The Evolutionary Dynamics of Cultural Change
(As Told Through the Birth and Brutal, Blackened Death of Metal Music)

Bernard J. Koch[1], Daniele Silvestro[2,3], and Jacob G. Foster[4,5,6]

[1]Department of Sociology, University of Chicago, USA
[2]Department of Biology, University of Fribourg, Switzerland
[3]Department of Biological and Environmental Sciences and Global Gothenburg Biodiversity Centre, University of Gothenburg, Sweden
[4]Indiana University Bloomington, Department of Cognitive Science, USA
[5]Luddy School of Informatics, Computing, and Engineering, Indiana University, Department of Informatics, USA
[6]External Faculty, Santa Fe Institute, USA

Abstract

How does culture change? We unify disconnected explanations that focus either on individuals or on public culture under a theory of cultural evolution. Culture is found both in the brains and bodies of individuals (i.e., personal culture), and in the products of social action (i.e., public culture). By shifting our analytical lens from actors to public cultural ideas and objects, our theory explains change over large and long frames of analysis using formal evolutionary mechanisms. We operationalize the theory through novel computational methods that can test for the action of these mechanisms in dynamic populations of cultural ideas/objects (e.g., music groups, hashtags, organizations). We deploy our theory and methods to study the evolution of Metal music, using a complete dataset of all bands active between 1968 and 2000. Empirically, we find that the genre has been fundamentally shaped by key innovations and competition between ideas for the finite cognitive resources of actors.

1 Introduction

How does culture change? Major cultural shifts—from political polarization, the emergence of new market categories, or the rise and fall of popular music genres— are challenging to explain. This is due in no small part to the complexity of culture itself. Culture is found both in the brains and bodies of individual actors (i.e., personal culture) as well as in the products of social action (i.e., public culture) (Lizardo, 2017). Theoretically satisfying explanations of cultural change must be grounded in "actor-centric," cognitive accounts of the acquisition and usage of personal culture by individuals. It must also articulate "culture-centric" mechanisms that can explain public cultural change across thousands or millions of actors.

Unfortunately, contemporary sociological explanations of cultural change typically proceed from only one of these two perspectives. Most "actor-centric" accounts of cultural

change (e.g., practice theories, network theories) view culture from the eyes of the individual to explain the learning, transmission, and production of cultural ideas (i.e. beliefs, values, skills, or practices) (Swidler, 2001; DiMaggio, 1997; Fuhse, 2009; Centola, 2020; Bourdieu, 1996; Fligstein and McAdam, 2015). In contrast, a smaller literature of "culture-centric" accounts (e.g., systems theories, some evolutionary theories) focuses on change in the heterogeneous ideas, material objects, institutions, and relational structures that make up public culture over larger and longer frames of analysis (Lieberson, 2000; Hannan, 2005; Luhmann, 1995).

These approaches provide unsatisfying accounts of cultural change because few adequately bridge the gap between the "actor-centric" and "culture-centric" perspectives. Actor-centric perspectives articulate cognitive explanations for the individual acquisition of culture and its transmission across groups, but often do so by homogenizing and stabilizing public culture as a static idea, institution, category, or Bourdieusian habitus. But if public culture is monolithic and homogeneous, it is difficult to explain change without invoking an extra-theoretical *deus ex machina* like an event, exogenous shock, or potent social action—none of which are explicitly connected to individual cognition or transmission (Swidler, 1986; Knorr-Cetina, 1988; Collins, 1981; Fligstein and McAdam, 2015). In contrast, several culture-centric theories articulate clear, endogenous mechanisms for change in heterogeneous ideas and public cultural objects distributed across groups of actors. But these theories tend to portray actors as static, passive, or even non-existent (Lieberson, 2000; Hannan, Pólos, and Carroll, 2012; Luhmann, 1995).

We propose an evolutionary approach to culture that unifies actor-centric and culture-centric explanations of change. This approach focuses on two linked populations and their dynamics: ideas (the elements of culture found in brains and bodies) and cultural objects (the non-human materials that embody, transmit, and reproduce those ideas) (Griswold, 2008; McDonnell, 2010; Taylor, Stoltz, and McDonnell, 2019). Our approach links the personal cultural learning of ideas to the reception and production of public cultural objects. Variation between lineages of objects and ideas is *birthed* through transformative learning and creativity (Sperber, 1996). Cultural *death* results from forgetting and disuse. These processes create *cultural forms*: populations of ideas and objects circulating amongst actors that are recognized as instantiating or belonging to the same abstract cultural type.[1] Our theory allows for an explicit definition of cultural change: *Cultural change is a shift in the amount, diversity, or character of cultural ideas and objects circulating amongst a population of actors over time.*

The dynamics of cultural forms are driven by what we call a *cultural carrying capacity*. In ecology, carrying capacity refers to the number of distinct individuals or species that can occupy a niche; this number might be determined by the food, space, breeding sites, or other important resources available in the niche (Holt, 2009; McPherson, 1983). Building upon (Mark, 1998), we use *cultural carrying capacity* to denote the number of distinct ideas that a population of actors can sustain. On the cognitive level, the carrying capacity is constrained by the limited time, attention, motivation and memory actors can dedicate to cultural learning and reproduction. On the cultural level, the carrying capacity is limited

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[1]In the language of (DiMaggio, 1997), we would say that actors have a (sufficiently similar) schema to recognize these ideas and objects as participating in the same form.

by the requirement that novel ideas be distinct from ideas that are already circulating in actors' brains.

Our framework equips sociologists with new formal language to answer questions about *how* culture changes by drawing on explicit carrying capacity mechanisms. The evolutionary mechanisms featured in this paper include competition between ideas, key innovations that expand the cultural form, and mass extinctions of ideas that make space for new ones. To move from theory to data, we introduce a statistical framework that uncovers patterns consistent with each of these mechanisms influencing the birth and death rates of real cultural ideas and objects (e.g., political tweets, firms, musical artists).[2]

To illustrate the utility of our framework, we apply our theory and methods to a population-scale dataset of bands active in Metal music between 1968 and 2000. Art genres like Metal are ideal model systems for studying cultural change because their dynamics are largely driven by cultural (as opposed to economic or political) processes. It is also easier to see the evolutionary nature of such change: musicians draw inspiration from previous musical ideas, and dueling pressures to affiliate with an existing genre tradition and expand it through innovation drive high-fidelity transmission and variation, respectively (Kahn-Harris, 2006; Prior, 2008).

Our analysis provides a unique perspective on the tumultuous history of Metal music. While Metal experienced pervasive commercial success for much of the late 1980s, its history has also been peppered by mass hysterias, a precipitous fall from MTV grace at the hands of Nirvana, and a proliferation of highly differentiated subgenre cultures. We conclude that Metal's evolution was not determined by exogenous historical events like the rise of Grunge. Instead, Metal experienced rapid expansion due to key subgenre innovations in the early 1980s, followed by enduring competition between ideas for the limited time, attention, memory, and motivation of actors.

The paper is organized as follows. First we articulate four questions that a complete theory of cultural change should answer, and propose a cultural evolution theory that meets these requirements. Next, we formalize a statistical framework for discovering evidence that our theoretical mechanisms are effecting change in real cultural data. To showcase our theory and methods–and show readers how they can be translated to a concrete case–we deploy the framework to explain the historical dynamics of Metal music.

2   A Theory of Cultural Change

(Martin, 2001) argues that sociological theories explaining the existence of public culture generally proceed along one of two tracks.[3] "Weak" theories tell general, dialectical stories of *why* public culture exists as it does, but they provide no mechanistic explanations of *how* public culture emerges. In contrast, "strong" theories explain both *why* public culture exists and *how* it emerges, but their mechanisms are often quasi-deterministic (i.e., they don't allow

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[2]While we apply these models to cultural dynamics, these statistical methods also represent a significant contribution to human demography. They could be used to project population sizes, understand constraints on growth, or isolate the effects of disasters on birth and death rates.

[3]Martin uses the language of "social order," but this concept is consistent with the maximalist "everything is culture" perspective favored in contemporary social theory.

for alternative public cultures beyond what is actually observed). Moreover, Martin criticizes these papers for generally obscuring ("fudging" in his words) how these general mechanisms arise from actor behavior. Below, we lay out questions a theory of cultural change should answer to avoid these criticisms. Most importantly, such a theory should be satisfying from both actor- and culture-centric perspectives. We call such a theory a "complete" theory of cultural change.

1. **What is culture?** Recent scholarship (Sperber, 1996; Lizardo, 2017; Foster, 2018) has pushed sociologists to be more specific about the material foundations of culture. Explaining cultural change requires a definition of culture that is coherent and consistent across both personal culture and public culture.

2. **What is cultural change?** To explain whether cultural change will occur, a complete theory must be precise about what cultural change *is*. To avoid Martin's criticism of deterministic theories, this definition should not be biased towards change or stability; instead, it should have both as equally plausible options, depending on the circumstances (Bloor, 1984). For the theory to be satisfying, its definition of change should also be coherent from both the personal *and* public cultural perspectives, i.e., definitions of change in personal culture should be consistent with definitions at the level of public culture.

3. **How does cultural change occur?** Explaining *how* culture changes requires mechanisms that can generalize to different cultural and historical contexts. For coherence, these mechanisms should articulate how personal cultural change gives rise to public cultural change, and vice versa. Many theorists "freeze" personal culture to explain public cultural change; others hold public culture constant to simplify the explanation of change in personal culture. In a complete theory, actor-centric and culture-centric mechanisms should operate simultaneously.

4. **Does the theory imply concrete hypotheses or predictions?** Finally, a complete theory is defined by its ability to make sharp, distinct hypotheses in real scenarios. The value of general mechanisms is that they imply testable claims about the causes of cultural change in varied empirical data (Watts, 2014).

We now develop an evolutionary theory of cultural change that meets these requirements. To answer the first three questions, our theory synthesizes contemporary sociological literature on culture and cognition with mature theories of cultural evolution, especially the approach called the "Epidemiology of Representations" (also known as "Cultural Attraction Theory") (Sperber, 1996; Sperber, 2006). Beyond providing a comprehensive framework for studying cultural change, our key theoretical contribution is the concept of cultural carrying capacity and the subsequent mechanisms and hypotheses about public cultural change it entails. These mechanisms and hypotheses allow us to operationalize our theory in a statistical framework, and demonstrate its application in an empirical case study. For clarity, key theoretical constructs are centralized in Table 1. To make the exposition of our theory concrete, we focus on simple examples from music. However, our theory has much broader scope, and we develop other examples in the discussion.

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2.1 What is culture?

In our theory, this question has two answers. One answer looks at culture from the perspective of actors; the other from the perspective of circulating cultural ideas and objects.

Personal culture

From the perspective of actors, culture consists of internal ideas and external objects. The personal culture (Lizardo, 2017) of a specific actor is the set of cultural ideas stored in their brain.[4] The way these ideas are schematically organized varies from person to person as a function of their experience (Sperber, 1996; DiMaggio, 1997; Foster, 2018). Ideas are "cultural" when they are common due to social interaction and sufficiently similar that they are recognized by participants and analysts alike as tokens of the same type (Foster, 2018; Vaisey and Valentino, 2018).

In their social lives, actors encounter cultural objects: Material things that produce, recognize, reference, or are otherwise associated with cultural ideas.[5] Cultural objects include textual, visual, and aural media (Taylor et al., 2019). The term embraces both persistent materials (like printed text, film reels, cassette tapes) and ephemeral ones (like speech, gesture, live music, and more general practiced behaviors). Actors make sense of cultural objects with their existing repertoire of cultural ideas. They use and produce cultural objects to communicate ideas and co-construct the social world. Encounters with unfamiliar cultural objects can spark the learning of new cultural ideas.

Public culture

From the "culture-centric" perspective, culture is made up of populations of ideas and associated objects circulating *across actors*. This populational view is essential to an evolutionary theory of cultural change (Claidiere, Scott-Phillips, and Sperber, 2014). We use the term *cultural form* to index populations of ideas and objects that are recognized by actors and analysts as belonging to the same abstract cultural type.[6] In the language of (DiMaggio, 1997), objects and ideas are recognized as belonging to the same cultural form because actors have sufficiently similar schemata for interpreting them.

Stable forms can be further institutionalized by linguistic labels that serve as shorthand for ideas and objects that are common across schemata. For example, the label "Madonna" refers to a concrete person, but also a cultural form consisting of circulating ideas and objects. As a direct consequence of how cultural ideas are schematized in actors' brains,

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[4]We borrow this understanding of culture from the Epidemiology of Representations (EOR) (Sperber, 1996), but replace their term "mental representation" with "idea" for broader legibility.

[5]Sperber and the subsequent EOR literature use the the term "public representations" for cultural objects; we stick to the term object, which is familiar to culture and cognition scholars in sociology.

[6]Our cultural forms are theoretically consistent with "organizational forms" in the organizational ecology literature (Hannan, 2005; Hsu and Hannan, 2005) and categories in the later categories literature (Hannan et al., 2019), as well as Fuhse's and Mark's uses of the term (Fuhse, 2009; Mark, 2003). Cultural forms are described as "cultural cognitive causal chains" (Foster, 2018) or "cultural attractors" in EOR (Scott-Phillips, Blancke, and Heintz, 2018).

cultural forms may be defined in relation to other forms or nested hierarchically (i.e., the cultural form *Madonna* is nested within the cultural form *Pop music*).[7]

Music genres are a textbook institutionalized cultural form. In the mind of an individual actor, a music genre is encoded as schematic associations of musical, aesthetic, social, and even ideological ideas. For example, an actor may musically recognize Disco music by its "four-on-the-floor" bass drum beats, groovy syncopated basslines, or orchestral accents. Actors may have ideas about other associated aesthetics like the iconic disco ball and glowing dance floors. Socially, they may recognize certain artists (e.g., the Bee Gees, Donna Summer) or subcultural practices (e.g., drinking martinis and wearing ostentatious clothing) as related to the genre. Not every actor will be familiar with all of these ideas, or recognize all of them as common to the form Disco. But actors can build similar schematic understandings of the form through the creation of and exposure to objects from this cultural population, like recordings by artists understood as Disco artists, or dance halls known as Disco clubs.

Rather than following actors, their ideas about Disco, and their encounters with cultural objects, we can instead follow the population of ideas and objects as they swirl between actors. No object is more seminal to the Disco form than the movie "Saturday Night Fever" (Badham, 1977). A love-letter to the genre, "Saturday Night Fever" synthesized many ideas about Disco into a cultural object that produced coherent schemata for a broad swath of new actors who saw the film when it was released in 1977. A film like "Saturday Night Fever" helps to stabilize the cultural form, and its continued consumption is important for the ongoing survival of knowledge about Disco. It contributes to this cultural form "staying alive."

Structurally, the group of actors that supports a cultural form like Disco may be as formal as a field or as flexible as a social network. This group includes anyone who holds relevant cultural ideas: explicit creators of cultural objects (artists, label managers, media), intentional consumers of these objects (fans), as well as those actors who absorb them passively and subconsciously (casual radio listeners).

2.2   What is cultural change?

Change in public culture

This populational, "culture-centric" view leads immediately to an explicit definition: Cultural change is a shift in the amount, diversity, or character of cultural ideas and objects circulating amongst a group of actors. This definition is evolutionary in its essence; cultural change is about changes in a population of ideas and objects.

Perhaps no musical form is more dynamic than Jazz. Over the past century, this form has changed dramatically with the ebb and flow of subgenres like Swing, Bebop, Modal Jazz,

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[7]The distinction between ideas and forms is dependent on the level of analysis. In many empirical cases–including the metal case–there is an -emic taxonomy that individuals use to differentiate their ideas and the cultural forms they participate in from each other. Metalheads speak of bands as a legible and distinguishable unit; they likewise make distinctions between subgenres, and distinguish Metal from related genres. Their -emic taxonomy also describes the nesting of "lower-level" forms (like bands) within higher-level forms like sub-sub-genres, sub-genres, and genres. We believe that analysts should defer to this -emic taxonomy if it exists, unless there are (very) strong reasons to challenge it. In other cases, the analyst may need to make etic distinctions appropriate to their research questions.

and Free Jazz. Each of these moments of cultural evolution corresponds with the rise and fall of distinct ideas and objects within the form. Consider how ideas about improvisation–a defining element of Jazz schemata–changed between 1940 and 1970. In the 1940s, Bebop improvisation was constrained by strict chord progressions. Eventually, the convention of chord scaffolding gave way to improvisation within modal scales, as in 1959's "Kind of Blue" by Miles Davis, widely considered one of the best albums of all time. In the Free Jazz of the 1960s, these constraints were further relaxed by abandoning scales altogether.

It is not only musical ideas that evolve within genres, but also social ones. For example, the white bandleader Paul Whiteman (actual name) was considered the prototypical Jazz artist of the 1920s and Duke Ellington was advertised as the "Paul Whiteman of Colored Orchestras" (Phillips, 2013). In the intervening decades, of course, the massive influence of Ellington has become more recognized and Jazz is universally acknowledged as a cultural form with deep roots in the Black community.

Change in personal culture

This evolutionary definition of cultural change is also entirely compatible with a common-sense definition of change in personal culture. Cultural change for an individual actor occurs when they acquire or create fresh ideas, when they restructure schemata based on new experiences, or when they forget ideas that aren't frequently used or communicated (Lizardo, 2017; Foster, 2018). Such changes, in turn, refactor the "cultural toolkit" they use to interpret cultural objects and co-construct cultural forms (Swidler, 1986).

Consider how an actor learns about a cultural form like Jazz. In *Shaping Jazz* (Phillips, 2013), Damon Phillips describes a transformative experience with the 1973 *Smithsonian Collection of Classic Jazz* recordings:

> I initially disliked many of the tunes... After reading those liner notes, the confusing songs became clearer, annoying songs became art and everything seemed to naturally belong in the jazz canon. I began to understand... that there was an auditory and stylistic inventory that gave jazz its logic.

Phillips started with a narrow schema for Jazz, leading to his initial distaste for much of the music in the catalogue. But through his consumption of the recordings and liner notes, his preconceptions of what "good" Jazz sounded like were jettisoned and forgotten, while new ideas were built onto and out of his existing schemata.[8] These experiences augmented his toolkit for navigating and understanding the form (Swidler, 1986).

2.3 How does culture change occur?

How personal culture changes

Our definition of cultural change *at the individual level* highlights the acquisition or creation of fresh ideas; the reconfiguring of existing ideas; and the forgetting of old and unused

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[8]Recall that schemata are hierarchically organized, so his original "Jazz schema" was built out of many lower-level schemata.

ideas. This definition explicitly invokes several concrete actor-level mechanisms for cultural change: learning, creativity, and forgetting. Learning can be further subdivided into actor-level mechanisms that shape *which* ideas are learned, and those that shape *how* ideas are learned. The former has been developed extensively in the network diffusion and cultural evolution literatures, so we focus on the latter.[9]

How actors learn creates opportunities for cultural change. Cultural ideas are not copied from one mind to another (Wrong, 1961). Instead, they are transmitted between actors through complex chains of learning from and re-production of cultural objects (Sperber, 1996; Foster, 2018). The details of this cycle of learning and re-production matter. Learning some cultural ideas—especially complex ones—may require repeated exposure to appropriate cultural objects, up to and including (in)formal instruction. The complexity of an idea also depends on the existing stock of ideas in the mind of the learner.[10] It is easier to learn a cultural idea that participates in a known cultural form than it is to acquire an entirely new form (Rossman, 2014; Foster, 2018)

This cycle of learning and reproduction not only transmits ideas between individuals; it also creates opportunities for cultural change, because learning is fundamentally transformative (Sperber, 1996). Transformative learning occurs because ideas are filtered through and scaffolded upon individuals' existing cultural schemata. Individuals have limited cognitive resources (time, attention, memory, motivation) to dedicate to cultural learning; they will typically learn ideas if they are salient, useful, and not too complex (DiMaggio, 1997). Given these cognitive limitations, actors later reproduce ideas with simplification or modification to make them fit better with existing ideas. In other words, actors reproduce cultural ideas with variation.

Sometimes actors intentionally introduce variation in the cultural objects they produce. In other words, they are *creative*. A detailed discussion of creative invention is beyond the scope of this discussion; see (Foster and Evans, 2019a; Foster, Shi, and Evans, 2021; Perry et al., 2021) for synthesis of the relevant literature. Broadly speaking, creative invention can involve tinkering with an existing idea or recombining multiple existing ideas. Along with the accidental changes of transformative learning, these novelty-generating processes create a constellation of more or less similar ideas and objects circulating amongst actors (i.e., a cultural form). In some cases, however, novelty-generating processes may produce a

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[9]Behavioral and cognitive factors modulate *which* ideas an actor learns; they also modulate the ideas they reproduce, and therefore the population of cultural objects available for encounter by others. Many of these factors correspond to familiar network diffusion mechanisms, as well as the "transmission biases" that play a central role in the "Dual-Inheritance" approach to cultural evolution (Richerson and Boyd, 2008). Transmission biases include "model-based biases", where actors select models based on similarity (i.e., homophily) or prestige (i.e., status), and therefore sample the population of cultural elements in a biased way; "frequency-based" biases, where actors prefer either rare or common variants of ideas (distinction or conformity/complex contagion mechanisms, respectively); and "content-based" biases, where actors adopt ideas based on the perceived functionality, usefulness, legitimacy, or other social success of the idea (Rossman, 2014; Perry et al., 2022). These mechanisms play a critical role in what ideas become common in a particular population and are extensively developed– both theoretically and methodologically–in the cultural evolution and network literatures (Rossman, 2014; Foster, 2018; Perry et al., 2022). We further note that these behavioral and cognitive factors are themselves cultural; for example, actors must have an idea of who is prestigious in a particular group, and notions of usefulness or legitimacy are also culturally contingent.

