

# FROM PROGRAM MUSIC TO SONIFICATION: REPRESENTATION AND THE EVOLUTION OF MUSIC AND LANGUAGE

*Stephen Taylor*

School of Music, University of Illinois  
1114 W. Nevada St. Urbana, IL 61801, USA  
[staylor7@illinois.edu](mailto:staylor7@illinois.edu)

## ABSTRACT

Research into the origins of music and language can shed new light on musical representation, including program music and more recent incarnations such as data sonification. Although sonification and program music have different aims—one scientific explication, the other artistic expression—similar techniques, relying on human and animal biology, cognition, and culture, underlie both. Examples include Western composers such as Beethoven and Berlioz, to more recent figures like Messiaen, Stockhausen and Tom Johnson, as well as music theory, semiotics, biology, and data sonifications by myself and others. The common thread connecting these diverse examples is the use of human musicality, in the bio-musicological sense, for representation. Links between musicality and representation—dimensions like high/low, long/short, near/far, etc., bridging the real and abstract—can prove useful for researchers, sound designers, and composers.

## 1. INTRODUCTION

The emerging field of bio-musicology [1] and research into the origins of music and language [2], [3] can shed new light on musical representation, including program music and more recent incarnations such as data sonification. Although sonification and program music have different aims—one scientific explication, the other artistic expression—similar techniques, relying on human and animal biology, cognition, and culture, underlie both.

Two of the earliest and most successful examples of sonification, the Geiger counter (1928) and Morse code (1836), are still widely used today. The Geiger counter, a radiation detector, emits a series of clicks: the faster the clicks, the greater the danger [4]. It capitalizes on instincts shared by humans and primates: the chimpanzee pant-hoot follows the same rising curve of acceleration and intensity, as do musical topics such as the Mannheim rocket (the term comes from 18th-century symphonies that begin with an ascending arpeggio and crescendo).

Morse code on the other hand is abstract but general. While it is unintelligible unless you know the code, it can encode literally any message; it is a kind of musical cryptography, similar to Bach's use of gematria. These sonic techniques recall two recent hypotheses for the evolution of music. One [5] holds that musicality is innate, encoded in our genes. The other sees music as a “transformative technology of the

mind,” akin to the control of fire [3]. Although the knowledge of fire is not built into our DNA, it has nonetheless profoundly affected our culture, our bodies, our biology.

Human musicality likely comprises both of these ideas, and others as well, as Bruno Nettl writes: “...I have become convinced that the things we call music began in a number—maybe a lot—of different ways, some going back beyond the evolution of homo sapiens. Some are no doubt older than others, but the ‘younger’ ones did not necessarily develop from older ones.” [6]. W. Tecumseh Fitch, similarly, advocates for the study of bio-musicology: “the biological study of musicality in all its forms... While music, the product of human musicality, is extremely diverse, musicality itself is a stable aspect of our biology and thus can be productively studied from comparative, neural, developmental and cognitive perspectives” [1]. This essay explores the continuum from innate musicality to learned, symbolic representation; or, from music that mimics extra-musical things, to music built on extra-musical information.

## 2. ICON, INDEX, SYMBOL

Morse code and the Geiger counter can also be understood using the semiotic triad of icon-index-symbol, developed by the American Charles Peirce (1839-1914; see also Turino [7] for a detailed discussion from a musical perspective). The Geiger counter is indexical (the greater the radiation, the greater the speed of the clicks); Morse code, by its assignment of letters to patterns of dots and dashes, is symbolic. (For the English codebook, each pattern is chosen for how often its letter appears; while the result might sound arbitrary, careful listening reveals which signals occur most often.) Another early sonification device, the stethoscope, can be interpreted as iconic. Dombois and Eckel consider the stethoscope a kind of audification: “...one of the few important examples of an accepted scientific device using audio” [8].

The quasi-arbitrary, symbolic nature of Morse code is shared with spoken language, as Fitch notes in his 2010 book *The Evolution of Language*: “...arbitrariness is almost automatic if you start with a vocal system, for the realm of the iconic is rather limited in vocalizations. Onomatopoeia can buy you some animal names, and some emotional expressions, via imitation, but not much more. But the flip side of the coin—too often overlooked—is that arbitrariness is a crucial step to a fully open field for semantic reference, and this is something that we gain almost automatically with the capacity to link meanings to vocal signals...” [9], p. 467.

Seen from this semiotic perspective of icon, index, and symbol, program music and sonification both span a



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continuum (Figure 1), which is indebted to Kramer’s classification of sonification from analogic to symbolic [10].

