Article

Interleaving as Cultural Technique in the Audio CD and the End of Archaeophonography

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Abstract

This article discusses a significant if imperceptible feature of how audio compact discs (CDs) inscribe sound: interleaving. It shows how CDs materialize interleaving—the microtemporal re-ordering of data—as a cultural technique of contemporary digital media, and, as such, how the CD's surface testifies to much more general operations of cultural data processing than those that appear to be at stake in the few media-theoretical discussions of the format to date. First, I provide a brief overview of the CD's operating principles, followed by a closer examination of the error-correction and detection system used in CD media. I explain how interleaving co-operates with this system to improve the resilience of disc media to both pre-sale defect and post-sale damage. I interpret this tacit and little-remarked-upon operation of CD players in cultural-technical terms. The perplexities of digital sound media push the principles of contemporary sound reproduction well beyond the kind of efficient and effective critical scrutiny we may associate with what I here call archaeophonographic sound media (for example, tape and vinyl LPs), unless we are willing to confidently assert the value of the media-technical explanatory register to digital media history.

Keywords

compact disc, cultural techniques, interleaving, digital audio, media archaeology

Introduction

Scholars have long implicated the audio compact disc (CD) format in changes in the late-twentieth century music and multimedia industries. CDs have been charged with reorganizing our notions of album, track, and cover art, and reconfiguring consumer expectations about both audio-reproductive definition and its cultural correlate, "fidelity" (Downes, 2010. See also, 2009; Guberman, 2011: 431; Lingard, 2013; Rothenbuhler, 2012). CDs afforded novel protocols for the manufacture, distribution, sale, resale and exchange of music (Eriksson and Johansson, 2017; Straw, 2009; Symes, 1997). Some of these new cultural forms, including reformatted releases of pre-digital sound recording and compilation discs, have been credited with rescuing the industry from its late-1970s slump (Chanan, 1995; Laing, 1991: 109–10). Ironically, that the sound-recording industry made near studio-quality sound available to consumers on CD without an effective copy-protection mechanism may very well have been also responsible for the end of the industry as the twentieth century knew it (Knopper, 2009; cf. Hesmondhalgh, 2009). The CD's creators—including engineers at Sony and Philips among many others—had both posed and solved the many industrial design problems involved in using optical media to effectively and cheaply inscribe digital data on the surfaces of durable and inexpensive plastic discs (Lang, 1996). Indeed, by mastering the principles of digital optical media recording in the sound domain, the audio CD paved the way for scores of new products in the home theater and home video gaming sectors, including those based on its descendant data CD-ROM formats and their many variants.[1]

A parallel critical discourse about CDs has been more concerned with more ambitious claims about the meaning of the format and the digital consumer audio landscape more generally; we might call this the media-philosophical CD literature. In a recent review-essay, Adam Harper has astutely noted the specious metaphysics of presence at play in contemporary vinyl apologetics, whose values derive, in part, from an opposition between the character of analog and digital sound recording formats (2019). The microscopic illegibility of the CD and its tactile (an)aesthetics have been repeatedly contrasted in specialist discourse with the effusion of sensory affordances of the tangibly grooved vinyl LP (Downes, 2010; 2009, esp. ch. 6; See also, O'Connell, 1992). The LP's tactility has inspired accounts of the relative "richness" and "warmth" of the sound of the latter, and the "dry", "sterile", "choppy" character of the CD (Evens, 2005: 11; Chivers Yochim and Biddinger, 2008: 188–90; see also, Prior, 2018: 61). Despite being largely speculative and sometimes incoherent, folk media-philosophical claims such as these have concrete effects. The fetishization of physical media represented in this literature co-operates with the myth of music's latter-day dematerialization (Devine, 2019) as we are said to have passed from vinyl through CDs to dematerialized, cloud-based streaming services (Curtis, 2018; Daniel, 2019; see also, less acutely, Roy, 2016). Though aspects of the CD's ecosystem have been seen by scholars as refracted in early media player software and the metadata infrastructure that dovetailed with early 2000s file-sharing networks (Morris, 2015), the audio CD has by-and-large been figured in a largely proleptic role within a procession of formats. It has been condemned to anticipate a digital transformation of the music industry that post-dates its appearance in the early 1980s, when it is perhaps more accurate to say that the format in fact fueled that transformation (Ingraham, 2020). Indeed, it continues to do so today, as proven by the very occasional skipping-CD sounds that are preserved in the track databases provided to commercial music streaming platforms.

A more durable and self-sufficient account of the CD, given in media-theoretic terms, is possible. Toward the end of the twentieth century and under the sign of Adorno's writings about radio (2009) and the phonograph (1990a; 1990b; see also, Levin, 1990), Eric Rothenbuhler and John Durham Peters jointly declared that "the popularization of digital recording and playback techniques"—among them DAT and CD—was the harbinger of "the end of the age of phonography" (1997: 272). For Rothenbuhler and Peters, the question (at least partially begged) was whether digital recording techniques can be properly understood as a kind of sound writing, as the etymology of *phonography* suggests to them they ought.[2] Interestingly, Rothenbuhler and Peters' argument—nominally cashing out the critical consequences of the broader analog/digital divide in phonography—is developed with respect to a *particular* digital audio format, despite its ambitions to generality. Many of the apparent criticisms of digital audio in general were in fact about audio CD technology in particular, and it remains perhaps the most sustained media-theoretical discussion of the format to date, despite their disinterest in the technical particulars of that format. One solution may be to generalize their discussion: consider the challenging but generative exercise in "retrofitting" a Benjaminian theory of mechanical music reproduction for the digital age by John Mowitt (1987).

Here, I go in the other direction—specialization—by drawing on historical and technical details of the same format, not as theoretical end in its own right but as a prelude to the same. I largely set aside media-philosophical questions of *what* CDs represent, their sound, their alleged fidelity. Similarly, I suspend sustained consideration of the CD in political-economic terms, without prejudice to the value of such an investigation. Instead, I focus in some detail on one of many yet-to-be-explored media-*technical* aspects of *how* CDs inscribe sound. Eschewing the interpretation of the content of these discs either as texts or commodities in favor of the techniques of inscription they deploy situates my analysis within the tradition of "media materialism" cogently summarized by Liam Cole Young (2017: 35–43; see also, 2015). Despite this focus on technique, I seek to avoid an atavistic rehearsal of a specious form of a quasi-philosophical analog–digital debate whose outlines I've sketched above and that has been amply discussed elsewhere in relation to audio formats (Sterne, 2016; see also 2003: 218–9). The argument can certainly be made that the audio CD's launch represents the first moment a genuinely digital media artifact made the leap from the specialist discourse of academics, IT professionals, and computer enthusiasts to the general public (Schröter, 2004: 16). But this, like much of what follows, is a media-historical claim, which is concerned only with ontologies of the digital insofar as archival research can denaturalize and relativize their terms of reference.