[10]There is a reason that most college courses on quantum mechanics start with differential equations (which are familiar to the typical physics undergraduate) and not with Hilbert spaces (which are not).

population so different from the original lineage that it corresponds to a new cultural form.

For an idea to remain salient and coherent, it must be periodically refreshed; this can occur when an actor encounters a cultural object that corresponds to the idea in question, or when they actively re-produce the idea by generating a cultural object themselves. Cultural ideas that are neglected are eventually forgotten; once actors forget a particular idea, they can no longer contribute to its continued circulation by producing or consuming related cultural objects.

Because an actor has limited time, attention, memory, and motivation, there are also limits to the number of cultural ideas that they can maintain as part of their personal culture.[11] Cultural learning and reproduction can only occur when two actors have sufficiently similar cultural schemata to recognize a circulating idea as relevant to the same culture form. An actor's inability to grow their schemata infinitely leaves some communicated ideas forgotten, insofar as they do not comport with existing understandings of the form. An individual human mind is therefore a finite resource for a particular cultural form, and for cultural forms more generally (Mark, 1998). A relatively serious lay consumer of Western "classical" art music may only retain detailed knowledge of a handful of minimalist composers (e.g., Glass, Adams); likewise for Baroque (e.g., Bach, Handel); and so forth across various sub-forms of the classical music form.

The birth and death of public cultural ideas

We can now extrapolate these concrete micro-mechanisms from the level of actors to the level of cultural populations, where they combine to produce macro-mechanisms for cultural change. When transformative learning or intentional creativity lead to the introduction of new ideas that spread, are stabilized by the circulation of objects, and are consistently reproduced, this corresponds to the *birth* of a new idea within the cultural form; if the idea is distinct enough, it may even give rise to the birth of a new cultural form. Likewise when actors rarely invoke or re-produce a particular cultural idea, leading to individual forgetting, the lineage in question will *die* from lack of circulation.[12] Combining these two processes, we can characterize cultural change at the macro-level in terms of the rates that new ideas are born and die. This is analogous to the perspective often taken in the study of biological macro-evolution, which focuses on the origination and extinction of species, but not so much on their relative prevalence.

Public cultural change through carrying capacity dynamics

Our key theoretical insight is that the birth and death of ideas within a form are modulated by a *cultural carrying capacity* across actors. Carrying capacity[13] is the fundamental driver of competition between ideas; the fact that cultural forms compete for carrying capacity

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[11]As well as the number of cultural objects that they can encounter

[12]A cultural idea never truly dies, so long as some of its corresponding objects remain; like the works of Plato or great Cthulhu, it merely sleeps.

[13]In macroevolution[18], the carrying capacity corresponds to the number of distinct species (typically of a given category) that an environment can support. In our case, it corresponds to the number of distinct ideas within a cultural form that can circulate among a group of supporting actors.

is responsible for the evolutionary character of cultural dynamics, and leads to a series of concrete and distinctive hypotheses.

Cultural carrying capacity emerges from phenomena at the level of both personal culture and public culture. At the level of personal culture, cultural carrying capacity is a direct consequence of the limited time, attention, memory, and motivation of actors supporting the form, i.e., the human resources on which the ideas depend for their continued existence. At the level of public culture, carrying capacity is constrained by the broader landscape of related public culture.

How does this work? Recall that forms are populations of related ideas and objects widely and inter-subjectively recognized as corresponding to an abstract type. Forms can thus only grow until they push up against the boundaries of other established abstract types. Cultural meaning comes from difference; the cultural form *Metal music* gets meaning not only because actors identify it with a finite set of common ideas, but also because schemata for Metal are distinct from existing understandings of Punk, Jazz, or Indie Rock. Empirical work in the organizations literature has shown repeatedly that novel ideas on the boundaries of forms (e.g., genre-defying films or companies) often struggle because actors are unable to align them with their existing schematic representations of public culture (Hsu, 2006); in some cases, these novel ideas might be interpreted by actors as constitutive of the adjacent form instead. The same "principle of sufficient difference" applies to ideas within a particular form as well; a band that merely plays the songs of another is a cover band, and new artists that are too similar to existing ones may be denounced as derivative–the curse of death in fields that prize originality and distinction.

Even as supporting actor populations grow, these twin bounds of cognitive constraints and existing public culture ultimately circumscribe the space in which cultural forms can grow and flourish. This circumscribed niche, which translates into a fixed carrying capacity, makes a number of classic evolutionary mechanisms relevant. It follows from this perspective that such mechanisms (e.g., competition, mass extinction, and key innovation discussed below) are potential explanations of actual, observed dynamics of change and stability in cultural forms.

Black Sabbath: A case study for how culture changes

As a concrete example of these processes, consider how "Black Sabbath," widely credited as one of the first Metal bands, developed their completely novel "heavy" sound in the mid 1960s.

At the age of eighteen, guitarist Tony Iommi's hand was crushed in a factory accident. He had the tips of his middle and ring fingers amputated, and doctors told him he would never play guitar again. This news was devastating for Iommi and his nascent musical career (Wall, 2015; Iommi and Lammers, 2011).

Well-established, actor-centric mechanisms of cultural transmission played a critical role in Iommi's return to music. He heeded the advice of his factory foreman, a man he respected.[14] The foreman insisted that Iommi listen to the work of gypsy jazz guitarist Django

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[14]As described in Footnote [9], this selective attention to an admired individual illustrates status or prestige bias).

Reinhardt, who had lost two fingers in a fire. Iommi was so impressed with Reinhardt's virtuosity that he decided to give guitar playing another go.

Iommi drew on his creativity to intentionally craft new musical ideas and circumvent the constraints imposed by his injury. Because he experienced significant pain when placing his amputated fingers on the guitar fretboard, he fashioned thimbles for himself by melting and filing dish soap bottle caps. He also replaced his strings with lighter weight banjo strings, and detuned his guitar to making playing easier. To accommodate his injury, he moved away from solos with a single-note melody line and began to favor specific types of chords like power chords that were easier to play. Iommi enjoyed the sonic density created by this approach, and began plugging his guitar into the "Bass" jack of his guitar amp to lean into this sound. Black Sabbath doubled down on this dense, "heavy" aesthetic as bassist Geezer Butler began doubling Iommi's parts on his own distorted, detuned bass rather than complementing them with a distinct bass line.

The band's first song, the eponymous "Black Sabbath," emerged by combining these new musical ideas with transformative learning. As the story goes, the song took shape because Butler was trying to recreate the famous opening passage of "Mars" from Holst's "The Planets" on his detuned bass. Iommi then began improvising on top of Butler, transforming the motif into Black Sabbath's distinctive devil's tritone (Wall, 2015).[15] During this translation of Holst's orchestral composition into a rock song, many musical ideas were no doubt discarded, while others were radically transformed by Iommi and Butler's distinctive approaches to their instruments.

The ideas encapsulated by Black Sabbath's signature "heavy" sound are considered integral to the development of the Metal form, and the Doom Metal subgenre in particular. As power chords and distorted, detuned guitar work spread to new actors through Black Sabbath's recordings and radio play, new artists began to reproduce these ideas and "birthed" them into the cultural form that became Metal. Along with social and aesthetic ideas introduced through singer Ozzy Osbourne and Geezer Butler's obsession with the occult, the "heavy sound" remains core to the Metal form today. On the other hand, the Blues ideas introduced in Black Sabbath's early music (e.g., the use of harmonica) have largely faded into the background and "died" within the form.

We can explain why Blues influences may not have survived in Metal by invoking cultural carrying capacity (i.e., cognitive constraints and the principle of sufficient differences). From an actor-centric perspective, inchoate Metal was likely incredibly diverse, including both Blues and heavy sounds. But due to limited time, attention, motivation and memory, fans and musicians were forced to converge on a core set of ideas (heavy sounds) so that they could understand they were talking about the same form. From a culture-centric perspective, Blues influences were also pervasive in the Rock music of the late 1960s[16]; because Rock already claimed these sounds, Metal was forced to evolve as something distinctly different.

The story of Black Sabbath also illustrates that bands can be viewed from two distinct and complementary perspectives. First, they can be viewed as a group of actors playing distinct roles who engage in invention and creativity. Second, they can be viewed as the

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[15]The tritone in music is an augmented fourth/diminished fifth interval. Iommi claims not to have known this at the time, but this interval is infamously known as the *diabolus musica* in western music theory for its exceptional dissonance.

[16]Perhaps best exemplified by the work of Jethro Tull, of whom Iommi was briefly a member.

collection of social and aesthetic *ideas* that animate (and transcend) this group of actors (i.e., cultural forms). These ideas circulate "beyond the band" through a range of cultural objects, thereby constituting the cultural form(s) in which the band participates. Just as we have the link between Madonna the person and Madonna the cultural form (nested within the cultural form of Pop Music), we can draw a link between Black Sabbath the group of actors and Black Sabbath the cultural form, nested in the larger cultural form of Metal music, which they helped to create.[17]

2.4 Does the theory imply concrete hypotheses or predictions?

The presence of a finite carrying capacity suggests that three concrete mechanisms from macroevolutionary biology[18] can explain cultural dynamics: competition (between species), mass extinction (which leads to a sudden increase in unfilled carrying capacity) and key innovation (which unlocks extra carrying capacity). Complete theories are only useful to the extent that they explain empirical data. These mechanisms provide distinct hypotheses for how cultural context (e.g. major events, decisions by influential actors) and evolutionary dynamics together effect public cultural change.

To make these hypotheses testable, we follow macroevolution and organizational ecology by formalizing competition, mass extinction, and key innovation in terms of the birth and death rates of ideas within cultural forms over time (Carroll and Hannan, 2004; Etienne et al., 2012; Silvestro et al., 2015; Rabosky, 2009; Ruef, 2000).

$$\text{Birth Rate} = \frac{\text{Number of ideas ``born''}}{\text{Number of ideas in form}} \quad \text{Death Rate} = \frac{\text{Number of ideas ``dying''}}{\text{Number of ideas in form}}$$

The birth rate (ratio of new ideas to existing ones within the form) captures the process of ideas begetting other ideas through transformative learning and innovation. The death rate (ratio of ideas disappearing to existing ones within the form) captures the process of ideas ceasing to circulate and ultimately being forgotten. Shifts in birth and death rates capture shifts in the overall diversity of ideas, consistent with our definition of cultural change.

Below we articulate the conditions under which these mechanisms act on cultural forms. We also define birth/death rate signatures that allow analysts to test for the action of each mechanism. In later parts of the paper, we define statistical models that generate these signatures and deploy them to compare their adequacy in explaining the observed dynamics of Metal music.

Competition. Competition between ideas sets in when the carrying capacity of a cultural form saturates. As circulating ideas begin to push up against cognitive limits of actors or the boundaries of adjacent forms, ideas can either die completely through forgetting and lack of reproduction, or be interpreted as constitutive of adjacent cultural forms instead.

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[17]Note that this presentation is consistent with the view that bands are organizations. The term "organization" refers (somewhat ambivalently) to both the specific group of people and the cultural form. We defer this conversation to the Discussion.

[18] Biological macroevolution is the subfield of evolutionary biology that seeks to "[explain] the origin, development, and extinction of major taxonomic groupings: species, genus, family" (Sepkoski, 2008).

Table 1: **Key theoretical concepts.**

Idea:	The basic unit of personal culture stored inside brains and bodies.
Objects:	Any physical material that produces, recognizes, references, or otherwise is associated with a cultural idea.
Cultural Form:	Public culture. Circulating populations of associated ideas and objects across actors.
Complete Theory of Cultural Change:	A theory that links actor-centric and culture-centric views on culture, with testable mechanisms of change that are interpretable from both perspectives.
Cultural Carrying Capacity:	The number of distinct ideas that a population of actors can sustain within a cultural form. On the cognitive level, the carrying capacity is constrained by the limited resources (i.e., time, attention, motivation, and memory) that actors can dedicate to cultural learning and reproduction. On the cultural level, the carrying capacity is limited by the requirement that novel ideas be distinct from ideas that are already circulating in actors' brains.
Transformative Learning & Creativity:	Mechanisms of innovation that can lead to the birth and variation of ideas within a cultural form. Transformative learning is the imperfect reproduction of ideas due to limited actor resources. Creativity is the intentional innovation of new ideas.
Birth & Death of Ideas:	The *birth* of a new idea within a cultural form occurs when new ideas spread, are stabilized by the circulation of objects, and are consistently reproduced. Ideas *die* when actors rarely invoke or reproduce them, leading to individual forgetting.
Competition:	Competition between ideas sets in when the carrying capacity of a cultural form saturates. As circulating ideas begin to push up against cognitive limits of actors or the boundaries of adjacent forms, ideas can either die completely through forgetting and lack of reproduction, or be interpreted as constitutive of adjacent cultural forms instead.
Mass Extinction:	Significant stochastic events or social action can transform cultural forms through mass extinctions. In mass extinctions, these historical contingencies catalyze the death of a large number of ideas, creating space for new ones to flourish in the cultural form.
Key Innovation:	Novel ideas that radically expand the carrying capacity of viable ideas within a form and potentially open it to new audiences. Cognitively, these influential ideas give structure to new schematic templates on which actors can build an understanding of the form.

To test if ideas are competing for a finite cultural carrying capacity, analysts can look for a signature of simultaneously slowing birth rates and accelerating death rates. When the carrying capacity completely saturates, birth and death rates should converge, indicating a constant churn of ideas (Fig. 1B).

Mass Extinction. Significant stochastic events or social action can transform cultural forms through mass extinctions.[19] In mass extinctions, these historical contingencies catalyze the death of a large number of ideas, creating space for new ones to flourish in the cultural form.

To test if historical events have caused mass extinctions, analysts can look for a signature including a spike in death rates after the event, followed by a rise in birth rates (Fig. 1A).

Key Innovation. Key innovations are novel ideas that radically expand the carrying capacity of viable ideas within a form and potentially open it to new audiences. Cognitively, these influential ideas give structure to new schematic templates on which actors can build an understanding of the form.

To test for key innovations, analysts should look for a signature of sudden increases in the birth rate, reflecting an increase in the carrying capacity. Fig. 1C shows how this growth in carrying capacity modulates endogenous competition.

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[19]For example, Knorr-Cetina's micro-interactionalist theory focuses on choices by organizational and influential actors, who are likened to individuals with more power (Knorr-Cetina, 1988). Collins and Swidler argue that historical contingency creates space for transformative action. Collins points to "the introduction of new technologies of communication" or "emotional technologies" (i.e. key innovations) that realign the distribution of sociocultural resources to make some actors more powerful than others (Collins, 1981). Swidler contrasts "settled times," where habitual practice reign supreme, to "unsettled times" where social turbulence leads to collective action around strong semiotic symbols (Swidler, 1986). Note that the "settled/unsettled times" dichotomy is used to explain changes in behavior both over the individual lifecourse and in collective populations. In a field context, collective action can set the stage for mass extinctions or key innovations by rapidly changing the composition of the actor-population supporting the form (Fligstein and McAdam, 2015).
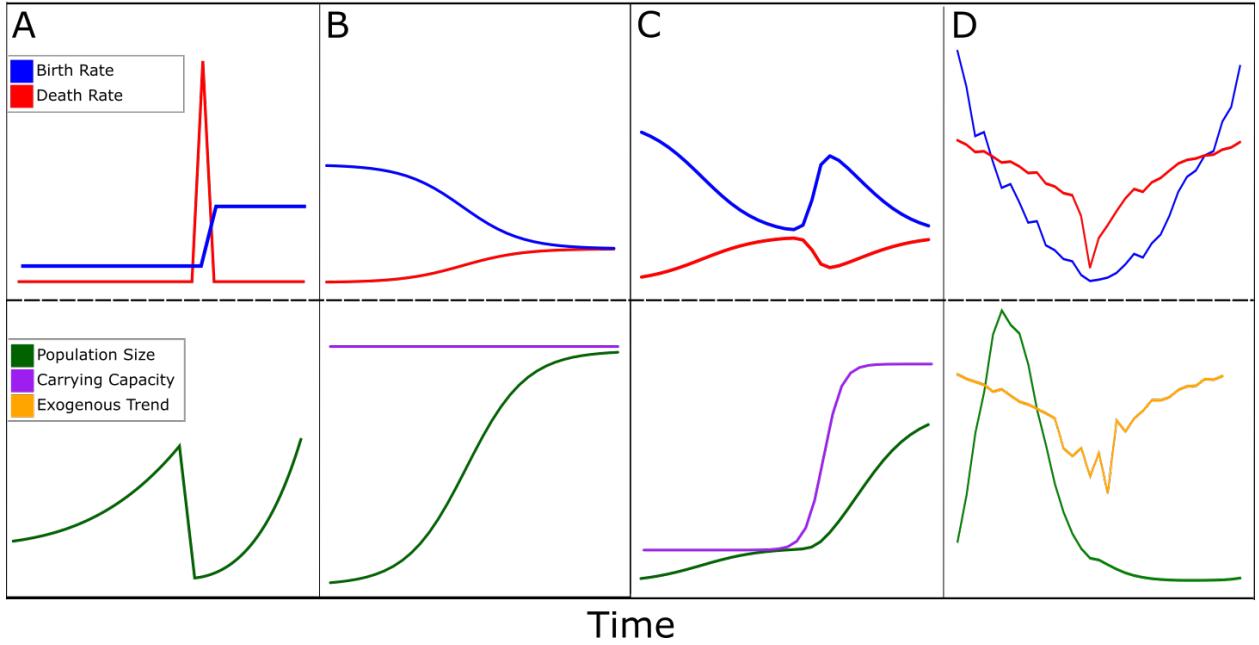
Figure 1: **Theoretical Rate Signatures.** Top row shows theoretical rates corresponding with evolutionary mechanisms, bottom row shows population size and, when appropriate, carrying capacity or exogenous trends. Theory and rate signatures proposed in Section 2.4. **Column A: Significant extinctions.** Death rates spike, creating space for new lineages in carrying capacity (rising birth rates). Statistical model to identify significant extinctions and study of Metal bands in Anal. 1. **Column B: Competition.** Rates converge and population size plateaus as population approaches cultural carrying capacity (Anal. 2). **Column C: Competition + Key innovation.** Key innovations permanently expand the carrying capacity creating space for new lineages. As in B, but carrying capacity grows according to a logistic growth curve (Anal. 3). **Column D: Exogenous Trend.** Rates are a function of some exogenous influence (orange line) outside normal evolutionary dynamics (Anal. 4).

3 Comparison to Existing Literature

To underscore why the theory in Section 2 is needed, we consider how prominent cultural theories address our four requirements for "complete theories." These theories have rich and varied definitions of culture from both actor- and culture-centric perspectives (Question 1). Most describe some version of cultural change. However, all fall short in explaining how change in personal culture and public culture occur simultaneously and endogenously (Question 2). In particular, we highlight a pervasive micro-/macro "fudge:" in order to explain how individuals learn, transmit, and use personal culture, actor-centric perspectives must present public culture as homogeneous and static (i.e., a single idea, institution, category,

or habitus), making it hard to articulate public cultural change (Question 3). In contrast, presenting public culture as heterogeneous (i.e., sets or combinations of ideas and material objects) makes it easy for culture-centric approaches to explain dynamics within public culture endogenously, but makes it challenging to connect these endogenous mechanisms to individual-level processes. As a consequence of their inability to reconcile this duality, many of the mechanisms proposed to create cultural change are underdeveloped from one of the two perspectives and rarely provide a comprehensive explanation about how ideas are innovated, transmitted, and forgotten. Furthermore, these mechanisms generally do not allow for testable hypotheses that are coherent from both actor-centric and culture-centric perspectives (Question 4).

3.1   Primarily Actor-centric Theories

In the late 20th century, **practice theories** used the learning and performance of practices to explain personal cultural change, but rarely provided an account of change in public culture (Swidler, 1986; Collins, 1981; Knorr-Cetina, 1988). This neglect of public cultural change was necessitated by the fact that these theories treated public culture as purely constructed from practice (Swidler, 2001). The tight coupling between individual practice and a homogeneous, stable public culture (as in Giddens' structuration theory or neo-institutionalist theory) thus left little room for the endogenous birth or death of new practices at scale (DiMaggio and Powell, 1991; Giddens, 1984). In populational settings, practice theorists gravitated towards heteronomic shocks like historic events or transformative action by powerful actors—instead of mechanisms emergent from the birth, death, or spread of practices—to explain public cultural change (Swidler, 1986; Collins, 1981; Knorr-Cetina, 1988). Our framework explicitly captures the endogenous transmission of ideas (through practice) as the primary vehicle of change, while also allowing analysts to formulate testable hypotheses about how this endogenous change is modulated by evolutionary mechanisms.

