BEATS THAT COMMUTE:
ALGEBRAIC AND KINESTHETIC MODELS FOR MATH-ROCK GROOVES*

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Math rock's most salient compositional facet is its cyclical repetition of ostinati featuring changing and odd-cardinality meters.[1] Theo Cateforis provides a concise definition of the genre: "Math rock can be distilled to a few main features. The most prominent of these is the extensive use of asymmetrical or 'odd' time signatures and shifting mixed meters."[2] Within the looped presentation of these grooves,[3] the conventional rhythmic structures of rock, such as backbeat and steady pulse, are deformed in such a way that a listener's sense of metric organization is initially thwarted. Nonetheless, observing both listeners and performers in live concert settings reveals that such complicated rhythmic structures—as foreign as they may sound to

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1 Although the terms "odd" and "asymmetrical" are often used to describe the same metric phenomena, they should perhaps be used with caution. Although odd-cardinality meters cannot be divided into isochronous tactuses, an odd number of pulses is every bit as symmetrical as an even number—perhaps more so, as the symmetrical division of an odd number of pulses falls *on* a beat instead of *between* two beats. I prefer the terms "odd-cardinality" (which also clarifies that the meter itself is not "odd" or "peculiar," but rather consists of a number indivisible by two) and "non-isochronous."

2 Theo Cateforis, "How Alternative Turned Progressive: The Strange Case of Math Rock," in *Progressive Rock Reconsidered*, ed. Kevin Holm-Hudson (New York and London: Routledge, 2002), 244. While Cateforis construes math rock as a variant of alternative rock, I wonder what he would have to say about the so-called "math metal" that became popular after his 1980s and '90s data pool. This essay does not discriminate between math-"rock" bands like Helmet and Don Caballero (mentioned by Cateforis) and later math-"metal" bands, including Dillinger Escape Plan and The Chariot. For more on math rock, math metal, and other post-millennial experimental rock genres, see Brad Osborn, "Beyond Verse and Chorus: Experimental Formal Structures in Post-Millennial Rock Music" (Ph.D. dissertation, University of Washington, 2010).

3 I am using the term "groove" as roughly equivalent to "ostinato," as has become common in recent scholarship on popular music.

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unseasoned outsiders—are successfully (and even artfully) interpreted by the bodies and instruments of those immersed in the genre.[4]

In this paper, I will formalize an algebraic model for these characteristic rhythmic structures, but first I want to emphasize the phenomenology (and indeed, physiology) informing such systemization. Perhaps David Lewin's most enduring contribution to music theory is the active model he provided for transformational theory. Rather than thinking of transformations in Cartesian space, Lewin emphasized a phenomenology of *action*, one that encouraged listeners and performers to envision themselves as participants in musical space. An exemplary quote from *Generalized Musical Intervals and Transformations* reads:

> [W]e tend to imagine ourselves in the position of *observers* when we theorize about musical space; the space is "out there," away from our dancing bodies or singing voices. . . . In contrast, the transformational attitude is much less Cartesian. Given locations s and t in our space, this attitude does not ask for some observed measure of extension between reified "points"; rather it asks: "If I am *at* s and wish to get to t, what characteristic gesture [transformation] . . . should I perform in order to arrive there?"[5]

Rather than generalize transformational theory as synonymous with "transformation" or "difference,"[6] my theory of changing meter relies on an algebraic property integral to transformational theory: commutativity. The double entendre in my title verb "commute" is

[4] This is similar to the "learning" that Ève Poudrier claims must take place in order to perform (or groove to) Elliott Carter's late music: "Carter's use of complex polyrhythms as a basis for a composition, from the deep levels to the surface, calls for a better understanding not only of what *can* be perceived by the average listener but what can *become* perceivable by a listener/performer/analyst with specialized skills" (Poudrier, "Toward a General Theory of Polymeter: Polymetric Potential and Realization in Elliott Carter's Solo and Chamber Instrumental Works after 1980" [Ph.D. dissertation, City University of New York, 2008], 33).

[5] David Lewin, *Generalized Musical Intervals and Transformations* (New York: Oxford University Press, 2007), 159.

[6] This is the case with Christopher Doll's recent essay, "Transformation in Rock Harmony: An Explanatory Strategy," in which he explicitly states that his idea of transformation has no actual mathematical basis: "This loose approach to the term transformation makes sense if we consider musical difference and sameness to be defined only according to some level of abstraction" (Doll, "Transformation in Rock Harmony: An Explanatory Strategy," *Gamut* 2/1 [2009], 2).

instructive; math rock's idiosyncratic rhythmic patterns respond well to mathematical formulation *and* stimulate characteristic movements in performers and listeners. Algebraically, two elements x and y of a set s are said to be commutative under a binary operation $*$ if and only if $[x * y] = [y * x]$.[7] Additionally, the algebraic descriptions provided in this paper can be applied to the headbanging bodies and screaming voices of math-rock performers and listeners in an attempt to understand how they negotiate *movement* (i.e., commute) amidst looped presentations of changing, odd-cardinality meters, entraining to a pulse stream I call the "pivot pulse."[8]

I. NOTES ON DRUM-SET PERFORMANCE PRACTICE

The experiential foundation of this research stems from a simple performance nuance that transcends many styles of drumming: maintaining a constant left-foot pulse on the hi-hat. While I will formulate the following discussion utilizing terminology from drum-set performance practice, the same can be said of tapping feet, banging/bobbing heads, dancing, or any other musico-physiological kinesis.[9] This convention is most familiar in a standard swing pattern,

[7] See Eric W. Weisstein, "Commutative," in *MathWorld*—A Wolfram Web Resource, http://mathworld.wolfram.com/Commutative.html. Thus, elements a and b are commutative under the familiar operations addition and multiplication, but not under subtraction and division. For insight on how non-commutative operations work in sets, including "polysemic nets," see John Rahn, "Cool Tools: Polysemic and Non-Commutative Nets, Subchain Decompositions and Cross-Projecting Pre-Orders, Object-Graphs, Chain-Hom-Sets and Chain-Label-Hom-Sets, Forgetful Functors, Free Categories of a Net, and Ghosts," *Journal of Mathematics and Music* 1/1 (2007): 7–22. Also of significant inspiration to my connections between commutativity and performance are the imaginative connections between group-theoretical operations and the Deluzian "machinic assemblage" found in John Rahn, "*Mille Plateaux*, You Tarzan: A Musicology of (an Anthropology of (an Anthropology of A Thousand Plateaus))," *Perspectives of New Music* 46/2 (2008): 81–92.

[8] John Roeder defines a pulse stream as "a series of successive, perceptibly equal timespans, marked off by accented timepoints." He is careful to note that a pulse is "not the same as a beat, which is a series of regularly spaced timepoints" (John Roeder, "Interacting Pulse Streams in Schoenberg's Atonal Polyphony," *Music Theory Spectrum* 16/2 [1994], 234). However, the non-isochronous nature of math-rock tactuses necessitates departure from the "regularly spaced" definition of beat. To avoid this confusion, this paper uses Justin London's term "tactus" instead, using "beat" only when naming numbered tactuses in a measure (e.g., "beat 1"); see London, *Hearing in Time: Psychological Aspects of Musical Meter* (New York and Oxford: Oxford University Press, 2004).

