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The materiality of digital media: the hard disk drive, phonograph, magnetic tape and optical media in technical close-up

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Abstract

Popular discourses surrounding contemporary digital media often misrepresent it as immaterial and ephemeral, overlooking the material devices that store and generate our media objects. This paper materially 'descends' into a selection of prior media forms that make up the genealogy of the hard disk drive (HDD) to challenge our reliance on conceptual misrepresentations. This material analysis is used to situate digital media in a genealogy of prior media forms, to enrich our understanding of how media's affordances arise from the interplay of both formal and forensic materiality, and to demonstrate the value of reintegrating materiality back into the study of media.

Keywords

materiality, history, hard drive, digital, media,

Introduction

In this paper I hope to reintroduce materiality into the study of new media. More specifically I'd like to reintroduce the hard drive back into discussions of digital media, situating it in a genealogy of other analogue media technologies. Much of the perceived newness of digital media arises from a focus on its effects, and its formal materiality as 'code', 'software', 'binary', or simply 'digital'. Yet beneath these operations, like in all media previous, there is a material substrate, the state of which will determine what will happen when it is read again. By reading I mean a mechanical or electrical reading, a manipulation of matter to form a signal from substrate. In historical considerations of media, the substrate has been king; the stone tablet, papyrus, paper, the phonograph cylinder, the gramophone record, the film reel, the cassette tape, the compact disc. Yet once media moved into the realm of the computational, the substrate disappeared, encased in the opaque box and indiscernible from the other magical components that generated the interface in front of us. The increasing implementation of cloud computing and storage in consumer grade services further obscures the hardware by moving all but the interface off site. However, the material realities of the digital remain, and affect us every day. It is the reason why your smartphone can run out of space, why a scratch on a CD can make the music jump and skip, why the files on long abandoned laptops corrupt and disappear. The material is where our media persist, act and are acted upon. We focus on effects, rather than the devices which deliver them. We dream of the digital as the final medium, of unmediated knowledge (Peters, 1999). At its most tame, this dream leads us to muddied debates that speak through grand narratives of media change. At its most insidious the dream obscures the ethical consequences of an ontological misrepresentation that discards digital media's underlying materiality (Carlile et al., 2013).

The value of media descent

The consequences of including materiality back into discussions of media can be broadly categorised into three groups. The first relates to the representation of what digital media is and how it relates to other things. The second addresses the role that materiality plays in affording us agency. The third cuts across the first two, and relates to the way in which our metaphors for reality are often linked to key technological developments.

Beginning with our first consequence: recognising digital media's materiality, breaks down false historical and conceptual boundary divisions that separate digital media from other media forms. Once we materialise the digital, we can situate those devices within a historical lineage, and see it technically prefigured. This prefiguring complicates the clean divisions drawn between "old" and "new", "analogue" and "digital", "discrete" and "continuous" as well as the broader division of the "digital" from the "physical", popularised in the cyber-utopianism of the early 1990s. Prefiguring can demonstrate the old digital, new analogue and the historic continuity of media's lineage.

This 'descent' into the historical and material genealogy of media technology is the central focus of what is broadly referred to as 'media archaeology' (cf. Parikka, 2012; Parikka, 2011). An anarchic field, media archaeology is inclusive of much more than materiality and history. For the aims of this article, what is particularly fruitful about media archaeology is its utilisation of Foucault's work on the archaeology of knowledge and the genealogical method. This approach, which looks back to explain why the present is as it is, with a strong focus on power, highlights ‘descent’ as a key conceptual tool in the study of media.

‘Descent’ in this context refers both to the descent back into history to uncover how a medium developed, focusing less on the myth of progress and inevitable continuity, and more on the idea of possibility, rupture and contingency. However ‘descent’ also refers to descending down into the machine itself (Parikka, 2012). This new materialism associated with Kittler (1999) and the broader discipline of what has come to be known among Anglophone scholars as ‘German media theory’ takes this technical ‘descent’ very seriously. The descent into media should recognise software, hardware, materials, mechanics and form. New materialism asks us to look to technical specificity the ‘aspects of media that would otherwise escape the discourse of cultural history’ (Ernst, 2011: 240). By fusing new materialism with historical enquiry, we can hope to enrich our ontology of digital media, what it is and how it relates to other media forms.