In 1997, Rothenbuhler and Peters were justified (and relatively timely) in their response to the apparent break represented by the then-relatively recent adoption of digital technology in sound recording. But their view on the matter was necessarily partial, as was the view presented on the format they discussed—at least when it comes to media-technical detail. Since then, only a handful of other accounts of the CD have sought to shed light on the question of contemporary phonography by examining the particulars of how the CD *in particular* represents sound on its surface and measuring it up against other techniques of sound writing and writing more generally (Allen-Robertson, 2017; Cornford, 2015; Coy, 2015; Häsler and Volmar, 2017; Volmar and Schrey, 2018).[3] The inscriptive operation that is the focus of this essay is interleaving: the strategic reordering of data on a medium to improve its resilience to defect and damage. My discussion of interleaving in the audio CD format is largely within *Kulturtechniken* (hereafter, "cultural techniques"): a media-theoretic framework which has presented a heady mix of cultural history, the philosophy of media, and the history of technology. Advocates of cultural techniques research are largely agnostic on the historical figure of the "digital"-as-radical-break and thus the framework is well suited to exploring the contention that how CD format implements interleaving amounts to the deployment of a much more general media-technical strategy for storing and preserving symbolic culture, sitting within the longer history of writing and other inscriptive mnemotechnics.

Cultural techniques of digital media

Interleaving is a cultural technique. It is a technique that has been paid little attention to date as such, despite its manifestation in an array of seemingly disconnected fields. As such, the CD's surface testifies to much more general operations of cultural data processing than those that appear to be at stake in any one particular format war. Such a perspective on the CD format instead emphasizes the inscription practices that it instantiates: how culture is formatted, stored, and processed on the iridescent surfaces of digital optical media. Cultural techniques is a loose but vibrant approach to media culture in the wake of the media theorist Friedrich Kittler and his acolytes that resists straightforward summary, a task complicated by its predilection for increasingly assorted bearers of data-processing operators: doors, pianos, card-files, patent documents, DJ turntables, and, naturally, microprocessors. Bernard Dionysius Geoghegan concisely captures the common interest of its practitioners in "how signs, instruments, and human practices consolidate into durable symbolic systems capable of articulating distinctions within and between cultures" (2013: 67).

Where the cultural techniques perspective adopted here diverges perhaps most strikingly from that of classical cultural-studies or material-cultures approaches to sound media technologies (Bull, 2000; Du Gay et al., 2013; Manuel, 1993) is in its overt interest in what symbolization affords the users of media technologies. Theorists of cultural techniques have repeatedly drawn attention to how writing—an act that necessarily spatializes inscriptions in media—can be used to confer additional meaning to a sign by virtue of the location of marks in space. Bernhard Siegert explains that in the decimal system, "the spatial extension of the paper is an integral part of the sign" (2015: 25).[4] In a place-value system for writing numbers, the meaning of an individual numeral—its value—changes depending on its position in space with respect to its neighbors. For example, in the ubiquitous (but not universal) decimal or base-10 convention, the leftmost '1' in 1991 stands for one thousand whereas the rightmost '1' represents just one, a single unit. We will pick up precisely this space-dependency in the discussion of the CD below. Relatedly, Sybille Krämer emphasizes the spatial dimension of "media" more generally by drawing under its umbrella any and all "practices that use strategies of spatialization to enable one to manipulate the order of things that progress in time" (2006: 106; see also, Kittler, 2017).

The CD is a repository of such practices; below, we will discover its cultural-technical capacity to draw out two critical distinctions, a capacity that is intimately connected to one of the many media-technical operations that the CD system's sophisticated error-detection and correction techniques put in play: interleaving. First, a distinction between the two major kinds of readout error in digital optical media systems—eventually called "burst" errors and "random" errors—is shown to be defined principally in relation to the use of interleaving in the CD system, rather than with reference to the physical features of the damaged portions of the data-carrying medium. Second, the fact of interleaving's autonomous and inscrutable operation in the first instance generates an operative distinction that underwrites the operation of all computational media: between user and used. Following Vismann and Krajweski (2008), I suggest the launch of the CD, a novel digitally mediated system for consumer audio, marked the further escalation of the process—long underway—by which we have become abstracted from the processes of sound reproduction, an understanding that once enabled our self-identification as listeners. In both cases, we come to see how concepts ascend from their material instantiation as "ontic" operations of the media themselves, to the place of "ontological" operators within the discourse that co-determines them: cultural techniques' intellectual leitmotif.

Grimly, evidence of the CD system's operation will remain inscribed in the perdurable polycarbonate surfaces of at least some of the hundreds of billions of units sold since its launch. Thus, what follows also shares some goals with that of media archaeology, insofar as it uses a media-technical register to speculate about what the CD, as "an archive of cultural engineering by its very material fabrication" (Ernst, 2013: 60), might disclose to the imaginary archaeologist of the future, left only with the pits and lands of its gnomic surface to go on. Focusing on a particular format's details and eschewing the tendency to speak about "CD media" in a general sense, this essay also contributes to the growing area of format theory (Jancovic et al., 2020), which takes a more ecumenical approach to various multimedia formats in the wake of Sterne's important text on the MP3 format (2012) as well as more recent developments in German-language media theory (Volmar, 2020), while remaining committed to differentiating between formats at a fairly granular level. Not all that removed from the concerns of format theorists, cultural techniques is similarly interested in how symbol systems cultivate their distinctive literacies: indeed, it can be characterized as an attempt to carefully reintroduce human subjects back into the media-discourse analysis that reputedly expelled them (Krämer, 2003).

Cultural techniques' expansive notion of media extends the courtesy of this power to cultivate literacies to tools that have not been traditionally considered as media. It also explores the "cultivating" force of techniques whose mediatic character has not yet been fully explicated (Geoghegan, 2013: 71–3). Even forty years after its introduction, I claim that the audio CD format fits this bill. The growth in popularity of cultural techniques in Anglophone literature during this period (thanks to key translation efforts) coupled with the critical distance enabled by the format's relative decline in popularity both afford new insights into how digital audio formats store and process sound culture with symbol systems. It has likely not escaped the reader that the present task is doubly belated in a certain sense: it concerns a format which appears to be long behind us, and draws on a media-critical literature perhaps already passing out of fashion. First, despite the early efforts sketched above, the audio CD format is at the root of a family tree of a whole plethora of digital media formats not yet adequately historicized: CD-ROM, recordable CDs, and, indeed, DVD, Blu-ray and the scores of not-exactly-"failed" experiments in optical media used widely in games consoles and outside the global North, such as the Video CD format. Second, theories, like media, never really die: in their "zombie" state they continue to shape practices of media consumption, analysis, and reappropriation, the newness of successor techniques and formats always qualified by their situation in media history (Hertz and Parikka, 2012). The reward of retrospect that is both historical and theoretical affords a glimpse at the media-technical situation *circa* the CD's commercial launch in 1982, and, not without irony, the promises and the limitations of the media-theoretical situation not all that many years after.

