On Mapping as a Technoscientific Practice in Digital Musical Instruments

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ABSTRACT

This article provides historical context for the emergence of "mapping" as a key conceptual metaphor in the context of digital musical instrument (DMI) design and use. In addition to a consideration of different technical implementations, we offer a critical assessment of the tendency to over-generalise mapping as a universal model for both building instruments and analysing them in retrospect. This reification of mapping as a design model, as well as of the dimension spaces of sound and gesture being mapped, is read through a media-theoretical lens, drawing on recent work from interface studies to show how mapping actively constructs ideological relationships between performers and underlying systems of musical representation. While acknowledging the practical utility of traditional formulations of mapping in DMIs, we focus on issues arising from their over-generalisation, including the sometimes-misleading impression of representational stability, the suitability of spatial metaphors, and the assumption of unidirectionality and temporal stasis. In closing, the article explores alternatives based on a relational approach to mapping as an "intra-active" process that is bidirectional at every step, fluid in its distinction of categories, and more dynamic across its variegated temporalities.

KEYWORDS

Mapping; digital musical instrument (DMI); dimension space; symbolic representation; ideology

> *...In that Empire, the Art of Cartography attained such Perfection that the map of a single Province occupied the entirety of a City, and the map of the Empire, the entirety of a Province. In time, those Unconscionable Maps no longer satisfied, and the Cartographers Guilds struck a Map of the Empire whose size was that of the Empire, and which coincided point for point with it. The following Generations, who were not so fond of the Study of Cartography as their Forebears had been, saw that that vast Map was Useless, and not without some Pitilessness was it, that they delivered it up to the Inclemencies of Sun and Winters. In the Deserts of the West, still today, there are Tattered Ruins of that Map, inhabited by Animals and Beggars; in all the Land there is no other Relic of the Disciplines of Geography.*
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> – Suárez Miranda, Viajes de varones prudentes, Libro IV, Cap. XLV, Lérida, 1658

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1. Introduction: Mutually Determined Maps and Territories

In Jorge Luis Borges' 1946 short story, "On the Exactitude of Science," a fictional account of 17th-century cartography points to the futility of attempting to make maps that cover the whole of a territory, "point for point," as though symbolic representations could ever fully contain physical realities.[1] And yet, while such a map fails to account for exact details of the space it seeks to inscribe, it succeeds at another level, shaping the viewer's imagination through an imbrication of signs with things in the material world. Through its interpellation of subjects as inhabitants of a semiotic space, the vast "Map of the Empire" affords a certain level of control, acting as a tool for the reproduction of social relations and the reinforcement of boundaries in any domain (Borges, 1998).

In music, the most familiar example of map-making is the score–that original scene of severance where the sonic imagination was split from action and symbolically bound to notation. Music scores spatialise a temporal phenomenon, visualise an auditory (or is it tactile?) sensation, and discretely categorize what might otherwise register as continuous experience. They also turn listeners into readers, and in extreme cases (e.g., the *Werktreue* ideal), suggest that performers are merely imperfect interpreters of musical works best understood as existing in virtual form. Theodor Adorno touches on this in his *Theory of Musical Reproduction* (2014 [2001]), arguing "the truly precise idea gained from reading can serve as the ideal for performance that cannot be attained as such" (p. 162). Building on this decentring of the performer by prescriptive notation (as opposed to descriptive transcription), Adorno offers an intriguing critique of the oft-repeated story that scores originated as mnemonic devices, arguing instead that "music notation is an element of discipline… it dispossesses the memory by supporting it… 'all reification is a forgetting'–making available what has passed at once makes it irretrievable" (p. 52-53). According to Adorno, the intervention of notation into musical practices scuttled a prior unity of imagination, physical gestures, and sounding materials, and it did so by giving musicians a script to follow based on an aesthetically bounded set of sonic parameters. And while it's true that conventions for notating scores in western classical music have tended toward greater exactitude when it comes to identifying certain aspects of sound (e.g., discrete pitches and rhythms), they have struggled to represent others such as timbre, and contextual information regarding playing techniques and instrument design methods are traditionally left outside the frame of the musical text, despite being fundamental to its interpretation. In this way, scores reproduce a hierarchical system of musical values, setting a priori limits on composition and performance practices and offering a vivid illustration of how symbolic representations do not only act as storage containers for memory (à la Bernard Stiegler's *hypomnesis* [1998]), but rather inflect memory and condition access to its content.

In terms of musical instrument design, bodies have long been mapped to acoustic sound-producing mechanisms via playable interfaces, but it wasn't until the introduction of digital data into this equation that a technoscientific concept of "mapping" as such became necessary for describing the control of a technical system. This has to do with the fact that, unlike acoustic instruments, electronic and digital instruments do not abide by physical laws for how gestures and materials produce sounds, so these laws must be programmed. We thus see an extension of writing from sound to gesture,

[1]Epigraph is the 1946 short story "On Exactitude in Science" by Jorge Luis Borges, reprinted from his book Collected Fictions (1998), translated by Andrew Hurley. The story is ascribed to the fictional character of Suárez Miranda.

with both domains described numerically to coordinate their mapping in the context of Digital Musical Instrument (DMI) design (Miranda & Wanderley, 2006). These mappings may be formed between an *ad hoc* assembly of individual parameters or they may be guided by standard protocols, such as MIDI or OSC; either way, they rely on the articulation of musical interactions to a necessarily limited definition of both sound and gesture. The resulting DMI can thus be understood as an instance of what Philip Agre characterizes as a "representational artifact" (1997), in that it models a version of the activity it seeks to be used for. Such representations are neither good nor bad in any inherent or absolute sense, but they pose problems when they become reified and start to function as a source of false objectivity for people unaware of their historical specificity and unconcerned about the consequences of their distributed effects. It is at this point, according to Agre, that a representation becomes "constituted as a kind of imperialism... [because] it aims to reinvent virtually every other site of practice in its own image" (1997, p. 131).

From a slightly different angle, we can think about the mapping of a performer's actions to an underlying system of musical representation by referencing critical interface studies scholars like Wendy Chun and Alexander Galloway. For them, interfaces act as an "allegory" (Galloway 2012) or "functional analogue" (Chun 2011) of ideology by bringing users into relation with a virtual world. As Chun puts it, digital interfaces "concretize our relation to invisible (or barely visible) 'sources' and substructures... they induce the user to map constantly so that the user in turn can be mapped... they offer a simpler, more reassuring analog of power, one in which the user takes the place of the sovereign executive 'source,' code becomes law, and mapping produces the subject" (Chun 2011, p. 59). And yet, as both Chun and Galloway note, interfaces can also be interrogated, and critical approaches to interface design and use can be adopted as a mode of ideological critique by drawing attention to the effects of mediation that are usually concealed. There is, in this sense, a double valence to mapping in digital music interfaces which should temper any analyst's suggestion of technological determinism: designers are not forced to follow well-worn paths suggested by their tools; instead, the introduction of creative mis-uses and the potential to design endless re-mappings around different representations of sound and gesture offer ways to highlight and challenge familiar assumptions around interactive digital technologies.