The second group of consequences relate to our understanding of digital media’s agential role. Recognising digital media as material resituates it into discussions of media power, capital, agency through design, durable effects and social shaping – what Carlile et al. (2013) refer to as the ‘ethical dimension’ of a ‘sociomaterial sensitivity’. We separate the social from the material, however the authors argue that the social is an irreducible entanglement of actors and artefacts, a constellation of ‘interobjectivity’ (Carlile et al., 2013: 7). Within this constellation the subject/object dichotomy is replaced with the recognition that objects both shape our activity and influence our opportunities to act. This raises questions regarding accountability and responsibility. As Yates (1989) argues, the way we instantiate and organise information can have drastic implications for our practices and interpretations of that information. Recognising the digital as material situates it as another object within the constellation of interobjectivity and recognise the agential 'consequences of form, and forms of consequence' (Dourish and Mazmanian, 2013: 96).

Finally a more abstract consequence that cuts across both the ontological and the agential, is the use of technological metaphor. Many of our metaphors for ourselves and society arise from society's most pervasive technologies. These metaphors privilege and focus on certain ways of thinking, reframing or discarding those ways that do not fit. Today, '"[i]nformation" becomes the universal solvent for both what the world is and how it can be framed' (Dourish and Mazmanian, 2013: 100). Furthermore the very attribution of materiality is culturally and historically contingent, and a powerful rhetorical tool. For Miller (2005) to claim something is material is to make it immutable and certain. Conversely, with digital media it is the attribution of immateriality that has situated it in a rhetoric of inevitability, as beyond human control and free from pre-existing power structures.

A material approach to media

Lievrouw's (2014) review of STS and of communication studies indicates that both have an uneasy relationship with the material. STS was significantly defined by the 1980s response to technological determinism via the constructivist turn with subsequent developments sharing a particularly cautious take on materiality. In STS Materiality is framed as at least on par with social and political factors, emphasising technology's heterogeneous nature as multiple artefacts, practices, relationships and knowledge. STS's complex recognition of technology's social construction has, not necessarily intentionally, led to a fuzzy conflation of the material with determinism. This dissuades a focus on materiality for fear of being charged as 'determinist'.

Communication studies also has a history of unease with the material, blurring the boundary between the technology of dissemination and the meaning it conveys. By focusing on media effects or media as text the field has disavowed deterministic models of media consumption and emphasised the role of interpretation. The outlier is Medium theory, most commonly associated with the Toronto School which has embraced the materiality of media to a near deterministic stance. However their conclusions tended to focus on a macro scale such as civilisation (Innis, 1964), or human capacities (McLuhan, 1964). The more recent cultural historical approach to media (Peters, 1999; Gitelman, 2008) has given more space to technical details, but still tended to frame technological materiality as having arisen from a cultural milieu or as reflecting one. Across all these fields materiality is present yet weaved together with the social. It is made palatable in the face of determinism through being subsumed into social processes making it difficult to determine what consequences, or how much of a consequence, can be attributed to the material form (Lievrouw, 2014).

To better situate materiality and its consequences whilst recognising the social, we must be specific about what we mean by materiality and recognise both have a part to play in shaping human practice. However identifying what we mean by 'materiality', is not a straightforward process. Dourish and Mazmanian offer 'that which takes physical form, and that of consequence' (2013: 96), focusing on the inanimate 'stuff' of the world, and that which has influence in that world. Leonardi (2010) offers three possible definitions: to paraphrase, 'consisting of matter'; 'as opposed to formal' meaning the practical aspect father than theoretical aspect of something; and 'that of significance or consequence'. Leonardi posits that when considering the digital object, we should focus less on physicality, and more on the latter two definitions as digital objects and their consequences arise from interaction. Though I would agree that a software object is much more a process or performance than physical object, the underlying code, or at least a prerequisite signifier that will be transcoded, has to be somewhere for it to persist, to act, and to be acted upon. The formal requires the physical to be of material consequence. The groove of a vinyl disc does not exist independently of the disc, and its form will be partly informed by it.

Kirschenbaum's (2008) work offers a suitable framework for materiality which recognises the interdependence of the formal and the physical. 'Forensic' materiality refers to the mechanical operation and the physical substrate of the devices, things of atomic substance. 'Formal' materiality refers to a logical organizational structure that is both reliant upon and supportive of the forensic form. In the case of the vinyl record, the shape and organisation of the inscription is formal, the physical substrate and the mechanics of its reading are forensic. They are interdependent but by conceptually separating them the case studies are able to articulate the operation of the devices with greater finesse.

