sound, he goes on to explain, is actually composed of infinitely many individual sounds, each corresponding to a single wave.[65] Our ears and brains may process these small perceptions "in the confused assemblage of all the others," but each and every one of them must belong to a separate entity, because, logically, "a hundred thousand nothings cannot make something."[66] For Leibniz, the world is a continuum of infinitesimal elements: each phenomenon must logically consist of many smaller ones, ad infinitum. What humans perceive as the noise of the sea in all its indivisible complexity, an all-knowing God perceives as an infinitely complex assemblage of infinitesimally small, but perfectly self-contained, discrete sounds. Broken down into its infinitely many infinitesimal elements, noise is not noisy at all.[67]

[62] Siegert, *Passage*, 16–17. I translated the German phrase "Entzug des Grundes" as "removal of the foundations," but the German word *Grund* has multiple meanings in this context. Although "foundations" is close to the most literal meaning as "ground," *Grund* also means "reason" (as in "the reason for something") or "cause."

[63] Siegert, *Passage*, 16.

[64] Leibniz, *Essays*, 295.

[65] Leibniz, *Essays*, 295.

[66] Leibniz, *Essays*, 296. As Deleuze puts it, "there has to be something simple, if there is something composite." *Lectures by Gilles Deleuze*, February 2007, accessed February 14, 2014, deleuzelectures.blogspot.nl/2007/02/on-leibniz.html.

[67] Regarding the role of God, Leibniz writes: "eyes as piercing as those of God could read the whole sequence of the universe in the smallest of substances." Leibniz, *Essays*, 296. Based on this idea, media scholars Peter Bexte and Werner Künzel put forward the thesis that the possibilities of digital computing, realized three centuries later, approximate the perception enjoyed by the Leibnizian supreme being. Like Leibniz's God, this argument goes, computers are capable of disentangling the most inextricable noise. Peter Bexte and Werner Künzel, *Allwissen und Absturz: Der Ursprung des Computers* (Frankfurt am Main: Insel Verlag, 1993), 156.

This notion of perceptual integration, however, ultimately corrupted the rationalist foundation of Leibniz's philosophical system. With the introduction of the mathematical concept of the infinitesimally small, Leibniz's rationalist order was doomed to remain forever incomplete. This is because representation only asymptotically tends toward the represented, but never actually coincides with it. To uphold the continuity that his worldview dictates, Leibniz resorts to the calculus, which, as Serres writes, "lumps everything into the differential, and under the numberless thickness of successive orders of integration."[68] The Leibnizian concept of continuity therefore represents, in Deleuze's words, "a fold" that is "folded within a fold, like a cavern in a cavern."[69] For Leibniz, only God can unravel this enmeshed continuum, for only God can actually perceive its complexity. In this understanding, human beings, with their imperfect senses, must either rely on a higher power or use mathematical analysis to penetrate the infinitesimally entangled or confused.

These compromises between continuity and discreteness indicate a fundamental tension running through Leibniz's philosophical system. The gradual working out of this tension eventually caused the Leibnizian "ontology of the noise of the sea," as Siegert calls it, to give way to "a non-Leibnizian order of things."[70] Indeed, despite their origin in the law of continuity, infinitesimal calculus and mathematical integration made possible a form of analysis that no longer assumes the possibility of complete representation. Together, the disappearance of the rationalist ideal of complete representation and the advent of mathematical analysis thereby opened a gap between representation and represented. Slowly, description and the described, word and world drifted apart.[71] This "drift of the non-representational" was completed about a century after Leibniz's death, when Joseph Fourier's applied Euler's discontinuous trigonometric functions to his *Analytical Theory of Heat*, first conceived in 1807.[72]

I will discuss the mathematical and physical principles behind "Fourier analysis" (as it is known), and their importance for the modern concept of sound, in more detail in the next chapter. What is important to emphasize here, in relation to the origins of digital signal processing, it that Fourier analysis puts an end to the ideal of continuity that defined Leibniz's worldview. When Georg Simon Ohm and Hermann von Helmholtz applied Fourier analysis to the study of sound waves in the latter half of the nineteenth century, it became