1.1. Finding bearings: how to read this paper

Examining the multiple valences of *mapping* as a conceptual metaphor in different fields is a helpful starting point for rethinking what it means in the context of DMI design and use. On one level, mapping is a design material. Like brass tubing, steel wire or silicon transistors, mapping can be put to widely varying uses both obvious and obscure. But like linear time-invariant (LTI) systems in engineering, mapping is both a tool and a way of thinking – a practical simplification which can be useful for both analysis and design. Also like LTI systems (and indeed any other conceptual model), mapping is limited rather than universal: just because it can help make sense of the world does not mean the world inherently works that way. Cartography and navigation are two different activities, and problems can arise when a productive metaphor comes to be seen as a neutral paint-by-numbers template rather than a deliberate ideological act.

In probing what happens when a tool becomes a worldview, this paper mixes discourses from engineering, music, science and technology studies (STS) and critical theory. The paper adopts the premise that every technical system is non-universal and ideological (Haraway, 1988), inevitably carrying a host of cultural and political commitments. Our use of the word *ideology* is descriptive rather than pejorative: to interrogate these commitments is not to suggest that alternative technologies could transcend ideology or achieve artistic neutrality (Lepri & McPherson, 2021). The encounter between mapping and the "acid tools of critical discourse" (Haraway, 1988, p. 577) should not be read as an exhortation for designers to abandon current approaches to mapping, nor as a suggestion that instruments which follow the assumptions described in Section 3 must be musically inferior to any other class of instruments. Instead, identifying assumptions and probing associations offers an opportunity to imagine alternate musical worldviews which could coexist alongside current ones.

1.2. Querying assumptions of design as inverted analysis

In this paper, we aim to interrogate mapping in DMIs as an enactive form of notation, showing how it entails constructing a representation of a phenomenon, then inverting that representation into the generative basis of the phenomenon itself. The most ideologically loaded decisions are in the construction of the underlying representation: codifying the complex physical-experiential phenomena of musical instrument performance into symbolic dimensions connected to language and numbers. Such a construction is a necessary step in every DMI design, and a sensitive approach may be one factor that supports what Jordà (2005) describes as the *craftsmanship* of digital lutherie, as distinct from its scientific aspects, or what Cook (2001) describes as "more art than science". Nonetheless, much of the published literature on mapping pushes this construction to the periphery, focusing instead on forms of relationships between already-theorised representations of gesture and sound, and adopting metaphors from engineering and mathematics to make a discourse about relationships intelligible. In doing so, current discourse borrows from a number of historical antecedents in telecommunications engineering, modular synthesis and music theory which come with their own ideological baggage. We want to shine a light on some of this history, examine its role in shaping present-day discourse, and ask questions about other ways we might conceptualise DMIs as relational entities, with both interior and exterior relationships.

In the next section, we will first examine several key periods in the development of mapping discourse: its early origins as a technical concept and a term of art with roots in engineering and mathematics; the period of the late 1990's and early 2000's when much of the present-day theoretical infrastructure was formalised; and recently renewed interest in mapping-by-demonstration and machine learning which, though remediating ideas from decades earlier, serve to move mapping beyond an explicit formal specification and bury its effects more deeply within the fabric of an instrument. We will then step back to examine the way that mapping systems, and indeed all DMIs, reify musical and technical descriptors into the essential ingredients of design. We highlight three specific assumptions which, though not necessarily universal, are widely accepted in the mapping discourse:

(1) *Representational stability*, in which concepts, once described, can then act as ingredients for design without disrupting the validity of the original description;
(2) *Spatial metaphors*, in which musical systems are proposed to consist of two more dimension spaces whose relationships are specified through mapping;
(3) *Unidirectionality*, in which mapping is conceived as a directed flow of control data drawing on an engineering model of modularity and impedance bridging.

In the final section, we will conclude by speculating on extended or alternative mapping discourses, in which temporality is given equal importance to spatiality, systems act through a bidirectional process of equilibration rather than unidirectional control, and in which musical concepts and representations are themselves malleable through processes of design, exploration and performance. We situate these alternative views in an emerging discourse of so-called *entanglement* theories of human-computer interaction (Frauenberger, 2019), drawing on post-humanist theories in sociology and science and technology studies. Ultimately, the purpose of the paper is not to propose an ostensibly "better" or more universal framework for instrument design, but to highlight that no discourse or notation system can ever be universal, and to call attention to prevalent habits and assumptions while asking how else a designer might operate from within an entangled state with their technical, aesthetic and social context.

2. Background: Origins and Influences of Mapping as a Concept

"Mapping" describes and specifies relationships. In the musical instrument literature, the salient relationship is typically between action and sound – between numerical measurements of (mainly) human activity and control parameters of sound-producing technical systems. Every musical instrument, regardless of technology or design process, could be described as having action-sound relationships, and centuries of musical acoustics literature is concerned with describing and modelling them. Our focus in this paper is more specifically the use of mapping as a generative principle of instrument design, where mapping moves beyond retrospective analysis to become a formal specification or notation system for creating new (mostly digital) instruments.

The origins of mapping far predate the emergence of the term as a focal area of DMI research. Teboul (2024) explores the origins of modular audio synthesis, which burst into the popular imagination in the 1960's with the analog synthesisers of Robert Moog and Don Buchla (T. Pinch & Trocco, 1998) but whose engineering foundations date to earlier work by Hugh Le Caine (Young, 1989), Harald Bode and others. As Teboul explores, the logic of modularity draws on a long history in telecommunications engineering and industrial infrastructure. Two basic principles of modular systems have important implications for understanding present-day discourse in mapping:

(1) *Impedance bridging* (Teboul, 2024, p. 26), an electrical configuration in which low-impedance outputs are connected to high-impedance inputs. Impedance bridging allows the conceptual separation of circuits into independent modules, where the output of a module is minimally affected by what it connects to, and each module can be analysed as a self-contained entity. Impedance bridging also allows the ready reuse, substitution and reconfiguration of black-boxed modules, a foundational principle across many industrial systems.
(2) *The association of signals and concepts*, a material and discursive phenomenon wherein "signals are voltages and currents, physical quantities whose meanings are socially (re)constructed" Teboul (2024, p. 22). The control voltage (CV) is the canonical example, wherein a musical phenomenon can be conceptualised, quantified and turned into a means of control through particular material configurations, be that an analog device such as an operational transconductance amplifier (OTA) or an analog-to-digital converter (ADC) and digital signal processing algorithm.