However, we must not overlook the social within which the material acts and is acted upon. Lievrouw 's solution lies in Hutchby's (2001) theory of 'affordances'. To say a technology has certain 'capacities' implies an essentialist claim of inherent traits and, it follows, specific social impact. However a claim that a technology has a particular 'affordance', frames the interaction between the material and the social, as a sociomaterial constellation. Affordances recognises that the *implementation* of a technology is socially determined, but does not concede that it itself is a blank slate. No matter how hard one tries, a slot machine cannot be used as a telephone. The reading and impact of a slot machine can alter from its intended design, but not so radically that it is used in a way that disconnects the object from the constraints of its material form. The affordances of a technology are not negotiable as a product of subjective experience, but neither do they necessarily impose themselves on an individual. Affordances provides us a way of discussing the sociomaterial constellation, recognising both the material and the social as co-constituent parts of any potential action.

In presenting the following media technologies – the hard disk drive, the gramophone, magnetic tape, and optical media - I hope to achieve two things. First, the case studies are descriptive technical explanations of how each technology operates through forensic and formal materiality and the affordances this supports. The case studies are also designed to demonstrate the genealogy of contemporary digital technology, challenging the conceptual boundaries we have formed around digital media and enriching our understanding for it.

The hard disk drive

I begin with the hard drive for two reasons. First it is the prime material site of the digital object. Secondly, it sits within these case studies as a central point of comparison. By addressing it first, we can later illuminate past technologies in a way that highlights the technology's genealogical prefiguring.

The first commercial version of the contemporary hard disk drive (hereafter referred to as HDD) came from IBM in 1973, and was popularly known as the 'Winchester'. The drive was a breakthrough in direct access data storage, and a significant departure from the removable magnetic tapes widely used for data storage at the time (Ceruzzi, 2003). Contemporary HDD's still operate on the same basic principles as the original Winchester drive and forensically consist of two key parts: a disc of metal coated in an incredibly smooth layer of magnetic material known as a platter; and a read/write head on the end of a magnetically driven actuator arm.

The platter is a single circular ‘planographic’ (Kirschenbaum, 2008) surface on a spindle that is able to rotate at speeds of approximately 5400-7200 RPM. The surface, though apparently smooth, is made up of tiny grains of magnetic material which are formally grouped together, a few hundred at a time, into ‘regions’. Each region represents a single ‘bit’, the smallest unit of data. How this collection of magnetic grains translates into meaningful data is derived from the formal materiality of the drive’s structure and will be addressed later.

To manipulate and read these regions the drive relies on a read/write head floating above the platter at the end of the actuator arm. The arm is capable of incredibly fine, movement shifting in response to power changes in electromagnets rather than to wheels and cogs. Moving laterally, in conjunction with the spinning platter, the arm is able to move the read/write head from any region, to any region, facilitating random (rather than serial) data access. The head is suspended 10 to 100 nanometres above the platter on a cushion of air generated by the spinning disc.

The head sits this close to the platter to allow it to manipulate, and be manipulated by the magnetic polarity of the regions. The early ‘Metal-in-Gap’ style head (popular in the 1980s) was made of a horseshoe-shaped piece of magnetised metal, with a tiny nanometre gap between the two prongs. A coil of wire attached to the head would pulse with electrical current, causing a strong magnetic field to form in the gap. However, because the gap was filled with a small amount of magneto-resistant metal, the field was forced to traverse the gap via the platter surface. As it did, the magnetic polarity of the grains were switched. The head could also read these regions as it passed overhead, the polarity of the grains manipulating the electrical signal of the coil. Contemporary drives now use a type of head known as ‘Thin-Film’, operating on the same principles, but flying even closer to the surface.

If the head is too far from the surface, it may struggle to accurately sense a region's polarity if contiguous regions are oppositely charged. However, by closing the distance between head and platter, the density of data storage can increase. Data density refers to the amount of information that can be stored in a spatial area. Increasing density means the spatial measurement remains the same, but the amount of information retained by it increases. In the case of the HDD, as the head is able to pinpoint smaller areas of grains, it can divide those grains up into more regions, and thus more bits.

The forensic construction of the HDD is intertwined with the formal materiality of how signals are interpreted and the surface is rationalised. As a digital storage device using opposing polarities one might expect that what is being written to the platter surface is a series of positive 1's and negative 0's. However, digital encoding does not work through direct representation of states, but is instead *differential*. Differential encoding means that it is the change in polarity that matters, rather than the polarity itself. In a series of eight regions, a change in polarity indicates a 1, whilst no change indicates a 0 (see Table 1). That pattern of eight states represents a single byte of information, with 256 possible combinations of 1's and 0's. The combination is then translated by the computer into something meaningful (very often in conjunction with many other bytes). For example one byte can represent any number up to 256, or a single character by assigning that character a value between 1 and 256. No matter how complex the data, when you descend down to the platter, it all starts with eight bits that form a byte.