[9] This electronic format allows the reader to experience directly the sorts of kinesis I am describing, by following the links (in figure captions) to audio clips.

where the performer operates a pedal with the left foot, compressing two hi-hat cymbals on the backbeat with a distinctive *tszzt* sound.[10] Hi-hats occurring on the two and four backbeats can also be heard in straight-ahead rock music at fast tempi, although performers may fill the longer temporal gap between two and four with hi-hats on each ♩ pulse at slower tempi.[11] Further tempo decelerations often prompt drummers to pat hi-hats on every ♪, entraining to a finer subdivision to facilitate steady time-keeping.

Because maintaining a steady pulse with the left foot has obvious benefits for rhythmic stability, performers usually do it even when no audible hi-hat sounds are present.[12] In some cases, periodic hi-hat pulses may create a metric grid too rigid for the intended musical effect. Often, louder rock idioms (such as hardcore and metal) require drummers to play open ("wash") hi-hats, necessitating a constantly open hi-hat pedal. Whatever the musical prompt, performers compensate by patting the left foot just beside the hi-hat pedal, either allowing the open cymbals to ring, or avoiding the hi-hat altogether by keeping time on a ride or crash cymbal. Figures 1a–c provide examples of the three most common speeds of audible left-foot pulse-keeping.[13]

Although preserving a steady pulse over a consistent metrical surface (e.g., the $\genfrac{}{}{0pt}{}{2}{4}$, $\genfrac{}{}{0pt}{}{3}{4}$, $\genfrac{}{}{0pt}{}{4}{4}$, and $\genfrac{}{}{0pt}{}{6}{8}$ meters common to rock) poses no problem, changing meter[14] complicates pulse regulari-

[10] The drummer's left foot (or right foot, if playing on a left-handed drum set) operates a pedal that pulls an attached rod up and down. While the bottom hi-hat cymbal rests stationary on a rubber cup, the top one is screwed onto the pull rod by a clutch. When the performer pushes down on the pedal, the two cymbals come together, then come apart again when the performer releases the pedal. Physiologically, the pedal's down/up operation maps onto any desired rhythmic value (in jazz, a half note ligature) through the performer's left foot.

[11] Although most rock music is not notated, many have suggested the utility of speaking of written rhythmic values insomuch as they relate to established paradigms, such as the rock/jazz backbeat, where it is assumed that the hi-hat (jazz) or snare (rock) has its primary attack points on beats two and four. This analytical paradigm is justified further by Christopher Doll, "Listening to Rock Harmony" (Ph.D. dissertation, Columbia University, 2007), 8.

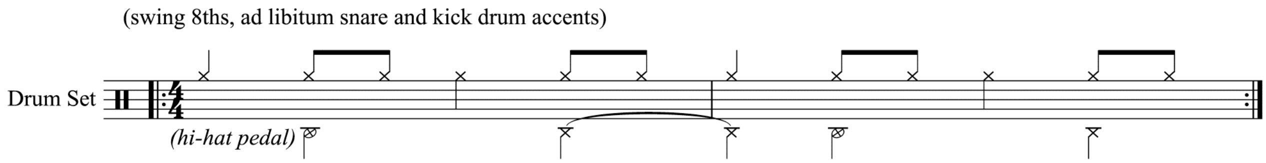
[12] Such left-foot practice is obviously not audible in recordings, but it can be observed in live performances. Of course, patting one's foot silently while performing an instrument is not specific to drumming.

[13] See Appendix I for conventions of the drum-set notation and the ensuing transcriptions.

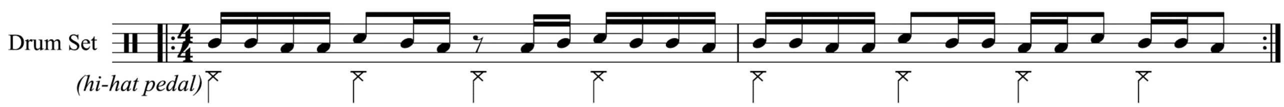
[14] Meter changes, like meter, can be inferred without the use of a score by measuring against stylistic norms (e.g., backbeat) or idiomatic subdivisions (e.g., clave patterns). These inferences become fixed upon transcription,

FIGURE 1. Three speeds of left-foot pulse-keeping

(a) Paradigmatic swing backbeat: Wayne Shorter, "Fee-Fi-Fo-Fum" (1965, 2:25) = even 𝅗𝅥



(b) Tool, "H" (1996, 0:39) = even ♩



(c) Smashing Pumpkins, "Muzzle" (1995, 1:01) = even ♪

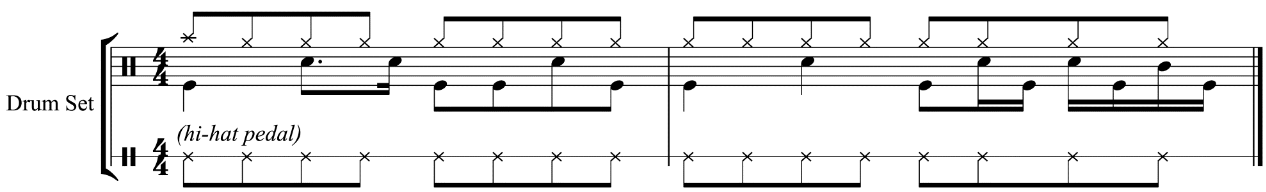
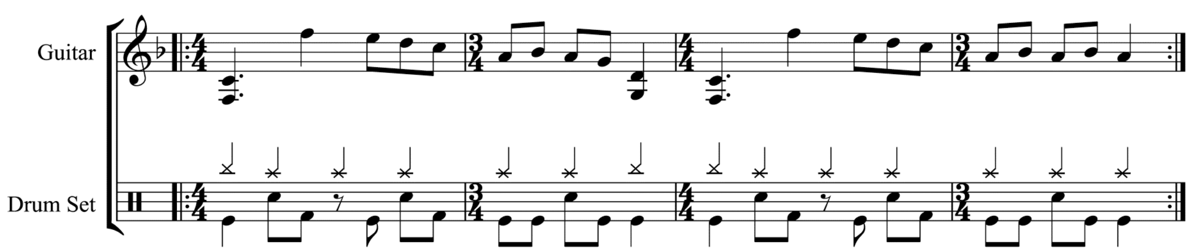


FIGURE 2. Hey Mercedes, "Our Weekend Starts on Wednesday" (2001, 0:01)



ties. Figure 2 provides a transcription of the recurring groove in Hey Mercedes's "Our Weekend Starts on Wednesday." At this fast tempo (♩ = ca. 200), a drummer will likely choose the back-beat 𝅗𝅥 pulse for the left foot, rather than pat the quicker ♩ pulses. However, the meter change from $\frac{4}{4}$ to $\frac{3}{4}$ prohibits a left-foot pattern based on 𝅗𝅥s, due to the odd-cardinality pulse total (i.e., 7). To maintain a steady left-foot pulse through this repeated groove, a performer must pat at the

forcing the analyst to make decisions about which value (e.g., ♪) best represents the pulse, and which meter that choice imposes upon the example.

faster ♩ level. I call this temporal level the *pivot pulse*—the slowest pulse stream shared between two meters of different numerators and/or denominators.[15] Because math rock highlights precise metronomic timing as an aesthetic ideal (much like marching drumlines), a performer's entrainment to such pivot pulses is advantageous as a rigorous chronometric tool.