These two principles of modularity underpin nearly all formalisations of mapping in digital instruments. Figure 1 shows an example block diagram based on an illustration

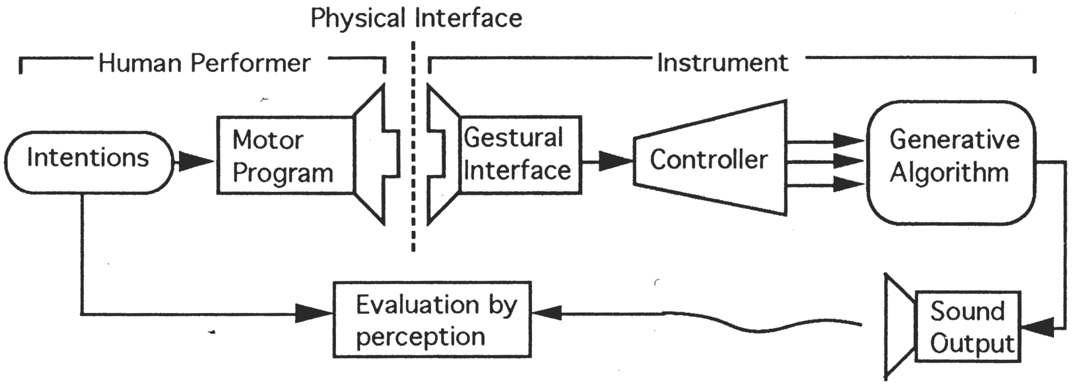

Figure 1. Caption: Schematic diagram of digital musical instrument and mapping, originally from Lee and Wessel (1992) and frequently remediated and extended by other authors. **Alt Text:** A black diagram drawing representing a mapping system, with labelled boxes connected with directional arrows. Left to right on the top row: Intentions, Motor Program, Gestural Interface, Controller, Generative Algorithm. On the bottom row, Generative Algorithm connects to a box labelled Sound Output. A box labelled Evaluation by Perception has arrows connecting from Intentions and from Sound Output.

by Lee and Wessel (1992). While the first instance in the literature of such a diagram is unclear, the general form behind Lee and Wessel's diagram has been widely reproduced and reconfigured over 30 years (see, for instance, similar diagrams in De Campo 2014; Rovan, Wanderley, Dubnov, and Depalle 1997; M. M. Wanderley and Depalle 2004; D. Wessel and Wright 2002). In particular, the signal-processing distinction between inputs and outputs, illustrated by directional arrows between discrete units, is made possible conceptually by impedance bridging and enabled materially by computing hardware and algorithms that distinguish between data sources and destinations. As we will see in Section 3, viewing musical systems in this way is a choice and not an inevitability.

According to Teboul's account, the relationship between early digital synthesis and analog modular synthesis was reciprocal; for example, Max Mathews developed the influential MUSIC-N languages contemporaneously with Moog and Buchla, with some evidence of common sources and mutual influences. Early digital synthesis was heavily influenced by Claude Shannon's information theory (Chowning, 2014; Shannon, 1948), and the digital musical instrument literature has taken Shannon's influence in other directions, such as considering interaction bandwidth as a marker of "control intimacy" (Jack, Stockman, & McPherson, 2017; D. Wessel & Wright, 2002). In turn, the associations between information theory and musical interaction point to an ongoing line of influence from early human-computer interaction (HCI), particularly HCI's so-called "second wave", "organized around a central metaphor of mind and computer as symmetric, coupled information processors" (Harrison, Tatar, & Sengers, 2007). However, it is important not to overstate the centrality of HCI to present-day mapping discourse, as the field inherits from many traditions (M. M. Wanderley, 2023).

2.1. Formalisation of mapping as a concept

There appears to be no single watershed moment when *mapping* enters the literature as a term of art. Early work focuses on assigning control parameters to musical systems, though without the specific term "mapping". D. L. Wessel (1979) speculates on how the recently-proposed model of "timbre space" (Grey, 1977) might be repurposed as a control interface: the “most natural way to move about in the timbral space would be to attach the handles of control directly to the dimensions of the space” (p. 51). Waisvisz (1985) writes of his instrument The Hands: “An important experience gained from playing with the Hands was of possibilities for control signal manipulation. Rescaling, patching, and other treatments, i.e. the application of a control-signal algorithm, are the main factors through which a controlling device derives its effectiveness” (p. 1). Similarly, the manual for the Buchla Thunder controller (McMillen, 1990) describes control “configurations” in similar terms to what the current literature would call mapping. But it wasn’t until the early 1990s that more computer music papers dealing directly with mapping strategies increasingly appear. See, for instance, Bowler, Purvis, Manning, and Bailey (1990), who present mapping as a mathematical projection from “articulation parameters” to “control parameters” using interpolation between known points; or Lee and Wessel (1992), who propose a control theory framework in which “controllers map musical intentions to the parameters of a synthesis or compositional algorithm”; or again, Fels and Hinton (1997), who examine mapping strategies for a glove-controlled speech synthesiser. Further context on the work of this era can be found in M. M. Wanderley (2023).

It seems likely that the term *mapping* would have been intelligible to researchers from the 1980’s and perhaps earlier. But in the second half of the 1990’s, a shift in discourse gradually emerges in which mapping moves to the centre of written accounts (even where the same papers also describe specific instrument designs). Rather than being an afterthought to accounts of specific sensor and synthesis technologies, mapping gains currency as an abstract and generalisable concept that can be freely transported to different systems and contexts. Topics of analysis include relationships between dimensions (e.g. one-to-one or many-to-many; linear or nonlinear; see Hunt and Wanderley (2002); Hunt, Wanderley, and Kirk (2000)); modelling mappings on traditional acoustic instruments (Rovan et al., 1997); multilayer mappings based on human perception which offer abstraction from specific sensors and synthesis algorithms (Arfib, Couturier, Kessous, & Verfaille, 2002; Hunt, Wanderley, & Paradis, 2003). The endpoints of mapping also begin to shift; rather than mapping specific individual sensors to synthesis parameters, the ideology is more abstractly expressed as relationships between gesture and sound, opening up further questions of how these endpoints are parameterised (M. M. Wanderley & Depalle, 2004). While this paper is not intended as a comprehensive review, the edited collection *Trends in Gestural Control of Music* (M. Wanderley & Battier, 2000) and the 2002 special issue of *Organised Sound* (vol. 7, no. 2) offer a wide-ranging contemporary account.