Polarity	+	+	-	-	-	-	+	+
Binary	0	0	1	0	0	0	1	0

Numerical	34
Alphabetical in Unicode	A

Table 1 – Differential encoding translated to binary, number and letter.

Differential encoding contributes to the achievable data density of the HDD, allowing the head to skim for change rather than read every bit. However as we have seen the density is also about nanoscale matter manipulation, and differential encoding alone does not lead to more efficient use of substrate space. On the HDD a letter requires eight units of data whilst human readable text just requires one. The contents of a library may fit onto a thumbnail sized memory card but not simply because it is digital, or binary, but because the nanoscale surface of inscription operates outside of human perceptibility.

Forensically the platter has no divisions or pattern, however there are various levels of formal rationalisation at play. Blank HDD's come with a formal structure already in place. This structure can be thought of as a series of markers ordered across the surface indicating where a specific area, known as a sector, begins and ends. These sectors are subdivisions of circular tracks that can be visualised as a series of concentric rings radiating from the centre to the edge. Radial lines cut across these tracks, dividing them up into the sectors. Each sector is then divided up into anything from 512 to 4096 bytes which as we have already addressed, are themselves each comprised of eight bits. Formally a highly rationalised surface, but forensically, hundreds of imprecise magnetic grains masquerading as singular, ordered data.

Many of the characteristics often thought to emerge from simply 'being digital', are surface illusions co-created by the HDD's forensic and formal materialities. Often the foremost characteristic is digital’s replicability. As we will see when discussing magnetic tape this is an important part of the process. However replication also requires a substrate upon which the copy can persist. An MP3 could be replicated as a differential signal in text, however it would not be of meaningful use in that form. Replicability relies on a substrate capable of inscribing the signal and of making it intelligible to us. The environment that makes the MP3’s digital signal persist, and intelligible, requires a host of different forensic and formal systems to support the speed, density, reading and writing of the drive.

The speed of the HDD is reliant on both forensic precision, and formal imprecision, through the conjunction of differential encoding, error correction and the high speed of the platter’s rotation. Regions are not magnetised to a specific polarity, as the head is only looking for a difference above or below a threshold. Though the polarities of the regions are in themselves continuous, those measurements are binned into one of two binary states. This speeds up both reading and writing as the head can be relatively imprecise. Unlike the continuous waveform of a vinyl disc where the precise inscription matters, at the region level, the hard drive works on rough approximation.

If a data point is missed by the head, a predictive system called Partial Response Maximum Likelihood (PRML) guesses which pattern would be the most likely based on the remainder of the data. This alongside other error correction routines allows the operation of the HDD to be much more ‘inaccurate’ than the rhetoric of precise information machines would have us believe. The digital is not a clear precise deductive stream, but an inductive approximation, constructed from continuous magnetic fields as a best fit model. This best fit is then transmitted up to higher level software processes as objectively true. Even the idea of a coherent digital object occupying platter space is itself inaccurate. To compensate for the read/write head's speed limitations, data is often written non-sequentially, spread across the platter, in a way that is timed with the delay of the head. This process of 'interleaving' data means that a string of related bytes can be read sequentially, even though they are inscribed non-sequentially (Glass, 1990). Random access and sequential reading of non-sequential data is supported by the addressing system that keeps total record of what data is located in what sector. The device can afford to be haphazard with data placement, because the addressing system maintains total central awareness. The central storage device of our 'digital age' is one that reaps the efficiencies of a disordered population. The data can live wherever it likes on the platter surface, so long as that location is known by the central addressing system. If we are going to adopt 'digital' metaphors for our society and celebrate the decentralised disorder of data flow, we should not forget the centralised surveillance required to manage it.

If we descend into the material foundations of digital objects we tell a very different story from the immaterial mythos of the digital. The affordances of the digital, the characteristics that make it seem like it transcends material constraint, are inherently reliant on material realities. The HDD is a forensically continuous device that masquerades as discrete through approximation and imprecision. The replicability, speed and density of the digital world is reliant upon the interplay between the forensic and formal materialities of the devices upon which that code persists. This blurs many conceptual boundaries that separate the digital from other media forms, and resituates the digital as part of the technical media lineage, ready to be reintegrated through forensic and formal continuities.