Theorists have connected **social network analysis** to cultural change in two ways, but neither allows the methodology to explain personal and public cultural change simultaneously (Emirbayer and Goodwin, 1994; Fuhse, 2009). The first perspective views relations between actors and the associated social opportunities as determined by static public cultural categories (e.g. gender, class, party affiliation) (Fuhse, 2009).[20] This perspective is not conducive to understanding public cultural change (beyond the network's genesis) because such change would undermine the stable linkage between cultural categories and network structure assumed by the theory. The second approach views cultural ideas as transmitted across networks, and elucidates the mechanisms and network topologies that modulate patterns of cultural diffusion (Rossman, 2014; DellaPosta, Shi, and Macy, 2015; Goldberg and Stein, 2018; Centola, 2020). While this approach can explain the distribution of ideas across actors, the literature often represents public culture as a single, static idea for analytic simplicity. Moreover, the diffusion literature rarely treats the birth or death of ideas, and thus yields no insight into how heterogeneous public cultural forms emerge from transmission processes (Fuhse, 2009). Our theory connects the network diffusion perspective to public

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[20]Methodologically, this perspective is linked to centrality scores, block models, and exponential random graph models.

cultural change using cultural evolution. Our methodological framework complements actor-centric network methods by giving analysts a culture-centric perspective on the birth, death, and variation of ideas, without relying on actor-level data.

Field theories are actor-centric practice theories that situate actors within a structure (the field) where they compete for cultural capital. Bourdieu himself generally avoided discussion of public cultural change, instead elaborating on how a "habitus" (his static, homogeneous vision of public culture) is acquired, reproduced, and transmitted by actors within stable fields (Bourdieu, 1996; Sewell Jr, 1992).[21] However, further work on fields has bridged the gap between actor-centric and culture-centric perspectives by articulating how ideas within fields are born and die through actor turnover and heteronomic shocks (e.g., the unseating of powerful incumbents, historic events) (Fligstein and McAdam, 2015). Unfortunately, field theory is still limited to contexts where actors are unified by common cultural goals (e.g. professions, social movements) and the field-like social structure that follows from this common purpose. Cultural evolution makes no such constraints on personal or public culture. Methodologically, a lack of formalization in the fields literature has also made it difficult to hypothesize how, when, and why change should occur in populations of actors (i.e., fields) empirically.[22]

Culture and cognition scholars have begun to extend theories of cognition to explain cultural change. Theory in this space has largely focused on how the imperfect transmission of ideas can lead to variation and/or consolidation of ideas within a population of actors (Goldberg and Stein, 2018; Boutyline, Cornell, and Arseniev-Koehler, 2021; Hunzaker, 2016). Other work has considered how turnover of demographic cohorts can lead to turnover of ideas (Kiley and Vaisey, 2020).[23] Nevertheless, the culture and cognition work on change is quite limited (Cerulo, Leschziner, and Shepherd, 2021; Vaisey, 2021). Despite the implications for broad cultural change, this scholarship also remains focused on the actor-centric perspective of individuals, and does not consider the culture-centric perspective of ideas. Viewing culture as populations of ideas also frees us to move beyond the networks mechanisms of transmission favored by these scholars towards endogenous mechanisms of change. As in biology, we believe that evolutionary change is a natural extrapolation of actor-level transmission (Mohr et al., 2020).

3.2   Primarily Culture-Centric Theories

Lieberson's evolutionary theory of fashions drew on biological metaphors to explain public cultural change, but he largely ignored personal cultural change (Lieberson, 2000). Our view on public cultural change is consistent with Lieberson's: fashions in baby names, clothing, and music (i.e., public cultural forms) change endogenously through the birth, death, and distributional variation of ideas. Like us, he also articulates several culture-centric evolutionary mechanisms (e.g. the "ratchet effect" or "symbolic contagion") to explain observed dynamics. However actor-centric explanations of change were not necessary for his narrative, and his book tacitly assumes culture flows unilaterally from the public to the

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[21]For an exception see some of his later work on science (Bourdieu, 2004).

[22]F&M are agnostic on this point (Fligstein and McAdam, 2015, 185–186).

[23]In the discussion, we connect this perspective to our own analyses on bands which can simultaneously be viewed as organizational actors and cultural forms.

personal through imitation. Our theoretical contribution connects Lieberson's culture-centric perspective to actor-centric perspectives on culture (e.g. practices, networks, fields), and our statistical framework allows analysts to formalize Lieberson's ideas as testable hypotheses.

Our approach also takes inspiration from **Organizational Ecology**'s portrayal of public cultural change, but makes explicit the connection between these ideas and personal cultural change (Hannan and Freeman, 1977; Ruef, 2000; Carroll and Hannan, 2004). Organizational Ecology seeks to explain the variation within organizational fields and the birth, death, and longevity of individual organizations using many of the same culture-centric evolutionary mechanisms argued for here (e.g., competition within niches). A key insight from Organizational Ecology was that the diversity of types of organizations could be understood as populations of "organizational forms" (Hsu and Hannan, 2005; Hannan, 2005) or market **"categories,"** which we view as sub-types of cultural form. But rather than leverage this idea to describe populational change in other types of cultural forms, the community pivoted to studying how organizations and cultural objects should optimally position themselves in market categories (Hannan et al., 2012) with respect to the tastes and cognitive abilities of their audiences (Hsu, 2006; Hannan et al., 2012; Askin and Mauskapf, 2017). Although category theory has recently been situated more fully within cognitive sociology to explain the representation of categories in the minds of individuals, actor-centric explanations of change in these representations are still under-theorized (Hannan et al., 2019). Our work fills important gaps in this literature's treatment of personal cultural change, generalizes evolutionary mechanisms beyond market contexts, and clarifies the relationship between organizational ecology and the more recent, cognitively inflected literature on categories. Methodologically, we provide organizational ecologists with novel, contemporary Bayesian tools from biology that implement a range of evolutionary mechanisms.

4 From Theory to Statistical Methods

We now operationalize our mechanisms of change (competition, mass extinction, and key innovation) in a statistical framework. By looking for the characteristic birth and death rate signatures described in Section 2.4, we can use our theory to test falsifiable hypotheses about *how* cultural forms have changed in concrete, empirical cases.

The analysis of birth and death rates provides a direct, culture-centric perspective on cultural change that is agnostic to actor-level mechanisms.[24] We see this as a key strength of our approach: We can identify the action of evolutionary mechanisms empirically, without elucidating the actor-level dynamics that gave rise to them. We need not make strong assumptions on actor-level circumstances (as in agent-based simulations), or the exact sequence of transmission and variation events (as in networks and phylogenies).[25] It follows that we do not need high-resolution data about actor behavior; just the birth and death

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[24]Practically, we focus on the presence/absence of objects as a proxy for the birth and death rates of ideas. This is because we cannot peer into the minds of actors. Because culture can only be studied through cultural objects, it is extremely difficult to provide a fully mechanistic account of the actor-level conditions that led to historical change in cultural forms. Empirical work in the networks, fields, and cultural evolution literatures has therefore often focused on elucidating actor-level processes using simulations, small field/case-studies, and experiments, rather than applying the theory to population-scale historical data.

[25]This has been a point of criticism for phylogenetic analyses of macro-culture (Gould, 2010; Foster and

times of ideas or objects. In an era where online data about cultural objects in particular (e.g. Tweets) is likely to be more plentiful, accessible, and often higher quality than data on actors, we see this as a big advantage for computational social scientists.

4.1   Birth-Death Process Models

In order to find mechanistic rate signatures, we can calculate the birth rate λ and death rate μ of a population of ideas empirically as the number of ideas born B or dying D within a time window, divided by the total time lived by ideas during that time window S. If the window is a single unit of time (e.g., year), S reduces to the number of ideas alive in that single unit.

$$\lambda_{MLE} = \frac{\text{B (number of births)}}{\text{S (total time lived)}} \quad \mu_{MLE} = \frac{\text{D (number of deaths)}}{\text{S (total time lived)}}$$

However, the empirical rates are noisy, randomly fluctuating, and approximately measured representations of the "true" underlying birth and death rates of a population.[26] In the following analyses, we therefore fit data to models based on the stochastic linear birth-death process, a popular model of evolutionary change across biology (Crawford, Ho, and Suchard, 2018). The likelihood of the linear birth-death process (Kendall, 1948) is:

$$\underbrace{P(\mathbf{s}, \mathbf{e}|\lambda, \mu)}_{\substack{\text{Prob observed} \\ \text{B/D events} \\ \text{given rates}}} \propto \underbrace{\underbrace{\lambda^B \mu^D}_{\substack{\text{rates for each} \\ \text{B/D event}}} \times \underbrace{\exp(-\lambda S)\exp(-\mu S)}_{\substack{\text{B/D waiting times} \\ \text{over total time lived}}}}_{\text{stochastic linear birth-death (Poisson) process}} \tag{1}$$

Consider birth and death rates within the population of Metal bands. Let $\mathbf{s}$ and $\mathbf{e}$ be vectors of the birth ("formation") and death ("break-up") years of bands. The likelihood of $\mathbf{s}$ and $\mathbf{e}$ is a function of the unknown rates of birth λ and death μ, the number of birth B and death events D within the time frame, and the cumulative time lived by the population within this time frame S. As a generalized Poisson process, this likelihood can be understood as consisting of two event components λ^B, μ^D, and two components capturing the waiting time between events $\exp(-\lambda S), \exp(-\mu S)$. For a full exposition of birth-death processes, see (Crawford et al., 2018).

We can reformulate this constant birth-death process in equation 1 so that it is calculated for each individual idea i in each time unit t:

$$P(\mathbf{s}, \mathbf{e}|\lambda, \mu) = \prod_{i=1}^{N} \lambda(s_i)\mu(e_i) \times \exp\left(-\int_{s_i}^{e_i} \lambda(t) + \mu(t)\mathrm{d}t\right) \tag{2}$$

where s_i and e_i are the times of birth and death of idea i respectively. In the events term, $\lambda(s_i)$ and $\mu(e_i)$ indicate the birth and death rates at the time of i's birth and death. In the

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Evans, 2019b).

[26]A key assumption of our theory is that there is an underlying stochastic process with actual rates. The tightness of our estimates of these rates is contingent on the sparsity of our data and our formal modeling assumptions. Having more structured formal models allows us to make tighter inference of the underlying rates, conditioned on the same sparse data.

waiting times term, the integral captures the rates of birth and death for all the years the idea was alive. This expansion allows us to capture variation in birth and death rates across time or for different subgroups of ideas.

In our proposed birth-death process workflow, we first use an unsupervised machine learning model to find statistically significant rate shifts consistent with competition, mass extinction, or key innovation. If we find rate signatures suggestive of any of these mechanisms, we can then apply a formal hierarchical Bayesian model for that mechanism to the data and produce a distinct estimated birth and death trajectory. For hypothesis testing, these parametric trajectories can be compared visually and statistically to the non-parametric machine learning curves. If a mechanistic model correlates strongly with the machine learned rates using many fewer parameters, we consider that strong evidence for the action of that mechanism. The parameters of that model can then be interpreted for key inferential and predictive insights. This workflow is demonstrated in detail, with code, in the included tutorials using examples from the paper.

Developing Hypotheses and Finding Mass Extinctions Using Unsupervised Machine Learning

First, we introduce a new unsupervised (Bayesian non-parametric) machine-learning algorithm called *LiteRate*, adapted from current methods in macroevolutionary biology (Gjesfjeld et al., Feb. 2020; Silvestro et al., 2014b; Silvestro, Salamin, and Schnitzler, 2014a). LiteRate identifies statistically significant rate shifts consistent with real cultural change. It cuts through stochastic noise in empirical rates by concatenating an *a priori* unknown number of birth-death processes together to estimate rates in a population of cultural ideas. At the joints of these birth-death processes are statistically-significant shifts in rates that (in principle) correspond with major historical events and/or the action of evolutionary mechanisms. Given that the key signatures of mass extinction are sudden spikes in death and birth rates, we also use this model to formally test for mass extinctions.

In the LiteRate likelihood (equation 3), λ and μ are now vectors of rates Λ and M with length J and K corresponding to the number of time frames with different birth rates $\Lambda = \{\lambda_1, \lambda_2, \ldots \lambda_J\}$, and death rates $M = \{\mu_1, \mu_2, \ldots, \mu_K\}$, respectively. Similarly, B and D are now each vectors $B = \{B_1, B_2, \ldots, B_J\}$ and $D = \{D_1, D_2, \ldots, D_K\}$, each counting the number of birth or death events within that time frame. We also now need two new parameter vectors, $\tau^\Lambda = \{\tau_0^\Lambda, \tau_1^\Lambda, \ldots, \tau_J^\Lambda\}$, and $\tau^M = \{\tau_0^M, \tau_1^M, \ldots, \tau_K^M\}$ corresponding to the timings of the birth and death rate shifts, respectively. Lastly, the cumulative time lived by ideas in time frame j is denoted $S_{[\tau_{j-1}^\Lambda, \tau_j^\Lambda]}$, and the cumulative time lived by ideas in time frame k is denoted $S_{[\tau_{k-1}^M, \tau_k^M]}$:

$$P(\mathbf{s}, \mathbf{e}| \underbrace{\Lambda, M, \tau_\Lambda, \tau_M}_{\substack{\text{B,D rate vectors,} \\ \text{times of B,D shifts}}}) \propto \prod_{j=1}^{J} \underbrace{[\lambda_j^{B_j} \times \exp(-\lambda_j S_{[\tau_{j-1}^\Lambda, \tau_j^\Lambda]})]}_{\substack{\text{birth process likelihood} \\ \text{in time frame j}}} \times \prod_{k=1}^{K} \underbrace{[\mu_j^{D_k} \times \exp(-\lambda_k S_{[\tau_{k-1}^M, \tau_K^M]})]}_{\substack{\text{death process likelihood} \\ \text{in time frame k}}} \quad (3)$$

As an example, suppose that between 1968 and 2000 Metal had a single shift in birth rates in the year 1990 and no death shifts. Then the number of birth time frames is $J = 2$; the number of distinct birth rates is $\Lambda = \{\lambda_1, \lambda_2\}$, where λ_1 is the rate from 1968-1990, λ_2 is the rate from 1990-2000, $\tau^\Lambda = \{1968, 1990, 2000\}$; $B_{j=1}$ is the total number of bands founded from 1968-1990 and $B_{j=2}$ is the total number of bands founded from 1990-2000;

$S_{[\tau_0^\lambda, \tau_1^\lambda]}$ would be the total time lived by bands from 1968-1990 and $S_{[\tau_1^\lambda, \tau_2^\lambda]}$ would be the total time lived by bands from 1990-2000. The number of death time frames is $K = 1$; there is only one distinct death rate $M = \{\mu_1\}$, where μ_1 is the rate from 1968-2000; $D_{k=1}$ is the total number of bands that died from 1968-2000; and $S_{[\tau_0^\mu, \tau_1^\mu]}$ would be the total time lived by bands from 1968-2000. In LiteRate, the addition or removal of a rate shift from τ^Λ or τ^M is periodically proposed (with equal probability) throughout the chain using RJMCMC (Green, 1995). More details of the algorithm can be found in A.3 and in (Silvestro et al., 2019).

Is There Evidence of Competition?

Under the competition hypothesis, we would expect the birth rate λ to decrease over time and the death rate μ to increase over time as ideas vie for space within an increasingly saturated cognitive carrying capacity. (Figure 1B). Within the expanded birth-death likelihood specified in Equation 2, we can operationalize this theory by parameterizing $\lambda(t)$ and $\mu(t)$ so that they are functions of the fraction of an estimated cultural carrying capacity K filled at time t and converge to a common value when the carrying capacity is completely filled (i.e., birth and death rates become equal):

$$\lambda(t) = \underbrace{\lambda_{\max}}_{\substack{\text{B rate} \\ \text{at t=0}}} - (\lambda_{\max} - \kappa) \underbrace{\left(\frac{D(t)}{K}\right)^\delta}_{\substack{\text{Fraction} \\ \text{CC filled} \\ \text{at time } t}} \qquad \mu(t) = \underbrace{\mu_{\min}}_{\substack{\text{D rate} \\ \text{at t=0}}} + (\underbrace{\kappa}_{\substack{\text{B \& D} \\ \text{rate} \\ \text{when CC} \\ \text{filled}}} - \mu_{\min}) \left(\frac{D(t)}{K}\right)^\gamma \qquad (4)$$

Our model has four theoretically interesting parameters: the common rate κ at which birth and death rates churn after the carrying capacity has saturated, the maximum size of the carrying capacity K which can be used for short-term projections of population growth, as well as the maximum birth rate λ_{max} and minimum death rate μ_{min} when the population is growing at its fastest in the initial time step $t = 1$. We calculate the fraction of the carrying capacity filled as the size of the current population at time t, $D(t)$, divided by K. As the population grows, birth rates slow (and death rates increase) until λ and μ converge at κ. Additional parameters δ and γ allow the rates to vary non-linearly with the proportion of the carrying capacity filled. In other words, these parameters modulate whether earlier bands or later bands are more important drivers of competition (e.g., with $\delta < 1$ and $\delta > 1$, respectively). We place conservative priors on all parameters under the null hypothesis that there is no competition (see A.4).

Is There Evidence for Key Innovation?

Because the basic idea of key innovation is that the carrying capacity grows due to influential new ideas, we add another hierarchical layer to equation 5 that models the carrying capacity K as a logistic curve rather than a constant value. We speculate that the growth of cultural forms due to key innovations might resemble a logistic (S-) curve where the carrying capacity grows rapidly (thanks to the key innovation) before ultimately leveling off. We use a logistic curve because this functional form flexibly interpolates between two values of carrying capacity (pre- and post-key innovation) and, when suitably parameterized, allows that changeover to occur quickly or slowly. The entire hierarchical model now has 9

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parameters; 5 for base competition and 4 for the logistic function.

$$\lambda(t) = \lambda_{\max} - (\lambda_{\max} - \kappa) \left(\underbrace{\frac{D(t)}{K(t)}}_{\substack{\text{CC at} \\ \text{time t}}} \right)^{\delta} \qquad \mu(t) = \mu_{\min} + (\kappa - \mu_{\min}) \left(\frac{D(t)}{K(t)} \right)^{\gamma} \qquad (5)$$

where K now changes according to the parameters of a logistic function (Fig. 1C),

$$K(t) = \underbrace{d}_{\substack{\text{CC} \\ \text{pre-KI}}} + \frac{\overbrace{L}^{\text{CC added by KI}}}{1 - \exp(\underbrace{-k}_{\substack{\text{steepness} \\ \text{of KI}}} * (t - \underbrace{x_0}_{\substack{\text{time} \\ \text{of KI}}}))} \qquad (6)$$

By fitting the four extra parameters of this logistic curve, we can identify when in the history of the form the carrying capacity grew due to key innovation (x_0), at what rate (k), and to what maximum carrying capacity ($L + d$). We again place conservative priors on the curve for the null hypothesis that there is no key innovation.

Do Rates Follow Exogenous Trends? (Alternative Hypothesis)

To test alternative non-evolutionary hypotheses, we created a model that allows birth and death rates of a cultural form to follow exogenous trends (e.g., popularity in social or news media, economic trends). In this model, birth and death rates vary over time as a linear and/or exponential function of exogenous trend $C(t)$:

$$\lambda(t) = \lambda_{const} + \alpha * C(t)^{\delta} \qquad \mu(t) = \mu_{const} + \beta * C(t)^{\gamma} \qquad (7)$$

where λ_{const} and μ_{const} are intercepts, α and β are linear coefficients, and δ and γ are exponential coefficients. See A.4 for details on conservative priors.

5 From Methods to Case Study: Metal Music

In this section we introduce our case study, an evolutionary analysis of the history Metal music from 1968 to 2000. We begin with a qualitative history of the genre and description of our dataset to motivate four contextualized research questions about the action of evolutionary mechanisms on this cultural form.

5.1 Background

Metal's roots can be traced to the late 1960s and early 1970s as British rock bands like Black Sabbath, Deep Purple, and Led Zeppelin began incorporating blues and psychedelic influences into increasingly hard rock sounds (Christe, 2010). Throughout the 1970s, an underground UK Metal scene fermented these sounds with elements of Punk to converge on a core set of ideas: sonically, "Metalheads" sought to coax churning distorted guitar patterns called "riffs," energetic tempos, and virtuosic musicianship from a traditional rock band

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ensemble. Aesthetically and socially, they cultivated an irreverent, ultra-masculine aesthetic that was free from the political messaging that had charged popular music of the past two decades. Spearheaded by bands like Iron Maiden and Def Leppard, these key innovations rocketed a new cultural form known as the New Wave of British Heavy Metal (NWOBHM) into the 1980s mainstream. Despite being (or perhaps because it was) apolitical, Metal's transgressive aesthetic resonated with youth in the 1980s and achieved broad popularity and commercial success.