Starting in the 2000s, software toolboxes for creating mapping systems become more frequent, such as the MnM toolbox for Max (Bevilacqua, Müller, & Schnell, 2005), the Mapping Library for Pd (Steiner & Henry, 2007), the *libmapper* framework (Malloch, Sinclair, & Wanderley, 2013) and STEIM’s 2003 *junXion* by Michel Waisvisz and Frank Baldé (Torre, Andersen, & Baldé, 2016). This flourishing of both theory and software may be practical as much as ideological: the emergence of standard protocols like MIDI in the 1980’s created an opportunity for design frameworks to interpret and manipulate their data. Mapping theory also benefited from, and helped shape, software packages like Max (created by Miller Puckette at IRCAM in the late 1980’s) which promise control over abstract data relationships (Zicarelli, 2002), as well as later protocols like OSC which provide containers for abstract structured data. Puckette (2002) describes his efforts “to avoid [Max] imposing a stylistic bias on the musician’s output”, while acknowledging that stylistic neutrality may be unattainable in any tool. Indeed, mapping packages, like every other piece of music software, inevitably carries idiomatic patterns that invite certain ways of thinking about music (McPherson & Tahıroğlu, 2020); in turn, idiomatic patterns can have measurable effects on the decisions of instrument designers (Lepri & McPherson, 2021). We will return to some of these ideological questions in Section 3.

2.2. Explicit and implicit mappings

Mapping commonly involves the creation of explicit formulas or relationships between numerical parameter spaces. An alternate approach, which also dates to the early days of mapping as a formal concept, involves inferring mappings implicitly through known examples (Hunt & Wanderley, 2002). Goudeseune (2002) proposes "interpolation mappings" using simplex methods or bilinear/trilinear interpolation, building on a simplex interpolation scheme by Bowler et al. (1990). The premise is that continuous mapping relationships can be inferred by interpolating between example pairs of inputs and outputs. Similar logics of mapping-by-example underpin machine learning tools like the early neural network explorations of Lee and Wessel (1992) or the widely used Wekinator (Fiebrink & Cook, 2010). Many interpolation mappings struggle with extrapolation outside known examples. Some machine learning systems (though not all) can extrapolate beyond their training set under certain conditions (e.g. the DDSP timbre-transfer model which can extrapolate to pitches not seen during training (Engel, Hantrakul, Gu, & Roberts, 2020)). For a review of implicit mapping strategies, see Françoise and Bevilacqua (2018).

Implicit mappings face a challenge of how to identify training examples. Building on ideas of "sound tracing" (Godøy, Haga, & Jensenius, 2006), Fiebrink, Cook, and Trueman (2009) propose play-along mappings which invite a musician to listen and demonstrate gestures synchronously with a sound as a means of generating training examples, an approach that also underpins Françoise's "mapping by demonstration" (2015) and "mapping through interaction" (Françoise & Bevilacqua, 2018). These systems make the assumption that a motion a player produces in response to listening to sound can be effectively inverted as a controller of that sound. In turn, this assumption reproduces the way that mapping inverts analytical descriptors into means of control, and in fact makes this analytical inversion a direct part of the design process.

One concern with the influx of implicit methods is what it means for our ability to reverse-engineer what are essentially black-boxed algorithms (e.g., in auto-encoders); this task is critical to understanding the kinds of ideologies embedded in practices of digital instrument design and use, as well as for finding space to leverage critiques, and ultimately, for taking ethical responsibility for the specific systems of representations that musical devices perpetuate (Hayes & Marquez-Borbon, 2020; Jourdan & Caramiaux, 2023; Morreale, Bin, McPherson, Stapleton, & Wanderley, 2020).

2.3. Temporal mapping

Most early mapping is temporally static, proposing relationships between a perpetual "now" of sets of input and output parameters in what Caramiaux, Françoise, Schnell, and Bevilacqua (2014) call "instantaneous mappings". We will explore the implications of this framing in Section 3.2. Time gains an explicit foothold in recent work, where gesture is modeled as a trajectory in a parameter space over time. For instance, Gesture Follower (Bevilacqua et al., 2009) uses Hidden Markov Models to match parameter trajectories to template gestures, while Gesture Variation Follower (Caramiaux, Montecchio, Tanaka, & Bevilacqua, 2014) and subsequent work (Françoise & Bevilacqua, 2018) extend the temporal model to geometric movement features (e.g. scale, rotation) with respect to a template. In these models, classifying gestures and tracking their position can be performed in real time, though necessarily with latency.

These models offer a specific account of temporality which focuses on co-evolution and (re)synchronisation between movements and sounds that each evolve over time. Bevilacqua, Schnell, Rasamimanana, Zamborlin, and Guédy (2011, p. 137) describe the need for the user to "record a gesture while listening to an audio file" so the system can "learn a gesture template that is actually synchronous with the original audio recording". Having completed this training step, the performer can then navigate through a time-variant relationship between movement and sound parameters which evolves over the scale of seconds to minutes, dependent on the result of segmentation algorithms.

2.4. Mapping generative and compositional systems

Like many high-profile ideas, mapping has attracted critiques almost as soon as it gained traction. The most prevalent critique holds that mapping, particularly in its early formulations, unnecessarily constrains digital musical instrument design to behave like traditional acoustic instruments. In a keynote at the NIME conference, Chadabe (2002) argues that mapping is insufficiently suited to complex generative systems, reflecting a contemporaneous debate about instruments as "reactive" versus "interactive" systems (Bongers, 2000). Linson (2011) arrives at a similar critique by arguing that digital system designers inappropriately flatten human intentionality and physical causation into the same process. In Section 3.1 we will develop Linson's critiques in a different direction.

Mapping has also extended to a means of controlling generative systems (Doornbusch, 2002). A particularly enduring approach is the notion of the "composed instrument", where mappings become part of a compositional process (Murray-Browne, Mainstone, Bryan-Kinns, & Plumbley, 2011; Schnell & Battier, 2002). Echoing mapping as a form of notation (Section 1), Magnusson (2010, p. 65) writes of all DMI design: "Considering all the available parameters and functions, mapping should be defined as a compositional process that engenders a structure of constraints."