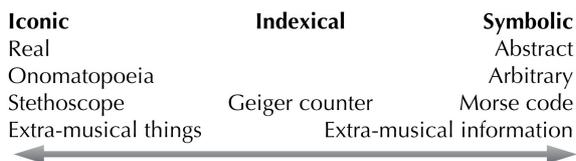


Figure 1. Sonification and program music both span a continuum from the real to the abstract.

Just as language and sonification range from onomatopoeia to arbitrary symbols, so does program music. Many composers have exploited the timpani’s resemblance to thunder, most notably Beethoven in his storm movement from the Symphony no. 6. At the opposite end of the continuum, the *idée fixe* in Berlioz’s *Symphonie Fantastique* is an abstract symbol, a musical theme representing the object of his infatuation (Wagner’s use of leitmotif works in much the same way: not only are there themes for different characters, there are also themes that represent abstract concepts, say, the renunciation of love). In this sense, sonification can be thought of as an updated version, or generalization, of program music.

### 3. PROGRAM MUSIC

Composers have explored this continuum from the real to the abstract for centuries. An early instance of program music is Marin Marais’ “Le tableau de l’Operation de la taille”, about kidney stone surgery (Figure 2).

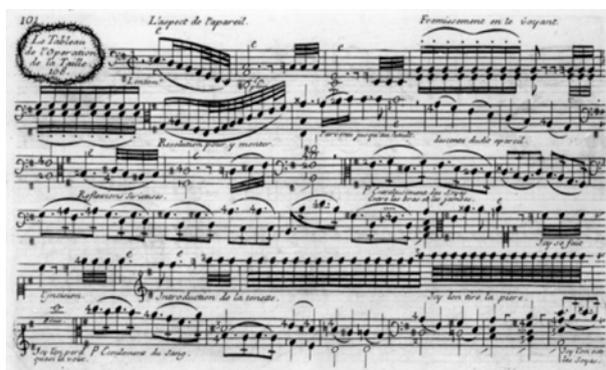


Figure 2. Marin Marais (1656-1728), “Le Tableau de l’Operation de la taille” for viol; an early instance of program music [11].

This work resembles many of Marais’ other works for viol. Without the accompanying explanations (“Appearance of the device”; “Here is the incision”; etc.), a listener might not have any idea that the piece is about kidney stone surgery (although Marais does indulge in word painting: e.g. “Descent of the device” at the end of the second line is depicted by a slow, descending scale). But the form of the piece is unusually choppy, jumping suddenly from one musical idea to another; the short explanations scattered throughout dictate the sudden changes, thwarting the music’s formal cohesion. In fact the piece is almost always performed with the words spoken as narration: the music becomes a kind of illustration of the text, a historical precedent to works like Prokofiev’s *Peter and the Wolf*. The explanations are a kind of caption, and they raise questions: is music somehow

less “valid” if it can only be understood via a caption or program? Does a caption’s presence somehow obviate the music’s role, to “sound like” the thing or information it’s representing? Can music be simultaneously abstract and descriptive? How to represent something, caption or not, that lacks a sonic analogy in the real world? We will come back to these questions, and the issue of captions.

I have already mentioned the thunderstorm in Beethoven’s Symphony no. 6, but the second movement (Figure 3), “Scene by a brook”, is just as evocative. At the end of the movement the orchestra drops out, leaving a single flute, who starts a trill; Beethoven’s sketch shows that this is a nightingale. An oboe joins in (quail), followed by a clarinet (cuckoo). At this moment—among the most famous passages in the history of program music—a particularly striking feature is the interval of the descending third. Beethoven chose it carefully. When highlighted by the solo clarinet, it becomes a cuckoo (and at least for me, this is the most “bird-like” of the three); but for the entire movement, the interval has been embedded in the flowing accompaniment. It is as if Beethoven uses the same musical fabric to weave both an abstract design and a vivid portrait.



Figure 3. Beethoven, passage with birds from Symphony no. 6, II. “Szene am Bach” [12]. An example of aural mimicry, or icon; the birds are nightingale, quail, cuckoo. The cuckoo’s interval of the third is also embedded within the movement’s flowing accompaniment.