Designing a resilient technical medium

In 1980, after months of negotiation drawing on decades of research and development conducted across two multinational corporate giants, Sony Corporation (Japan) and Philips (Netherlands) agreed on the final text of a technical standard which specified in great detail a new digital medium for the storage and playback of recorded sound: IEC 60908 ("Audio recording - Compact disc digital audio system"), nicknamed the "Red Book" in a reference to the cover color of the proprietary document from which it was adapted (Korst and Pronk, 1994). The CD format was standardized as a circular plastic disc, 11.5 cm in diameter and no more than 1.5 mm thick with (optionally) a screen-printed label on one side and a silvery reflective surface on the other. On the data-carrying surface of the CD is a dense, spiral trail of bumps, whose rise and fall is sensed by the reflected light from a low-powered red laser as it impinges on a light-sensitive electronic component. The specific geography of these depressions ("pits") and plateaus ("lands") stands for a stream of binary data that, after a cascade of electronic transformations, becomes reconstituted as a smoothly varying voltage fluctuation that animates a loudspeaker cone. Thus, *grosso modo*, the CD's principles are common to all other (viable) audio-carrying technical media: a material inscription is rendered audible in readout.

However, perhaps the most important innovation in phonographic technique that the CD introduced to the sound-media mainstream was its laser-based optical pickup system, which supplanted the gramophone's combination of stylus, cartridge, and tonearm. Because there is no longer a mechanical coupling between the recording medium and the optical "stylus", the rate at which audio data is read from the CD's surface during playback is liberated from the negative effects of friction from the read head (Allen-Robertson, 2017). Robert Barry has recently argued, concurring with Damon Krukowski (2018: 89–90), that "until the invention of the CD, friction had been an essential component of almost all previous sound reproduction technologies" (2020: 10). Barry and Krukowski are more-or-less correct: leaving aside optical sound-film, the contactless medium used for sound reproduction in cinema, the CD was the first commercially successful consumer audio-only format to eschew friction and, with it, its several attendant problems. It obviated the need for replacement styluses. Careful calibration of styli, balancing tonearms, dialing in anti-skate forces became a thing of the past, to the dismay of tweakers (Perlman, 2003). Optical readout eliminated the interminable "locked groove" condition sometimes caused by damage or defect (or, at least, displaced the problem onto the servomechanical systems responsible for keeping the laser pickup on track, which, when malfunctioning manifests in the format's distinctive "skipping" sound). It even increased the player's resistance to moderate vibration, physical shock, and the feedback effects of reproduced sound itself, which occasionally caused styluses to leap out of the phonogroove and disrupt playback.

Most usefully, this decision practically eliminated wear through regular playback, an affliction of both vinyl and tape (Nakajima and Ogawa, 1992: 180–1). Since contact was no longer maintained between the medium and the player read head, the CD was infamously claimed to be invulnerable to the patina of scratches and dust that working media invariably acquire after purchase: two classical afflictions of phonographic records. Heitaro Nakajima and Hiroshi Ogawa, two Sony engineers intimately familiar with the CD standard, wrote that "[f]or the 100 years since discs first appeared, 'How wonderful it would be if this contact problem did not exist,' is a thought that has occurred over and over to both makers and users. So when we say that in the CD system […] laser light is used to detect the signal that has been cut into the disc without contact, it is the realization of a hundred-year-old dream. The life of both the discs and the players is extended to semipermanence" (1992: 181). On the back of this engineering confidence, manufacturers and publishers of CDs made various extravagant claims for the durability and reproductive definition of the format even when carelessly handled: "'you can touch the disc surfaces with your fingers,' 'you can play Frisbee with them,' 'the sound quality is perfect'" (Ranada, 1983: 61). As soon as the format was released, audio equipment reviewers and creative artists alike probed these claims, deliberately damaging discs in order to examine the limits of the CD's innovative digital system for the detection and correction of errors caused by such damage (Kelly, 2009: ch. 3).

But the format's widely touted resilience to dirt and mishandling was incidental, from the perspective of one researcher at Philips who worked on optical media in the mid-1980s: "[w]hile the [CD's] advanced error-correction was originally developed in order to ease the unrealistic manufacturing tolerances which would be involved in producing discs completely free of errors, a very welcome side-effect is immunity from *most* surface scratches and blemishes on the disc" (McGee, 1987: 18–9). CDs are nanoscale objects, after all, and their manufacture requires a clean-room environment at certain crucial stages in the manufacturing process. High reject rates experienced in the first-generation of CD manufacturing plants built between 1982 and 1984, were quickly ameliorated by increased automation: this reduced the incidence of the contamination of intermediate media by human plant operatives (Pohlmann, 1992: 309–10). Defects can arise from air bubbles unintentionally formed in the plastic substrate of the disc, from specks of dust trapped in between the layers of the disc that occlude the data carrying surface, from masters with damaged or imperfect pit patterns, from “pinholes” caused during the metallization of the disc’s back surface (Pohlmann, 1992: 300). The many kinds of defects that can occur when digital optical media are manufactured were studied in detail by engineers at Sony (Doi, 1982: 148; see also, Doi et al., 1979: 976). The designers of the CD system could therefore not assume that discs would ever be in “bit perfect” condition; even those brand new, unused discs leaving the pressing plant.

Its resilience to pre-sale defect and its potential to lead to slacker manufacturing tolerances was one of the motivations behind the use of digital audio representation in the CD format in the first place: indeed, the use of digital audio in the compact disc system cannot be considered a historical given. The origins of the format reach back (on the Philips side) to at least as far back as their mid-1970s experiments with the analog representation of audio on an optical disc. In 1974, the same analog optical storage principles that were in use in an analog optical video disc system— eventually marketed as LaserDisc, to relatively limited commercial success—were also trialed for use in a new audio-only disc medium by the Audio Long Play (ALP) team at Philips (Peek, 2010). By the end of 1975, however, this team concluded analog representation of audio on an optical disc was a “dead end”: intermittent and temporary losses of audio signal due to defects in the media—what the researchers called “dropouts”—caused “too many audible clicks and other disturbances” (Peek, 2010: 12). By switching from a continuously variable, frequency-modulated representation of audio signals to the discrete representation offered by pulse-code modulated (PCM) sound—in other words, digitally sampled audio data—a well-established body of research in digital coding theory could be leveraged to allow any digital error caused by defects and damage to be repaired by microcircuitry in each CD player.