The phonograph and gramophone

The phonograph and the gramophone are well known amongst media scholars, indicating the beginning of technical media and analogue recording. They have also been considered from a multitude of cultural, economic and social angles by many writers, such as Eisenberg (2005), Katz (2010), Kittler (1999) and Sterne (2003). The devices are predated by mechanical music boxes of the early 19th century that utilised pin coated rotating cylinders to produce a series of notes by brushing the pin against a metal comb. Whilst the music boxes 'produced' sound via their programmed cylinders, the phonograph and gramophone are widely recognised as the first devices to record and 'reproduce' sound. The first analogue inscription of sound happened around 1856-7 with Leon Scot's phonoautograph, designed to mimic the operation of the ear. The device involved a sensitive diaphragm of parchment that vibrated when affected by a loud noise. A pig bristle attached to the diaphragm scratched a waveform onto a glass cylinder coated in smoke dust and sound inscription became a thing (Library of Congress, 2014).

This principle was applied by Edison in 1877 to create a machine that could both inscribe and reproduce sound waves. By using a metal stylus and tinfoil wrapped around a rotating cylinder as the inscription substrate, a significant indentation was made, allowing the stylus to travel back along the inscription, reversing the process and emitting sound (Library of Congress, 2014). The metal stylus was placed on top of the cylinder, and moved laterally along a rod across the cylinder's length as part of the sound reproducer. This lateral movement of the reproducer and the rotation of the cylinder were powered by a hand wound spring which would drive the device for the duration of a song.

The formal layer of both the phonograph and the later gramophone is the pattern of the inscription itself. This form cut into the substrate needed, in the absence of sensors to correct for error, to conform to specific standards for replaying. The Archimedean spiral maximised data density by utilizing as much of the space as possible without cutting across grooves. Incremental improvements in density occurred through balancing rotation speed against groove depth and stylus angle, however this was inexorably intertwined with the forensic materiality of the substrate.

The forensic materiality of the cylinders altered significantly during the phonographs' development. Further work on finding appropriate substrates by Edison and others such as the Bell Volta Laboratory brought the phonograph to a marketable quality. The original tinfoil substrate could not withstand repeated playback and so was replaced with wax which was resilient enough to allow the sale and rental of pre-inscribed cylinders. The cylinders measured approximately 4.25 inches by 2.19 inches and so were small enough to be carried from the shop or sent through the post (Library of Congress, 2014). The density of sound storage on a cylinder was much greater than the space needed to move performers and their instruments. Performers were instead adapting to this new device and the restrictions it placed on performance. Songs had to be kept to two minutes, reflecting the maximum space on the cylinder surface, and the arrangement of instruments had to be carefully considered as some were less perceptible to the diaphragm than others. Often performers compensated by playing with greater force than normal and swapped out instruments to better accommodate the device. Cylinder production relied on real-time recording, using the same phonographs as sold to the consumer. This meant mass production consisted of performers performing multiple times for multiple machines, significantly slowing down production. Limited editions became things (Katz, 2010).

The read/write affordances of the phonograph extended outside the studio to the home user. Blank cylinders were sold allowing users to record themselves, or pre-recorded ones could be 'erased' by shaving off the surface. This relief inscription was destructive, but re-writable with enough wax depth to write and wipe the medium up to one-hundred times (UCSB Library, 2014; Tewksbury, 2013/1897). This changed with developments in mass production. More popular and durable 'read-only' cylinders made of celluloid replaced the rewritable wax cylinders. This social and material shift changed the role of the phonograph from home recorder to commodity player. Around 1890 Emile Berliner produced the gramophone which further established read-only practices. The gramophone utilised a disc shaped inscription surface and like the HDD relied on an actuated arm that could move the stylus along the radius of the disc surface as it rotated. Rather than rely on gears to move the stylus, it followed the spiral groove of the inscription, dragging it to the centre of the record. This dragging motion meant discs degraded faster than the cylinders, but easier mass production made them more accessible, further framing them as consumables rather than durable artefacts. Disc mass production still relied on wax inscription, but then from this a metal master was moulded which allowed reproduction via pressings into a hard rubber substrate, echoing the genealogy of the Gutenberg press (Read, 1952). Despite faster degradation, the change in form caught on as discs could hold three rather than two minutes of audio and were easier to transport, store and collect. Music, as an attainable recorded commodity, became a thing (Eisenberg, 2005).