We use language in a similar way, as Fitch describes above, when we use onomatopoeia in a sentence: spoken language can use the same sound in an iconic or symbolic way, depending on context. In his 2005 book *The Singing Neanderthals*, Steven Mithen discusses several studies in which onomatopoeia plays a role in non-obvious subjects ([2], p. 170). As he describes, in the 1920s Edward Sapir “undertook an intriguing and quite simple test. He made up two nonsense words, *mil* and *mal*, and told his subjects that these were the names of tables. He then asked them which name indicated the larger table and found... that almost all of them chose *mal*.” (As an exception that proves the rule, the writer David Foster Wallace kept lists of words which, counter-intuitively, sounded like the opposite of their meaning; one of his favorites was “pulchritudinous” [13].)

Mithen speculates that these kinds of sounds may have played a role in the evolution of language. Beethoven, again in sketches for the Sixth Symphony, argues for a similar idea in music (Figure 4). Both in language and music, this kind of musical mimicry can be considered as indexical in the Peircean sense; as the sound changes, so does the thing it describes.



Figure 4. From Beethoven's Eroica sketchbook: "The bigger the stream, the deeper the tone" [12]. This phrase can be interpreted as indexical, in the Peircean sense (in nature, bigger things are associated with lower frequencies).

There are far too many other examples of musical onomatopoeia to list, but we must mention Olivier Messiaen's magnificent depiction of birds in works like *Oiseaux exotiques* for piano and wind orchestra (1959), and the massive *Catalogue d'oiseaux* for solo piano (1956-58). These can be heard as a kind of updated version of Beethoven's birds, famously realistic, although sometimes they are slowed down and distorted to the point of unintelligibility, invoking gigantic, imaginary creatures [14]. Today with modern sampling technology it is easy to use recorded sounds from anywhere, both as an iconic reference and as an abstract element embedded into the music (like Beethoven's thirds). Two examples illustrate this point: Debussy evokes the feeling of walking in the snow with his piano prelude "Des pas sur la neige" (1909-10), while Björk, on her song "Aurora" from the 2001 album *Vespertine*, uses a Foley-like sample of someone actually walking in the snow to create the song's percussion (performed in concert by a live snow-walker).

Finally, despite my emphasis on musical mimicry, it is important to recognize that this notion has not gone unchallenged. Werner Wolf [15] notes that in English we have words for description (writing), and depiction (visualizing), but we have no verb "to desound". He continues: "[Music] is the most **abstract and non-referential medium** of all the arts and media, and it is therefore sometimes claimed that a piece of music does not consist of signs at all, in other words that music has no semiotic quality like verbal language... One should, however, be more precise, for music can be said to be 'referential', but mainly in the sense of 'self-referential' rather than of 'hetero-referential'. The reason for this is that music consists mainly of signs whose signification resides in their ability to point to other signifiers within the same system, usually by iconically imitating or repeating them (but also by forming contrasts to them)" (his emphasis, p. 59; canons are good examples of this self-referential quality).

Franz Liszt, quoted by Roger Scruton in the *New Grove Dictionary*, moderates this view: he did not "regard music as a direct means of describing objects; rather he thought that music could put the listener in the same frame of mind as could the objects themselves" [16]. Berlioz, in his groundbreaking essay "On imitation in music" [17], confronts this kind of thinking head on: "The famous naturalist Lacépède ... says somewhere that 'since music has only sounds at its disposal, it can act only through sound. Hence in order to produce the signs of our perceptions these signs must themselves be sounds.' But how can one express musically things that make no sound whatever, such as the denseness of a forest, the coolness of a meadow, the progress of the moon? Lacépède answers, 'By retracing the feelings these things inspire in us.'... I am far from sharing that opinion ... Is there, for example, any single fixed manner in which we are affected by the sight of a forest, a meadow, or the moon in the sky? Assuredly not" (p. 43-44). Rather than

"retracing the feelings these things inspire in us", which Berlioz notes is hopelessly subjective, I will argue that we can find ways of representing information that, even if not iconic, follow paths laid down by our innate sense of bio-musicality, shared among humans and other animals.

#### 4. TOPIC, GESTURE, AND INDEX

Keeping these caveats in mind, but moving nevertheless along the continuum from onomatopoeia, we find musical topoi and gestures [18], [19]. A common example of a topic is the march, which bears an obvious relation to walking: the duple meter reflects our bipedal nature (guitarist Mark Stewart in a 2017 personal communication wonders if alien life, or even the octopus, could have different musical meters). Topics are not necessarily iconic, in the Peircean sense. Maybe the march can be considered a kind of index: the faster the march, the faster one marches. Other topoi include dance music, fanfare, lament, serenade, lullaby, etc. From the bio-musicological perspective, musical topoi go quite deep: Brown and Jordania, in their list of musical universals, note that "Music-induced emotions vary widely, from arousing (e.g., marching music) to soothing (e.g., lullabies...)" ([5], p. 240).