Digital encoding would allow for the *ex post facto* reconstruction of missing data, leading Wolfgang Coy (2015) to point out that the CD is in fact a "self-healing" medium: subsequent copies of discs, which may be damaged between generations, are not necessarily any more damaged than their parent, source media. However, the embrace of digital notation also raised the stakes for those errors caused by defect and damage caused by reproduction and handling that *did* manage to slip past the error detection and correction stage. This is a well-known consequence of the fact that digital representations of audio (such as those used in the CD system) use a place-value system: every digital audio sample is represented as a 16-bit binary (base-2) number, in which the location of each individual mark determines its magnitude in powers of two. A single bit error—say, an 800nm pit or land mistaken for the other—in just the wrong place could cause unexpected and significant peak in the sampled audio values, which may be converted in the player's digital-analog converter into a brief but distinctive high voltage. This error would be heard as a loud click or other so-called "transient" sound by even the most inattentive listener and disrupt continuous playback (Watkinson, 2001: 16–7).

Siegert's remarks about place-value systems quoted above clarify the point: digitization raises the stakes for the representation of sound in sound precisely because the spatial location of the marks of media change their numerical meaning. The difference between ***pp*** (*pianissimo*) and ***ff*** (*fortissimo*) could be a single ill-placed binary digit. Materialized on a CD, this is a matter of micrometers. Indeed, transient clicks such as these came to be aestheticized by "glitch" and "microsound" musicians in the 1990s and the 2000s, whose music encodes this particular idiosyncrasy of their contemporary media-technical situation (For contemporary accounts of 'glitch' music, see Cascone, 2000; Szepanski, 2001; for a corrective, begin with Bosma, 2016; Tobias van Veen quoted in Ashline, 2002). But like the dropouts encountered by researchers working with analog optical disc prototypes at Philips, these digital glitches were determined by the CD's designers to be incompatible with the audio-definitional standards they sought for their product. Fortunately, these engineers had a venerable communications-theoretic strategy in their arsenal: redundancy, or the provision of surplus information in a communications system with the intention of protecting against data loss in transmission.

In his exemplary guide to the technology of compact disc media, Ken Pohlmann makes the striking claim that "audio data is in a minority position on a compact disc. […] [O]nly 32.65% of the disc holds audio bits. The rest is given to overhead" (1992: 83). Some of this overhead is due to the aforementioned error-correcting technology, which will be described in greater detail below. But other additional non-audio data stored on the disc's surface includes: a table of contents of the audio tracks and their extents, information about how each track is mastered, even primitive (and almost always ignored) copy-protection information. Unlike a turntable or a tape player, an operative CD player is always discriminating between sounded and unsounded data. Any given CD player routinely processes, analyses, and rejects data incidental to the reproduction of sound *as part of its normal operation* (Hainge, 2007: 37; Thompson, 2017: 52–3). In a CD player, digital buffers that are implemented in once-costly RAM modules sit in between the disc medium and the sound-producing circuits, and are used to temporarily build up a head of digital data. These buffers allow the digital signal to be processed before it passes to the digital–analog circuitry in the player to be realized as audible sound.

This is done, in part, to account for minuscule variations in the speed of the disc rotation as well as sub-millimeter imperfections in the disc's geometry, which cause the data rate at the moment of readout to vary slightly. Thus, this processing takes place in the moment that Wolfgang Ernst calls "delay time" (*alias* "dead time"): the gap "between signal transmission (caused by the inertia of channel matter) and run time" (2016a: 40–1). In the CD's delay time, all manner of operations can take place: resynchronization, filtering, and, as we will shortly see, error-correction. Indeed, the history of audio CD players, post-standardization, might be told as the gradual accretion of backward-compatible signal-processing techniques that add computational features that go above and beyond the basic operations envisaged in the technical standard: shuffle playback, anti-shock protection, and increased "playability". What is key, for our purposes at least, is that this delay time afforded the designers of playback devices an opportunity to manipulate the *order* of the sonic inscription as data leaves the disc medium—that is after it had been demodulated into a binary sequence of zeroes and ones—but before it reached the listener. It is at this level, ordinarily imperceptible to the user, that the CD system implements the cultural technique of interleaving.

Error detection, error correction, and interleaving in the audio CD format

The goal in this brief section is to expand in a technical sense on Ernst's observation that "data stored on a compact CD […] is stored not serially in the temporal playback sequence, but rather dissipatively" (2016a: 26), with reference to the specific technique of interleaving. This brief section is necessarily technical, and largely follows Pohlmann's peerless guide to the format (1992; see also, Nakajima and Ogawa, 1992). Pohlmann's account is, in turn, based on manufacturer documentation as well as the technical standard that specifies the audio CD format. In short, the designers of the CD used a communications engineering technique called forward error-correction to make discs resilient to both manufacturing defect and after-sale damage. Crucially, they also used the reordering technique called interleaving to improve the ability of this technique to correct errors.