The gramophone was revolutionised by the introduction of electricity as signal conduit and addressed many of the production and quality issues that had been faced by acoustic. The continuous, relief based inscription form remained the same. However in electrical recording, the stylus was magnetically manipulated in response to fluctuations of electrical current rather than the effect of sound waves on a diaphragm (Maxfield and Harrison, 1926). This process was largely reliant on the development of the condenser microphone. The casing of the microphone housed two parallel metal plates, one fixed, the other vibrating in response to sound waves. This vibration caused variation in distance between the plates, altering the amount of insulating air between them, and modulating the electrical current as it passed between them (Read, 1952; Alkin, 1996).

Comparing the material development of the phonograph and gramophone to the hard drive we can observe a variety of continuities. The most striking is the overall form of a rotating platter, an actuated arm and a read/write head. The surface of both platters is highly rationalised with the gramophone relying on a strict serial structure, whilst the HDD thrives on non-serial data arrangement. Whilst both share the mechanical ability to reach any point on the substrate, the gramophone does not rely on this capacity. In comparison to the HDD's chaotic yet totally surveilled surface, the gramophone is unaware and instead relies on order and predictability of place. With the introduction of electric recording, fluctuations in magnetism are utilised to guide the inscription process in both devices, though only one inscribes in magnetism. Both are signal processors; though the gramophone does not process from analogue to digital, it does process from sound wave to fluctuations in electrical signal and vice versa. However it is not a differential signal but one that arises from a fluid indexical relationship between sound and inscription. This inscription is stored as a single continuous signal each aspect of which is contributory to the whole. The HDD is instead a surface of multiple, separate continuous signals, formally coded as binary.

Though occupying distant ends of the technical media timeline, by contrasting the phonograph and the gramophone with the HDD from a material standpoint, the historical distance between them narrows. Further interrogation of other contributory media forms may further close the gap.

Magnetic tape

The history of magnetic tape cuts across the timelines of music and computing, demonstrating the malleability of magnetic inscription and further blurring the boundaries between the two. Magnetic recording was developed in 1899 by Danish engineer Valdemar Poulsen in the form of magnetic wire recording. Poulsen's device, the Telegraphone, passed steel wire through a small gap (between .001 and .002 inches) in an electromagnet. As the wire passed through the gap it would be magnetised according to the fluctuations of the electrical current. At a speed of 24 inches per second the system required 7,200 feet of wire for a one hour spool. The write head could also act as the read head by reversing the process, inducing electrical fluctuations by passing the magnetised wire through the head (Read, 1952). The result was a new non-volatile, non-destructive rewritable medium.

Various adaptations of the wire substrate were made throughout the height of the gramophone, but magnetic tape as we know it was not developed until 1930. Rather than a solid core of steel wire, this tape was a flexible base of paper, acetate or polyester coated in a ferrous magnetic material like iron-oxide (Hall, 2011). Rather than passing between a gap in the electromagnet, the tape passed underneath it. The electromagnet gap was filled with a magnetic resistant material, forcing the field to jump to the tape to traverse the gap like the HDD (Rumsey, 2014). This pinpoint accuracy, together with tapes' wider area of substrate allowed a greater variety of formal data arrangements making it particularly versatile.

First was a move to multiple recording heads which laid down parallel continuous tracks along the length of tape. This multi-tracking allowed tape to be written to from multiple sources simultaneously, improving sound fidelity over the single track gramophone. Multi-tracking also afforded the practice of overdubbing, allowing artists to record tracks separately yet have them play synchronously, recreating time after the event. Multiple takes could be strung together to form a simulacra event, and tapes could be written and rewritten to layer more and more complexity into a single song. Tape solved the gramophone's problem of recording multiple musicians at once, and delivered more on top. This versatility meant tape entered the gramophone timeline as it became the studio standard from which recording masters were made before consumer level vinyl was pressed.

By re-orienting the read/write head across the tape length tape could be used for discrete digital inscription as well. Like the sectors on a HDD, the tapes were formally structured into blocks of uniform length. Within each block, the polarity of the tape is altered in a sequence to be read differentially as was demonstrated earlier in figure 1. The historical IBM UNIVAC 1 computer used eight-track tape as its short and long term memory. Six tracks were used for data, one for the clock speed and the last as a parity track to manage error checking (Ceruzzi, 2003). Though forensically tape was sequential (i.e. access to point C required passing A and B) the clock track allowed the computer to wind the tape to a specific location on the reel. A hybrid sequential random-access medium. Data was also interleaved –written non-sequentially like the HDD - as a counter against error. If the tape was damaged forensically sequential bits would be lost, but formally only single bits were lost from multiple bytes. Error correction could then be used to rebuild the missing data via similar methods of approximation used with the HDD.