Gesture is a more general concept than topic, and harder to pin down. Hatten [19] defines a musical gesture as a "perceptible and significant energetic [intensity] shaping [frequency, timbre] through time [duration], regardless of modality or channel" (p. 108). These changing energies again recall the idea of an index, which also changes through time. Gestures can allow for greater subtlety than topics (although composers skillfully combine topics to create emotional nuance): "How, in other words, might one go beyond the major versus minor, happy versus sad correlation, when there are more complex expressive meanings at work?" (p. 13).

Ascending and descending gestures are common in music, language and beyond (see the Mannheim rocket and chimpanzee pant-hoot mentioned above), but they raise an interesting "polarity" problem, as noted by Grond and Berger, [20]: "When one of the authors' daughter started studying the 'cello she confused pitch direction and the verbal descriptions of 'higher' and 'lower'" (p. 385); the cellist must move their arm lower down the fingerboard to produce a higher pitch. Barrass and Vickers [4], in the same volume, also describe sonification experiments on subjects with impaired vision, who don't necessarily use the words "higher" and "lower" to describe pitch in the usual manner (p. 148).

Although we may not all use the words "higher" and "lower" in the same way, we (humans and other animals) have similar reactions to higher and lower frequencies. Animal researchers have studied emotional communication among primate young who are temporarily separated from their mothers [21]. The authors acknowledge that experiments like this cannot be done with human subjects—but they find a surprising bio-musicological relationship with opera. "Duets in which the partner addressed is in sight or approaching and subsequently a unification of separated partners are not yet studied in human real-life scenarios but can be found in numerous reunion scenes in operas. These duets start by increased frequency of alternating interjections ('vocal rate'), increased pitch, loudness, and highly modulated rising pitch

contour. Subsequently, a duet, symbolizing the unification of separated partners follows. Obvious examples for such a sequence of vocalizations can be found in the operas *The Magic Flute* by Mozart, *Fidelio* by Beethoven, *Othello* by Verdi, *Carmen* by Bizet, and *Three Penny Opera* by Brecht/Weill...” (p. 347). These gestural changes in pitch, loudness etc. are indexical, analogous to changing emotions and arousal: not only for humans but for other mammals as well. A response which runs that deeply within us should be able to be put to use for other purposes, to represent a variety of phenomena. In this sense, sonification can use our bio-musical instincts in a way that recalls Stephen Jay Gould’s “spandrels”: an evolutionary adaptation, co-opted for another purpose.

Composers in the 20th century experimented with other ways of using extra-musical phenomena as musical indices. Heitor Villa-Lobos (*New York skyline* for piano, 1957) and others converted the New York City skyline into a melody, by mapping it onto staff paper (Figure 5). Here we begin to approach the idea of sonification, the representation of data as non-speech sound; or, if you prefer, data-driven music. We can’t say that Villa-Lobos is “mimicking” the skyline, because the skyline doesn’t make any sound: instead he is using the skyline as an index to musical pitch. (Earlier composers such as Bach would notate melodies and fugue subjects to represent the Cross; this kind of orthography goes back at least into the Renaissance.) As noted in the caption to Figure 5, this kind of reference can be seen as a gimmick, and indeed has been for centuries. In a letter to his parents, Mendelssohn [22] complained bitterly about the sensational, programmatic quality of Berlioz’s *Symphonie Fantastique*: “How utterly loathsome this is to me, I don’t have to tell you. To see one’s most cherished ideas debased and expressed in perverted caricatures would enrage anyone. And yet this is only the program. The execution is still more miserable: nowhere a spark, no warmth, utter foolishness, contrived passion represented through every possible orchestral means...” But it must be said that the Villa-Lobos is quite beautiful: the skill of the translator matters greatly when converting data to music (also see Kramer [10]: “The craft of composition is important to auditory display design”).

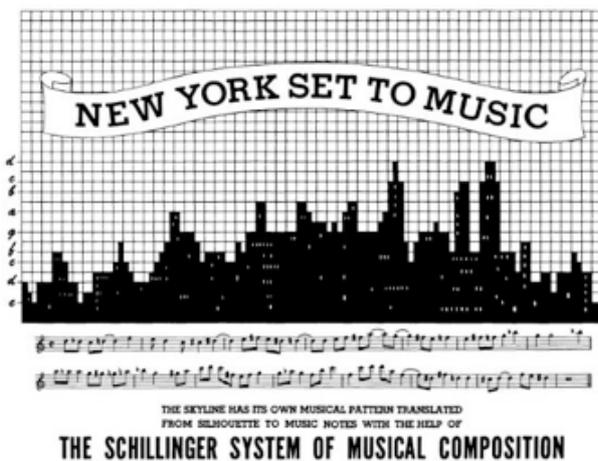


Figure 5. Heitor Villa-Lobos and others have used the New York City skyline for musical compositions, an example of data-driven music. Note the possibility (or danger) for sensationalism and gimmickry.