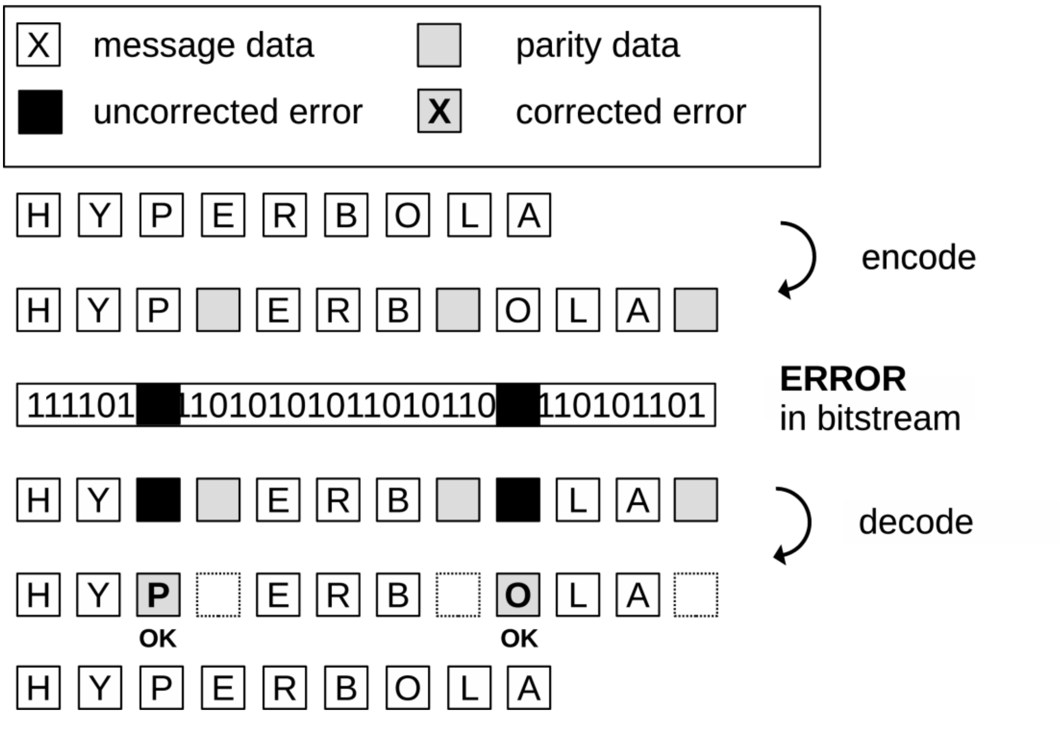

Figure 1: Depiction of the principle of a forward error-correcting code. Legend shows the meaning of each symbol. Author's work.

Forward error-correcting codes add redundant information to digitally encoded data to improve the resilience of this data to degradation in transmission. This extra information, sometimes loosely called parity data, is carefully structured in accordance with predefined mathematical expressions so that the stored data can be fully reconstructed, even if the read out of stored data is interrupted by errors (Figure 1). The correcting power of an actually existing forward error-correcting system is not unlimited. To this end, the gray shading in the data depicted here represents how parity data added during an encoding step. The diagram suggests how this information is "used up" during decoding to reconstruct any missing data caused by damage in the channel medium.

The design of an effective error-correction system always involves trade-offs between the amount of additional information added to stored data and the number and size of errors which may be corrected upon error-correction. For example, the notional system described here can only correct one symbol error for each three-symbol data chunk. A longer error—more than one symbol in a row—that exceeds the code's specification is uncorrectable, assuming the parity data is received by the decoder. (In this example, the parity data is shown as "attached" to each data symbol, as this more closely approximates how signals are coded for CDs). On the other hand, scattered, shorter errors are fully correctable. The precise capacities of a code are a consequence of the mathematical structures used as the basis of the error-correction scheme. In the specific case of the CD, these are algebraic structures known as Galois fields. One way to improve the capacity of an error-correction system is by drawing up a new code based on more intricate mathematical objects, though this can increase amount of overhead needed for correction, thus reducing the data density and perhaps even the cost-effectiveness of the product.

A different technique can be used to improve the performance of an already given error-correcting system without revising the mathematical codes that underlie it: interleaving. Interleaving deals with long, multi-block errors by effectively converting them into short, single-block errors—as viewed from the perspective of the decoder. Figure 2 demonstrates how reordering data using a simple interleaving scheme before it is encoded by an error-correcting encoder improves the performance of the system as a whole. Once it has been de-interleaved, a burst error that was once three symbols long, which would not normally be correctable by the decoder represented in this toy example, becomes scattered into three single-symbol errors. It can therefore be corrected and the original data is entirely recovered. This surprising result is a consequence of a strategic reordering of the audio data before it is encoded by the error-correcting encoder. It is the simple reordering of data—the interleaving step—that makes this possible.[5]

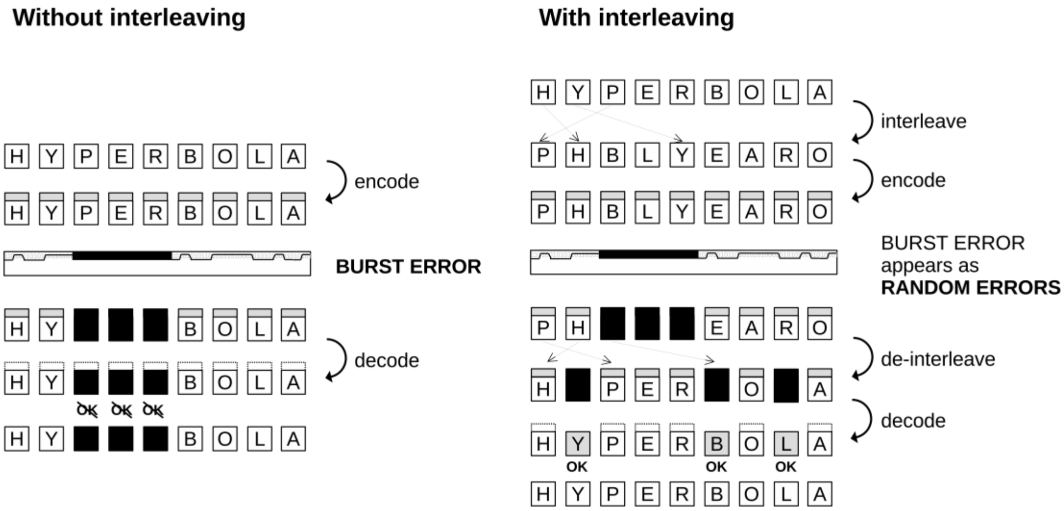

Figure 2: Depiction of two hypothetical error-correction systems, one without interleaving and one with interleaving, but with identical error-correction codes. This demonstrates how interleaving can improve the capacity of a given error-correction system to deal with relatively small ("burst") errors. The toy system depicted here on both the left- and right-hand side can successfully recover one missing symbol per three-symbol block, assuming the neighboring two symbols are received intact by the decoder. Author's work.

We are now in a position to understand what made the CD's error-correction system distinctive: its novel combination of well-established error-correction techniques with interleaving. The particular error-correcting scheme used in the CD system is called the Cross-Interleaved Reed-Solomon Code. Its name refers, in part, to the elegant and ubiquitous forward error-correcting code developed by Irving Reed and Gustav Solomon in 1960, as well as the integral role played by a technique called interleaving in its design (1960; for Reed's own reflections on the history of the Reed-Solomon code, see Reed, 2000). In the CIRC system, audio data is interleaved according to a two-dimensional interfiling scheme. Unlike in the toy examples depicted so far, *two* Reed-Solomon codes operate in the CD system. So-called "cross-interleaving" distributes the symbols of blocks across the surface of the disc in such a way that when sequences of burst errors are de-interleaved by the player, they *present as* smaller errors to the second of these two interlocking error-correcting decoders. Longer errors that would have been uncorrectable can be now —thanks to the joint action of the two encoder/decoder circuits—completely corrected. Any shorter errors are corrected by the first ("outer") code alone. The CIRC scheme is considerably more intricate than the abridged version of the scheme depicted in Figure 3, but is conceptually similar to it.