Magnetic tape provides us with a crossover point between the histories of music and computing and a valuable case to examine the differences afforded between continuous and discrete encoding, when the substrate is forensically similar. Replicating a continuous signal tape results in a slightly degraded copy as extra signal noise is introduced with every copy, similar to how a photocopy of a photocopy degrades in clarity. However, replicate a digital tape and noise has little impact as the recorder only needs to know which polarity to write, not the exact measurement of it. Any signal degradation is overcome because the recorder does not replicate the signal, it replicates the pattern. A digital signal only becomes unreadable when it has degraded to the extent that it can no longer be approximated. A continuous signal can always be read, but the meaning it conveys may alter to the extent that it no longer has relevant meaning. We can therefore attribute the replicability of digital signal to the formal aspects of its inscription. However we cannot discount that digital signal’s longevity partly relies on constant checking and re-affirming of the signal by the host device, relying on the non-destructive inscription process. A wax cylinder could have a digital signal, constantly checked and re-engraved as bits became unreadable, but it would not last for long.

Optical media

Optical disc technology was announced by Phillips in 1972 but it was not until their work was merged with Sony’s developments in error correction that the popular compact disc format reached the market in 1982. The materiality of a compact disc is fairly simple, consisting of a plastic substrate engraved with a series of pits to denote a discrete pattern. The plastic is coated in a reflective surface so that a laser directed at the surface is reflected into a photodiode. The laser moves laterally across the disc like the HDD and gramophone heads which, working in conjunction with the motor that spins the disc at 539RPM, allows it to access any part of the disc surface. The reflectivity of the surface varies with the pits causing a continuous variation in signal which, like tape and the HDD, is then read as a binary value (Pohlmann, 1992). The inscription of a compact disc mimics the gramophone and is arranged as a spiral, with data being read serially. This differs from the HDD which, to reiterate, arranges data into sectors and can be read randomly via addressing.

Though it mimics the spiral layout of the gramophone it differs by using tiny discrete pit indentations rather than a continuous groove. A gramophone groove is estimated to have contained approximately one-hundred bits of data per square-millimetre, whilst the compact disc is approximately one-million. To put this scale into perspective, the length of a pit in a 12 cm diameter disc is about the same as the length of a grain of rice, on a plate with a half-mile diameter (Pohlmann, 2011). This level of data density meant the disc could hold between 74-80 minutes of audio using 44,100 data samples per second. This audio standard is still used in many computational formats like the MP3 but actually has its roots in tape. In the mid-1970s studios transitioned to digital tape formats for their music mastering (Pohlmann, 2011) .The audio was recorded digitally, but had to align to the formal video standards used to inscribe the signal to the tape. Every second of video was comprised of 30 frames and each frame had 490 useable lines of data to make an image. It was found that each line could accommodate three samples of audio. The result was 30 frames, by 490 lines of data, by 3 samples of audio; 44,100 audio samples per second of video tape (Pohlmann, 2011).

The scale of CD inscription required an incredibly precise laser to track the pits along the spiral, and an error-correction system to predict and approximate missing data. The serial sequence on the disc is far from indexical to the original audio. Audio data is arranged into frames followed by non-audio data for error checking, and data is interleaved to account for spin speed like an HDD. Audio is generated through a mix of unscrambling, reconstruction, error correction and prediction. Highly robust, but a great distance from the gramophone records it mimics.

The original compact disc is a commodity object, a 'write-once' medium. The production of the master is a complex mix of laser etching in glass, silver plating, and the formation of a nickel die. In a process reminiscent of Berliner's gramophone discs, injection moulding is used to swiftly 'press' plastic discs from this master which are then coated in a reflective surface (Pohlmann, 1992). The introduction of writeable and rewritable discs blur the write-only nature of the CD somewhat. These discs are pre-inscribed with a groove and then coated in a heat sensitive dye followed by a reflective layer. In home recording, a laser is used to heat the dye, causing it to compress and form pits. The re-writable versions use a substance that when heated, changes from a crystalline to amorphous state which absorbs light, mimicking a pit. A different temperature applied to the same point will reverse the process. Though rewritable it is destructive, with a limited amount of state changes. Furthermore due to formal structures like the interleaving pattern and the use of a spiral rather than addressed sectors, specific data cannot be rewritten and the whole disc must be started anew further increasing wear (Pohlmann, 2011). The forensic affordances of optical media means that though it is less volatile than magnetic inscription, it is also inflexible, and predominantly read-only.