3. Assumptions and Limitations

The previous section offered a brief historical and critical account of several issues underpinning mapping as a generative principle of instrument design. By the 2010s, in a process that STS scholars would describe as "stabilisation" and "closure" (T. J. Pinch & Bijker, 1984), mapping had become pervasive to the point of being conventional wisdom: not merely one useful tool for design or analysis, but an essential and indispensable ingredient of what all DMIs are – a situation not necessarily foreseen or endorsed in the key papers from the 1990's and early 2000's which introduce the concepts that have since come to be taken for granted. Mapping in a particular canonical form is now deeply ingrained in most introductory syllabi on DMI design (De Campo, 2014), arguably because the very definition of a digital musical instrument has evolved to make mapping an integral part of we take a DMI to be.

In this section we offer three critiques of current mapping discourse, drawing out areas where the prevailing consensus obscures or sidelines promising alternatives. Our take is ultimately optimistic, and in Section 4 we speculate on how mapping could be expanded beyond current perspectives to suggest new approaches to instrument design.

3.1. Mapping reifies descriptors about music into its generative ingredients

Designing computational systems inevitably entails making symbolic representations of worldly phenomena (Agre, 1997). The challenge is how not to forget that a process of representation took place and subsequently "conflate representations with the things that they represent" (ibid, p. 8). Linson (2011) observes a similar pitfall in DMI design, explaining that "it is a common practice in some fields of social research to observe how humans act in the physical world and to extrapolate from the data a formalisation of what must be going on. Identified by Pierre Bourdieu and elaborated upon by Dreyfus (1992), the common mistake is the supposition that 'the rules used in the formalization of behaviour are the very same rules which produce the behavior'" (p. 422).

In a related vein, Van der Schyff (2015) comments on the tendency of designers and educators toward *reification*: "seeing the world through conceptual categories which, if not carefully seen through, gives the seer the illusion that reality inherently comes in these categories." (Bai 2003, p. 8, quoted in Van der Schyff 2015). So, if control signals in modular music systems are "physical quantities whose meanings are socially (re)constructed" (Teboul, 2024), who constructs these meanings, and how? According to Van der Schyff (2015), "reified notions of music emerge from and reinforce ingrained cultural ideologies.... it assumes music to be an objective 'thing' rather than an interactive, relational, multi-modal activity".

One of the mapping literature's greatest strengths is also its greatest liability: the proposed generality of mapping strategies. Analysing structures of connected parameters as engineering formalisms, independently of what musical scenario those parameters are intended to represent, promotes transferable technical knowledge. However, it also means that most of the ideological heavy lifting takes place in formulating the conceptual space itself. Constructing a conceptual and numerical representation of music (and typically of human gesture) is a precondition of theorising functional relationships between elements. And because mapping assumes these representations to be the defining elements of the interface and sound generator, descriptors *about* music get inverted into its generative ingredients: the digital musical instrument is indeed a "representational artifact", with the corresponding risk of reinventing musical practice in its image (Agre, 1997; Magnusson, 2021).

Representation is unavoidable in symbolic systems. It can be handled carefully and artfully, and it may be exactly what the designer wants to do. Nonetheless, designers should also maintain awareness of which musical ideologies are represented in an instrument and how (McPherson & Tahıroğlu, 2020). A challenge is that having initially forged an association between concepts and signals, the designer may struggle to rethink what else those signals might mean, even if the very act of using the signal as a lever of control might alter its meaning; it often takes another musician to reinterpret and rediscover such alternative meanings (Magnusson, 2010; Tahiroğlu, 2021). In other words, mapping as currently formulated tends to take conceptual meanings of signals as fixed and stable reference points around which other design decisions can be made, rather than seeing them as contingent and malleable qualities.

3.2. *Abstract spatial metaphors lack grounding and obscure other important factors*

Dimension spaces loom large in the mapping literature, particularly in literature on implicit or interpolation mappings. In mathematics, "map" or "mapping" denotes a function which specifies a relationship between two domains. Musical mapping is often concerned with the dimensionality of input or output spaces, commonly describing design problems as relating N control parameters to M synthesis parameters (Bevilacqua et al., 2005; Bowler et al., 1990) and the subsequent geometrical and computational properties of doing so (Van Nort, Wanderley, & Depalle, 2004). Technology-centred approaches to mapping tend to focus on the dimensionality of sensor systems and synthesiser controls, while perceptually-motivated approaches instead seek multidimensional representations of abstract notions of gesture and musical sound (M. M. Wanderley & Depalle, 2004). In both cases, discussions of dimensionality are bolstered by an information processing model of sound and listening, which finds its early expression in the spatializing practices of psychoacoustics and auditory cognition, as can be seen, for instance, in the historical rise to prominence of "timbre space" as a conceptual metaphor for the multi-dimensionality of timbre perception (Morrison, 2024).

The mapping of dimension spaces in the sciences can be better understood when read against the grain of a larger "spatial turn" in the humanities (Warf & Arias, 2008). Emblematic of this turn, historians of science like Lorraine Daston and Peter Galison (2007) have traced paradigmatic shifts in representations of objectivity through an extensive analysis of images in scientific atlases ranging from the Enlightenment to Modernity, showing how evolving instrumentation elicited successive representations of objectivity based on what they describe as "truth to nature," "mechanical reproduction," and "trained judgement." More specifically, regarding knowledge of sound, Krämer (2023) has drawn attention to "flattening as cultural technique" in the production of musical scores and analytical diagrams, and Seaver (2021) has analyzed the use of "spatializing techniques for analyzing cultural data" in the context of digital music recommendation systems. But perhaps most apropos for the current consideration of mapping is Henri LeFebvre's post-Marxist theory of the "production of space" (1991), which recounts how abstract spaces spawned by science tend to become the "locus of a 'theoretical practice' which is separated from social practice and which sets itself up as the axis, pivot or central reference point of knowledge" (p. 6). We see here a clear concern with the epistemic import of inscribed surfaces and spatial modes of representation, which don't passively depict reality, but rather actively mediate people's access to it, setting conditions on what counts as scientific (and musical) knowledge.

In the context of DMI mapping, attending only to the properties and relationships of dimension spaces leaves unanswered whether a spatial metaphor is appropriate to begin with. This is because spatial metaphors dangle the promise of insights by leveraging our physical intuition and by repurposing geometric formalisms that apply to (typically Euclidean) mathematical spaces. But it is unclear how often an intuitive analogy of physical space extends far enough to be insightful, or when an amalgam of quantified musical descriptors meets the formal definition of a Euclidean space. Hence, the very detachment that gives spatial approaches to mapping their apparent generality also risks making them overly fixed and unresponsive to the variability of social practices.