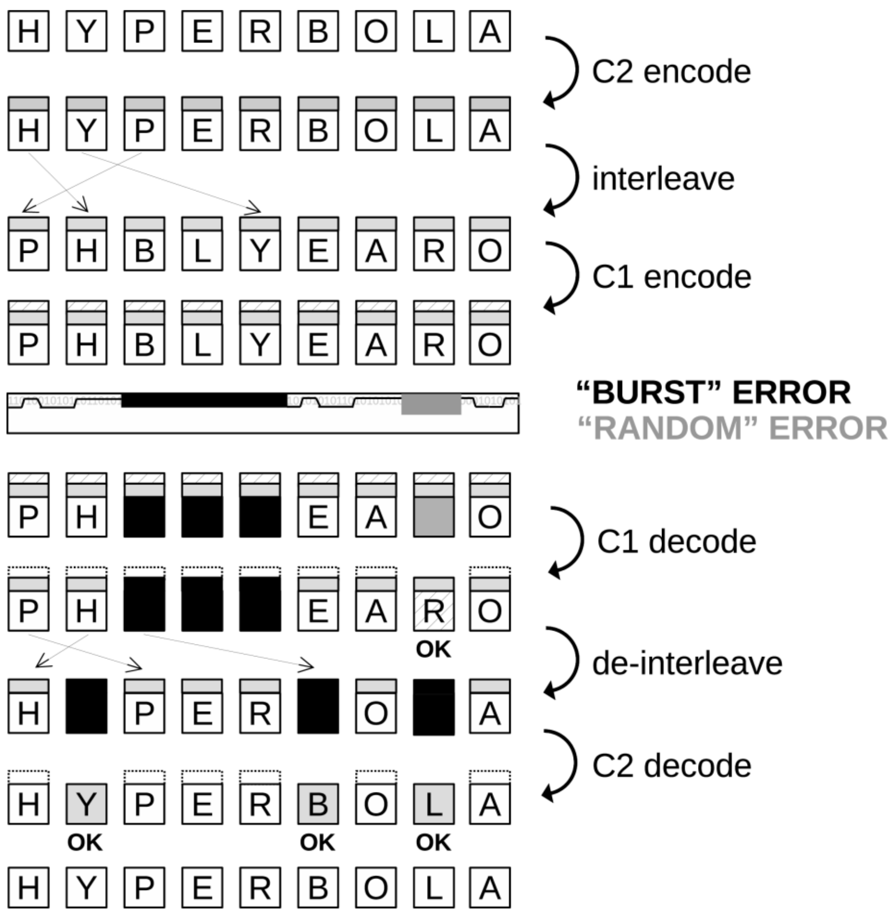

Figure 3: Illustration of how the combination of two Reed-Solomon encoder/decoder circuits along with the interleaving step are used to improve the resilience of audio CD media to both relatively large ("burst") and relatively short ("random") errors. Author's work.

In theory, the system negotiated by these technical partners during the format standardization meetings can detect and correct—which is to say, completely reconstruct absent data—a run of such missing data up to approximately 4,000 bits in length, which corresponds to a 2.5 mm long segment of the track (Immink, 1994: 54). On the CD, however, the distance between tracks is only 1.6 μm: many times smaller than the cross-section of a human hair. In reality, defects don't perfectly follow the track of the CD's data-carrying spiral. They are more likely than not to occur at an angle to the track and interfere more than one adjacent track. Nevertheless, the final design of the interleaving scheme used in the CIRC system proved highly effective in combination with the CD's laser-based optical pickup. By carefully choosing a cross-interleaving pattern, and by performing the interleave step between applications of two separate encoders, its designers ensured the correction of small errors—like those caused by manufacturing defects—and larger errors, such as those caused by a longer, post-sale damage like a scratch or fingerprint. Interleaving was a key pillar in this design for a resilient yet viable and, ultimately, inexpensive digital audio format that once towered over its competitor formats, in both financial and cultural terms.

Interleaving as cultural technique

More than that, however, the interleaving operation introduced a distinction between kinds of errors encountered by the users of CD media, providing not only the conditions for their existence in the first instance but also a criterion with which disc defects can be classified. Under the heading "Defects", the technical standard for the audio CD format (IEC 60908) refers *first* to "random" vs. "burst" errors—that is, properties of the CD's data stream—before it goes on to describe how those errors might be materialized as properties of the disc's physical substrate. Thus, from the point of view of the standard, defects are not primarily categorized by their physical extent and frequency on the disc but instead by their impact on the detected error rate as the disc is read in a player. Scattered, small, and generally unpredictable errors became known as "random" errors while, longer, more sustained errors caused by larger defects were known as "burst" errors. But these labels only make sense in the context of the distinctive cross-interleaved structure of the CD's error-correcting codes described above: random errors are, by definition, those "caught" by one encoder/decoder circuit, before de-interleaving; burst errors are those addressed by the other circuit, after de-interleaving. This distinction was not academic: it came to be mobilized in CD players and test rigs in a commonly used measurement called the block-error rate (BLER), which is proportional to the number of random errors detected by the CIRC decoder and becomes a proxy for the number of non-local defects on the disc, and, in turn, for the quality of the reproduction processes in a given industrial context (Pohlmann, 1992: 304–6). In this way, the cross-interleaved structure of the CD's error-correcting systems processes and produces distinctions between digital objects—in this case, defects—both independently and autonomously, as the consequence of a symbolization technique in operation: a hallmark of a cultural technique.

To summarize the story so far in engineering argot: interleaving in the CD system effectively converts longer "burst" errors into shorter "random" errors by scattering errors across an intermediate representation, which arises from the strategic reordering of the digital audio data before it is error-correcting encoded and written to the storage medium. We may restate the situation at play in the CD in other words, not to endorse their Lacanian resonances but to at least gesture toward what a more comprehensive account of interleaving puts at stake for media theory. Interleaving in the CD system makes those marks corresponding to events which are contiguous in the real (i.e. the sound originating in the studio) dis-contiguous in the symbolic (i.e. the alternating pits and lands as they are demodulated by the CD player's laser). The inverse process, de-interleaving, is applied during decoding and has the effect of making defects which are contiguous in the real (i.e. on the surface of the disc) dis-contiguous in the symbolic (i.e. the de-interleaved data before the crucial error-correcting step is applied). The discontinuous/continuous paradigm for sorting out analog and digital sound media now seems even less fit for purpose: the CD stands instead for radical dis*contiguity*.