[68] Serres, *Genesis*, 20.
[69] Gilles Deleuze, *The Fold: Leibniz and the Baroque* (New York: Continuum, 2006), 6.
[70] Siegert, *Passage*, 234, 182.
[71] Siegert, *Passage*, 182.
[72] Siegert, *Passage*, 192.

theoretically possible to represent all frequency components of a sound as a series of sine waves: individual, singular, noise-free frequencies.[73] This mathematical analysis of sound would only become fully operational with the high processing speeds of digital computers, which are able to implement the much more efficient "Fast Fourier Transform." Nevertheless, Fourier analysis made it conceivable that the inextricable could be analytically unraveled—that the noise of the sea could be split into its singular components. This analytical order far transcends what human senses can achieve alone.

By separating complex sound waves into all their individual frequency components, Fourier's analytical method symbolically (that is, by processing discrete signs such as numbers and letters) seemingly achieved what remained fundamentally inconceivable in Leibniz's rationalist order: accounting for every element contained in the roar of the sea. Far from confirming Leibniz's law of continuity, however, Fourier analysis only deepened the rift that the infinitesimal calculus had opened up in the classical order of representation. Despite the ideal of full representability, physical wave phenomena such as sound, heat, and light had proven to be fundamentally unrepresentable in the classical order of representation. With Fourier's method, these phenomena did become symbolically representable. The resulting representations, however, could never live up to ideals of full representation, because they were fundamentally based on the asymptotic approximations and discontinuous limit cases introduced by modern mathematical analysis. As such, the analytical clarity allowed by Fourier analysis came at the cost of leaving behind the rationalist ideal of unbroken continuity and complete representation once and for all.

Over the course of the nineteenth and early twentieth centuries, finally, this analytical trajectory in turn facilitated the development of technical media that substitute symbolic representations in the form of written signs for physical reproductions in the form of physical signals. Like the inherently asymptotic nature of the representations produced by mathematical analysis, however, the presence of analog noise or digital error in technical reproductions remains inevitable. Born from efforts to mathematically analyze the entangled, inextricable, confused, and infinite, technical media emerged in and through the "drift of the non-representational" that ran from Leibniz, through Euler, to Fourier, and beyond. In turn, the limitations of

[73] Leibniz's description of the noise of the surf returns in Helmholtz's *On the Sensations of Tone*, first published in 1863, in which he writes: "I must own that whenever I attentively observe this spectacle [of waves in the sea, MJK] it awakens in me a peculiar kind of intellectual pleasure, because it bares to the bodily eye, what the mind's eye grasps only by the help of a long series of complicated conclusions for the waves of the invisible atmospheric ocean." Helmholtz, *Sensations*, 40.

analog and digital transmission channels (caused by the presence of random background noise or the inability to represent infinitesimal amplitude values) are an unavoidable symptom of the asymptotic logic of modern mathematical analysis, which enabled the development of these media technologies in the first place.[74]

The Noise Resonance of Sound Media

The conceptual basis of both digital and analog technology, then, is bound up with the long history of analytical representation. As Siegert has shown, modern mathematical analysis marked a rupture in the classical order of representation, in which analytical descriptions might fully correspond to the world they describe.[75] Given this close historical entwinement of the theoretical principles behind analog and digital media, locating fundamental differences between the two is more difficult than one might think. Despite their radically different approach, both digital and analog technologies transduce physical sounds into different, though analogous forms.[76] Although magnetic tape and digital media, for instance, store electrical voltage levels in the very different forms of magnetic flux and binary code, both storage formats are equally analogous to the original waveform.[77] Neither representation is inherently closer to, or further removed from, the "original" sound wave.[78] The difference between the two, however, consists in the representational logic through which these representations are produced. Whereas analog media work by inscribing continuous signals in a continuous way, digital media are based on discontinuity and discreteness. This difference between continuity and discontinuity is constitutive of a different relation between representation and the represented.[79]

Siegert traces the conceptual roots of this difference back to the famous Macy Conferences on cybernetics, held between 1946 and 1953, at a time when "the concepts of the analog and the digital had barely begun to be

[74] Siegert, *Passage*, 389.