From NWOBHM, three independent sub-cultural forms emerged (Weinstein, 2000). One form was the industry-supported glam or hair Metal bands like Cinderella, Motley Crue, and Europe. Characterized by their flamboyant costumes, hair, and makeup, glam bands controlled a major slice of popular music radio-time in the second half of the 1980s. This lineage of pop Metal bands is often derided by Metal purists as "not truly Metal," and is conspicuously absent from our dataset, the Encyclopedia Metallum (EM). A second form was mid-1980's Power Metal. Pioneered by American bands like Manowar in the US and Helloween in Europe, power Metal curated symphonic elements, virtuosic guitar solos, clean vocals, and fantasy themes to create an epic sound. These bands enjoyed moderate commercial success in the U.S. in the second half of the 1980s, but were also successful in Europe through the mid 1990s.

Lastly, a parallel underground movement called Thrash emerged in the early 1980s as a reaction to the decadence and technical flashiness of pop Metal. With foundations laid by bands like Motorhead, Venom, and Void, Thrash Metal emphasized a raw Punk-like sound with fast simple riffs, gruff vocals, and "extreme occult imagery" (Kahn-Harris, 2006). This harsher, more masculine aesthetic also gained commercial success, peaking in the late 1980s and early 1990s through bands like Metallica, Megadeth, Slayer, and Anthrax. In the last three years of the 1980s, bands from these three forms consistently occupied the top 20 albums on the Billboard 200 (Klypchak, 2007). The mid to late 1980s on also saw a proliferation of Extreme Metal subgenres speciating from Thrash that dominate Metal today (e.g., Black, Death, Doom, Metalcore).[27] In general these subgenres took the aggressive, masculine, and macabre themes of heavy music and intensified them with even more abrasive distortion, guttural melody-less vocals, minor/dissonant harmonies, and vivid imagery.

Metal has a rich culture and history punctuated by popular peaks, moral panics,[28] and even sensational acts of terrorism[29] (Christe, 2010; Kahn-Harris, 2006; Klypchak, 2007;

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[27]A reticular cross-pollination with Hardcore Punk spawned Metalcore (e.g., Converge), and the even farther afield Grindcore (e.g., Napalm Death, Pig Destroyer), a subgenre famous for chaotic "microsongs" lasting just a few seconds. The most prolific, and perhaps most "scenic" Metal subgenre, Black Metal, took its name from a Venom album and embraced minor modes and dark, satanic imagery (Christe, 2010). Death Metal took Black aesthetics and re-infused the technical virtuosity that had been de-emphasized by the Thrash movement, along with growled vocals and ultra-violent, gory lyrics. Doom Metal and its popular subgenre Funeral Doom took the opposite approach, slowing down tempos to create bleak, suffocating soundscapes.

[28]In the 1980s, Metal was at the epicenter of a "Satanic Panic" that the subgenre was eroding the Christian values of the United States. The panic apexed with senate hearings of Metal musicians, a controversial parenting book by Tipper Gore, and the introduction of parental advisory labels for recordings. For the interested reader, Dee Snider of Twisted Sister's testimony before congress is a highlight.

[29]The history of the early Norwegian Black Metal scene active from 1993-1995 is a saga of suicide, church burnings, and murder. Perhaps because of its notoriety, it was formative in shaping Black Metal's musical

Walser, 1993; Weinstein, 2000). However, one event we are particularly interested in is Metal's decline from popularity in the late 1980s and early 1990s as a possible mass extinction. The commercial Metal landscape at this time was profoundly reshaped after the release of Grunge band Nirvana's *Nevermind* in 1991 (Kahn-Harris, 2006; Klypchak, 2007). As Kahn-Harris puts it, "It is no hyperbole to state that an entire generation of bands had their careers ended overnight [by Grunge rock]" (Kahn-Harris, 2006, 1). The implications of the Grunge Rock takeover were long-lasting, effectively removing Metal as a cultural tradition from popular music, particularly in the United States. Popular hard rock forms like Alternative and Nu-metal drew heavily on Grunge and Punk, and any relationship with Metal of the 1980s was mutually disavowed. However, the effect of Grunge on the broader diversity of Metal ideas has not been studied.

5.2 Data

We study the history of the Metal genre primarily through the birth and death rates of artists ("bands"), as well as the birth of subgenres played by those bands. While the term bands ambiguously refers to a material organization of actors, it also captures a set of ideas. The name we give to a band is shorthand for this evolving complex of social, aesthetic, and musical ideas.

For our analyses, we draw on a complete dataset of bands active between 1968-2000 archived in the Encyclopedia Metallum (www.metal-archives.com; EM). The EM is a database of Metal music/musicians founded in 2002 containing over 157,000 Metal bands (March 2022), with exhaustive data on bands' dates and places of formation, discography, personnel, and record labels (Fig. D1). The EM is remarkable for its manual curation of genre information: Bands may only be included after a moderator vets a recording sample and approves that their music is indeed "Metal." Bands that are deemed to fundamentally be rooted in another music genre, for example Glam Metal bands in Pop, or Metalcore bands in Hardcore Punk, are excluded. Once a page is active, only experienced community members may edit a band's genre information. Although subjective, we find that EM subgenre labels are remarkably consistent with co-listening/co-labeling of bands in another online music community, Last.FM (Appendix B.2). We thus view the EM as a manually curated approximation of the complete population of Metal bands from 1968 through today, with emic subgenre form labels generated by and for the community itself. In Appendix B.1, we show that individual musicians reproduce Metal subgenres when moving between bands. This finding, along with the consistent labeling of bands by subgenre across multiple online communities, gives us confidence that bands can be viewed as distinct ideas within a cultural form.

Although the database is currently active, we limit our primary analyses to the 30,217 bands that released an album before the year 2000 for a number of reasons. First, by focusing on bands active before 2002, we minimize the effects of both curatorial lag and any possible curatorial bias due to fluctuations in website usage over time. Second, we study this period because there is strong qualitative scholarship covering this era (Klypchak, 2007; Kahn-Harris, 2006; Walser, 1993). Third, this cutoff occurs before the widespread adoption of the

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and cultural aesthetics (Christe, 2010).

internet, which significantly altered how Metal culture was shared and reproduced globally (Mayer and Timberlake, 2014).

We approximate the birth of a band's ideas within the form through the circulation of a cultural object: the release of the band's first album. We use the band's dissolution to approximate their "death." For the 15.6% of bands where it was unclear whether the band was extant or broken-up, we imputed their dissolution time stochastically and show this procedure does not affect our main findings (Appendix A.2; Fig. D2).

5.3 Research Questions

Our theory suggests four evolutionary mechanisms that can effect cultural change: mass extinction, competition, key innovation, and exogenous drivers. We now translate these mechanisms into research questions that are legible in the context of Metal music; they would obviously be different in detail in explaining cultural change in other cultural forms and contexts. Because our historical analyses evolved abductively (Brandt and Timmermans, 2021; Lieberson and Lynn, 2002; Timmermans and Tavory, 2012) we present the following as research questions instead of hypotheses. Each of the first three research questions addresses the impact of a specific evolutionary mechanism (i.e., mass extinction, competition, and key innovation), while the fourth allows for alternative explanations:

RQ1: *Did the rise of Grunge music cause a mass extinction of ideas within Metal writ large?* (Analysis 1)

We might expect the replacement of commercial Metal with Grunge in the early 1990s to depress the diversity of Metal ideas more generally (Kahn-Harris, 2006). However, given that Metal was a truly international (albeit Western) music form in the 1990s, it is hard to know how impactful this event was on the genre's global trajectory. We will use the LiteRate model to test this question.

RQ2: *Is there evidence that cultural carrying capacity shaped the diversity of ideas within Metal between 1968 and 2000?* (Analysis 2)

Our account suggests that competition between ideas for cultural carrying capacity is endogenous to cultural forms. Nevertheless, it is possible that historical events or other evolutionary mechanisms (e.g., repeated key innovation) could obscure or counter the impact of competition on the diversity of Metal ideas. We will use the competition model in equation 5 to test this question.

RQ3: *Is there evidence of key innovations in the history of Metal music?* (Analysis 3)

We might expect key innovations to emerge early in the trajectories of cultural forms. In inchoate music genres, we imagine a slow churn of ideas being and born and dying until early leaders define the sonic, aesthetic, and social parameters of the new genre (Lena, Peterson, and Peterson, 2011). Once these key innovations materialize, the form is named, the population of supporting actors grows, and new artists will enter the genre. We will test this question with the hierarchical model described in equations 5 and 6.

RQ4: *As a non-mechanistic alternative explanation, has the diversity of ideas within Metal simply tracked the form's visibility within popular culture?* (Analysis 4)

Under this alternative non-mechanistic explanation, we might expect diversity in Metal to grow through the 1980s as the genre's popularity increases, and then decline as Metal enters its "Dark Ages" in the 1990s (Kahn-Harris, 2006).

6 Analyses: Cultural Change in Metal Music

We now apply our birth-death process models to abductively characterize cultural change in Metal Music between 1968 and 2000. Our core analyses (Analyses 1-4) study change through the birth and dissolution rates of bands active during this period.

6.1 Analysis 1: Generating Hypotheses with LiteRate And Looking for Mass Extinctions (RQ1)

Motivation: We apply LiteRate to identify statistically significant shifts in the birth and death rates of bands; these shifts should correspond to major events in the history of Metal, the action of evolutionary mechanisms, or exogenous drivers of cultural change.

Results: The rates estimated by LiteRate largely support the multi-stage trajectory observed in the empirical birth and death rates (Fig. 2 dashed lines). For clarity, we partition this trajectory into five stages that have both largely monotonic slopes and are separated by statistically-significant $(2 * \log(Bayes\ Factor) > 2)$ rate shifts.
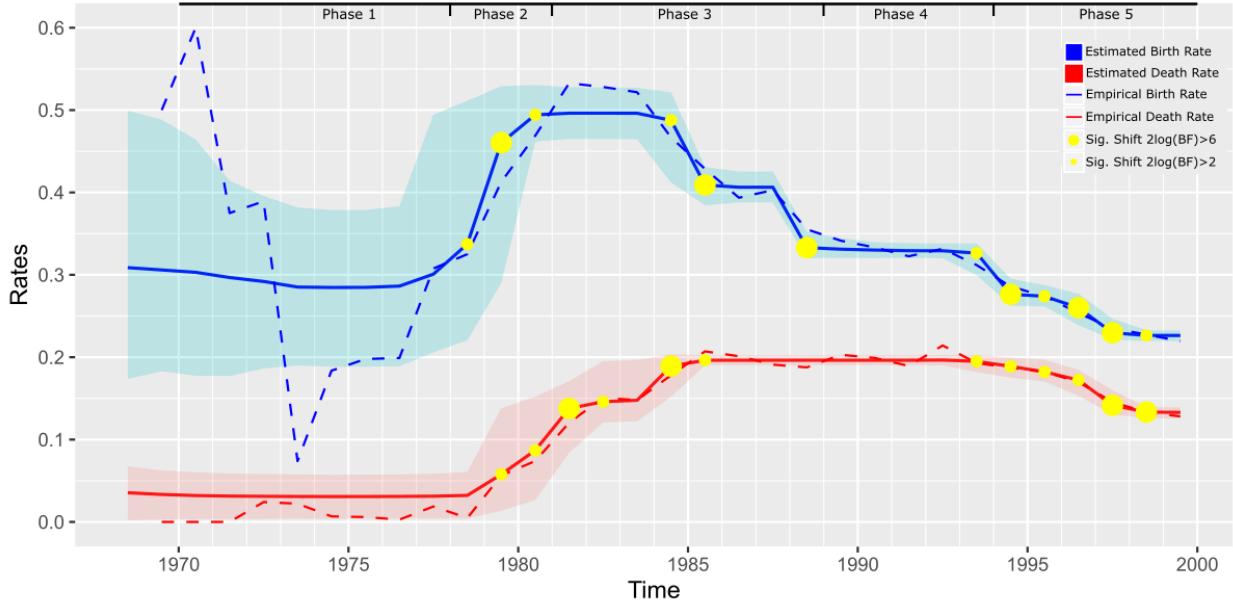
Figure 2: **Estimated Diversification Rates from Analysis 1.** Dashed lines indicate empirical birth (red) and death (blue) rates of EM Metal bands (first year dropped for clarity). Estimated rates and their 95% highest posterior density intervals shown in solid colors. Significant rate shifts shown as yellow circles. Five historical phases visible in estimated rates (partitioned by significant rate shifts) denoted at top of plot.

We interpret Phase 1 as early experimentation in Metal from 1968-1978 with a U- or V-shape in which birth rates start out high, decline, and begin to rise again. The extent of this fluctuation is hard to gauge from the relatively unstructured LiteRate model, given the sparsity of the data during this period (large 95% credible interval [CI]).[30] By 1978, the genre form appears to solidify around a few key innovations (i.e., sub-genres and associated musical, aesthetic, and social ideas) and there is a sharp increase in the birth rate through 1981, coupled with increased turnover as bands rapidly explore the genre space (Phase 2).

We identify Phase 3 as 1981-1988. From 1981-1984, birth rates are stable and high, while death rates rise.[31] From 1984-1988, birth rates fall while death rates stabilize. The overall signature of converging birth and death rates in Phase 3, is consistent with competition (Fig. 1B). In Phase 4 (1988-1993), birth and death rates are stable. Finally, Phase 5 (1994-2000) begins with another competition signature, before both birth and death rates slow, stabilizing the population of bands that make up Metal.

It is striking that not only are birth rates greater than death rates *on average*, they are *always* greater than death rates. If the genre is undergoing competition in Phases 3-5, it does not appear to reach its maximum cultural carrying capacity by 2000. Death rates are not nearly as dynamic, suggesting that this is a birth-driven process.[32]

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[30]In general, the consistency between empirical and LiteRate-estimated birth rates has to do with the large size of our dataset. In contrast, the discrepancy between the observed V-shape and estimated, moderated U-shape in Phase 1 has to do with the sparsity of data in Phase 1 (1968-1978). LiteRate seems to average over the interesting heteorgeneity in rates with large credible intervals during this period due to limited data.

[31]In biology, the rapid churn of species early in a clade's history has been interpreted as necessary for clades to build a population of fit species that stabilize the clade's existence (Budd and Mann, 2018).

[32]This is evident in the net diversification rates (birth minus death rate), which bear similar contours to

It is also striking that the enduring competition signature (Phases 3,5) is interrupted by a shelf with stable rates in Phase 4.[33] The fact that this shelf corresponds with Metal's peak in commercial appeal suggests that, for the majority of bands, the rise of Grunge music did *not* cause a significant extinction (RQ1). However, the contraction in rates in Phase 5 suggests that what scholars call the Metal "Dark Ages" (the second half of the 1990s, after the fall from commercial appeal) is a real phenomenon (Kahn-Harris, 2006; Christe, 2010).

6.2 Analysis 2: Competition Between Bands (RQ2)

Motivation: We interpret the LiteRate competition signature across Phases 3-5 as evidence that bands are competing for available cultural carrying capacity. Once the sonic, aesthetic, and social parameters of the genre solidify in the early 1980s, there is only so much cultural space for new bands to occupy while still being understood as Metal by actors. We now test this formally using the competition model defined in equation 5.

Results: This model produces birth rates that closely match both the empirical and LiteRate birth rates from 1986 onwards (second half of Phase 3). However, it misses the initial dynamics of the genre from 1968-1982, averaging over the experimentation in Phase 1 and explosive growth in Phase 2, as well as the shelf in Phase 4.

The model is a significantly poorer fit for death rates, and the exponential parameter effectively shrinks the model to a constant death rate over time. Although this result is not consistent with the LiteRate model, it suggests that competition (at least over a constant carrying capacity) is not a driving force behind the death rates we observe.

We estimate a mean overall carrying capacity of 15,400 (95% CI 14544,16296), suggesting that this is the maximum number of bands the form could have supported over our analysis period (Fig. 3C).

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the birth rates (Fig. D3).

[33]Note that there is a smaller shelf which we do not discuss between 1986-1988 to avoid over-complicating the narrative. Fig, D4 suggests that this shelf reflects staggered competition setting in at different times in the U.S. and the rest of the world.
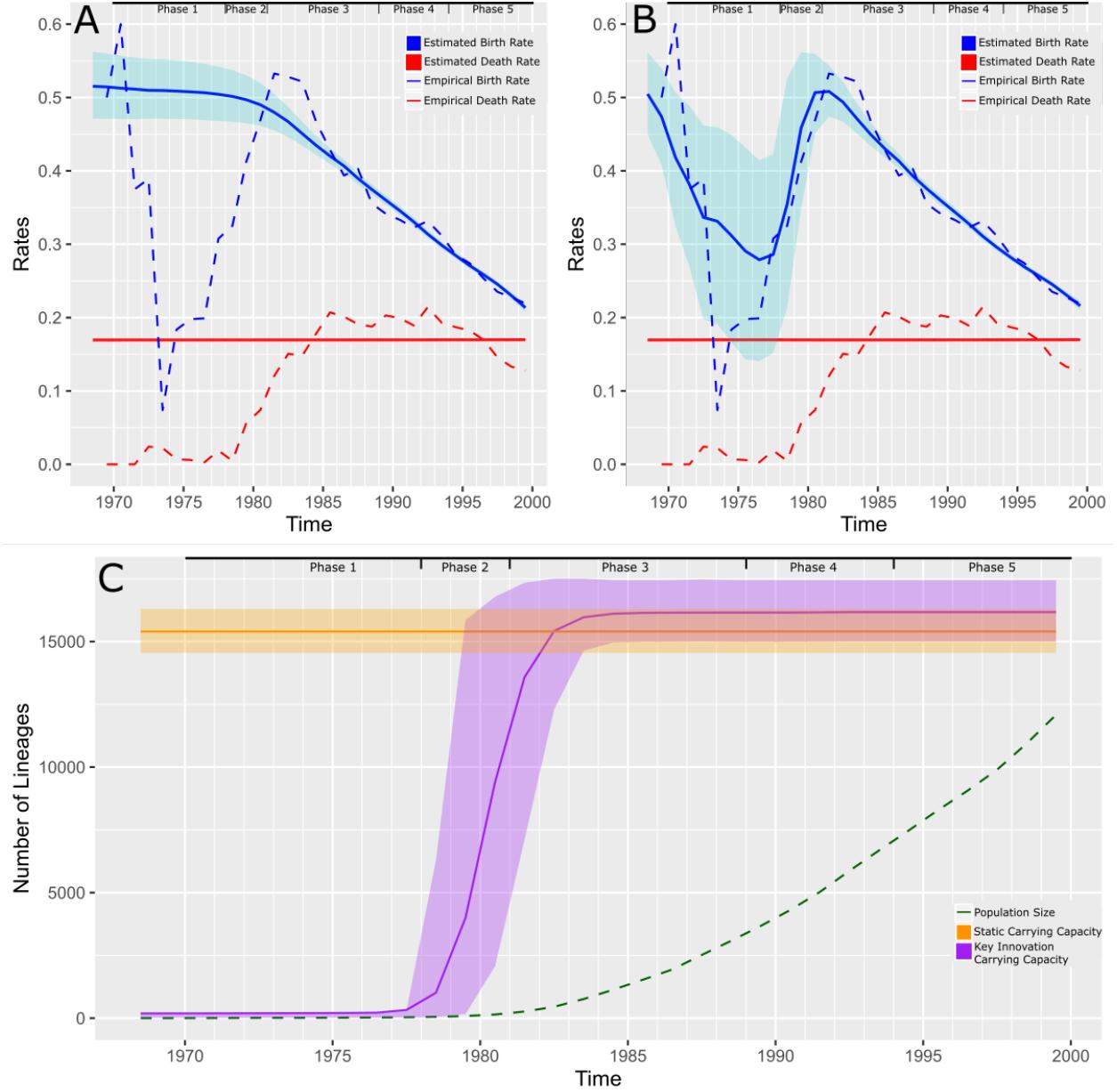
Figure 3: **Estimated Diversification Rates and Carrying Capacities from Analyses 2 and 3.** Dashed lines indicate empirical birth (red) and death (blue) rates of EM Metal bands (first bin dropped for clarity). Estimated rates and their 95% highest posterior density intervals shown in solid colors. **A**: Estimated birth and death rates over time for diversity-dependent competition model in Analysis 2. **B**: Estimated birth and death rates for diversity-dependent competition with carrying capacity expansion due to key innovation in Analysis 3. **C**: Estimated carrying capacities over time in Analyses 2 (orange) and 3 (purple) with 95% highest posterior density intervals. Empirical population size shown in green.