II. THE PIVOT PULSE: DEFINITIONS AND ILLUSTRATIONS

The pivot pulse is the slowest pulse stream preserved in a given meter change. This shared pulse stream facilitates smoother transition between meters of different numerators and/or denominators—a modulatory technique reminiscent of tempo modulations in the music of Elliott Carter.[16] Pivot pulses can even be seen as analogous to pivot chords in tonal modulations, which facilitate smoother transition between keys by highlighting a shared sonority.[17] Phenomenologically speaking, I hypothesize that preservation or disruption of the primary pulse is of paramount importance. For example, a modulation from $\frac{4}{4}$ to $\frac{3}{4}$, which preserves the ♩ pulse, will be less disruptive to a listener's metric organization than a change from $\frac{4}{4}$ to $\frac{7}{8}$ or from $\frac{7}{8}$ to $\frac{15}{16}$, both of which divide the primary pulse in half. Throughout this essay, I invite the reader to validate or

[15] Although one should acknowledge the potential fallout of discussing time signatures in heard (as opposed to notated) music, the terms "numerator" (the top number in a time signature) and "denominator" (the bottom number in a time signature) are commonly used for these purposes, and can be useful for discussing the mathematical properties of meter.

[16] Interestingly enough, this aspect of Carter's music is often called "metric modulation," although it is more specifically a change of tempo rather than meter. Just as tempo changes require no meter change *per se*, meter changes can be achieved without using tempo changes. I would argue that this paper addresses "metric" modulations (i.e., changes of meter), while Carter's music frequently employs "tempo" modulations (i.e., changes of tempo). For a detailed discussion of the intricacies of conflicting tempi in Carter's late music, as well as a thorough literature review on the topic, see Poudrier, "Toward a General Theory of Polymeter."

[17] David Temperley describes hypermetrical transitions that act like pivot chords, insomuch as they smooth the transition from odd-accented to even-accented hypermetric sections (see Temperley, "Hypermetrical Transitions," *Music Theory Spectrum* 30/2 [2008]: 305–326). The aim of the present essay differs from Temperley's in many ways, most notably in its focus on shorter metrical spans (Temperely is only concerned with hypermeter). Additionally, while Temperely's hypermetrical transitions always preserve one-measure spans (always in 2- and 3-measure groupings), this essay is concerned with more disruptive changes, especially those that only preserve the ♪ or 𝅘𝅥𝅯 (e.g., a $\frac{4}{4}$ measure modulating to a $\frac{7}{8}$ or $\frac{15}{16}$ measure).

FIGURE 3. Pivot-pulse terminology

Primary pulse: The temporal level at which a listener's or performer's primary kinesthetic involvement (e.g. dancing, foot tapping) with a groove occurs. Primary pulse is often measured against genre conventions and expectations (such as backbeat) and style-specific subdivisions (such as clave rhythms).

Pivot pulse: The slowest temporal level preserved in a given meter change (the quickest level is always infinite). Pivot-pulse calculations take the form *PIV* (*a*, *b*) = *c*, where *a* and *b* are meter signatures expressed as numerator/denominator, *PIV* is an operator acting on the unordered set (*a*, *b*), and *c* is the pivot pulse expressed as numerator over denominator. Pivot pulses expressed as numerator/denominator intuitively map onto rhythmic values [$\frac{1}{16}$ = 𝅘𝅥𝅯].

repudiate this hypothesis by consulting audio clips of my transcriptions and analyses of the math-rock literature (click the 🔈 icon in the figure captions, and see also the alphabetical list in Appendix II). Before doing so, two concise definitions are necessary; see Figure 3.

Using transcriptions from math-rock artists Tool, Emery, and Every Time I Die, the following three examples illustrate pivot-pulse calculations,[18] progressing through increasing levels of what I call "disruption." Meter changes in which the primary pulse is preserved are considered less disruptive than those in which the primary pulse is halved or—more disruptive yet—quartered. In Figure 4, the meter change preserves the ♩ pulse;[19] Figure 5 preserves only the ♪ pulse; and the slowest value preserved in Figure 6 is the 𝅘𝅥𝅯 pulse.[20]

[18] When transcribing recorded music, the choice of a primary pulse level around which all note values are measured is important. In each of the examples, I have based my choice of rhythmic values on the assumption that beats two and four receive backbeat accents in rock; thus, the space between those two beats can be measured as a half note. Any deviations from this axiom are noted.

[19] While math rock typically distinguishes itself by utilizing more jarring meter changes (such as those that preserve only the ♪ or 𝅘𝅥𝅯), tactus-preserving modulations are common across many divergent rock idioms. Even radio-friendly rock music sometimes features meter changes with this low level of disruption (e.g., Stone Temple Pilots's "Adhesive," and Panic! At The Disco's "We're Oh So Starving"). Joti Rockwell uses similar ♩-preserving analysis to examine changing meter in American roots music (Rockwell, "Listening to Meter in American Roots Music," paper presented at the annual meeting of the West Coast Conference of Music Theory and Analysis, Seattle, March 2008).

[20] Since these are cyclical phenomena (observing repeat signs), pivot pulses can also be modeled in the opposite direction. Figures 4–6 label pivots in a uniform order [*PIV* ($\frac{4}{4}$, x)] in order to highlight the increasing disruption between the three. Since pivot-pulse calculations are commutative under the *PIV* operator (see Figure 7), *PIV* (*a*, *b*) and *PIV* (*b*, *a*) yield the same pivot-pulse value.