In the previous section, we argued that much of the ideology of mapping happens in the process of constructing representations rather than how they are subsequently manipulated, and that this process receives insufficient attention. Similarly, the construction of spaces – the choice of N control dimensions and M sound dimensions – receives less attention than the possible relationships once they are chosen. Without careful grounding, these choices can be essentially arbitrary. The number of sensors affixed to a control interface, or the number of movement features extracted from a complex hand- or body-tracking camera, could vary by an order of magnitude. Whether the dimensions chosen are orthogonal or even linearly independent is also not guaranteed (Jacob, Sibert, McFarlane, & Mullen Jr, 1994); an arbitrary collection of features might not even obey the principles of a metric space (e.g. distances being symmetrical and obeying the triangle inequality). Without such guarantees, formal mathematical techniques lose applicability. Mapping as spatial analogy may still function as a post hoc descriptor of how an instrument works, but even where mapping has been used to create excellent instruments, the abstracted spatial theory may lack predictive power as to what design choices are likely to be the most successful in other contexts.

Spatial thinking in digital musical systems also tends to be temporally static. Aside from a stream of literature concerned with temporal alignment of gesture and sound trajectories (Section 2.3), most mapping strategies focus on translating a point in space X into a point in space Y, at one particular instant in time (Caramiaux, Montecchio, et al., 2014).[2] Time is implicit in this formulation: to play an instrument is to create a trajectory in control space which is mapped isochronously to a trajectory in musical parameter space. In the most stringent formulation, the relationship between X and Y is memoryless, with the current position in output space Y dependent only on the current position in input space X, allowing no path dependency, hysteresis or other influence of prior samples. Temporal preprocessing of sensor signals, such as accumulation or differentiation, can be factored out of the mapping diagram to a *signal conditioning* step to preserve the conceptual clarity of the instantaneous mapping while allowing certain types of memory and path dependency within individual parameters (Van Nort, Wanderley, & Depalle, 2014).

Returning to the mapping diagram in Figure 1, an issue with elevating spatial thinking over temporal thinking is that different parts of the diagram need not unfold on the same time scale. Human intentionality is complex, containing both high-level cognition and low-level sensorimotor skills with different time scales. Instruments may have intrinsic mechanical or electrical behaviours that unfold on a faster timescale than human muscular movements, and can neither be reduced to a theremin-like continuous association nor a MIDI-like discrete trigger. When an instrumental model contains feedback loops, these might be delay-free in certain cases (e.g. modelling the behaviour of interconnected analog circuits in a guitar amplifier) while involving significant delays in others (e.g. sound travelling within a space). Audio signals themselves may contain patterns which are only meaningful with respect to a significant window in time (e.g. frequency), while other patterns in the same signal might be salient on a much shorter timescale (e.g. transients or edges).

Bowed string instruments exemplify the challenge of temporally static mapping relationships. When the performer first begins to draw the bow, a complex transient will unfold over tens of milliseconds – non-instantaneous but also faster than any performer can consciously controls moment-by-moment. Though the performer may set their bodily conditions (e.g. force or stiffness of different joints) in anticipation of how the string will react, on the millisecond scale the performer and instrument do not constitute a classical feedback system (listen, feel and react).

[2]Some mapping strategies are even more temporally reductive, translating a point in space to the triggering of a sound of fixed duration.

A designer seeking to create a violin-like DMI might draw a mapping diagram based on familiar concepts like pitch, dynamics and note onsets. But these are post-hoc analytical frames rather than the literal acoustic basis of the instrument (Reed, Benito, Caspe, & McPherson, 2024), and the concepts lose meaning when trying to understand complex transient behaviour on a scale of milliseconds. Alternatively, the designer could create a detailed mathematical model of the violin's acoustics, using audio-rate signals throughout the system and localised feedback loops where resonant systems couple to one another, and possibly even extending to force-feedback devices (Florens, 2003). However, such an effort quickly explodes in computational complexity, and it does not immediately yield musical insight on how to design violin-like DMIs not based on those literal physics. Ultimately, there is no simple way that varying timescales of activity can be reconciled within any static diagram which assumes equivalent snapshots in time across the whole system.

3.3. Mapping diagrams artificially suggest unidirectional relationships between well-defined subcomponents

A ubiquitous characteristic of mapping diagrams such as Figure 1, and replicated in nearly every mapping model, is the unidirectionality of the arrows. Mapping is characterised as a directed graph with signals flowing in a mostly forward direction except for limited channels of feedback such as listening. Unidirectionality is a conceptual and practical convenience. It allows modularity through impedance bridging (Teboul, 2024) where subsystems can be separately analysed and reconfigured (see Section 2). Digital microprocessors as material and algorithmic artefacts are designed to to work in a single direction; the distinction between data source and destination is ingrained at an electrical register level. Many familiar audio synthesis techniques, from FM synthesis to sampling and granular synthesis, similarly assume clear distinctions between inputs and outputs. Unidirectionality, like LTI systems in engineering, can be a useful approximation for design. But it is crucial to keep in mind that these are approximations and do not completely define or represent worldly phenomena.

This limitation been pointed out early on by Castagné, Cadoz, Florens, and Luciani (2004). Indeed, unidirectional connections, while well representing the flow of data from interface to synthesiser (e.g., through a MIDI connection), fail to consider the complexities of systems where their outputs might influence their inputs, for instance, in the case of loading effects. It is interesting to note that interpolation models also have the same limitation, even when representing more complex mappings. The truly pioneering work at the Association pour la Création et la Recherche sur les Outils d'Expression (ACROE), in Grenoble, France, summarized in M. M. Wanderley and Frisson (2023), focused on developing responsive systems involving physical modelling of sounds and force-feedback output. These systems took into account many of the complexities lacking in the unidirectional mapping model at the expense of more expensive input devices due to the need for high-quality actuators to display forces.

Several stages of any performer-instrument relationship have bidirectional dependencies. We can begin with the apparent flow of volitional control from performer to instrument. Sheridan describes couplings between the human and the environment as "two-way interactions which are sufficiently tight that causality between human and environment is obscure and even arbitrary": the human and environment have a constant effect upon each other, sharing the same dimension space (Sheridan, 2002). Musical instruments exert a substantial influence on the performer; they "are not only in charge of transmitting human expressiveness like passive channels. They are, with their feedback, responsible for provoking and instigating the performer through their own interfaces" (Jordà 2005, cited in Gurevich and Treviño 2007). The way that intentionality is shaped and guided by the instrument is frequently discussed in the literature (Magnusson, 2010; Nijs, 2017; Tahiroğlu, 2021). However, it is difficult to reconcile this mutual influence with the simplified model of feedback often found in engineering, wherein unidirectional inputs feed a system consisting of a chain of modular elements with a single aggregated feedback route from output back to input. Lee and Wessel (1992) acknowledge as much about their diagram: "One aspect that is not well captured by it is the way in which performers' intentions are elaborated upon by discovery of new possibilities afforded by the instrument."