6.3 Analysis 3: Competition + Key Innovation (RQ3)

Motivation: The U- or V-shaped signature of high-low-high empirical birth rates between 1968-1981 (Phases 1,2) suggests that—after early trendsetters defined the parameters of the genre—the available carrying capacity was filled, leading to a precipitous drop in birth

rates. For the birth rates to rise again, competition must be relaxed; this corresponds to an increased carrying capacity, creating space for new bands/ideas between the late 70s and the mid-80s. This increased carrying capacity allows the actor population to expand as people acquire or broaden their understanding of what the form means, and more overall actor resources are dedicated to consuming and producing cultural objects in the form. We explore this key innovation hypothesis because the competition model in Analysis 2 does not adequately capture the birth dynamics in Phases 1-2; to do so, we allow the carrying capacity to grow according to a logistic curve (equation 6)

Results: Broadly speaking, fitting a logistic curve to capture key innovation alongside competition reproduces the trends observed in the empirical and LiteRate rates: the birth rate starts high, declines, and then re-emerges to enter a characteristic competition signature (1981-2000). The fitted parameters show that Metal's most explosive expansion occurred in 1979.89 (95% CI 1977.96, 1981.59), which corresponds closely with the spike in LiteRate-estimated birth rates attributed to key innovations in Phase 2 (Fig. 3C). We can again estimate a maximum carrying capacity of bands between 1968 to 2000, 16,172 (95% CI 15003,17437), which is higher but has statistically overlapping credible intervals with the estimate from the pure competition model (Table 2).

6.4 Analysis 4: Rates Follow Popular Trends (RQ4, Alternative Hypothesis)

Motivation: The previous account—in which early carrying capacity expansion is followed by competition—provides a compelling evolutionary explanation of Metal's broad historical trajectory from 1968-2000 (Phases 1-3,5) (Fig. 3B). However, the model from Analysis 3 averages over the large shelf in rates in Phase 4 (1988-1994). This period corresponds with Metal's surge in popularity in the second half of the 1980s and the emergence of Grunge music in the early 1990s. Both of these phenomena are evident in the number of songs charting on the Billboard 100 music chart (Fig. 4A). As an alternative explanation, we therefore consider a model where rates are simply correlated with Metal's popularity on the BillBoard 100 US pop music charts. This exogenous-driver model does not invoke a worked out evolutionary mechanism like competition or key innovation.

We measure Metal's popular success using any song that is labeled as some subgenre of Metal on Discogs (*Discogs API*, 2019) or is released by an artist who is listed as Metal (including Glam Metal) in their Wikipedia sidebar (using the DBPedia API) (Auer et al., 2007). We also manually checked the Wikipedia abstracts for descriptions as "Metal" for boundary cases that were not genre-labeled in either dataset or are labeled as "Hard Rock" in Discogs. Overall we found 560 broadly understood Metal singles out of the 14,608 unique songs on the Hot100 chart between 1968 and 2000.

Results: Even with the extremely flexible model defined in equation 7, these data do not seem to capture the empirical or LiteRate estimated rates in Phase 4, or the rest of Metal's history (Fig. 4). We thus reject the hypothesis that the birth and death rates of Metal bands broadly follows the genre's success in popular music.
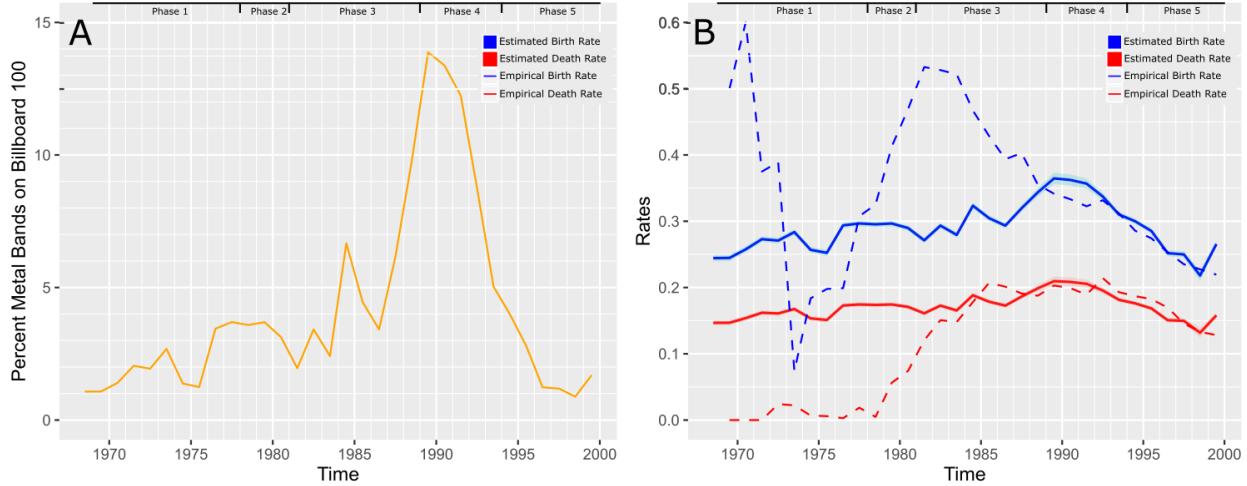
Figure 4: **Estimated Diversification Rates from Analysis 4.** Estimated diversification rates when rates are a function of the proportion of broadly-understood "Metal" bands (i.e., labeled as Metal in Wikipedia or Discogs) on the Hot 100 chart 1968-2000 (**A**). Dashed lines in (**B**) indicate empirical birth (red) and death (blue) rates of EM Metal bands (first bin dropped for clarity). Estimated rates and their 95% highest posterior density intervals shown in solid colors.

7   How Does Cultural Carrying Capacity Emerge?

The previous analyses seem to strongly favor competition and key innovation as the twin drivers of the history of Metal music. This leaves us with one final puzzle: What, exactly, are the key innovations that play a pivotal role in the history of Metal music? How do those innovations expand Metal's cultural carrying capacity? In this section, we show that these key innovations are most plausibly interpreted as new subgenres. Emergent subgenres create space for novel ideas in musical forms by formalizing and naming schemata that can be leveraged to expand understandings of the form. To explain why carrying capacity cannot expand infinitely, we also provide corroborative evidence that subgenre innovation is bounded by limited cognitive resources and the existence of adjacent forms.

Subgenre innovations explain the growth of Metal's carrying capacity

Recall that key innovations are novel ideas that radically expand the cultural carrying capacity of a form. They do so by providing new cognitive templates–new schemata–for organizing the reception or production of cultural forms. In music, these new schematic templates are called subgenres. Inchoate subgenres are autonomous cultural forms that encompass distinct musical, aesthetic, and social ideas, but nonetheless nest within the parent genre. When these ideas circulate broadly enough, labels emerge as shorthands for commonly shared schemata that are distinct to that subform [34]. For example, the label "Doom Metal" captures a common cultural schema parameterized by slow tempos, distortion, and detuned guitars. The spread of this schema (and associated cultural ideas/objects) expands the parent form's carrying capacity by creating scaffolding, conventions, and templates for actors to create and interpret novel ideas.

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[34]Note that such labels also facilitate the learning and spread of the schema; see Lupyan, Rakison, and McClelland, 2007

To test our theory that carrying capacity expands through the introduction of new subgenres, we constructed an approximate trajectory of Metal's carrying capacity by stacking the carrying capacities of Metal's seven largest subgenres. These largest subgenres collectively label 95% of bands. We first estimated the carrying capacity of each subgenre using the simple (fixed carrying capacity) competition model in equation 5.[35] We then sequenced these carrying capacities in the order of each subgenre's emergence (i.e., the birth year of the first band with that subgenre label): Heavy, Doom, Power, Progressive, Thrash, Black, and Death. Finally, we cumulatively summed these carrying capacities to construct a piecewise carrying capacity trajectory (Figure 5).
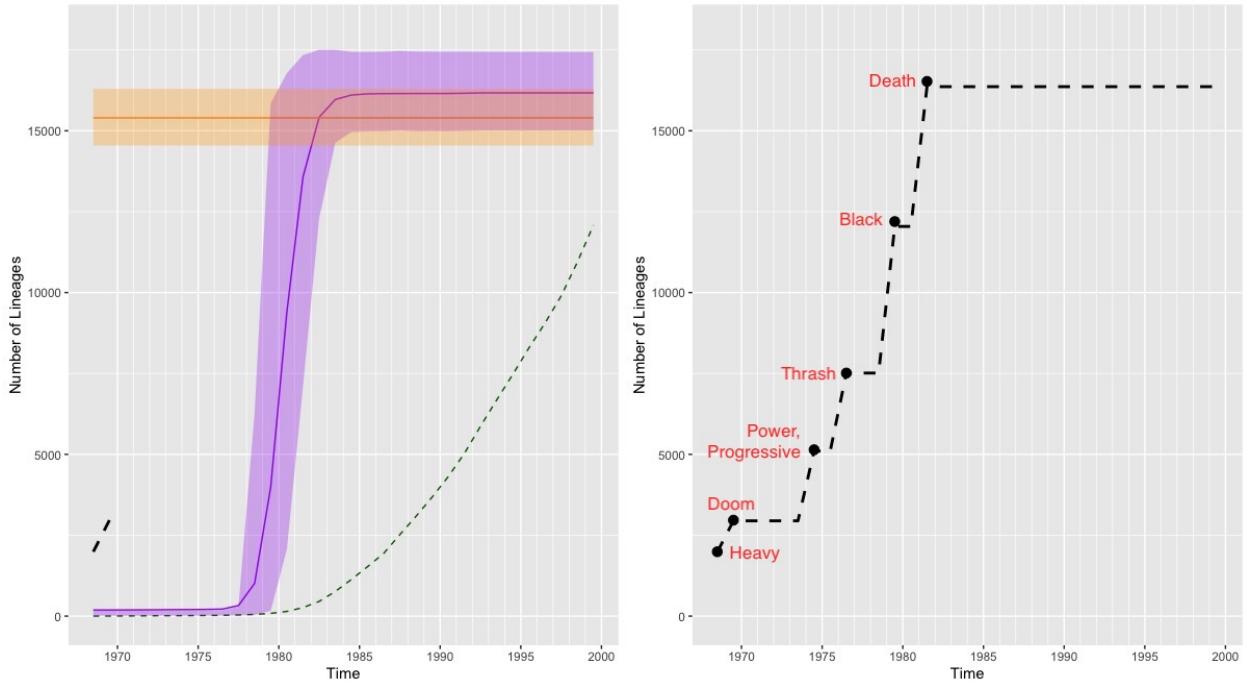

Figure 5: **Estimated Key Innovation Model versus Stacked Subgenre Carrying Capacities. Left:** Estimated carrying capacities from Fig. 3C. **Right:** Cumulative sum of sequenced maximum carrying capacities estimated for each of the seven largest Metal subgenres, collectively labeling 94.9% of all bands.

This procedure yields an S-curve remarkably similar to the fitted logistic curve modeling carrying capacity expansion via key innovation (Analysis 3). We stress that this result was neither expected or inevitable; the logistic function was chosen *a priori* for formal reasons and is commonly used in biology to model carrying capacity growth—not to fit cultural data. Nevertheless, the cumulative carrying capacity of these subgenres falls well within the 95% credible interval of the maximum carrying capacity estimated in Analysis 3 (Figure 5). Moreover, the period of maximum carrying capacity growth in Phase 2 aligns with the emergence of what would ultimately become Metal's three biggest subgenres (Thrash, Death, and Black). Collectively, these correspondences provide strong evidence that Metal's carrying capacity expanded through the key innovation of new subgenres.

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[35]Before fitting a simple competition model, we ran LiteRate to confirm that the diversification rates of these subgenres were only consistent with competition, not key innovation or mass extinction.

Adjacent forms and cognitive constraints limit carrying capacity expansion

The results above invite a second question: Why can't carrying capacities expand infinitely? In Section 2, we argue that forms are fundamentally bounded by actors' limited bandwidth (i.e., cognitively) and by the pre-existence of other cultural forms (i.e., culturally). To make this more concrete: Black Metal cannot grow infinitely baroque and complicated; its meaning would become incoherent for actors who lack the time, attention, motivation, and memory to learn and reproduce ideas that are too diverse, or schemata too complex. Black Metal likewise cannot infinitely subsume all possible ideas within Metal; these ideas may have already been claimed by adjacent forms like Death Metal, Thrash Metal, or Hardcore Punk.

If the growth of Metal is bounded by cognitive constraints, we would expect limits not only on the diversity of bands, but also on the diversity of schemata used to categorize such music (as well as on the language used to label it). To test this, we examined the birth rates of new subgenres throughout Metal's history.[36] We operationalize the birth of a subgenre as the first appearance of a band with that label within the EM.[37] A LiteRate analysis on the birth rates of the 46 Metal subgenres (listed in Table C1) shows a pure competition signature, consistent with cognitive constraints on the number of distinct schemata (and therefore terms or labels) that actors can accommodate to describe Metal (Fig. 6, top row). In contrast to bands, these rates decline until they are effectively zero by 1997 (Phase 5), suggesting that Metal cannot substantively accommodate any new vocabulary or formal categories beyond this point. This evidence for cognitive constraint is supplemented by a Shannon entropy analysis showing that annotators in the EM never use the full vocabulary available to them to describe music (Appendix B.3), and a LiteRate analysis showing similar competition signatures for the creation of sub-subgenres within the major subgenres (e.g., Funeral Doom within Doom); see Fig. 6, middle row. Even though Metal fans relish systematizing the nuanced differences between subgenres and sub-subgenres, these findings suggest that cognitive limits bound the infinite growth of new ideas. As further evidence of the role of cognitive limits, note that only the largest subgenres—and a handful of adjacent cultural forms like Rock or Punk—sire sub-subgenres (Table 2); the others subgenres (e.g., Neoclassical or Viking) are already too niche and intricate to permit further differentiation.

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[36]We exclude subgenres in the EM with fewer than ten bands.

[37]We focus on birth rates because genres rarely die; At least one band is often active at all times. Commercially successful bands may remain active for decades (e.g., Metallica).
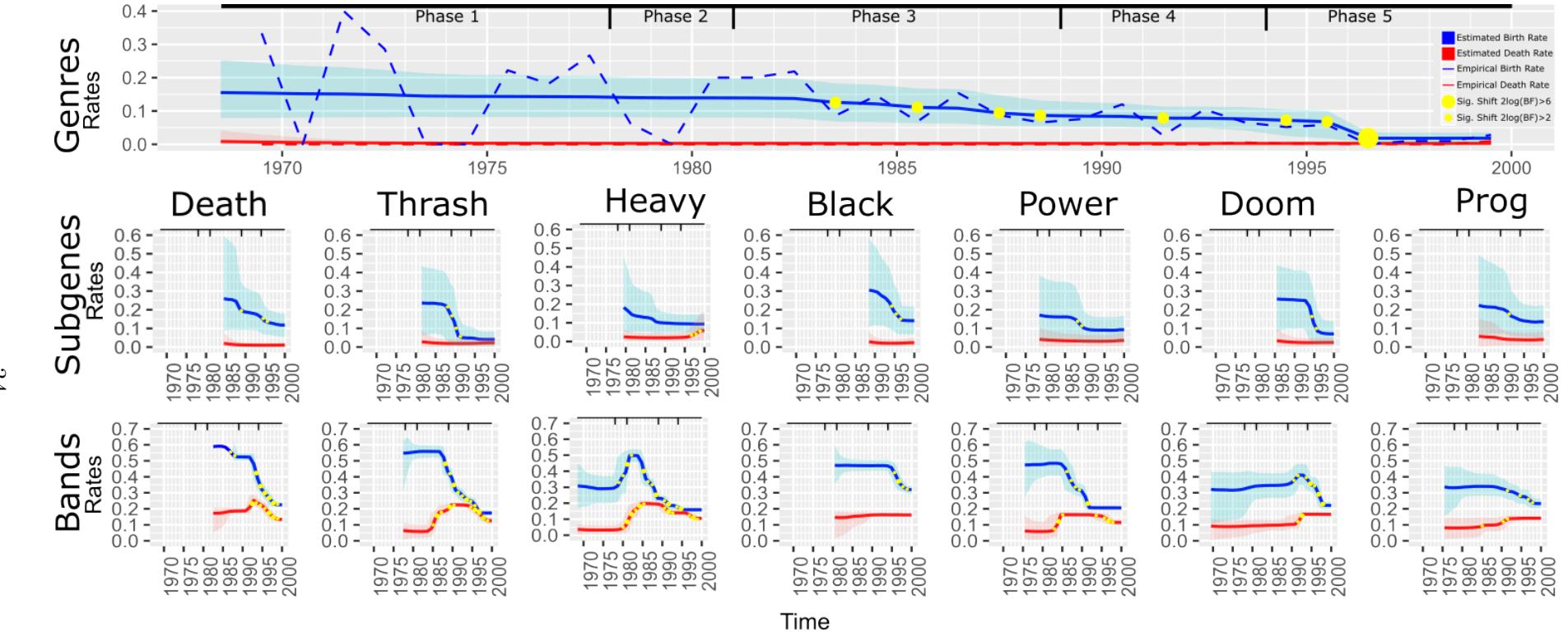
Figure 6: **Estimated Diversification Rates from Analysis 7.** Estimated diversification rates for new subgenres (top row), sub-subgenres in the seven largest genres (middle row), and bands within these subgenres (bottom row) using LiteRate. The inset subgenres, presented from left to right in order of size, collectively label 94.9% of all bands. Estimated rates and their 95% highest posterior density intervals shown in solid colors. Statistically significant rate shifts marked in yellow.

Our evidence for cultural constraints is more circumstantial. In Fig. 6 (bottom), we show competition between bands in each of the seven largest subgenres. In most of these subgenres, birth and death rates converge, suggesting that bands are born until they fully saturate each subgenre's carrying capacity (Fig. 6A). However, these subgenre-level constraints on carrying capacity cannot arise from limited space for ideas in Metal as a whole; the Metal form itself has yet to reach a carrying capacity for bands (Analysis 4), and continues to generate new subgenres through 1997. We thus conclude that the band-level carrying capacities of subgenre forms are constrained by the presence of adjacent subgenre forms within Metal itself.

For a rough picture of how this works, imagine that the birth of a given subgenre is associated with a prototype band, which sets the subgenre's rough schematic parameters. The number of distinct ideas—in other words, possible bands—that can be associated with that subgenre is limited by the number of ideas that are closer to that prototype than they are to any other (while keeping in mind that bands must be sufficiently distinct from one another, even within a subgenre). While our dataset of Metal artists does not allow us to show this, it is plausible that the same mechanism of cultural constraint operates for higher-level cultural forms as well: the expansion of Metal as a genre is bounded by the presence of pre-existing forms like Rock and Punk (or even EDM or Jazz) that have already laid claim to adjacent ideas.

8 Discussion

This paper provides a complete theory of cultural change that is coherent at multiple levels of analysis: actors, their personal culture, and public culture. Our theory understands cultural change as an evolutionary process driven by the dynamics of cultural carrying capacity. Carrying capacities for cultural forms emerge from (1) cognitive constraints on the time, attention, memory, and motivation of actors (actor-centric perspective) and (2) competition from already existing public cultural forms (culture-centric perspective). In our theory (Section 2), we introduce three evolutionary mechanisms for cultural change entailed by our key concept of cultural carrying capacity: mass extinction, competition, and key innovation. We then introduce powerful statistical methods (Section 4) to test for the action of these mechanisms in real data. In Sections 5.3 and Analyses 1-4, we deploy our theory and methods to show that competition and key innovation drive the history of a prototypical cultural form, the music genre (Metal). In Section 7, we return to our theory and provide empirical evidence that carrying capacity growth in Metal has both cognitive and cultural origins. In this section, we reflect on our findings and the broader implications of our theory.

8.1 The History of Metal:
Key Innovation and Enduring Competition

How do we understand the history of Metal Music from the perspective of cultural evolution? We began by using the unsupervised LiteRate model to identify statistically significant shifts in the birth and death rates of all Metal bands active between 1968-2000 (Analysis 1). We then partitioned this diversification rate trajectory into five phases separated by significant shifts and changes in slope (Fig. 2). Next, we checked whether the rate patterns in any

of these phases were consistent with the evolutionary mechanisms described in Section 2.4: mass extinction (RQ1), competition for cultural carrying capacity (RQ2; Analysis 2), or key innovation (RQ3; Analysis 3). Finally we considered the alternative explanation that band diversification rates simply follow popular music trends (RQ4; Analysis 4). We find that competition modulated by key innovation provides the most compelling overall explanation of (public) cultural change in Metal between 1968 and 2000, both qualitatively and statistically.

A theoretical interpretation of our results contextualizes these models within the five historical phases delineated by the LiteRate analysis (Fig. 2). Here we interpret these phases using our own theory of culture, as well as Lena and Peterson's four-stage lifecourse for music genres (i.e., an experimental phase, a scene-based phase, a popular phase, and a traditionalist phase) (Lena and Peterson, 2008; Lena, 2012).

In Phase 1 (1968-1978), a few trendsetting bands are experimenting with new sounds and trying on different ideas for the form. Because the circulation of these ideas is so limited, the effective capacity of listeners to collectively recognize these different sounds, aesthetics, and practices as Metal music is also limited. Bands creating music adjacent to early Metal bands may thus be interpreted as "not Metal" because available schemata for the genre are narrow. The only model to adequately capture the birth dynamics during this period—with a high initial birthrate rapidly dropping toward the death rate—invokes competition between bands for an extremely limited carrying capacity (approximately 50 bands) (Analysis 3; Fig. 3B,C).