FIGURE 4. Every Time I Die, “Pigs is Pigs” (2007, 1:02)[21]

PIV $(\frac{4}{4}, \frac{3}{4}) = \frac{1}{4}$ (♩)

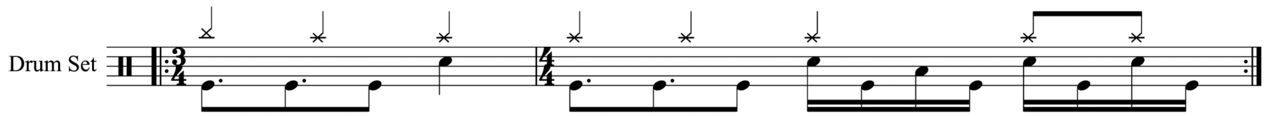


FIGURE 5. Emery, “The Weakest” (2005, 0:01)[22]

PIV $(\frac{4}{4}, \frac{7}{8}) = \frac{1}{8}$ (♪)

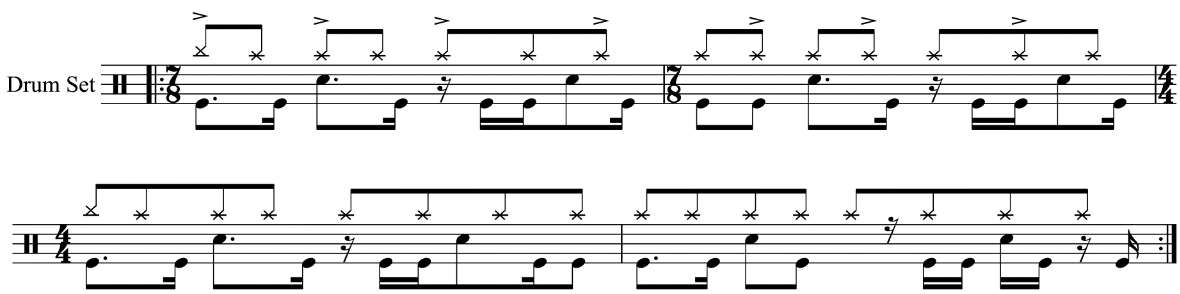


FIGURE 6. Tool, “Intolerance” (1993, 0:21)

PIV $(\frac{4}{4}, \frac{13}{16}) = \frac{1}{16}$ (𝅘𝅥𝅯)

FIGURE 7. Calculating pivot pulse [*PIV* $(\frac{4}{4}, \frac{13}{16}) = \frac{1}{16}$] using *GCD* and *LCM*

GCD (4, 13) = 1
LCM (4, 16) = 16
GCD (4, 13) / *LCM* (4, 16) = $\frac{1}{16}$, or (𝅘𝅥𝅯)

[21] The groove shown repeats once as written, but the third time the $\frac{4}{4}$ bar is elongated by one ♪, producing a feel much like the phenomenon of added pulse found in Figures 13 and 14. It should also be noted that this example deviates from the axiom 𝅗𝅥 = backbeat. Performers often call this a “half-time” feel, meaning that the tempo stays the same and the snare attack falls on beat 3. The alternative, following a strict axiom of backbeat = 2 and 4 would be to notate the tempo at half its value, which distorts the primary pulse felt by listeners and performers.

[22] The grouping dissonance between the drummer’s hi-hat accent pattern and his kick/snare pattern (2 vs. 7, respectively) lends additional metrical complexity to this excerpt.

After demonstrating pivot-pulse calculations for Figures 4–6, it should be apparent that the methodology maps onto two mathematical operators: greatest common divisor (*GCD*) and lowest common multiple (*LCM*). The pivot pulse between two meters, each expressed as numerator/denominator (n_1/d_1, n_2/d_2), can always be defined as [$GCD\ (n_1, n_2)\ /\ LCM\ (d_1, d_2)$], as shown in Figure 7.[23] Because elements *a* and *b* of any set *s* are commutative under the operations *GCD* and *LCM* [*LCM* (*a, b*) = *LCM* (*b, a*); *GCD* (*a, b*) = *GCD* (*b, a*)], so those elements are commutative under pivot-pulse operations [*PIV* (*a*, *b*) = *PIV* (*b*, *a*)]. While this way of modeling pivot pulses may seem abstract, I find it helpful in performing these meter changes (especially as a drummer), and it is a faithful depiction of the relative disruption a listener encounters upon entraining to these metric shifts.[24] Faster pivot pulses correlate with more disruptive meter changes.

The level of formalization made possible by the commutative properties of the pivot pulse, combined with its ability to describe the phenomenological experiences of changing meter, make the pivot pulse a compelling methodology for analyzing most types of metric shifts. The following section of this essay will develop the approach (referred to as the "LCM model") in more complex metrical analyses, each of which applies a different nuance of the pivot-pulse methodology to a specific type of musical phenomenon.

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[23] This notation for the operators *GCD* and *LCM* acting on elements *a* and *b* of an unordered set [*GCD* (*a, b*)] is favored by Daniel Zwillinger, "Greatest Common Divisor," in *Standard Mathematical Tables and Formulae*, ed. Zwillinger (Boca Raton, FL: CRC Press, 1996). I will therefore use parenthesis for enclosing elements *a* and *b* of the set, while using square brackets only as a way to set off enclosed formulae from the surrounding text.

[24] I am currently making use of this methodology in preparing for a performance of Steve Reich's *Music for Pieces of Wood*. At faster tempi, it feels more comfortable to subdivide the $\frac{6}{4}$ ostinato into three 𝅗𝅥 pulses (rather than six ♩ pulses), which is perfectly suitable for Clave Two's modulation to $\frac{4}{4}$ in the second part of the piece, as this meter change preserves the 𝅗𝅥 pulse to which I had been entraining. However, Clave Two's modulation from $\frac{4}{4}$ to $\frac{3}{4}$ in the final section of the piece requires entrainment to the faster ♩ pulse, which feels somewhat uncomfortable at faster tempi.

III. NUANCED PIVOT-PULSE APPLICATIONS

Type 1: Pivot Pulses between Non-Isochronous Tactuses.

In modeling meter changes thus far, we have (1) assumed that primary pulses divide measures evenly, and (2) ignored idiomatic subdivisions for meters of odd cardinality. Put succinctly, we have only modeled meter changes between measures, assuming each measure to exhibit a uniform metric profile. My hope is that pivot pulses may help connect the studies of "meter" and "hypermeter," as pivot pulses do not discriminate between short and long spans of music. While the LCM model elegantly systematizes metric shifts in longer spans (such as those recently described by David Temperley and Joti Rockwell),[25] its applicability to non-isochronous (hereafter "NI") tactuses in Figure 8 demonstrates that the model works equally well for any span long enough to be considered properly metric.[26]

Notice that Figure 8 features three distinct 𝅘𝅥𝅯 groupings: 2, 3, and 4.[27] The solitary 3𝅘𝅥𝅯 grouping feels like an elongation of the 2𝅘𝅥𝅯 grouping, which then proceeds uninterrupted through the second bar until it is elongated to 4𝅘𝅥𝅯 in the third bar.[28] In modeling NI-tactuses, we must pivot between individual adjacent pulses, not measures, as those measures no longer feature a

[25] See Temperley, "Hypermetrical Transitions," and Rockwell, "Listening to Meter in American Roots Music." Both are relevant to this paper insomuch as they examine (albeit in very different ways) the metric spans preserved between (hyper)metric shifts. Temperely's methodology always preserves measure-length units, while Rockwell illuminates metric shifts that only preserve the 𝅗𝅥 or ♩ pulse.