[75] As Siegert writes in the introduction to *Passage des Digitalen*: "the digital and the analog are not episodes in the history of media; rather, technical media are an episode of the digital and the analog, the era of the *graphé*." Siegert, *Passage*, 15, emphasis in original.

[76] Huber and Runstein, *Recording Techniques*, 200.

[77] Watkinson, "History," 110.

[78] Sterne even remarks that "analog tape is just as discontinuous as the 0s and 1s in digital storage." Jonathan Sterne, "The Death and Life of Digital Audio," *Interdisciplinary Science Reviews* 31, no. 4 (2006): 341.

[79] Anthony Wilden, *System and Structure: Essays in Communication and Exchange*, Second Edition (London: Tavistock Publications, 1980), 188.

clarified."[80] Given that both concepts were still relatively unstable and undefined, participants in the conferences discussed fundamental aspects of the difference between these two modes of reproduction. Most poignantly, the proceedings focused on the question of whether the digital is "part of the real or the symbolic."[81] Von Neumann, on the one hand, was not interested "in the implementation of the digital within the real"—to him, matters concerning the digital were the exclusive preserve of symbolic machines (in other words, computers). Several neurophysiologists, on the other hand, "tried hard and desperately to localize the digital within the real," for this would allow for new interpretations of brain functioning.[82] Norbert Wiener attempted to unify these positions by suggesting that (in Siegert's paraphrase) "the digital was a function of time and [. . .] its basis was the creation of a 'certain time of non-reality' that lies between two stable states."[83] This means that digital machines are able to create accurate representations of physical (real) phenomena, precisely because they symbolically exclude the instant that an electronic circuit requires for the analog switching operation between two binary states (1 or 0). This instant of switching is what Wiener calls a "time of non-reality."

It was this exclusion of the analog switching operation, Siegert suggests, that allowed digital machines to "permit only sharp discrete values and [. . .] prevent the noise generated by inaccuracies."[84] These "inaccuracies" are random events that occur at the level of analog circuitry (the random noise of analog transmission channels). The whole purpose of excluding the "time of non-reality," which results in the fragmentation of time into discrete samples, is to prevent this analog noise from propagating in the digital domain. Through the symbolic exclusion of the time of physical switching operations (and thus the noise of analog circuitry), noise reduction became systemic in digital media.[85] In short, both continuous analog and discrete digital media are based on "analog" representations of physical phenomena. Nevertheless, they deal with the noise of their basic physical operations, and bridge the gap between representation and represented, in fundamentally different ways. By symbolically excluding the surplus noise produced by analog circuitry, digital technology leaves any material reference to the physical reproduction process behind. Instead, it creates a symbolic order from which noise and randomness are expunged entirely.

[80] Bernhard Siegert, "Coding as Cultural Technique: On the Emergence of the Digital from Writing AC," *Grey Room* 70 (2018): 8.
[81] Siegert, "Coding," 8.
[82] Siegert, "Coding," 8.
[83] Siegert, "Coding," 8.
[84] Siegert, "Coding," 9.
[85] Siegert, *Techniques,* 30.