From 1978 to 1981 (Phase 2), a critical number of actors (e.g. musicians, fans, passive listeners) coalesce around a shared set of ideas to create a coherent, mutually intelligible conception of the Metal form. The key innovation of new subgenres like Thrash, Death, and Black Metal within the broader form allows the birth rate of bands to explode by establishing a larger space of sonic, aesthetic, and social parameters which new artists can explore in subgenre scenes (Fig 3; Fig 5) . Again, the only model that can explain observed dynamics is one in which the carrying capacity of the form expands rapidly due to key innovation (Analysis 3; Fig. 3B).

Phase 3 (1981-1988) sees bands rapidly fill up "sonic niches" within the form. By 1984, competition sets in for the time, attention, memory, and motivation (i.e., cultural carrying capacity) that the actor population can devote to Metal (RQ2). Even though the number of listeners is growing, a coherent understanding of the genre and its formal distinctions and possibilities can only expand so much. By 1984, our modeled carrying capacity is fixed, and the competition (Analysis 2), and competition + niche expansion (Analysis 3) models are functionally equivalent (Fig. 3).

Phase 4 (1989-1994) corresponds with the climax of Metal as a popular form and its subsequent dethronement by Grunge rock; neither LiteRate (Analysis 1) or a model that tracks Metal's pop chart market share (Analysis 4) show that the mass extinction observed in commercial Metal bands (Klypchak, 2007; Christe, 2010; Kahn-Harris, 2006) generalized to Metal bands writ large (RQ1).

During Phase 5, Metal's "Dark Ages," birth rates resume declining, and death rates begin to decline as well (1994-2000) (Kahn-Harris, 2006). We speculate that the contraction in death rates in Phase 5 reflects relaxing competition as the genre transitions from a popular form into a combination of traditionalist and scene-based Extreme forms (Lena, 2012). The gradual convergence of birth and death rates is consistent with competition as the fixed

carrying capacity carved out by earlier rounds of key innovation is filled. When we fit a LiteRate model to band dynamics out until 2016, these rates eventually converge (Fig. D7), consistent with the filling of a fixed cultural carrying capacity.

Overall, the competition + key innovation model provides a more compelling explanation of the dynamics of Metal bands between 1968 and 2000 than either competition alone, mass extinction, or the hypothesis that band dynamics track the genre's commercial success. Statistical comparison corroborates this assessment. To compare the models in Analyses 2-4, we concatenated birth and death rates and OLS regressed them on both the mean empirical rates and the mean rates estimated by LiteRate. The coefficient of determination (R^2) of these regressions is a measure of the models' *adequacy* in capturing the linear variation in both the stochastic empirical and estimated rates.[38] Table 2 shows that the competition + key innovation model has the highest adequacy among mechanistic models in capturing the LiteRate rates. It is relatively parsimonious with only 9 parameters compared to the roughly 26 LiteRate parameters. Table 2 provides estimates for two interesting quantities: The year when key innovation had the greatest impact on carrying capacity and the maximum carrying capacity that the cultural form can theoretically sustain. The first estimate is consistent with the musicological literature on the genre, which points to the early 1980s as a period of peak expansion and creative innovation (Christe, 2010; Klypchak, 2007). The second estimate—implying a fixed carrying capacity that will ultimately be filled—is consistent with the eventual convergence of birth and death rates in the 2010s, as shown in Fig. D7 [39].

Table 2: **Comparison between diversification rate models for band analyses.** Each row corresponds to a model: LiteRate (Analysis 1), diversity-dependent competition (Analysis 2), competition and key innovation (Analysis 3), and popular music trends (Analysis 4). "Parameters" are the number of parameters in the model (or average number of parameters across chains in the LiteRate model), R^2_{emp}, a measure of model adequacy, is the coefficient of determination of this model to the empirical rates, $R^2_{LiteRate}$ is the coefficient of determination to the LiteRate rates, "Max Carrying Capacity" is the maximum of parameter K in Analysis 2 & $L + d$ in Analysis 3. "Max Growth Date" is the midpoint of the logistic curve (parameter x_0) in Analysis 3. 95% highest posterior density intervals shown in parentheses where appropriate.

Analysis	Parameters	R^2_{emp}	$R^2_{LiteRate}$	Max C.C.	Max Growth Date
LiteRate (1)	25.68 (23,31)	0.85	N/A	N/A	N/A
Competition (2)	6	0.55	0.62	15400 (14544, 16296)	N/A
Comp. + Key Innov. (3)	9	0.77	0.78	16172 (15003, 17437)	1979.89 (1977.96,1981.59)
Popular Music Trend (4)	6	0.55	0.69	N/A	N/A

Limitations of Case Study

In this paper, we made the simplifying assumptions that all ideas are equally important to the dynamics of a form, and that this importance does not vary over an idea's lifecourse. The first assumption is reasonable because schemata are heterogeneous across individuals; ideas that are crucial to one actor's conceptions of the form might be absent from another's.

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[38]We also calculated the harmonic mean of the likelihood (Raftery et al., 2007). For bands, the ordinal rank of this statistic corresponds with R^2_{emp} except that the LiteRate model has the highest harmonic mean and competition + key innovation has the second highest. However, we do not include this statistic in Table 2 because it is not a reliable estimate of the marginal likelihood due to its infinite variance.

[39]That said, the quantitative value of the maximum carrying capacity does increase above the earlier estimate; this is, perhaps, unsurprising given all of the changes in the intervening decades, most notably the widespread use of the Internet to disseminate and consume music.

For the garage and touring bands that comprise the majority of our dataset, we also think it reasonable to draw a primary distinction between a band's ideas being "alive" (when the band is active and circulates them) or "dead" (when the band dissolves and stops actively circulating them).[40] These simplifying assumptions allowed us to analyze tens of thousands of bands not found in commercial datasets like Spotify or Apple Music, for which saliency data (e.g., album sales) are not available. Focusing on cultural salience that varies between bands or changes over the lifecourse would have resulted in a bias towards commercially successful and recent bands. Nevertheless, we consider modeling cultural saliency an important direction for future work (Candia and Uzzi, 2020). One possible approach to incorporate this into our framework would be to alter the diversity-dependent competition model and couple death rates to salience.

Future work might also explore why we infer flat death rates within the population of bands—contrary to the standard evolutionary assumption that competition for fixed carrying capacity should lead to declining birth rates (which we see) and increasing death rates (which our models do not infer). One possibility is that competitive effects on extinction only become visible in this cultural form when the carrying capacity has been reached (after our window of analysis; Fig D7)[41]. An alternative explanation is that band break-ups are not driven by competition, but by changing life circumstances for actors that are exogenous to the form. A third possibility is that competition affects the death rates of younger, less-established bands disproportionately, as observed in several biological systems and industries (Hagen et al., 2018; Singh, Tucker, and House, 1986). Richer actor-level data and age- or salience-dependent extinction models could tease these hypotheses apart.

More ambitiously, we could try to clarify the ambiguous status of bands as actors/organizations and bands as cultural forms, nailing down the relative importance of organizational and cultural factors in their population dynamics. This would require further elaboration of our models and much more detailed data; we do not believe it would change the broad contours of the story.

Substantive Contributions of Case Study

Within the sociology of culture, our work makes inter-related contributions to the sociology of music genres, Metal Studies, and the theory of creative fields. Our population-scale analysis of Metal music largely squares with a four-part trajectory for individual music genres (Lena and Peterson, 2008; Lena, 2012), and with nuanced histories of Metal Music that focus on events in popular music (Christe, 2010; Weinstein, 2000; Klypchak, 2007). By looking at tens of thousands of bands with limited economic motivation, our analysis suggests that changes in Metal in the late 1980s and early 1990s represent more of a phase transition between senescing popular forms and emerging Extreme forms, rather than a generalization of the sudden Grunge-driven mass extinction observed in commercial Metal music.

Our approach also challenges analysts of creative fields like science and art to broaden their focus beyond competition between actors for social and cultural capital; they should also consider how cultural ideas compete for the cognitive resources of actors. For example, reimagining Bourdieu's habitus in light of our theory might yield insight into how habitus

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[40]A supplemental analysis showed that keeping bands "alive" across periods of inactivity stretching as long as 15 years did not substantively change our results (Data not shown).

[41]In principle, we may be able to capture this by making the dependence of death rates on fraction of carrying capacity in equation 5 filled more flexible, e.g., by making the priors on γ less conservative.

evolves over time and shapes the decisions of actors within a field (Bourdieu, 1996).

8.2 Methodological Innovations for Demographic Rate Analysis of Cultural, Organizational, and Human Populations

In this paper, we introduce a suite of cutting-edge, Bayesian models of birth-death processes. This suite has broad application; it can be used to explain population change in demography, social fields, organizational ecology, *and* the computational analysis of culture. The unsupervised LiteRate algorithm can discover significant shifts in rates and help generate hypotheses, while our mechanistic models can be used to test hypotheses about key innovation, competition, and the influence of exogenous trends on rates. Consider the following illustrative examples. For human demographers, *LiteRate* could be used to identify and quantify the statistically-significant impact of major events (e.g., Hurricane Katrina, the COVID-19 pandemic) on birth and death rates. For management scholars, parametric estimates of the timing of key innovations and theoretical maximum carrying capacity could yield insights on the historical dynamics and future prospects of organizational forms and industrial sectors. For cultural analysts, our carrying capacity models could be applied to populations of political tweets to quantify the extent and frequency with which news cycles squeeze out important domestic and foreign policy topics. We are confident that scholars with substantive interests in these domains will conceive many further applications.
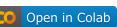
Despite their power and flexibility, our models are easy to apply. We have created four detailed tutorials to explain their usage. These tutorials are presented in the Google Colaboratory environment, so interested readers need not install any software on their computer to try them out.

- **Tutorial 1: Modeling the Dynamics of Cultural Diversification** `CO Open in Colab`

  This tutorial introduces diversification rate (i.e., birth/death rate) analyses, and highlights questions approachable through this framework. It features an interactive simulator for readers to build intuition about how changes in birth and death rates affect population size over time.

- **Tutorial 2: Birth-Death Processes and LiteRate** `CO Open in Colab`

  In this tutorial we introduce the linear birth-death process as a statistical model for cutting through stochasticity in diversification rates. We also introduce LiteRate, and show users how to run LiteRate on their own data.

- **Tutorial 3: Interpreting LiteRate Results** `CO Open in Colab`

  This tutorial shows users how to check the convergence of LiteRate's Markov chain Monte Carlo logs, as well as how to plot LiteRate results. Empirically, we walk users through the interpretation of the LiteRate results presented in Analysis 1.

- **Tutorial 4: Modeling Evolutionary Mechanisms** `CO Open in Colab`

  This tutorial introduces the formal models for competition, key innovation, and exogenous trends presented in Analyses 2,3, and 4 through interactive simulations. Users then empirically interpret the results of Analysis 2.

Our hope is that these tutorials, along with the paper, can model how sociologists can leverage large-scale historical datasets alongside rich qualitative scholarship to yield new historical insights. Demographic rate methods are particularly powerful for this type of approach because they allow analysts to abductively compare hypotheses explaining cultural change using only minimal data on the presence/absence of cultural objects. These methods do not require assumptions or quantitative data on actors, their behaviors, or their structural configuration.

8.3 Why We Need A Complete Theory of Cultural Change

Mid 20th-century social theorists portrayed cultures as grand systems of ideas with their own internal logic and dynamics (Berger, 1999; Luhmann, 1995; Parsons and Shils, 1951); in other words, their accounts focused heavily on the nature and structure of public culture. The "cultural turn" of the 1970s and 1980s rejected this systematic perspective along with the rest of structural-functionalism.

Over the past 40 years, cultural sociology has refocused the narrative on actors who use personal culture to solve problems of everyday life through the improvisation, acquisition, embodiment, and practical deployment of cultural elements (what we call ideas). Those elements may be more or less coherent and tightly coupled depending on the theorist (Swidler, 1986; Bourdieu, 1996; Foster, 2018). The more recent "cognitive turn" has refined this actor-centric perspective by detailing its underpinnings in contemporary cognitive science (DiMaggio, 1997). Simultaneously, social network analysis and related currents in analytical sociology have formalized mechanisms to explain how actors transmit ideas and how ideas become associated with different social or political groups (DellaPosta, 2018; Rossman, 2014).

In contrast, a smaller culture-centric literature has elaborated alternative mechanisms for broad public cultural change, focusing on the autonomous dynamics of cultural objects instead of their human carriers (Lieberson, 2000; Hannan, 2005). Culture-centric explanations—at least ones that emphasize populations of public cultural elements—are largely absent from current work on change in cultural, analytical, and computational sociology. For example, the recent book *Measuring Culture* highlights two actor-centric perspectives (i.e., culture in people or their relationships) sandwiching a beautiful chapter on objects. That chapter acknowledges that most scholarship on objects relate them back to people and their interpretations, instead of taking objects on their own terms (Mohr et al., 2020). In the categories literature, another recent text focuses only on the cognitive mapping of categories and not on endogenous mechanisms of change (Hannan et al., 2019).

We have argued that bridging these two perspectives is essential to providing a complete explanatory and predictive account of cultural change. Our theory directly addresses an underappreciated micro-/macro- duality first suggested in Elias' analysis of sociogenesis and psychogenesis (Elias, 1994): Explaining cultural change requires the analyst to choose between a focus on the *individual actor* who learns, embodies, and interfaces with a (relatively homogenous and static) public culture *or* a focus on dynamic, heterogeneous *public culture* that flows and changes across groups of (passive) individuals. As Elias anticipated, these two perspectives are analytical *conveniences* properly viewed as snapshots in a continuous process of people making culture making people. Insofar as they address cultural change

at all, current actor-centric perspectives (e.g. networks, fields, or organizations of actors) typically adopt the former perspective, focusing on the transmission of atomistic ideas across structures of actors (Mohr et al., 2020). But a "complete" theoretical explanation of cultural change must go beyond transmission between actors to present a model in which many ideas hang together, explaining how these relationships emerge, how they are created, and how they are lost. More than two decades ago, Ann Swidler identified "whether and how some cultural elements control, anchor, or organize others" as "the biggest unanswered question in the sociology of culture" (Swidler, 2001).

Our theory of cultural change explicates this process and begins to answer Swidler's question. We start from first principles by defining the building blocks of both personal culture and public culture. Personal culture is manifested through schematically-organized ideas in the brain and embodied practices. These schema and practices are transmitted and reproduced through the intentional creation and usage of material objects that include not only tools and text, but also evanescent speech and digital media. Public culture emerges as complex, sometimes nested and overlapping, populations of ideas called "cultural forms," sustained through the circulation of objects. This populational perspective allows us to articulate several culture-centric mechanisms that drive and birth the death of ideas over time. Our theory makes unique predictions about when and how these mechanisms should operate, and how they interrelate.

We also provide a catholic framework through which prominent actor-centric theories for explaining cultural phenomena can be articulated and connected. For example, the transmission of many ideas across a network extrapolates into multiple circulating cultural forms (Fuhse, 2009) in which some ideas affect the spread of others (Rossman, 2014). In the classic Bourdieusian presentation of fields, cultural forms of related ideas play a critical role through reproduced cultural constructs like *doxa* and *habitus*. Highlighting the role of durable and ephemeral cultural objects–in a spirit consistent with (Mohr et al., 2020)–brings scholarship on invention, innovation, and novelty (Foster et al., 2021) into conversation with work on cultural change (Swidler, 1986, 2001). And in organizational theory, the "culture" of an organization can be viewed as an emergent cultural form that persists even as contributing actors within (and beyond) the formal organization come and go. Indeed, we argue that all organizations manifest cultural forms: ranging from corporate cultures like McDonald's, to Black Sabbath, to artists with curated public images like Andy Warhol or Madonna.[42] We think this argument represents an important next step for several strands of organizational theory, from new institutionalism to the theory of categories, that view culture as everything but the organization itself. This is a fascinating direction for future work.

These connections provide some clarity about the circumstances under which different actor-centric theories yield insight into how culture changes. For example, field-based explanations are likely to be most satisfying when there is a widely shared cultural form which includes notions of position and competition. Our mechanisms of change provide a coherent way to talk about the dynamics of contestation, succession, and subversion through which the settled understanding of a field may be disrupted and multiple cultural forms compete to organize the field (Bourdieu, 2004; Fligstein and McAdam, 2015). When multiple cultural

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[42]In Appendix B.1, we demonstrate one way that organizations reproduce forms by showing that musicians tend to create/join new bands that belong to the same subgenre as their old ones.

forms are at play and there is no sense of common enterprise amongst actors, an explanation that focuses on the spread of competing ideas over networks may be more useful.

In this paper, we articulate mechanisms through which actors introduce (innovation, transformative learning) and remove (forgetting) ideas from a cultural form. But our most significant theoretical contribution is the formalization and theoretical development of cultural carrying capacity, a constraint on cultural forms that drives endogenous change within public culture. Cultural carrying capacity bounds the size and complexity of cultural forms because of cognitive limits on the complexity of schemata that actors can develop to interpret and reproduce the form. Carrying capacity also emerges from the presence of adjacent forms which already occupy some of the cultural space in which a focal form might expand.

Carrying capacity implies the action of several culture-centric mechanism that drive change: mass extinction, competition, and key innovation. Empirically, we demonstrate the plausibility of both competition and key innovation in driving the creation and dissolution dynamics of bands (and by extension, the behaviors of their constituent actors). We also show how key innovation works in our case, underlining the deep connection between individual agency and creativity (in developing new subgenres that ramify a cultural form), and the population dynamics of public culture through relaxed constraints on carrying capacity. We believe this dance between innovation and competition is a widespread driver of cultural dynamics and should manifest in many empirical cases.

Carrying capacity mechanisms can yield insight into how and why some idea persist and others senesce within any social category that is schematized. Such questions appear in a wide range of sociological contexts: in the analysis of political ideologies, in the dynamics of misinformation/conspiracy echo chambers, in the competition between religious sects, and even in the expansion of sexual identities. For example, carrying capacity mechanisms might yield insight into how Americans' cultural beliefs and values became subsumed under the umbrella of political ideology over the past decade (Boutyline and Vaisey, 2017; DellaPosta et al., 2015). Carrying capacity mechanisms might also be used to quantify the competition between foreign and domestic policy news that drives certain stories into and out of news cycles. Or consider the recent expansion of socially labeled and legible sexual identities from an older gay/straight binary to a more fluid landscape of queer identities including bisexuality, polyamory, asexuality, aromanticism, and so on. Similar analyses to the ones deployed here could tease apart how dueling pressures between cognitive constraints and the pre-existence of other sexual identities has shaped this proliferation.

Beyond the handful of examples offered here, we believe scholars in a range of sociological subfields will frame new questions in the language of carrying capacity and its attendant evolutionary mechanisms—questions that our new statistical methods (and the minimal requirements for their successful application) make empirically tractable. More broadly, our theory provides a new, unified way of talking about the structure and dynamics of culture and points to fruitful lines of inquiry at all levels: micro-, macro-, and the critical dynamics between.

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9 Appendix

A Methods

A.1 Lexical Parsing of EM Subgenres

In the EM, users describe the subgenre of an artist using an open text field. These descriptions can be extremely sophisticated.To parse these descriptions into meaningful subgenres we:

- Cleaned data for words like "(early)" or "(later)", removed any appended "with X influences" tags.

- Split subgenres on commas, semicolons, and slashes.

- Labeled the first word before a punctuation mark (as above) or the word "Metal" as a subgenre. If the word, "rock" appeared it was also labeled as a subgenre. In the Amorphis example the genres are: "Progressive," "Death," "Doom," "Heavy," and "Rock."

- Any words that appeared before a subgenre, but after a punctuation mark or the word "Metal" were preprended to create a sub-subgenre. In instances where the term "Metal/Rock" appeared, secondary terms were also prepended to the subgenre "Rock." In the Amorphis example, the sub-subgenres are "Melodic Heavy," and "Melodic Heavy Rock"

- We assume that later sub-subgenre terms are more meaningful. We therefore add all possible secondary tags that can be created by removing the first sub-subgenre term in a subgenre description to create additional sub-subgenres. For example a description of "Brutal Technical Death Metal" would yield the subgenre "Death," and the sub-subgenres "Brutal Technical" and "Technical."

A.2 Imputation of Band Death Times

For the 15.6% of bands that were not listed as "Split-up" (i.e., either "On-hold" or page not recently updated) but also had not released an album since 2000, we imputed death times **e** stochastically. We assumed that a band's lifespan since its last release is exponentially distributed, where the rate parameter is the band's average inter-album time. If a band had released only one recording, we used the population's average inter-album time. Sensitivity analyses assuming that all of these bands were either dead at 2000 or alive at 2000 conducted with the LiteRate model, suggest that these imputations do not bias our results (see Fig. D2). We also conducted a sensitivity analysis to make sure that bands that went on extended hiatuses were not biasing our results (not shown). We created 100 stochastic imputations of the data in this manner.