Cultural techniques emphasizes how technological media have long reconfigured time by the careful arbitrage between the characteristic affordances of space and data. This is a feature of its intercontinental inheritance from Harold Innis through Kittler. Indeed, there are historical precedents for interleaving, which date back centuries; possibly as far back as the sixth century BCE. A full account of the operative chain leading to interleaving in digital audio formats can only be sketched here, but would surely begin with book history, touching on the use of interfiled parchment to protect papyrus codices (Dean, 2007: 144), interleaved almanacs (McCarthy, 2013: 49–50), and range through to the use of interleaving in the analog TV system (Rohlfs, 2001: 137–65 esp. 142–145) and in magnetic data-storage media (Allen-Robertson, 2017: 461), including the pioneering PCM digital audio tape systems developed by Sony around the same time as the audio CD standard (Baert et al., 1992: 174–9). All this suggests that the strategic reordering of inscriptions to weather defect, damage, and decay is a media-technical trope which transcends its particular implementation in the microcontrollers of a given model of CD player. If the cultural techniques perspective is further ratified by the ambitious temporal sweep insinuated by this history, the media-theoretical question with regard to the CD is affirmed not as "how do CDs represent sound" but as "*where* does a particular CD represent sound?". All unplayed

CDs, like the VHS player (Ernst, 2016a: 21–3; see also, Zielinski, 2019) and the streaming multimedia infrastructures that followed them (Denson, 2020), silently aver a crisis of temporal correspondence between sound event and sonic record. Only a vestigial son-iconicity of the CD remains in the illusion of contiguity provided by the single spiral groove that contains the disc's sound data, as it winds out from center to edge.

As we have seen, data is laid out on the surface of the CD just so because its designers have considered, predicted and *attempted to control for* the medium's predisposition to pre-sale defect and its sensitivity to post-sale damage. Interleaving is key element of the remedy against the effective practical limitations on the mass manufacture of viable digital media using optical principles. Put more extravagantly, the spatial arrangement of the marks representing the data on a compact disc *is itself* a claim about both the baseline bit-level integrity of the digital medium itself as it leaves the pressing plant, as well as about its expected use-contexts, the threats that those use-contexts pose to the recoverability of the data it contains, and so on: the medium-as-technical–object's "scripts" (Akrich, 1992). To the extent that it attempts to predict and control for the conditions of its own destruction or fracture, the technical standard that specifies the CD format is the blueprint for a medium that attests, now in the very layout of its marks, to its own fragility. It is in this sense that we can think of interleaving (and the other data-processing operations of the audio CD format more generally) as attaining the self-reflexivity or "pragmatics of recursion" (Macho, 2013: 31) that are constitutive of cultural techniques proper.

In order to accommodate for this basic fragility, to which each extant disc bears witness, electronic circuits tacitly re-sequence, buffer, drain, and otherwise mutate dozens of symbolic representations of the once-integral sound wave. Shuffled, cross-interleaved, enriched with parity bits: the particular arrangement of the marks made on the substrate of the CD are designed to anticipate the performance of the CD-as-noisy channel. Inscribing a symbolic representation of sound that strictly maintained its original phonochronological order was quite literally un*supported* by the material properties of the media on which it was intended to be stored and mass-produced. Importantly, none of these operations are open to inspection by the end user. They are done instead with dispassionate—and ultimately inscrutable—"algorhythmic" speed, the sonic symptom of the computational era's new tempor(e)ality (Ernst, 2016b: 25–6; Miyazaki, 2012). The discretizing gesture of digital sampling is immediately mobilized in the delay time CD players to reorder the recorded phenomenon at sub-perceptible timescales, with the help of the principle of interleaving. As a consequence, the CD does not process aural culture in the open. We can think of the specific spatial ordering of audio data on CDs, taken out of their original order, as a sign of the conditions of their mass reproduction.

Re-enchanting CDs?

The microtemporal reordering of data is not just endemic in the audio CD system, but is a condition of possibility for its particular form of sound reproduction in the first place. This makes the family of the digital optical media formats it gave rise to rather unlike the gramophone, an important distinction to draw in view of how larger the latter apparatus looms in contemporary media theory, and, indeed, the history of sound technology at large. Kittler famously excavated the striking thought experiment in the poet Rainer Rilke's semi-autobiographical essay, "Primal Sound" (1919): that the undulating path of the coronal suture in a human skull might be played aloud with the assistance of the gramophone's needle, allowing it to transduce its patterns via its reproducing membrane, through the horn and onward out into the open air (1999: 38–46; see also the discussion in 1990: 317–9; Baer, 2014: 104–10; Connor, 2008). For Kittler, this "writing without an author" evidenced the media-technical *a priori* of the talking cure. But apart from making the seams of the skull plates newly legible as a sonic inscription, more prosaically (but perhaps more consequentially) the mechanical simplicity of what we are now in a position to recognize as the *archaeo*phonographic principle also engenders a kind of basic or primal legibility *for the technique of itself*, to human minds at least. The radically pedagogic scene of the science master's demonstration to the assembled schoolboys in "Primal Sound" attests to this.

Jump cut a century forward. The sixth of critic and self-confessed vinyl freak John Corbett's "Nine Explanations for the Vinyl Revival" holds that "[phonographic] records are magical; CDs are scientific" (2017: 13). I am hard-pressed to find a more concise contemporary articulation of the sense of disenchantment that CDs are held by their critics to represent: the compact disc being the fruit of a techno-rational society devoid of mystery; the vinyl LP evoking a prelapsarian state of wonder and awe in the presence of the disc. Indeed, Rothenbuhler and Peters—theorizing through the CD, as we have seen above—traced a similar path, analogizing vinyl true-believers to religious adherents with less ironic distance than perhaps they had intended (1997: 253; see also, Dotto, 2020). They went further, claiming that CD media was structurally less well suited to supporting the audiophile's quest for fidelity since its pits and lands do not signify sound indexically as phonographs do, which renders the older technique more suited to the pursuit of perfectibility (in both production and reproduction) than the former (Rothenbuhler and Peters, 1997: 253–4).

Rothenbuhler and Peters argued that the CD's alleged lack of indexicality meant that the format was unsuited to support the same quasi-religious pursuit of increasingly greater fidelity afforded by the more obvious relationship between the phonogroove's trace and the original sound event (Rothenbuhler and Peters, 1997: 48; see also, Rothenbuhler, 2012).[6] Corbett continues, in a symptomatic, and by now all-too-familiar, vein and deploys an almost Eucharistic analogy:

> Compact discs (and all their digital kinfolk) approach music like a very complex math problem to be solved by a number-crunching computer. We may not know how it works, but we're confident that the proper equations will be applied and the code will be read. That vinyl records are capable of producing music is harder to believe and understand, but the transformation of matter into sound is accomplished in public, on the stage of the turntable, where the needle is applied and … *presto* … music comes out (Corbett, 2017: 13).