Whereas analog media are never able to completely filter out the noise of their own physical operations, the symbolic order of digital code presupposes precisely this exclusion. Digital media transform randomness into sharp limits and clear differences. Somewhat counterintuitively, these sharp contours retain some connection with the noise of analog switching operations. Based, as they are, on mathematical analyses of the entangled and confused, technical media (re)produce signals that always contain what von Neumann calls a "small extra," added to the signal during its transmission or reproduction. In the case of continuous analog media, which are unable to completely keep their own physical noise from interfering with the signal, this extra is surplus random noise. For their part, discontinuous digital media, which are unable to represent amplitude values with full infinitesimal precision, add a surplus of nonrandom distortion caused by quantization error. By rounding-off binary number values, the analog-to-digital-converter introduces a hard limit in place of infinitesimally precise values. Much like the noise produced by analog channels, the statistical correlation between quantization errors and the original input signal reveals digital machines' inability to capture the full complexity of physical signals. Both analog noise and digital quantization errors indicate the rift in the classical representational order and confound the Leibnizian dream of complete representability.

The statistical equivalence between digital quantization error and analog noise highlights how the limits of technological reproduction show up in the analog and digital domains in equivalent ways. So too does the fact that dither transforms harmonic distortion back into a sonic artifact very similar to the random noise floor of analog media. Just as noise-reduction systems conceal noise and reveal silence, thereby sustaining the myth of perfect fidelity, dither conceals the sonic artifacts of digitization, thus preserving the belief that the output of a sound reproduction system can perfectly resemble the input. The addition of dither noise to digital recordings may seem to run counter to the goal of reducing noise. Still, in introducing "good noise" to fight "bad distortion," dithering ultimately supports the ideal of perfect signal transmission and the conceptual logic of noise reduction. In the case of analog noise reduction, unwanted noise is masked by a wanted signal. In the case of dither, unwanted quantization errors are eliminated by wanted noise. Noise, here, is included in the "things that you want." Hence, on a conceptual level, the process of dithering closely adheres to the same logic underpinning analog noise reduction technologies. Just as Dolby Laboratories argue that the encoded and decoded version of a recording is, in fact, the "original," the output of a digital recording chain with dithering is considered more accurate or "closer" to the supposed original than one without dithering.

This equivalence complicates the status of the "unwanted" background noise of analog media. In the statistical terms of information theory, dithering is nothing but a trade-off of one error for another—a substitution of harmonic distortion for a slightly higher noise floor. Nonetheless, engineers know that random noise is less disruptive for listeners than the harmonic distortion caused by quantization error.[86] It is considered more pleasing, natural, preferable because human beings more easily accept (and ignore) a slight layer of random noise than a more periodic artifact such as harmonic distortion. This preference for a uniformly distributed noise floor over semiperiodic harmonic distortion is supported by psychoacoustic research, which shows that our hearing is generally more sensitive to (semi)periodic signals. Like noise-reduction technologies, dither works by going unnoticed: whereas periodic or semiperiodic distortion stands out, random noise seamlessly fades in the background. In concealing artifacts of the reproduction process, both mean to create the impression of a close correspondence between output and "original" input. Both noise reduction and dither, then, attempt to conceal the "bad" influence of transmission channels. Evoking a supposedly "natural" and uninterrupted link between input and output—a connection so direct as to erase the channel altogether—both serve the ideal of fully transparent representation that defines the conceptual logic of noise reduction.

Nevertheless, the introduction of dither also problematizes the fundamental assumption at the heart of the conceptual logic of noise reduction: namely, that noise can be clearly defined, recognized, and therefore reduced in one way or another. This worldview—whose adherents, we have seen, include, Odysseus, Leibniz, and Dolby—is premised on the ideal of full representability and the world's essential continuity. Modern science, however, showed full representational correspondence to be fundamentally impossible. The fact that noise returns in the form of dither, despite rhetorics of digital purity, only emphasizes this impossibility. It reveals the gap between idealized visions of a "world without noise" and the asymptotical character of physical reproductions. No matter how sophisticated the noise reduction or