[26] Justin London states that the lower (quickest) limit to spans we can perceive as metrical is around 100 ms, while the upper (slowest) boundary is between 5 and 6 seconds (London, *Hearing in Time*, 27).

[27] London's revision of Lerdahl and Jackendoff's WFR (well-formedness rule) 3, which requires subdivisions to be of either cardinality 2 or 3, is only possible within specific tempo constraints, such as the fast one here, which allows the 4 subpulses of each pulse in m. 3 to fall within the specified tempo range for a subcycle. (See London, *Hearing in Time*; and Fred Lerdahl and Ray Jackendoff, *A Generative Theory of Tonal Music* [Cambridge, MA: MIT Press, 1983].) This example also fits London's WFR 6, which states that "all subcycles must be maximally even" (London, *Hearing in Time*, 103). London places this constraint on subdivisions that are not 2 or 3 (e.g., 4+4 in m. 3) in order to avoid otherwise *ad hoc* decisions about what constitutes a viable subdivision cardinality.

[28] When a notehead follows an Arabic numeral with no space between (e.g., 4𝅘𝅥𝅯), it designates a span of time equal to the numeral times the note value.

FIGURE 8. The Mars Volta, "Cygnus . . . Vismund Cygnus" (2005, 5:16)[29]

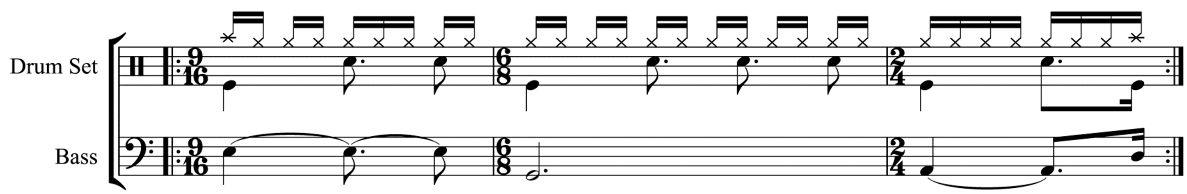
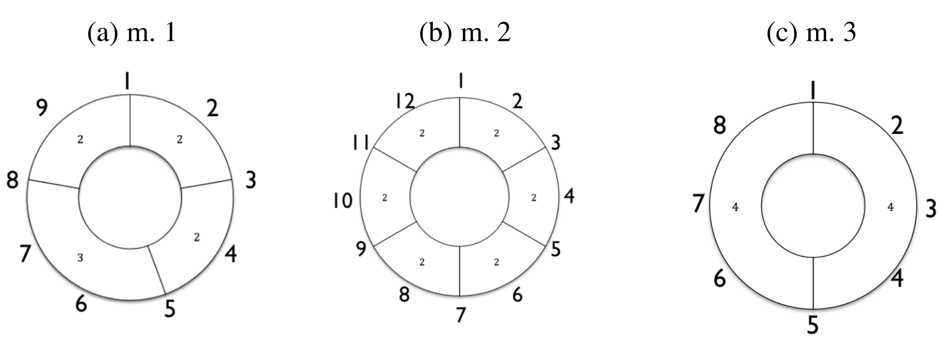


FIGURE 9. Pivot-pulse calculations for all adjacent pulses in "Cygnus . . . Vismund Cygnus"

Meas.	Pulse #	*PIV* (*a*, *b*)	Pivot Pulse
1	1	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	2	*PIV* ($\frac{2}{16}$, $\frac{3}{16}$)	$\frac{1}{16}$ (𝅘𝅥𝅯)
	3	*PIV* ($\frac{3}{16}$, $\frac{2}{16}$)	$\frac{1}{16}$ (𝅘𝅥𝅯)
	4	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
2	1	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	2	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	3	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	4	*PIV* $\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	5	*PIV* ($\frac{2}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
	6	*PIV* ($\frac{2}{16}$, $\frac{4}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)
3	1	*PIV* ($\frac{4}{16}$, $\frac{4}{16}$)	$\frac{4}{16}$ (♩)
	2	*PIV* ($\frac{4}{16}$, $\frac{2}{16}$)	$\frac{2}{16}$ (𝅘𝅥𝅮)

FIGURE 10. Clockface diagrams of groove of "Cygnus . . . Vismund Cygnus," mm. 1, 2, and 3[30]



[29] The song's full name is "Cygnus . . . Vismund Cygnus: A. Sarcophagi, B. Umbilical Syllables, C. Facilis Descenus Averni, D. Con Safo."

[30] Using London's terminology, each clockface is deemed a "metrical cycle," or perhaps the entire three-measure groove is such a cycle, as London defines it as "a particular attentional state, typically involving beats, beat subdivisions, and *measures*" (London, *Hearing in Time*, 76, italics mine). The numbers around the outside of the face (the 𝅘𝅥𝅯 pivot pulse) are the N-cycle, which London defines as the "lowest/fastest level of meter present; typically a level of subdivision that functions as a constraint on the formal organization of higher levels" (76). Thus, Figure 10a is a 9-cycle, 10b is a 12-cycle, and 10c is an 8-cycle. The NI-pulses inside the face are beat-cycles, insomuch as they are "the level of meter that carries the tactus," and they are also subcycles, as they are a "level of metrical structure about the N-cycle" (London, *Hearing in Time*, 76–77).

uniform pulse profile. Measuring pivots between all adjacent pulses in this groove can be done by zooming in (as shown in Figure 9), treating the LCM model like a telescopic lens to focus on any metrical level.

Justin London has utilized clockface diagrams to model the cyclical nature often exhibited by grooves built on NI-tactuses, such as the maximally even African bell pattern.[31] As math-rock grooves often appear in repeated units (like many rock grooves), the clockface method can also apply to NI-tactuses within any repeated span. Figures 10a–c feature two sets of numbers, one set contained within sections of the chart (in a smaller size), and one set around the outside of the chart (in a larger size). Pertaining to the Mars Volta groove in Figures 8 and 9, the smaller numbers inside the chart represent the number of 𝅘𝅥𝅯s comprising the individual pulses, while the larger numbers on the outside represent the total number of 𝅘𝅥𝅯s comprising each measure. The 𝅘𝅥𝅯 represents the pivot pulse between all three meters because $\frac{1}{16}$ is the [*GCD* (n_1, n_2, n_3) / *LCM* (d_1, d_2, d_3)] of meters $\frac{9}{16}$, $\frac{6}{8}$, and $\frac{2}{4}$ found in the excerpt.

Type 2: Multiple Pivot Pulses between Binary and Compound Meters.

Thus far, pulse groupings of odd cardinalities have only appeared as NI-tactuses within one measure. However, many rock styles utilize compound meters, which by definition feature *isochronous* odd-cardinality pulse groupings. Precise calculations provided by the LCM model only produce one pivot pulse between any two meters, as *GCD* and *LCM* operations produce only one product. However, musicians understand that there are two ways to modulate between compound and binary meters, one of which preserves the pulse, the other the tactus.[32]

[31] London, *Hearing in Time*.