The apparent extroversion of archaeophonographic sound reproduction and the simplicity of its operation to which Corbett attends is echoed in the scopophilic responses of other (male) vinyl collectors interviewed in a more recent ethnographic study of the perceived "liveness" of sound recording media (Chivers Yochim and Biddinger, 2008: 190–1; see also, Corbett, 1990).

To my mind, there is less here that separates the CD and vinyl than a first reading of Corbett might suggest. Specifically: Corbett confesses to a basic, if studied, ignorance to how *both* formats reproduce sound. If both vinyl and CD retain some kind mystery as to how they work, the problem with the CD to Corbett, evidently, is that it engenders the *wrong kind* of not-knowing, and, we assume, vinyl precipitates the right kind. The format agonism that Corbett relates is founded less on the structural differences between the way the two phonographic techniques represent sound. Rather, it traffics in a difference between how the mechanisms of sound reproduction are bracketed (or otherwise), with the role of explanation deferred to technical specialists. The interface effects of miniaturization, computerization, and software-ification have caused a marked escalation in the illegibility of contemporary sociotechnical systems, with which new media formats are increasingly entangled (Winthrop-Young, 2015: 84). These developments have been accompanied by a contemporary concentration of the understanding of these processes in a cadre of technicians and product designers: only when CDs and their players break down do we gain any purchase on how the sound they store is processed. Even then, most of us either delegate our expertise to service technicians or repair shops, or, increasingly, consign the media devices to landfill (Gabrys, 2011: ch. 3).

The CD foreclosed any understanding of its recording principle in terms of a straightforward mapping between a sonic event and its representation as it is inscribed on the medium: precisely the kind of intelligible mapping that featured above in characterizations of archaeophonographic sound media, *contra* the CD. The key to unraveling the new, interleaved ordering-relation between sound and inscription is submerged in the silicon chips that are pre-programmed to decode it. There is no doubt that commodity digital consumer electronics are designed to enclose symbolization, foreclose interpretation (Kittler, 2012), and even to pose challenges to the remit of well-established jurisprudence (Vismann and Krajewski, 2008). The cultural technique of interleaving, in its microtemporal implementation in the read-only chips of each CD player, delineates a clear line between inside and outside: the listener is played by the player and is, by and large, completely unaware of how it does so and unable to modify this behavior. But all this amounts to not as much a liberal lament for the loss of agency in the age of computer-mediated audio playback than a meditation on its conditions of possibility. As Vismann writes in respect to legal subjecthood, the goal of such investigations is to "[trace] the fiction of sovereign subjectivity, the myth of the subject as legislator, instigator or perpetrator, back to the techniques that make it possible in the first place" (2013: 88). We might, with minimal modification, say the same thing of listeners in the contemporary moment, whose autonomy as such is put at stake by the proliferation of "perceptual technics" identified in recent theories of sound media (Sterne, 2012).

Conclusion

The murky theoretical picture around the CD—the unwillingness to develop an account of the new phonographic regime it stands for with reference to its media-technical details—is, once again, symptomatic of this situation. As Krämer noted, "the technological thrives on its trick of separating operational methods from use" (Krämer, 2006: 106). Whether you prefer to understand this "trick" to be function of reification, alienation, blackboxing (deliberate or otherwise), cognitive chunking, hypermodernity, or simply boredom and disinterest, most of us have become increasingly precluded from understanding the cultural-technical operations of the media we use (and once used). Whatever your ideological persuasion, media critique presupposes at least some basic fact-finding about how media operate. As such, the current situation as it relates to the kinds of algorhythmic processes here exemplified by the CD, a format fading into obsolescence but still partially understood by its critics, continues to demand nothing from critics and historians, nothing less than a new "new media" literacy that sits uneasily within current disciplinary formations (Ernst, 2013; see also, Kittler, 2002; Siegert, 2013). The foregoing has suggested how debates over media change, or "format wars", which to date have largely been chronicled as struggles over media's affordances to fidelity (as representations) or fluidity (as commodities), can also be read reflexively as agonisms in which anxieties about the waning understanding of the contemporary cultural techniques of media are actively worked out.

The most salient point of contrast between the audio CD format and its archaeophonographic predecessors has been here revealed as having less to do with how it represents sound *as such* and more to do with whether it is expedient—or, even in the first instance, possible—for the average critic to daydream about contemporary computational sound media, much in the same way that Rilke once reasoned about the phonograph. As Kittler and other technopessimistic media theorists anticipated, such an integral "flashbulb" apperception of the complete chain of events that culminates in such non-imaginary digital inscriptions of sound culture is all but off the table in the era of microtemporal data processing. It is instead replaced by the piecemeal reconstruction of how the technical media that deploy these techniques operate, a task equally mired in the often-arcane and sometimes proprietary documentation written for technicians as it is in the traditional media-critical literature. In this article, I have attempted to lay out a case for, and to grasp towards, this kind of understanding by investigating just one of the many cultural techniques of media that the once-dominant audio CD materializes, a cultural technique that lies beneath the level of the everyday perception of recorded sound: interleaving.

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Notes

1 Almost all of the following discussion is relevant to how data CD-ROMs store and process information, because of the strict hierarchical relationship between data CD formats and the audio CD format that preceded them. DVD, Blu-ray, and other more recent optical media all build upon the same basic principles of optical data storage.

2 "Begged", since Rothenbuhler and Peters define phonography in the following way: "We use phonography as an umbrella term for a family of historically evolving techniques of sound recording that involve analog inscription on a mechanically rotating medium (wax, copper, vinyl, tape, etc.)." Rothenbuhler and Peters (1997: 261, fn. 1). See also, Magnusson (2019).

3 Kittler's own essay on the format is, regrettably, not especially enlightening. Kittler (2000).

4 Siegert continues, drawing on Serres: "place-value systems are codes that take into account the media employed to store and transmit them. The channel, the parasite, is not *supplementary*, but *the ground* for the operationality of numerals." Siegert (2015: 25).

5 If this seems like we have gained something for nothing, note that a particularly unlucky pattern of random errors could lead to a burst erasure on de-interleaving.

6 "Alleged" because their reading betrays the common misapprehension that indexical signs (on the Peircean account) must by connected by a mechanical–causal relation to their referent. Paulsen (2013).

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