[86] Bob Katz, for instance, argues that a properly dithered recording "always sounds better" than recordings without dithering. Indeed, Rumsey and McCormick describe how "a small amount of continuous hiss is considered preferable to low level distortion." Katz, *Mastering Audio*, 57; Rumsey and McCormick, *Sound and Recording*, 226. Nika Aldrich writes that "a true white noise floor [. . .] is a natural occurrence, and therefore more pleasing to our ears," and Watkinson argues that "the harmonics produced" by quantization error, can be "especially distressing to the human listener because it does not occur in nature." Aldrich, "Dither Explained," 8. Because of our greater sensitivity to (semi)periodic signals, we can pick even faint signals out of a much louder noise floor, as shown by the stochastic resonance effect of dither. Sterne describes how this preference for a uniform noise floor over more periodic sounds is put to good use in office situations, where a "continuous, not too loud, unobtrusive" noise can be used to drown out the sounds of "typewriters, telephones, office machines, or loud conversation." Sterne, *MP3*, 120.

precise the analog-to-digital conversion they employ, materially instantiated technologies will always limit and shape signals during the process of transmission. Like Dolby's companding process, the practice of dithering operates according to the conceptual logic of noise reduction.

Finally, however, the practice of dithering also allows for a different perspective on the role of noise in sound reproduction, which looks beyond the noiseless idealism of the myth of perfect fidelity. After all, in addition to randomizing quantization errors and creating an unobtrusive noise floor, a dither noise floor also triggers stochastic resonance by pushing low-amplitude signals over the threshold of registerability into digital representation. In this way, dither enables the digitization of parts of the signal that would otherwise not be reproduced. Their reproduction depends entirely on the addition of dither. In the case of this stochastic resonance effect, then, the presence of noise not only indicates the inherent limitation of technological reproduction. It also highlights the primary role played by the channel itself, as it variously affects, filters, and shapes the output signal.

Some argue that the term "stochastic resonance" is a misnomer, for dither noise and input signal do not "resonate" with each other in any conventional sense of the word.[87] Even so, I want to suggest that the overall effect of dither can be interpreted as resonance in a more conceptual sense: in randomizing quantization errors and pushing faint signals into the realm of registerability and representation, the combined effects of dither constitute a prime example of what I will call the noise resonance of sound media. Just as the strategy of fighting noise with noise problematizes the conceptual logic of noise reduction, so the stochastic resonance effect highlights how noise, distortion, and randomness shape signals as they travel through transmission channels. In calling attention to not just the inevitability but ultimately the necessity of noise in the transmission channel, the concept of the noise resonance of sound media emphasizes that we do not listen *through* the sound of the medium—as the myth of perfect fidelity would have it—but *to* the sound of the medium. Noise establishes recording as recording, ensuring that sounds flowing from speakers or headphones resonate as such with listeners.

The myth of perfect fidelity dominated the discourse on sound reproduction from Tainter's "acoustic transparency," through Dolby's "ideal audio device," to digital media's "nothing less than systemic" separation of signal and noise.[88] As my analyses of noise reduction and dithering has shown, however,

[87] Wannamaker, Lipshitz, and Vanderkooy, "Stochastic Resonance," 233. Gammaitoni instead calls it "noise induced threshold crossings," and Bart Kosko suggests the term "noise benefit." Gammaitoni, "Stochastic Resonance," 4698; Bart Kosko, *Noise* (New York: Penguin, 2006), 215.

[88] Sterne, *Audible Past*: 256; "Dolby® SR," 2; Siegert, *Cultural Techniques*, 30.

a different interpretation is possible. One that grasps noise not as nuisance or interference, but rather as an unavoidable, even indispensable element of sound reproduction. Despite its practical goal of optimizing signal transmission through maximal noise reduction, Shannon's model of communication also confirmed noise's inherence to the transmission channel. This constitutes nothing less than a recognition that no message can be produced, and no signal transmitted, without the presence of noise. The noise of sound media is therefore at least partly responsible for how a signal looks, sounds, or reads at the end of its transmission, for it always shapes the way in which technologically (re)produced sound resonates in listeners' ears.