Viewing the performer-instrument coupling as bidirectional and evolving helps address other scenarios. For instance, a snare drum roll, as O'Modhrain and Gillespie (2018) describe, is a mutual interaction between energy stored within the drum and within the hand and stick of the performer. To control the oscillation rate, the player modulates the stiffness – or mechanical impedance – of their hand. Such an interaction cannot be fully described with a unidirectional model of the instrument system. Even a model that describes the interaction as occurring in two directions does not fully capture the true coupling occurring in the process. It cannot simply be viewed as two discrete unidirectional channels of interaction but rather a constantly evolving equilibrium between instrument and performer; a continuous coupling that affects both entities. In this sense, when considering gestural interaction, there exists a mechanical sympathy between performer and instrument (Delfa & Garrett, 2024). This process develops alongside the performer's musical familiarity with the instrument, often subconsciously as a matter of sensorimotor learning.

Similar matters of bidirectionality apply within an instrument. Even leaving aside the relationship to the performer, it is often limiting to consider each element of an instrument as a one-way transfer function. For instance, one might be tempted to model a string instrument as a succession of unidirectional elements: energy is introduced to the system through the performer plucking or bowing the string, and that energy is then transferred through the bridge into the resonant body and subsequently into the air. In reality, however, each physical element imposes its mechanical impedance on the other elements (Gough, 1981). The coupling between body and air propagates back to the string vibration itself, which is why the banjo has a shorter sustain than the electric guitar. These mutual dependencies can even determine when and how stable pitched sounds can be produced at all, as in the complex coupling of string and body resonances known as the "wolf tone" on bowed string instruments (Woodhouse, 1993). Similarly, the impedances and nonlinearities of analog electronic components, such as those found in tube guitar amplifiers, exert a mutual influence all the way from the guitar pickup to the speaker cone.

Van Nort et al. (2014) describe mapping as a process that can be inverted, where a mapping function also has an equivalent inverse function that "undoes" the mapping. This lays some initial conceptual groundwork for bidirectional interaction and parameter manipulation through the process of mapping, but true bidirectionality will require both new theoretical and practical tools. One example comes from analog electronic circuits, which can be modelled through mathematical structures like wave digital filters, where each element connects to each other element with two signals running in opposite directions, and the whole system is tuned through iterative approximation (Werner, Bernardini, Smith, & Sarti, 2018). Acoustic systems can be computationally modelled using a variety of approaches that consider the mutual intercoupling of elements (Bilbao et al., 2019). These tools may offer helpful analogies for thinking about mapping in DMIs as a bidirectional process.

Bidirectional coupling between physical and digital domains remains a practical engineering challenge. Most sensors, actuators, speakers and microphones operate in a single direction only. While nods to feedback from listening (Lee & Wessel, 1992) or from haptic side-channels (O'Modhrain & Gillespie, 2018) offer partial remedies, realising true bidirectionality across every layer of a digital instrument will require new devices that function simultaneously as sensors and actuators (Davison, Webb, Ducceschi, & McPherson, 2024).

Recent work at ACROE has introduced a complete, real-time responsive system that overcomes many of the limitations of simplified unidirectional mapping models (Leonard, Cadoz, Castagné, Florens, & Luciani, 2014). However, reciprocal influences and and blurred human-machine causality are not limited to acoustic instruments or to sophisticated audio-haptic systems; reciprocality is a property of any instrument, even DMIs following conventional unidirectional design principles (Tuuri, Parviainen, & Pirhonen, 2017). Even without active haptic feedback, the feeling of knobs, buttons, keys and other physical elements of a DMI will affect the performer's relationship to it, as will the performer's anticipation of its sound. The challenge this presents to mapping discourse is not that all instruments must incorporate haptic side channels, but rather how to theorise these mutual couplings within a framework that is designed primarily for unidirectional data flows.

In other words, unidirectional connections raise the stakes for the modularisation of a system. When information can flow in one direction only, fixing the location of boundaries between modules becomes extremely important. Consider debates over where the player ends and the instrument begins – are the trumpet player's lips part of the human or the instrument? (Alperson, 2008) – or where the instrument ends and the environment begins (is the PA system part of the DMI?). These questions, and internal questions of where control layers give way to mapping layers give way to sound synthesis, lose some of their urgency when it is accepted that information always travels in both directions anyway.

Linson (2011), in addition to critiquing the conflation of human intentionality with mechanical cause and effect, urges attention to the larger context: "When our design concern is with the potential musical effects we can achieve, the human-DMI interaction model must be situated within the wider context of the music being performed." More generally, reconciling the directed graphs of mapping discourse with the complex mutual influences of ecosystemic perspectives of musical performance (Stapleton & Davis, 2021; Waters, 2021) remains an open challenge.

4. Discussion: Present and Future of Mapping as a Design Tool

4.1. The map is not the territory: flexible use of mapping tools

Section 3 highlights some of the ways in which mapping discourse is non-universal and non-neutral, elevating certain ways of thinking while struggling to account for others. However, as Chun (2011) and Galloway (2012) discuss, interface designers and users need not uncritically follow the most obvious paths suggested by their tools. Moreover, even instruments that wholly subscribe to aforementioned ideology can be musically successful: The Hands, the Radio Baton (Mathews, 1991) and the Yamaha DX7 all feature unidirectional control relationships and arguably rely on spatial metaphors and stable concepts, and all three have been highly influential in different ways. Even in an academic environment that values generalisable knowledge over individual design instances (Morrison & McPherson, 2024), the instrument is not the same thing as its mapping theory.

Returning to the LTI systems analogy from Section 1, several things can be simultaneously true: that a tool is useful; that it is partial and limited; that a skilled designer can work within those limits and know when to deploy other tools; and also that overstating its generality or objectivity can lead to problems. Take the example of digitally modelling (often nonlinear) analog audio effects such as classic distortion pedals: it is well-established that a static (memoryless) nonlinearity combined with linear filters will not provide an accurate simulation, so a whole research domain has emerged developing mathematically sophisticated and computationally complex approximations of the dynamic nonlinear behaviour of analog circuitry. But when the constraint of emulating a specific analog circuit is removed, for example in textbooks on digital audio effect programming (Reiss & McPherson, 2014; Zölzer, 2011), "distortion" as a class of effects often collapses down to simple static nonlinearities with optional LTI filtering – mainly because this is easy to conceptualise and implement. Along similar lines, a study of designing simple DMIs under tight time constraints (Lepri & McPherson, 2021) found that linear mappings were far more prevalent than any nonlinear relationships, even where the underlying domains (such as pitch perception and audio amplitude) operated on logarithmic principles, because linear relationships were easier to express with the available tools.