A.3 LiteRate Reversible Jump MCMC Algorithm

A.3.1 Statistical Significance of Rate Shifts

As a means to consider whether the posterior rate shifts estimated by the LiteRate Model are significant, we compute the sampling frequency of each rate shift and compare it to the results of an MCMC simulation where rate shifts are purely sampled from their priors (no data). The significance of a shift can then be computed as a Bayes factor of the posterior odds ($P(s|D)$) over the simulated prior odds ($P(s)$) as in equation 8. We consider significant rate shifts to be those supported by $2 \log BF > 2$ as "Positive" and $2 \log BF > 6$ as "Strong", following (Kass and Raftery, 1995).

$$BF = \frac{P(s|D)}{1 - P(s|D)} \Big/ \frac{P(s)}{1 - P(s)} \tag{8}$$

A.3.2 Reversible Jump Markov Chain Monte Carlo

Algorithmically, the addition or removal of a rate shift from τ^Λ or τ^M is periodically proposed (with equal probability) throughout the chain using RJMCMC (Green, 1995). When a new rate shift is added, a time window within J or K is randomly selected, and split into two. The timing of the rate shift within the chosen window is drawn from a uniform distribution, and a draw from a beta distribution is used to determine new rates that geometrically average (weighted by the length of their windows) to the old rate. Because the number of rate shifts in the model is considered unknown, we assign a Poisson distribution as a prior on J and K. The rate parameter of the Poisson prior is itself considered as unknown and assigned a Gamma hyper-prior. Lastly, the priors for the rates in Λ and M are again gamma distributions, but this time we place gamma hyperpriors on the gamma distributions' rate parameters. The use of hyper-priors makes the selection of these prior distributions less arbitrary as their shape is driven by the data (Gelman et al., 2006).

Compared to a simple MCMC, the acceptance probability in RJMCMC is complicated by the change in dimensionality of the parameter space. Let the acceptance probability be defined as $A(\theta, \theta)$ where θ is the current set of parameters of model W, and θ is the proposed set of parameters for model W with an additional rate shift. In RJMCMC, the acceptance

probability is thus the product of three terms: the standard *posterior ratio* and *Hastings Ratio*, but also the *Jacobian* of the parameter changes, separated in equation 9 with square brackets.

$$A(\theta, \theta) = \min \left(1, \quad \underbrace{\frac{\pi(\theta)}{\pi(\theta)}}_{\text{Posterior Ratio}} \times \underbrace{\frac{P(W|W)}{P(W|W)} \times \frac{P(\theta|\theta)}{P(\theta|\theta)}}_{\text{Hastings Ratio}} \times \underbrace{\left| \frac{\partial(\theta)}{\partial(\theta, \mu)} \right|}_{\text{Jacobian}} \right) \tag{9}$$

The first term in the acceptance probability, the *posterior ratio*, is the ratio of the unnormalized posterior probabilities of the new state over the current state. The *Hastings ratio* consists of two terms. The first term of the Hastings ratio includes the probability of proposing a new model W conditional on the current model W, where a model $W = \{J, K\}$ is defined by the number of birth and death rates. In our implementation we set equal probabilities to adding or removing a rate shift so that $P(W|W) = P(W|W) = 0.5$, thus making this term equal to 1. The second term in the *Hastings ratio* is the probability of proposing a new parameter state given the current one over the opposite scenario. The final term in the acceptance probability is the Jacobian of the mapping function that transforms the parameters of the current state to the proposed state. This term accounts for the change in dimensionality of the parameter space. The acceptance probability of removing a rate shift is simply the inverse of the addition: $A(\theta, \theta) = A(\theta, \theta)^{-1}$.

A.4 Further Details on Implementations of Restricted Models

All models are sampled with a simple MCMC sampled as described in Analysis 1.

A.4.1 Competition Models

The full competition and competition + key innovation models are specified as follows:

$$\lambda_{max} = \kappa + \lambda_{mul} * \kappa \qquad \mu_{min} = \kappa - \mu_{mul} * \kappa$$

$$\lambda(t) = \lambda_{\max} - (\lambda_{\max} - \kappa) \left(\frac{D(t)}{K(t)} \right)^{\delta} \qquad \mu(t) = \mu_{\min} + (\kappa - \mu_{\min}) \left(\frac{D(t)}{K(t)} \right)^{\gamma} \tag{10}$$

$$K(t) = K \; \forall \; t \qquad or \qquad K(t) = d + \frac{L}{1 - \exp(-k * (t - x_0))}$$

Priors:

$\kappa \sim \Gamma(\alpha = 1, \theta = 10)$ support: $\in \mathcal{R}^+$

$\lambda_m \sim \Gamma(\alpha = 1, \theta = 1)$ support: $\in \mathcal{R}^+$, null: 0

$\mu_m \sim \beta(\alpha = 1, \theta = 1.2)$ support: $\in [0, 1]$, null: 0

$\gamma \sim \Gamma(\alpha = 3, \beta = 2)$ support: $\in \mathcal{R}^+$, null: 1

$\delta \sim \Gamma(\alpha = 3, \beta = 2)$ support: $\in \mathcal{R}^+$, null: 1

For the competition model (static K) in Analysis 2:

$K \sim \Gamma(\alpha = 1, \theta = max(D_t))$ support: $\in \mathcal{R}^+$

For the competition + key innovation in Analysis 3:

$k \sim \mathcal{N}(\mu = 0, \sigma = 1)$ support: $\in \mathcal{R}$, null: 0
$d \sim \Gamma(\alpha = 1, \theta = max(D_t))$ support: $\in \mathcal{R}^+$
$L \sim \Gamma(\alpha = 1, \theta = max(D_t))$ support: $\in \mathcal{R}^+$
$x_0 \sim \mathcal{U}(a = min(t), b = max(t))$ support: $\in [min(t), max(t)]$

Proposals: All parameters have multiplier proposals except x_0 and μ_{mul}, which use sliding window proposals.

A.4.2 Trend Model

$$\lambda(t) = \lambda_{const} + \alpha * C^\delta \qquad \mu(t) = \mu_{const} + \beta * C^\gamma \tag{11}$$

All trends C are first normalized between 0 and 1 to improve convergence.
Priors for model in Analysis 4:
$\lambda_{const} \sim \Gamma(\alpha = 1, \theta = 10)$ support: $\in \mathcal{R}^+$
$\mu_{const} \sim \Gamma(\alpha = 1, \theta = 10)$ support: $\in \mathcal{R}^+$
$\alpha \sim \mathcal{N}(\mu = 0, \sigma = 5)$ support: $\in \mathcal{R}$, null: 0
$\beta \sim \mathcal{N}(\mu = 0, \sigma = 5)$ support: $\in \mathcal{R}$, null: 0
$\gamma \sim \Gamma(\alpha = 3, \beta = 2)$ support: $\in \mathcal{R}^+$, null: 1
$\delta \sim \Gamma(\alpha = 3, \beta = 2)$ support: $\in \mathcal{R}^+$, null: 1

B Supplemental Analyses

B.1 Transmission/Reproduction of Subgenres

Motivation: We wish to demonstrate that the movement of musicians between bands of the same subgenre is a plausible mechanism for cultural transmission, reproduction, and creation within Metal subgenre forms.

Methods: We performed a simple bivariate logistic regression analysis of the subgenre and sub-subgenre choices of musicians in the EM who have participated in two or more bands. For each band, we curated the identities of all members who played on a founding album, and then tabulated the subgenres of previous bands these founders played in. Limiting our data to bands with musicians with prior experiences in the EM reduced us to 12,155 bands.

Reducing our sample further to subgenres/sub-subgenres where we have at least 10 bands with data on band members' past band experiences, we have 19 subgenres and 26 sub-subgenres. For each of these subgenres and sub-subgenres, we then logistically regressed the subgenre (1 for in subgenre, 0 for not in subgenre) on the proportion of founding members who had previously played in a band of that subgenre. We used Firth's penalized likelihood model for highly imbalanced classes in the R "logistf" package (Heinze and Puhr, 2010). Exponentiated odds ratios with 95% confidence intervals and penalized likelihood ratio test shown in the second column block of Table C1.

Results: We find evidence that founders' past band experiences are significantly predictive of the current band's subgenre for 16 of 19 subgenres at a p-value threshold of .05. We similarly find significant evidence for 17 of the 26 sub-subgenres.

B.2 Stability and Validation of Cultural Forms

Motivation: We now wish to demonstrate that Metal music, its subgenres, and its sub-subgenres are stable, coherent cultural forms mutually understood and supported by a broad population of fan-actors.

Methods: We cross-tabulated EM subgenre affiliations of bands with another online music community, Last.FM (www.last.fm). Last.FM is a music radio and community website founded in 2002 with over 40 million lifetime users (Gallagher, 2012). The site allows users to journal artists, albums, and tracks they are listening to, tag these entities with descriptors, and annotate open-source abstract pages for both entities and tags. We collected tag information for 107,666 EM bands cross-listed in Last.FM, as well as up to 20 "similar artists" for each band that were co-listened or similarly tagged by Last.FM listeners (which we call "sonic neighbors").[43] Of our 30,217 bands of interest, there are 17,087 uniquely named EM bands with an artist entry page in Last.FM.

If cultural forms are coherent, actor-listeners should preferentially co-label and co-listen to bands in the same EM subgenre, and use the same subgenre labels for bands across both datasets. For Metal overall and each EM genre/subgenre, we therefore computed two statistics: the percentage of bands that share the genre label across both datasets (Table C1 column block 3), and the average percentage of sonic neighbors that are also in the same subgenre (in network terms, the proportion of edges pointing into the community) (Table C1 column block 4).

Results: For 24 of the 46 EM subgenres, a majority of bands are cross-labeled as within the same subgenre in Last.FM as well (Table C1 column block 3). This also holds for 9 of the 50 sub-subgenres. For Metal bands overall, we find that on average 52% of an EM band's sonic neighbors are also Metal bands. Furthermore, the majority of sonic neighbors are within the same subgenre for 12 of the 46 subgenres and 2 of the 50 sub-subgenres (Table C1 column block 4). We note that these estimates are likely biased downwards since a single Last.FM page does not disambiguate between similarly-named artists of different music genres (i.e., non-Metal artists).

Table C1: **Results from Analyses C.1 and C.2**. Rows sorted by size of genre (column 2) in full dataset, divided by subgenres and sub-subgenres. Column block 2 shows the number of bands with members in previous bands in the data, the exponentiated odds ratio, and 95% confidence interval for the Firth regression in Analysis C.1. * indicates p-value < .05 on a likelihood ratio test. Column block 3 shows the uniquely labeled bands in Last.FM and the % of bands in which the genre label is used in both EM and Last.FM (Analysis C.2). Column block 4 shows the number of bands with sonic neighbors, the mean and standard deviation of the percentage of sonic neighbors also in that subgenre, and the mean and standard deviation of the age of sonic neighbors. "-" indicates insufficient data (fewer than 10 bands). Subgenres with percentage > 50 or p-value < .05 are bolded.

	# Bands	Analysis C1			Analysis C2		Analysis C2		
		# Previous	OR	95% CI	# in LFM	% Label	# w/ SN	% SN	% SN Age
Whole Dataset	30217	NA	NA	NA	17087	NA	13207	**52**+/-33	1997.29+/-7.06
Death	9907	477	**5.7***	(4.58,7.14)	5097	**68**	3856	**73**+/-35	1998.45+/-5.58
Thrash	7868	127	**3.73***	(2.57,5.44)	4051	**51**	2925	**60**+/-40	1994.53+/-7.36
Heavy	6345	231	**12.08***	(8.97,16.45)	3796	50	2894	**62**+/-37	1990.98+/-8.05
Black	5333	284	**6.16***	(4.79,7.96)	3201	**87**	2586	**84**+/-28	2000.42+/-4.2
Power	2679	83	**5.89***	(3.63,9.4)	1529	49	1231	**52**+/-36	1995.04+/-7.46
Doom	1962	106	**8.23***	(5.37,12.46)	1191	**64**	968	**63**+/-39	1999.03+/-5.07
Progressive	1360	37	**8.0***	(3.33,17.22)	895	**52**	699	**51**+/-39	1998.78+/-5.74

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[43]We collect 100,000+ Last.FM bands because sonic neighbors for our 30,217 bands of interest may have been born after 2000.

	# Bands	Analysis C1			Analysis C2		Analysis C2		
		Previous	OR	95% CI	# in LFM	% Label	# w/ SN	% SN	% SN Age
Rock	1345	200	**10.71***	(7.39,15.35)	974	**54**	807	27+/-31	1992.46+/-9.64
Grindcore	1149	41	**6.14***	(2.72,12.6)	707	**60**	579	**51**+/-36	1998.25+/-4.87
Speed	1038	21	**10.41***	(4.05,25.18)	527	45	436	30+/-28	1988.98+/-6.39
Gothic	903	54	**7.03***	(2.59,15.95)	600	**52**	493	49+/-36	1999.79+/-3.74
Groove	726	19	7.24	(0.86,29.18)	482	17	344	22+/-31	1999.3+/-7.03
Crossover	612	13	**17.13***	(4.11,55.33)	414	28	303	37+/-37	1991.15+/-6.31
Punk	426	52	**21.65***	(9.64,44.63)	302	**60**	251	25+/-33	1993.92+/-7.5
NWOBHM	263	-	-	-	138	**81**	132	**77**+/-33	1981.87+/-2.31
Metalcore	223	-	-		173	**57**	148	42+/-36	2002.04+/-3.33
Industrial	211	17	**27.58***	(5.08,97.45)	151	**53**	127	25+/-31	1994.31+/-5.95
Folk	207	16	8.4	(0.43,43.94)	157	**61**	135	39+/-33	2000.72+/-3.8
Stoner	193	-	-		146	**54**	134	**63**+/-36	2000.87+/-3.73
Ambient	189	41	**23.21***	(10.18,48.58)	136	**66**	120	33+/-28	1999.83+/-5.04
Sludge	171	10	**128.11***	(32.78,455.46)	126	**84**	119	**66**+/-35	2001.24+/-3.5
Shred	97	-	-	-	86	31	71	47+/-40	1995.33+/-5.43
Dark	85	-	-	-	41	22	24	0	-
Pagan	73	-	-	-	58	**64**	50	17+/-18	2003.05+/-3.19
Viking	65	-	-	-	48	**77**	45	34+/-24	2000.12+/-3.61
Neoclassical	64	-	-	-	54	26	50	21+/-26	1996.77+/-5.04
Symphonic	57	-	-	-	38	47	31	13+/-16	2001.42+/-3.15
Goregrind	54	-	-	-	41	**80**	38	45+/-22	2000.25+/-4.19
Avant-Garde	50	-	-	-	40	**62**	33	28+/-25	1996.85+/-4.2
Experimental	42	-	-	-	31	23	24	1+/-4	2013.0+/-0.0
'N'Roll	40	14	13.04	(0.05,116.24)	29	21	27	17+/-28	1997.27+/-5.05
Alternative	39	-	-	-	32	16	26	0+/-2	1983.0+/-0.0
Noise	38	-	-	-	26	31	25	7+/-15	2005.34+/-5.55
Nu-Metal	37	-	-	-	23	4	19	3+/-6	1997.5+/-2.68
Melodic	32	-	-	-	18	22	16	0	-
RAC	32	-	-	-	23	**100**	21	48+/-44	1996.23+/-7.42
Deathcore	29	-	-	-	19	26	15	2+/-5	2005.0+/-0.0
Darkwave	27	-	-	-	23	43	21	25+/-32	1995.44+/-1.33
Glam	27	-	-	-	19	37	18	5+/-14	1984.25+/-1.75
Electronic	26	-	-	-	18	11	18	10+/-24	1991.97+/-5.12
Fusion	25	-	-	-	16	44	14	8+/-8	1995.88+/-5.37
Pop	21	-	-	-	18	6	18	0	-
Southern	20	-	-	-	18	39	14	18+/-24	1995.42+/-6.65
Drone	17	-	-	-	13	**69**	13	33+/-28	2003.09+/-1.64
Grunge	16	-	-	-	14	**56**	13	26+/-38	1990.33+/-2.72
Hard Rock	874	144	**18.08***	(11.58,27.82)	610	45	488	25+/-30	1988.62+/-9.0
Melodic Death	779	142	**16.99***	(10.43,27.1)	466	**55**	386	**50**+/-39	2000.4+/-3.98
Brutal Death	683	136	**29.2***	(16.79,50.0)	411	**59**	321	**54**+/-35	2000.87+/-3.98
Melodic Heavy	428	66	**22.02***	(8.88,48.82)	259	7	210	10+/-20	1995.35+/-8.32
Melodic Black	323	62	**9.88***	(3.73,22.18)	195	44	162	18+/-19	1997.92+/-3.89
Hardcore Punk	301	38	**29.21***	(10.63,69.93)	213	**56**	169	15+/-25	1991.18+/-7.07
Technical Death	203	44	6.46	(0.86,23.96)	117	**74**	100	41+/-30	1999.64+/-5.32
Symphonic Black	199	43	**10.57***	(2.72,29.62)	142	**56**	125	26+/-27	1999.89+/-3.73
Progressive Death	160	28	**24.2***	(7.25,64.91)	107	**53**	95	22+/-22	2000.07+/-6.09
Melodic Power	129	22	**41.85***	(7.77,150.17)	85	6	70	8+/-10	2002.02+/-4.16
Pagan Black	108	26	**56.5***	(18.75,148.45)	73	40	65	16+/-21	2000.8+/-3.79
Progressive Power	105	25	4.18	(0.01,34.24)	72	7	59	4+/-6	1996.52+/-6.73
Technical Thrash	105	19	14.53	(0.66,81.17)	49	49	40	11+/-19	1988.04+/-2.16
Raw Black	103	31	**93.71***	(36.47,226.81)	71	32	58	5+/-8	2003.23+/-4.59
Progressive Thrash	96	15	9.6	(0.02,89.89)	58	33	49	8+/-12	1991.64+/-3.74
Atmospheric Black	84	17	6.46	(0.03,52.08)	60	30	47	9+/-13	2002.22+/-4.62
Progressive Heavy	78	17	**95.55***	(8.77,555.96)	47	0	36	1+/-3	1998.5+/-9.76
Crust Punk	69	13	**183.55***	(44.77,654.08)	50	50	49	36+/-35	1996.18+/-6.91
Atmospheric Death	64	12	15.6	(0.09,134.58)	40	22	27	6+/-17	2002.64+/-3.43
Dark Ambient	64	29	**65.29***	(22.15,170.63)	46	**59**	40	15+/-16	1998.28+/-4.38
Industrial Death	60	16	30.82	(0.09,322.6)	42	26	28	9+/-12	1997.77+/-5.15
Atmospheric Doom	54	16	**46.61***	(4.74,220.41)	34	26	31	10+/-14	1999.33+/-4.9
Melodic Doom	51	13	**61.56***	(6.07,304.56)	36	8	28	10+/-11	1998.98+/-5.27
Melodic Thrash	50	-	-	-	27	11	19	1+/-4	2003.5+/-0.0
Melodic Progressive	47	-	-	-	30	0	24	1+/-2	2006.0+/-0.0
Epic Heavy	45	11	**83.26***	(3.76,583.7)	29	21	26	28+/-23	1996.58+/-5.3
Progressive Rock	41	-	-	-	28	**54**	25	6+/-13	1984.0+/-16.01
Alternative Rock	39	-	-	-	30	7	26	1+/-2	1999.67+/-3.86
Funeral Doom	33	-	-	-	21	**95**	21	**73**+/-28	2003.02+/-2.99
Death 'N'Roll	32	12	34.41	(0.1,373.66)	22	27	21	15+/-25	1996.71+/-5.45
Industrial Black	32	-	-	-	27	48	23	20+/-17	2000.63+/-3.66
Avant-Garde Black	29	15	20.11	(0.1,184.98)	21	43	20	15+/-27	2004.1+/-3.31
Brutal Technical Death	28	-	-	-	20	5	18	15+/-16	2000.43+/-2.35
Epic Black	27	-	-	-	22	32	18	8+/-10	2003.97+/-6.1
Melodic Speed	27	-	-	-	17	12	13	0	-
Gothic Doom	26	-	-	-	19	26	14	2+/-6	2002.33+/-0.0
Experimental Death	26	-	-	-	16	12	15	1+/-3	1998.0+/-3.0
Symphonic Power	25	-	-	-	17	28	17	19+/-14	2002.46+/-3.04
Symphonic Death	25	-	-	-	17	28	14	4+/-7	2007.92+/-3.67
Gothic Rock	21	-	-	-	17	28	16	1+/-2	2004.0+/-0.0
Punk Rock	21	-	-	-	15	20	11	0	-
Epic Power	20	-	-	-	13	15	11	0	-
Progressive Black	18	-	-	-	15	33	14	4+/-9	2001.28+/-3.91
Industrial Thrash	18	-	-	-	15	0	10	2+/-4	2006.0+/-0.0
Experimental Black	16	-	-	-	13	23	13	9+/-27	2001.67+/-2.05
Melodic Rock	16	-	-	-	14	0	12	0	-
Neoclassical Power	15	-	-	-	12	0	10	6+/-8	2000.5+/-5.67
Symphonic Gothic	15	-	-	-	12	0	12	10+/-11	2000.75+/-2.17
Hard Melodic Rock	15	-	-	-	12	0	10	0	-
Atmospheric Gothic	14	-	-	-	12	0	10	0	-

B.3 Entropy of Bands Across Subgenres

Motivation: To better understand the mechanisms of competition and causes of the Phase 4 rate shelf, we analyze the Shannon entropy of bands across subgenres and sub-subgenres. One interpretation of the Shannon entropy is as a measure of the evenness of the distribution of quantities across categories. Pielou evenness is a derivative metric from Ecology that normalizes the observed entropy over the maximum possible entropy (e.g., the scenario where there are an equal number of bands in each subgenre) (Pielou, 1966). Entropy dynamics can give insight into how bands explore the cultural carrying capacity over time. For example, a decrease in entropy over time would suggest that bands preferentially attach to larger genres, or that not all genre niches are equally accessible/exploitable. Pielou evenness dynamics contextualize observed exploration against the backdrop scenario where all genres are equally easy to exploit and bands do so equitably. A Pielou evenness close to zero indicates that bands are concentrated in a few genres, while an evenness of one suggests that bands are evenly distributed across all available subgenres.