[32] Here, the distinction between tactus and pulse is important. Although a pulse can be of any speed, a tactus must be slow enough that its constituent subdivisions can be perceived. Math-rock grooves, like most rock grooves,

FIGURE 11. Multiple formulae for compound/binary pivot-pulse calculation
(n_1, n_2) = numerators, (d_1, d_2) = denominators

Pulse-preserving: $1 \,/\, LCM\ (d_1, d_2)$

Tactus-preserving: $GCD\ (n_1, n_2) \,/\, GCD\ (d_1, d_2)$

Whether tactus-preserving or pulse-preserving, pivot-pulse calculations between compound and binary meters will provide for a numerator impossible within one of those meters. If the pivot numerator is odd [$PIV\ (\frac{3}{4}, \frac{9}{8}) = \frac{3}{8}$], the pivot pulse will be one not present in the binary meter, since, by definition, binary meters feature tactuses comprising an even number of pulses. Conversely, if the pivot numerator is even [$PIV\ (\frac{4}{4}, \frac{6}{8}) = \frac{2}{8}$], the pivot pulse will not be present in the compound meter, since, by definition, compound meters feature tactuses comprising an odd number of pulses. To reflect musical intuition about these two types of meter changes between binary and compound meters, pivot-pulse calculation must model both ways, as shown in Figure 11.

The fixed $n = 1$ for the formula in all pulse-preserving pivot operations is not arbitrary, but reproduces the pivot pulse obtained from any single compound tactus to any single binary tactus [$PIV\ (\frac{3}{8}, \frac{2}{8}) = \frac{1}{8}$]. In this manner, it is simply an extension of the same adjacent-pulse pivots demonstrated in Figure 9. Regarding tactus-preserving calculations, it should be noted that preservation of the tactus violates the "quickest level of pulse preservation is always infinite" clause, because a tactus-preserving meter change does not preserve the pulse, only the tactus. This should be no surprise, as tactus-preserving compound/binary meter changes are actually *tempo*

almost always preserve the steady pulse, or, put another way, the *subdivision* of the tactus. For example, in moving from $\frac{4}{4}$ to $\frac{6}{8}$, the ♪ is often kept steady, rather than the ♩-cum-♩. tactus. This correlates to the use of metronomes in studio recording. Whereas a change that preserves the ♪ requires no resetting of a metronome (as it is usually set to a subdivision of the beat), redividing a tactus into three parts instead of two requires a different setting.

modulations as well (they change the tempo of the pulse). Tactus-beating conductors exemplify this kinesthetically, as no change in baton speed is necessitated by a tactus-preserving modulation from binary $\frac{2}{4}$ to compound $\frac{3}{8}$ [*GCD* (2, 3) / *GCD* (4, 8) = $\frac{1}{4}$].

Although tactus-preserving compound/binary modulations are not unheard, math rock (like most rock music) almost always preserves the pulse in such changes.[33] This practice is exemplified in the Radiohead groove transcribed in Figure 12. The pivot from $\frac{4}{4}$ to $\frac{12}{8}$, utilizing the pulse-preserving calculation, yields a pivot pulse of $\frac{1}{8}$, and the movement from $\frac{12}{8}$ back to $\frac{4}{4}$, utilizing the same commutative calculation, yields the same $\frac{1}{8}$ pivot pulse. Commutativity faithfully models the performative aspect of such meter changes, as the performer can easily entrain to the shared ♪ pulse between the two meters pivoting in *either* direction. In fact, drummer Phil Selway's right-hand part makes this pivot pulse explicit by preserving the ♪ on the ride cymbal throughout the excerpt.

Type 3: Added and Subtracted Pivot Pulses.

Figure 13 provides a transcription from the verse of Killswitch Engage's "When Darkness Falls," which features a repeated groove comprising $\frac{4}{4}$ and $\frac{7}{8}$ measures. Underneath a metrically dissonant guitar (a extension of an intro predominantly in $\frac{7}{16}$), the drum set retains a stable backbeat for three iterations (3 𝅗𝅥 pulses)[34] before terminating the fourth iteration a ♪ early.

[33] An exemplary exception occurs in the opening of Stars's "Set Yourself on Fire" (2004, 0:28) ⏮. When the $\frac{6}{8}$ intro modulates to a double-time $\frac{4}{4}$ to begin the verse, the previous ♩. tactus is preserved as the new 𝅗𝅥 tactus.

[34] The practice of keeping a simple backbeat under metrically dissonant melodic layers was made famous by Swedish math-metal band Meshuggah. Jon Pieslak describes many of the metrical dissonance techniques Meshuggah has employed over the course of their career, most of which involve the drummer's right and left hands playing steady $\frac{4}{4}$ patterns, even when the kick drum is playing the same metrically-dissonant pattern as the guitars (see Pieslak, "Re-Casting Metal: Rhythm and Meter in the Music of Meshuggah," *Music Theory Spectrum* 29/2 [2007]: 219–245). Although Pieslak associates this technique with Meshuggah's early career, a more recent example

FIGURE 12. Radiohead, “Go To Sleep” (2003, 0:43)

FIGURE 13. Killswitch Engage, “When Darkness Falls” (2004, 0:10)

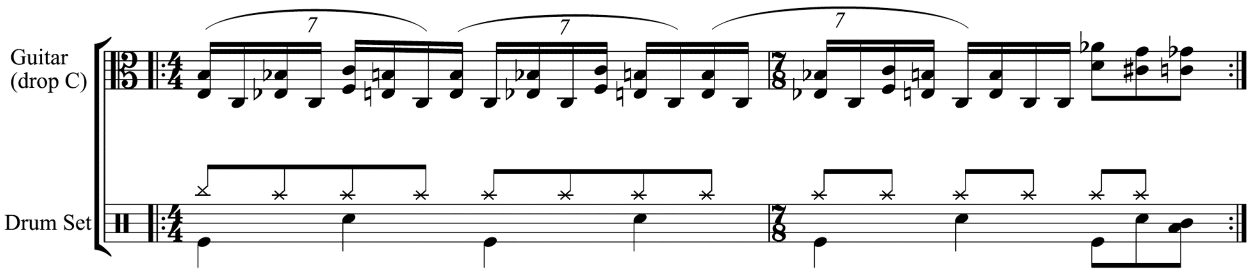


FIGURE 14. The Chariot, “Back to Back” (2007, 0:16)[35]

can be heard in the second verse of their song “Bleed” (2008, 0:51), where the drummer’s right and left hands maintain a slow $\frac{4}{4}$ backbeat underneath a $\frac{5}{32}$ pattern in the guitars and kick drum.

[35] Though the 3:5 notation for the last two screams of this transcription may look convoluted, it represents practical musical intuition: the singer is merely trying to place the same evenly-spaced triplet figure found in beats one and two over the fourth beat, which, in this case, is five 𝅘𝅥𝅯s long instead of four.