From these examples, we speculate that mapping in its classical forms may be at its most useful when counterbalanced with strong extrinsic constraints such as emulating well-known instrumental models (Rovan et al., 1997) or long-term public performance practices (Torre et al., 2016). Conversely, the greatest risk of reification in mapping theory may arise from under-constrained design activities, especially when conducted by novice designers or by engineers who do not bring well-defined musical aesthetics that can create productive dissonance with the technical ideology of mapping systems.

A notable case of such productive dissonance between artistic and technical ideology is the growing number of instruments based on electrical or acoustic feedback (Eldridge, Kiefer, Overholt, & Ulfarsson, 2021; Magnusson, Kiefer, & Ulfarsson, 2022). Even the most conventional unidirectional mapping system, when enclosed in a feedback loop, acquires a number of intriguing properties. Apparently tidy concepts become destabilised, as in the unusual behaviours of gain faders in no-input mixing (Mudd, 2023). A circular chain of causality means that every element potentially exerts influence on every other, producing emergent bidirectional relationships. Meanwhile, new temporal dynamics as well as new steady-state behaviours can emerge, giving rise to interesting inflection points for control (Mudd, Holland, & Mulholland, 2019). But what should be the proper role for formalised mapping theory in a practice built on deliberate subversion of technical systems? Perhaps future directions in mapping can balance the predictive and explanatory utility of engineering tools with greater flexibility toward exploratory design and more explicit acknowledgment of any theory's inevitable limitations and partialities.

4.2. Moving off grid with intra-active mappings

To the extent that this paper critiques the language of mapping, the critique is not around the methods themselves, but rather their over-generalisation as a universal explanatory mechanism for instrument design. No theory or formalisation is ever universal; they are a lens that puts certain ideas at the centre and moves others to the periphery. And yet, as evidenced by its ubiquity as a perennial topic of interest at the NIME conference, mapping has taken hold as an expansive and widely used model in DMI design (although there are others, e.g., Waters 2021 and Tahiroğlu 2021, who focus on the interpretation, appropriation and reconstruction of technical systems with a view to social context). We would rather emphasize the need for a more "relaxed grip" on designing with movable boundaries (Reed, Morrison, McPherson, Fierro, & Tanaka, 2024), working in a space where nothing is fixed a priori but everything comes into existence through mutual relations.

We can't and won't elaborate an entirely new theory of mapping in this paper, and following Agre (1997), the critiques in Section 3 should not be read as specifications for a technical system which would solve those problems and thereby constitute a quantifiable improvement on the state of the art. Instead, we will close by at least suggesting (as we have elsewhere at greater length; see Morrison and McPherson (2024)) that a relational theory of mapping might serve to elicit new ideas for design and analysis, and that one possible path in that direction might be found in the post-humanist sensibility of entanglement. As described by Barad (2007), entanglement holds that humans and nonhumans "intra-act," becoming mutually constitutive of one another in the context of relational phenomena formed without pre-existing relata. Similarly, mapping calls attention to relationality as a key factor in digital instruments, moving attention away from specific objects and systems (e.g., sensors, synthesisers) to how their internal relationships determine the orientation of a technical system in relation to a larger social-aesthetic context. But to make the most of this focus, we need to rethink the nature of mapping relationships: not necessarily as unidirectional control streams, connecting fixed and static representations through sophisticated but contestable analogies; but rather as dynamic and flexible connections that operate bidirectionally on several simultaneous registers (conceptual, informational, intentional, social) while also reconfiguring the endpoints that they connect.

Returning once more to the classic diagram of mapping posed in Lee and Wessel (1992), we might imagine an alternate arrangement where the arrows become bidirectional at every stage, and in fact, begin to point outside of the closed loop between intending performer and sounding instrument, thus incorporating epicyclic dynamics generated by the material conditions and cultural techniques that support any particular mapping. Going further, the boundaries between entities, and the very conceptual categories used to define the entities involved in mapping, might become less fixed and more fluid, contextual, and enacted through intra-active processes. And the impression of temporal stasis implied by an oversimplified reading of fixed spatial mapping diagrams might be swapped for a more dynamic conception of the relationships within those diagrams – one that attends to the variable timings that punctuate different layers of the phenomenon, showing how all of the elements get moving in relation to one another. But even then, the picture would be incomplete, as maps can only contain traceable associations, and they therefore miss bits of granular detail and lose something of the ineffable quality of performative networks. As Bruno Latour put it during his 2013 CHI Keynote address, "there is no collective phenomena, only collected phenomena" – i.e., for practical purposes, there is only that which can be observed, measured, and collected as data within the performance situation, and all else exceeds the horizon of mappability.

Mapping has become an integral part of many DMI designers' toolboxes, but most designers would never expect their designs to be fully reducible to a mapping process alone. Likewise, it should now be clear that mapping can never fully represent sound worlds or gestures. This is because reality and representation are never fully coterminus with each other, but nevertheless influence and co-determine and reciprocate one another. Maps may be reductive, but nevertheless, they inflect the imagination. In picking over what Borges describes as the "tattered ruins of the map," we have tried to reflect on what specific mappings make visible (or audible), interrogating which parts of the territory are drawn out, which parts remain hidden, and why. Our purpose is not to redraw a better, more fully realised map of musical interactions, but to reveal the partiality and contingency of existing maps, opening space for critical responses and for imagining otherwise. To this end, we insist on the double valence of mapping as at once ideological and a relational mode for generating possible critiques of ideology. In this latter view, DMI mapping interfaces are rendered as what Galloway (2012) would call "intra-faces," by which he means (primarily visual) interfaces that show their own framing of the central text, pointing beyond the screen to a social world outside and exhibiting a kind of self-awareness of the ideological functions of the mapping in reproducing relations between users and underlying systems of representation. This positioning of DMIs within a larger technoscientific (and technocultural) apparatus serves to draw attention to what is centered and what is peripheral in maps. It is the possibility of reconfiguring such inside-outside relations–and of rethinking representations of musical interaction in DMIs along the lines of what Donna Haraway would describe as "performative images that can be inhabited... [as] condensed maps of contestable worlds" (1997, p. 11)–that has driven our discussion here. We have recounted some of the historical antecedents for the mapping model in DMIs, and likewise gestured toward some alternatives, reformulations or extensions that might exist to the concept of mapping as it is currently understood. Through this kind of engagement with residual and emergent forms of mapping, and through our framing of mapping-as-control in relation to critical theoretical approaches, we hope to contribute to a broader conversation about the technoscientific practices underpinning dominant models of DMI design and use.

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