Methods: In each year y from 1968 to 2000, we compute the entropy $H(y)$ for the standing diversity of bands alive in that year D_y across all subgenres that have been previously introduced to Metal G_y before year y (up to 110 by 2000). Formally the entropy is computed as:

$$H(y) = -\sum_{g=1}^{G_y} \frac{D_{yg}}{D_y} \cdot \ln(\frac{D_{yg}}{D_y}) \tag{12}$$

We also compute the Pielou evenness (Pielou, 1966) $J(y)$ in each year by normalizing the observed entropy by the maximum possible entropy in each year:

$$J(y) = \frac{H(y)}{-\sum_{g=1}^{G_y} \frac{1}{D_y} \cdot \ln(\frac{1}{D_y})} \tag{13}$$

We further compute these metrics for bands across the sub-subgenres of the seven largest genres.

Results: Within both Metal overall (Fig. D5C) and the seven largest genres (Fig. D5D), we find that the evenness of bands across categories initially sharply decreases over time. This behavior is to be expected when the number of subgenres is small: bands concentrated in one of one subgenres are evenly distributed, while bands concentrated in one of seven subgenres are not. However, the evenness eventually levels off for Metal and six of the subgenres (not Death) suggesting that Metal overall and each of the seven largest subgenres settles into a stable arrangement of small genres and large genres that persists over time.

This surprisingly constant evenness must be interpreted against the backdrop of increasing numbers of actors and shifting popularity of subgenres over time. Given that the actor population is growing, we might expect the evenness of bands to increase across categories as additional actors can accommodate more categories. The fact that the evenness does *not* increase over time is evidence of a top-down cultural carrying capacity. The fact that the evenness does not drop below .3 is consistent with the shifting popularity of genres (Fig. D4), suggesting that a stable cultural dynamics might correlate with having a mixture of broadly-circulated and specialized lineages. Furthermore, the trend observed in subgenres

for Pielou evenness is similarly reproduced at the sub-subgenre level and across all 2,033 possible descriptions for a band that have ever been used, we see the same trend (Fig. D6B).

C   Supplemental Figures

Figure D1: Example Encyclopedia Metallum (EM) Band page. The EM contains information about the formation date, discography, status, personnel and subgenres of ~141,000 Metal bands as of 2020. Open subgenre classification field in top right.
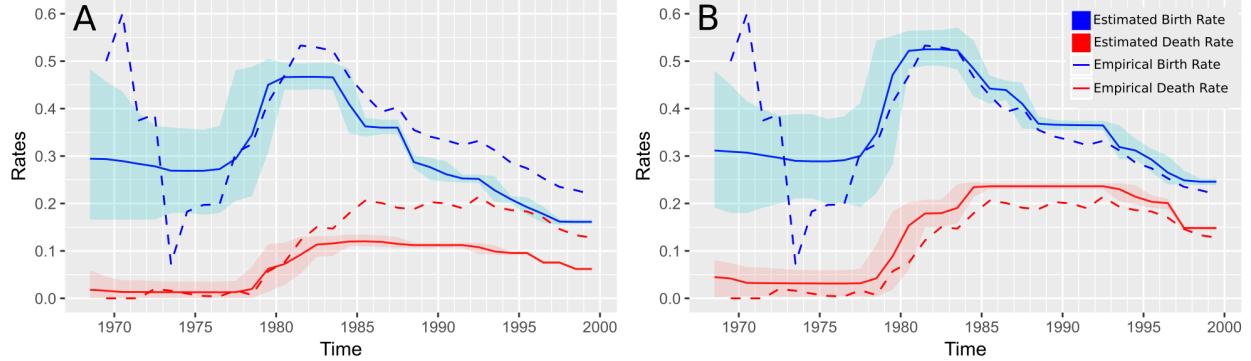
Figure D2: **Estimated Diversification Rates from Analyses 2B Without Imputation.** Dashed lines indicate empirical birth (red) and death (blue) of EM metal bands. The first bin of empirical rates is dropped for clarity. Estimated rates and their 95% highest posterior density intervals shown in solid colors. **A**: Estimated birth and death rates over time when the imputed 15% of band's death times are set to their last recording. **B**: Estimated birth and death rates over time when the imputed 15% of band's death times are set to 2000.
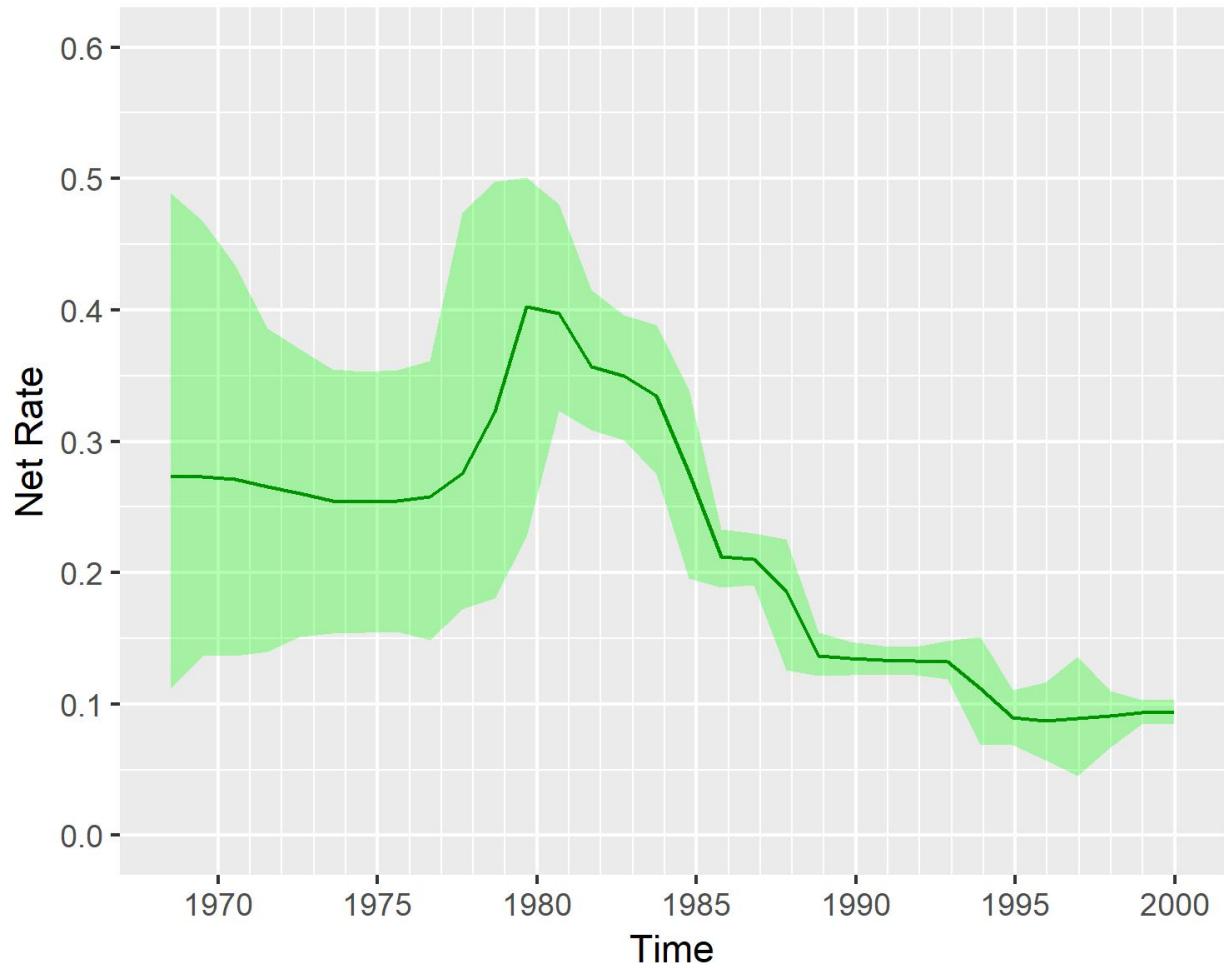
Figure D3: **Estimated Net Diversification Rates from Analysis 2B.** LiteRate-estimated net diversification rates (birth minus death) and their 95% highest posterior density intervals shown in green.
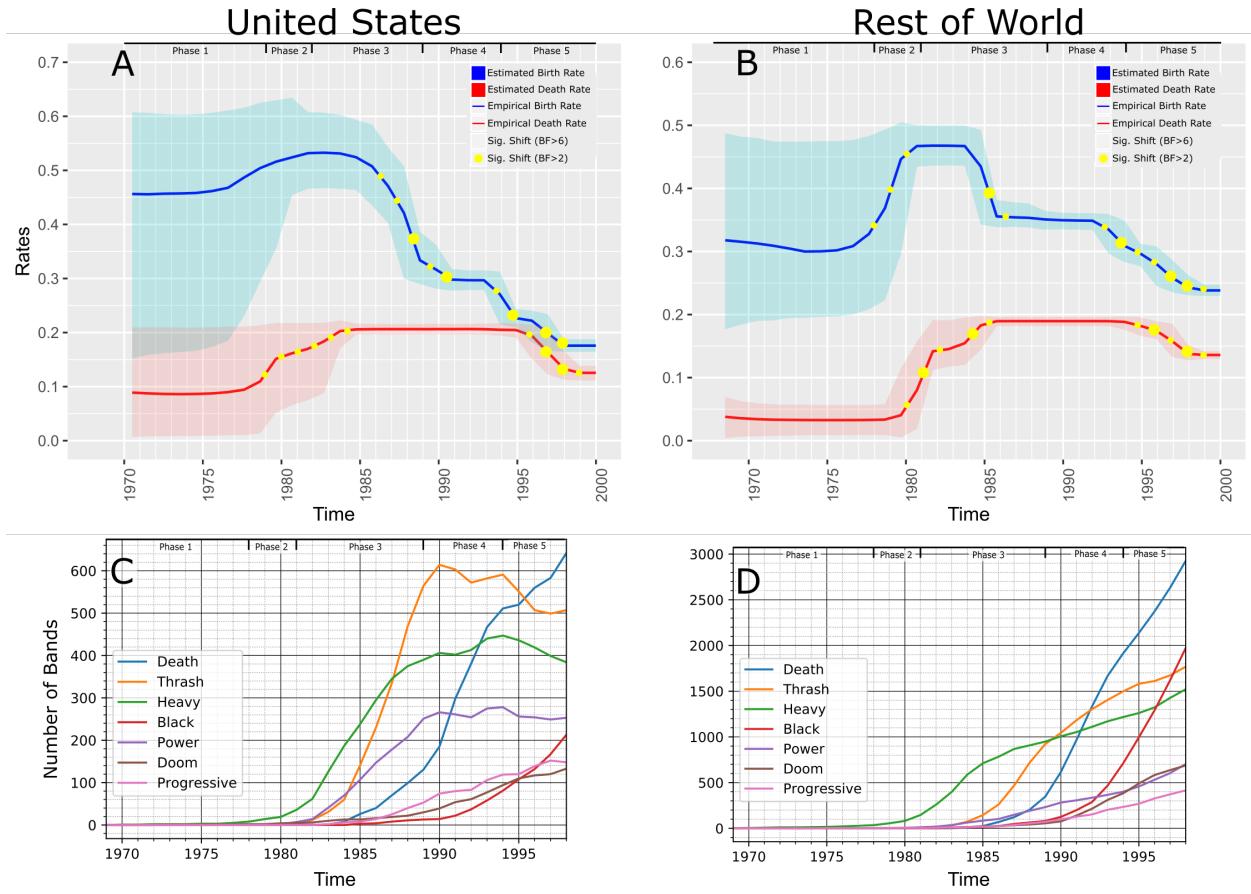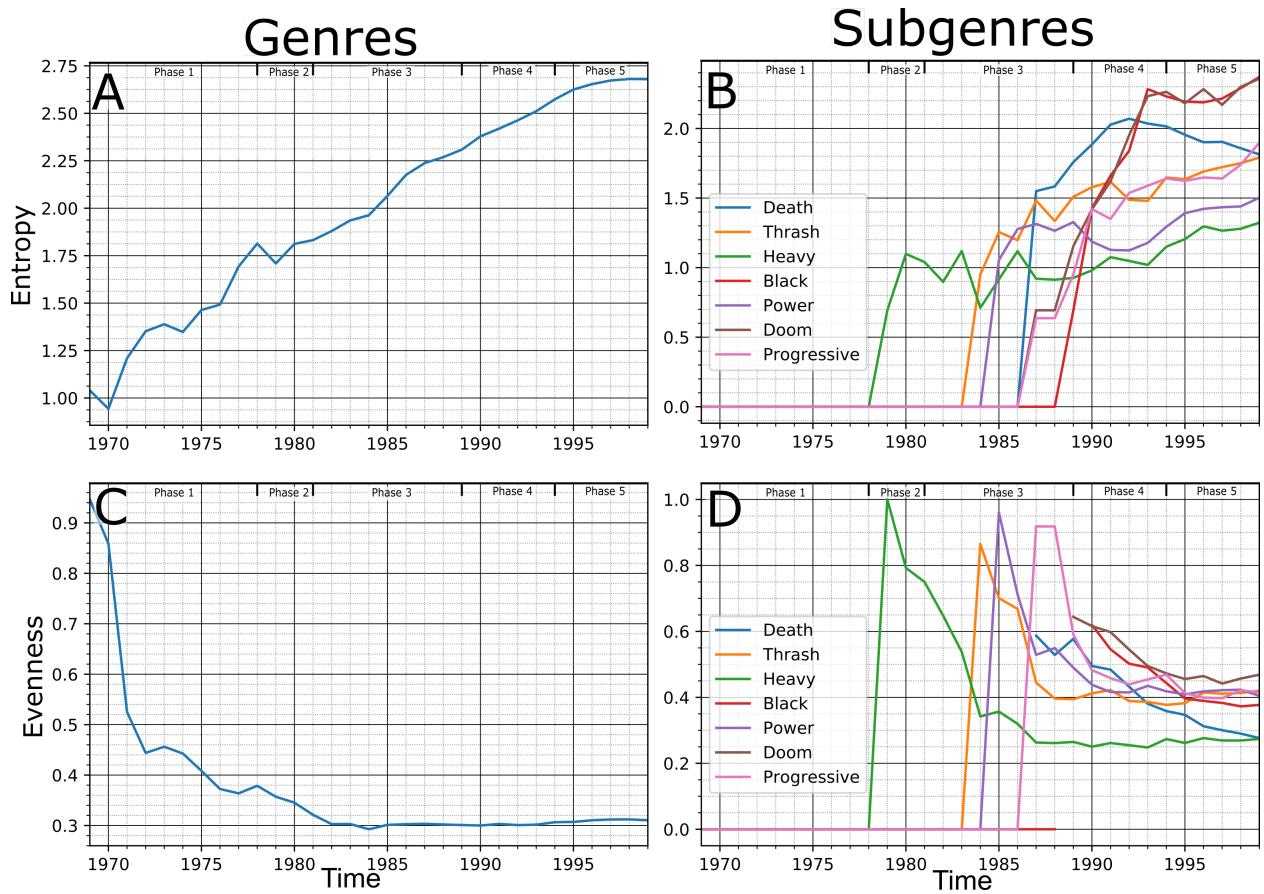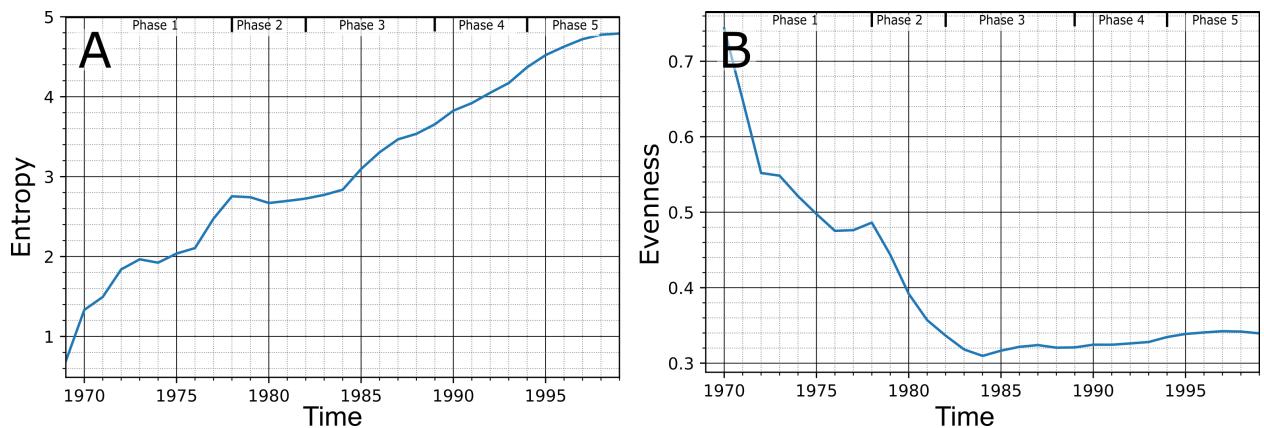
Figure D4: **Estimated Diversification Rates for US and non-US bands. A**: LiteRate-estimated diversification rates for bands born in the United States. **B**: LitRate-estimated diversification rates for bands born outside the United States. **C**: Standing diversity of US-bands for seven largest subgenres. **D**: Standing diversity plots for non-US bands in seven largest subgenres. Estimated diversification rates and their 95% highest posterior density intervals shown in solid colors. Yellow dots indicate statistically-significant rate shifts.

Figure D5: **Shannon Entropy and Evenness Plots from Analysis 3C. A:** Shannon entropy of all bands across all subgenres. **B:** Shannon entropy of all bands across all subgenres, normalized by possible entropy (Pielou evenness). **C:** Shannon entropy of bands in top seven subgenres across sub-subgenres. **D:** Shannon entropy of bands in top seven subgenres across sub-subgenres, normalized by maximum possible entropy (Peilou evenness).

Figure D6: **Shannon Entropy and Evenness Plots for all possible genre descriptors in EM A:** Shannon entropy of all bands across all 2,033 possible combinations of genre and subgenre descriptions used in the EM. **B:** Pielou Index of all bands across all genres (Shannon Entropy normalized by maximum possible entropy).
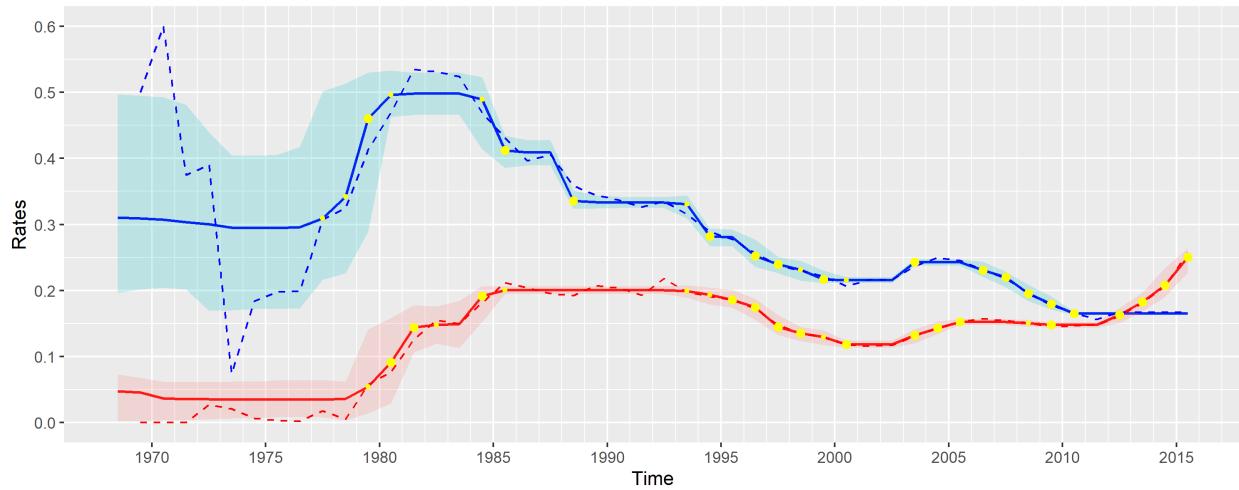
Figure D7: **LiteRate-estimated rates of all bands through 2016.** Death times were imputed using the procedure described in A.2.