Applying Hasty's projection methodology,[36] the potential 𝅗𝅥 duration projected by the first kick/snare backbeat on beats 1–2 is: (a) realized on beats 3–4; (b) realized again on beats 1–2 of the next bar; (c) then thwarted by the subtracted ♪ at the end of beat 4.

If we compare the pivot pulses in Figures 13 and 14, we see that, while the Killswitch example features a subtracted ♪, the Chariot example has an added 𝅘𝅥𝅯 at the end of the repeated measure. Analyzing this as a non-isochronous tactus within one measure, the LCM models the change from a ♩ tactus (beats 1–3) to a 5𝅘𝅥𝅯 tactus (beat 4) as $\frac{1}{16}$. However, at such a slow tempo, the tactus itself begins to take on the role of meter, insomuch as each ♩ pulse provides a framework through which to understand the hardcore triplets contained within.[37] Most of the rhythm fits a $\frac{1}{4}$ or $\frac{2}{8}$ meter (each tactus), while the 5𝅘𝅥𝅯 pulse feels like an elongation of those projections. While the transcription in Figure 14 bears the time signature $\frac{17}{16}$, which is accurate arithmetically speaking, it can also be interpreted as an idiomatic $\frac{4}{4}$ pattern with an added 𝅘𝅥𝅯 at the end.

The added-/subtracted-value approach is simply a different way of understanding the pivot-pulse phenomenon. Just as quicker pivot-pulse values are more disruptive than slower ones, so quicker added or subtracted values are more disruptive to a listener's metrical entrainment. Thus, while the Killswitch example only subtracts half of the primary pulse value from the expected meter (primary pulse = $\frac{1}{4}$, pivot = $\frac{1}{8}$), the Chariot example offsets listener expectation by a more disruptive fraction of the primary pulse (primary pulse = $\frac{1}{4}$, pivot = $\frac{1}{16}$).

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[36] Projection provides a useful analytical framework for discussing added/subtracted beats, as both phenomena are only possible relative to an expectation created by some metrical span that has happened previously. See Christopher Hasty, *Meter as Rhythm* (New York and Oxford: Oxford University Press, 1997), 84.

[37] Hardcore triplets are roughly equivalent to so-called "Broadway triplets," in which the actual performed rhythm is somewhere between a true evenly spaced triplet and the proportion 3+3+2, often expressed as |♪. ♪. ♪|. This rhythmic figure is common in metal-influenced genres, perhaps even more so than pure triplets themselves.

IV. ANALYTICAL CODA: DILLINGER ESCAPE PLAN'S "43% BURNT"

Having defined and demonstrated the pivot pulse through several concise analytical sketches, this essay will close with a demonstration of pivot-pulse methodology applied to an entire section from Dillinger Escape Plan's "43% Burnt," from their 1999 album *Calculating Infinity*. In choosing a band whose sound helped define the math-metal style,[38] I will also demonstrate the applicability of pivot-pulse methodology to this genre.

Serving as the song's memorable outro, the groove transcribed in Figure 15 appears several times at the track's ending before succumbing to a studio fade-out. Each of its three modules (represented by three systems in the transcription) consists of several $\frac{2}{4}$ bars punctuated by a measure of different numerator and denominator. Additionally, each of these module-ending measures differs among themselves in numerator and denominator. Thus, in entraining to the above example, the listener/performer is forced to pivot using a different pulse level in each module. In addition to this novelty, the guitar, bass, and kick drum employ a 3♩ metrical dissonance over the 2♩ grouping expressed by the crash-cymbal/snare-drum backbeat at the onset of each module (mm. 1–2, 6–7, and 10–11).

An analysis of Figure 15 using pivot-pulse methodology is relatively straightforward, yet the excerpt exemplifies many complexities. The pivot between mm. 5–6 is the 𝅘𝅥𝅯 [$PIV\ (\frac{2}{4}, \frac{5}{16}) = \frac{1}{16}$]; between mm. 9–10, the pivot is the ♪ [$PIV\ (\frac{2}{4}, \frac{3}{8}) = \frac{1}{8}$]; and from m. 14 wrapping around to m. 1, the pivot is the ♩ [$PIV\ (\frac{1}{4}, \frac{2}{4}) = \frac{1}{4}$]. Because the numerator and denominator of each module-ending bar are different, the pivot pulses between them and the invariable $\frac{2}{4}$ bars are also

[38] Pieslak places Dillinger Escape Plan alongside Meshuggah as a forerunner of the math-metal genre: "The tendency to focus on rhythmic and metric complexity is often the determining factor for qualification in the math subgenre" (Pieslak, "Re-Casting Metal," 244).

FIGURE 15. Dillinger Escape Plan, "43% Burnt" (1999, 3:10)

different. In this case, those pivot denominators also display the special property of growing exponentially smaller as the groove progresses from start to finish (i.e., 16, 8, 4).

Considering NI-tactuses, the $\frac{5}{16}$ grouping in m. 5 sounds most like 3+2, based on the three tritones in the guitar followed by two low-𝅘𝅥𝅯 palm mutes. While the modulation from $\frac{2}{4}$ to the $\frac{3}{16}$ opening pulse of m. 5 necessitates a 𝅘𝅥𝅯 pivot, the change from the $\frac{2}{16}$ pulse at the end of m. 5 to the subsequent $\frac{2}{4}$ in m. 6 could be expressed as a less disruptive ♪ pivot, as $\frac{2}{16}$ is equal to $\frac{1}{8}$. Although mm. 9 and 14 are of odd cardinality, they do not lend themselves to NI-tactus analysis.

Instead, they feel like subtracted pulses against the established $\frac{2}{4}$ framework. The $\frac{3}{8}$ in m. 9 feels like it is missing a ♪, not only because the cardinality three is one less than the established 4♪, but also due to the guitar/bass/kick-drum pattern. After the 4𝅘𝅥𝅯 tritone chords, there is usually a 2𝅘𝅥𝅯 low palm mute, followed by the 4𝅘𝅥𝅯 tritone exactly one ♩ later. Between mm. 9–10, this last 4𝅘𝅥𝅯 tritone comes a ♪ later instead of the expected ♩ later. Measure 14 features a previously unheard 2𝅘𝅥𝅯 tritone that renders the possibility for pattern deformation improbable in the same way as the 3𝅘𝅥𝅯 tritone of m. 5. Instead, the missing ♩ of m. 14 simply feels like a missing pulse, a reduction in cardinality from two to one.

Experiencing the left-foot pulse-keeping convention as a drummer, as well as the deformation of this convention stylistically associated with math rock, led me to formulate the pivot pulse as a mathematical generalization of a musical phenomenon. The strength of the pivot-pulse methodology stems from its foundation in musical practice coupled with its high degree of formalization due to its constituent operators *GCD* and *LCM*. Pivot-pulse methodology responds well to math rock's foregrounding of rapidly changing pulse levels presented in looped succession. Moreover, specific musical applications revealed complexities in the methodology, including the ability to model non-isochronous tactuses, the ability to model both types of compound/binary shifts, and the extension of pivot-pulse concepts to include added and subtracted pulse values as a complementary interpretation. Doubtless, other musical applications will highlight different nuanced features of this methodology, which could be rooted in stylistic features of that genre.