Though digital, the compact disc is often associated more with inflexible static vinyl records than the infinitely malleable MP3. Formally it is closer to the MP3 as a digital construct, yet forensic limitations distance it from the bricolage practices of magnetic inscription. As a materially static medium the compact disc is gramophone+. The utilisation of meta-data means the read arm can be random access at the nanometre level, and the use of laser rather than a stylus eradicates wear on the substrate. It is an iterative improvement, using digital signal for density, longevity and clarity, but not for non-destructive malleability. The compact disc sits as a complicated hybrid medium combining the dual lineages of magnetic tape and the gramophone, and bridging to the HDD. It expresses the disc, arm, head, spiral and forensic inscription of the gramophone. Yet it also uses the discrete serial encoding of magnetic tape, embodying tape's material limitations via the 44.1 kHz standard, and bridging them to contemporary music file formats. It undermines the conceptual physical/digital divide by being both, demonstrating again that a medium may be digital, but without the right substrate, it is not necessarily what we would call 'digital media'.

Conclusion

Behind the supposed immaterial virtual realities of digital worlds lie in fact many extraordinarily concrete, material realities, often deliberately blackboxed out of view, in urgent need of our perceiving and reasoning through. This article has pointed to a few of those realities. Furthermore, by illuminating those realities we are compelled to recognise the analogue past that sits within our most contemporary digital platforms, and the misrepresentations we make of our contemporary media machines.

The four case studies illuminated different contributions that arise from a material approach to media. The unpacking of the HDD demonstrated how the affordances we often attribute to the nature of digital signal arise from the interplay between the forensic and formal materiality of the HDD. The unpacking also challenged some of our metaphors and misconceptions, demonstrating it to be a material device of continuous signals, imprecision and approximation. Unpacking the phonograph revealed continuities of design between the HDD and this early technical medium, and later case studies also demonstrated their own prefiguring in the phonograph's history. Magnetic wire and tape provided a useful control to examine how the use of digital signal can alter affordances when the limitations of the substrate remains the same, and optical media demonstrated that a digital signal is not enough to afford the qualities of 'digital media'. All cases demonstrated that a technology's affordances arise from an interplay of forensic and formal materialities and that 'digital media' is no different. An intricate understanding of how our media machines, the devices that store and transmit our culture, operate, is crucial. The material realities of these machines afford and restrict the standards we establish, the practices we develop and the types of information we can store. Not only must a digital object have a materiality to persist, to act and to be acted upon, but that materiality will afford *how* the object persists, acts, and can be acted upon.

Throughout we have seen repetition of forensic and formal mechanisms, breaking down conceptual boundaries between different mediums and demonstrating a genealogy of digital media back to the phonograph and telegraphone. A material analysis enriches the assertion that all new media recapitulate the old, demonstrating that recapitulation, pointing to the mimicry of techniques, form, and affordances. We have also seen the crossover between the material histories of music and computing devices, a history that arguably extends further back with the discrete data of music box cylinders and Pianola rolls.

Our long relied upon conceptual distinctions of media being ,"old" and "new", "analogue" and "digital", "discrete" and "continuous" as well as the much broader fundamental division of the "digital" from the "physical" do not help us. They are inaccurate, misleading and materially false. This is not a digital media age, this is the age of digitally encoded, magnetically inscribed, highly rationalised, addressed, algorithmically approximated, nanoscale media. It may not be succinct but it is accurate, and it tells us a great deal more about the machines so intricately integrated into our everyday lives. Conceptual framings are themselves black boxes that obscure our devices operations that, as part of the constellation of interobjectivity, afford and deny us certain agency. We would recognise power in a shift from rewritable to read only cylinder substrate, yet we do not ask whether the material construction of our contemporary media storage also has inherent power biases.

Finally, if we consider that often we draw from dominant technologies to develop metaphors for our society, should we not be drawing from more accurate pictures? Network societies, information societies, digital societies, all drawing on metaphors of surface effects. Would our metaphors look different if we modelled them on the material foundations of that information? Perhaps a society of constant rewriting, algorithmic approximation and surveillance. Our metaphors have not been drawn from the right places, focusing instead on ideals of clean, faultless networks, immaterial free floating information, and freedom from the material structures of power that operated through old, physical media forms. If we intend to truly understand 'digital media', how it persists, how it acts, and is acted upon we must understand the material foundations that lie beneath it.

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