Although this essay has focused on relatively short metrical spans (from pulses to measures), the model applies without modification to longer spans, including those too long to be considered properly metrical (following London's cognitive constraints). Pivot pulses can therefore be construed as a further generalization of metric and hypermetric theories, able to model changes as small as those found in studies by London and Rockwell,[39] as large as the hypermetrical transitions of Temperley,[40] and even larger spans such as the pivot between sixteen- and eleven-measure sections in Radiohead's "There, There."[41] It is thus a reasonable analytical tool if one is interested in modeling metric shifts on a richer continuum without the customary distinction between meter and hypermeter.

[39] London, *Hearing in Time*; and Rockwell, "Listening to Meter in American Roots Music."

[40] Temperley, "Hypermetrical Transitions."

[41] This shift from sixteen-measure groupings (0:01–2:53) to eleven-measure groupings (beginning at 2:54), can be modeled by pivot-pulse methodology as [$PIV\ (\genfrac{}{}{0pt}{}{16}{1}, \genfrac{}{}{0pt}{}{11}{1}) = \genfrac{}{}{0pt}{}{1}{1}$ (𝅝)].

APPENDIX I

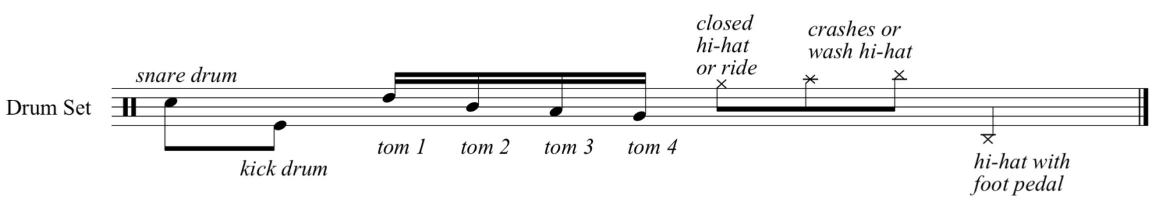
CONVENTIONS OF TRANSCRIPTIONS AND DRUM-SET NOTATION.

All transcriptions in this article are my own. They are intended to be illustrative reductions, not complete accounts of all musical material and certainly not performance-ready scores. In most cases, I have chosen to represent only the primary rhythmic layers heard in a given section.

Choosing the proper octave in which to notate rock music involves certain complications. Guitarists and bassists are already accustomed to transposing their written music down one octave. Furthermore, the overtone spectrum of a distorted electric guitar sometimes renders the perfect octave and the perfect twelfth above the fundamental as perceptible as the fundamental itself. For these reasons, I have notated all parts in the octave and clef that renders them clearest visually, without regard to the sounding pitch or doublings.

Because rock music is almost never notated in score form, and as rock performers often incorporate a significant amount of improvisation, literal repeats are almost non-existent. My use of repeat signs should therefore be understood as representing the repeat of a basic structure, not the literal parts. For example, if a verse contains two presentations of the same chord progression, the basic melodic/harmonic/rhythmic reduction will likely repeat, although the exact parts in the kick drum, lead guitar, and lead vocal (especially the lyrics) will likely be varied.

Drum-set transcriptions can be read using the key provided below. Because these examples are transcribed as analytical demonstrations only, I have reduced the number of distinct cymbal types to two. The top space of the staff represents all quieter time-keeping cymbals, including closed hi-hat and ride cymbal, while the ledger lines above represent louder time-keeping cymbals, including open hi-hats and crash cymbal.



APPENDIX II

ALPHABETICAL LISTING OF AUDIO CLIPS (BY ARTIST), AND THEIR POINTS OF REFERENCE.

The Chariot, "Back to Back" (2007, 0:16). Referenced in Figure 14.

Dillinger Escape Plan, "43% Burnt" (1999, 3:10). Referenced in Figure 15.

Emery, "The Weakest" (2005, 0:01). Referenced in Figure 5.

Every Time I Die, "Pigs is Pigs" (2007, 1:02). Referenced in Figure 4.

Hey Mercedes, "Our Weekend Starts on Wednesday" (2001, 0:01). Referenced in Figure 2.

Killswitch Engage, "When Darkness Falls" (2004, 0:10). Referenced in Figure 13.

The Mars Volta, "Cygnus . . . Vismund Cygnus" (2005, 5:16). Referenced in Figure 8.

Meshuggah, "Bleed" (2008, 0:51). Referenced in n. 34.

Radiohead, "Go To Sleep" (2003, 0:43). Referenced in Figure 12.

Radiohead, "There, There" (2003). Referenced on p. 62 and n. 41.

Wayne Shorter, "Fee-Fi-Fo-Fum" (1965, 2:25). Referenced in Figure 1a.

Smashing Pumpkins, "Muzzle" (1995, 1:01). Referenced in Figure 1c.

Stars, "Set Yourself on Fire" (2004, 0:28). Referenced in n. 33.

Tool, "H" (1996, 0:39). Referenced in Figure 1b.

Tool, "Intolerance" (1993, 0:21). Referenced in Figure 6.

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ABSTRACT

Math rock's most salient compositional facet is its cyclical repetition of grooves featuring changing and odd-cardinality meter. These unconventional grooves deform the conventional rhythmic structures of rock, such as backbeat and steady pulse, in such a way that a listener's sense of metric organization is initially thwarted. Using transcriptions from math-rock artists such as Radiohead, The Mars Volta, and The Chariot, the author demonstrates a new analytical apparatus aimed at making sense of the ways listeners and performers process these changing pulse levels: the *pivot pulse*. The pivot pulse is defined as the slowest temporal level preserved in a given meter change. The author suggests that the preservation or disruption of the primary pulse level (that is, the temporal level at which a listener's or performer's primary kinesthetic involvement happens, such as dancing or foot-tapping) is of paramount importance. For example, a change from $\frac{4}{4}$ to $\frac{3}{4}$, which preserves the quarter-note pulse, will be less disruptive to a listener's metric entrainment than a change from $\frac{4}{4}$ to $\frac{7}{8}$ or $\frac{7}{8}$ to $\frac{15}{16}$, both of which split the primary pulse in half. In order to formalize pivot-pulse methodology, the author presents an algebraic model based on the commutative operations *greatest common denominator* and *lowest common multiple*. Pivot-pulse methodology is also applied metaphorically to the kinesthetic interpretations of performers and listeners to better understand the complex movements incited by math-rock grooves.

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Brad Osborn is Assistant Professor of Music at DePauw University. His recent research focuses on the link between experimental forms and experimental genres in post-millennial rock music.

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