Karlheinz Stockhausen uses a more subtle approach to indexicality in his work *Gruppen* for three orchestras (1955-57). As he describes in his article “How Time Passes” [23], he looked at the mountains from his window in Switzerland, and traced their contour to provide the timbres (“formant-spectra”, Figure 6) for his instrumental forces. No less sensational perhaps, but not as directly audible to the listener—which raises problems for the researcher who wants to communicate data as clearly as possible. (Regarding the Stockhausen, I would argue that mapping the vertical y-axis to timbre does not make the best bio-musicological use of innate musicality; a dimension that captures the relation of dark to light, or near to far, may be more suitable for timbre.)

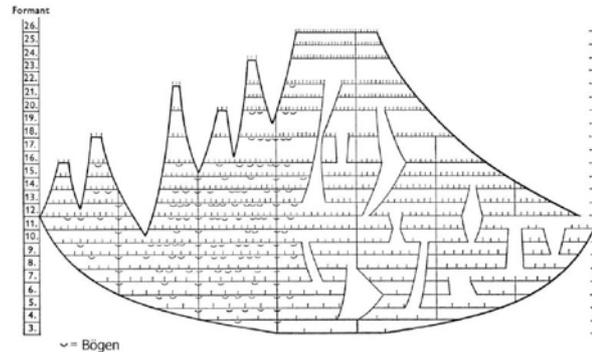


Figure 6. Karlheinz Stockhausen traced the contours of the Alps to provide the instrumentation for part of his composition *Gruppen*; an example of timbre controlled by extra-musical data.

As we saw with the Marais in Figure 2, this problem of communication can be addressed by a caption. In essence, the “program” in program music is a kind of caption that informs the listener about what they’re hearing, just like a caption for a graph or chart. Without its caption, a graph is an abstract design (think of the London Underground map without labels). Berlioz [17] also weighs in on the idea of caption: “...it is strictly required that the hearer be notified of the composer’s intent by some indirect means, and that the point of the comparison be patent. Thus Rossini is thought to have depicted in *William Tell* the movement of men rowing. In point of fact all he has done is to mark in the orchestra a *rinforzando* accented at regular intervals—an image of the rhythmic straining of the oarsmen, whose arrival has been announced by the other characters.”

The Paris-based composer Tom Johnson has come up with an ingenious way to incorporate captions in works like *Bedtime Stories No. 12* (1986), based on the stock market; and *Narayana’s Cows* (1989), based on an infinite series discovered by the 14th-century Indian mathematician (Figure 7). In these pieces, a narrator provides a spoken caption between each bar of music, explaining what the audience is about to hear. Johnson describes his approach to captions in the preface to *Narayana’s Cows*: “The text is neither musical analysis, nor a math lesson, nor comic relief. It should be delivered simply and directly as an integral part of the piece, either by the musicians or by someone else.” Higher, longer notes represent a mother cow; lower, shorter notes represent the mother’s calves, in an indexical relationship. The harmony mirrors the rhythmic mapping: the hexatonic mode on which the piece is based alternates between two unequal intervals, minor third and minor second. Thanks to the

narration, the relationship is so obvious that it's almost iconic. This obviousness in the wrong hands could lead to a cartoon-like caricature, as Mendelssohn complains about Berlioz. As with the Villa-Lobos, it is a measure of Johnson's musicianship, inventiveness and taste that the work is so successful.

**Les Vaches de Narayana / Narayana's Cows / Narayanas Kühe**  
Tom Johnson

Figure 7. Tom Johnson's *Narayana's Cows* (1989) uses a narrator to provide a spoken caption between each bar; after each caption the ensemble always restarts from the beginning and plays up to the next bar.

This kind of spoken caption for musical works is rare: besides the Marais, earlier examples include Prokofiev's *Peter and the Wolf* (1936) and Britten's *Young Person's Guide to the Orchestra* (1945), both composed for children (which makes Johnson stand out even more, as a contemporary composer who works with captions for general audiences). Another example of caption in Johnson's earlier work is *Failing: a very difficult piece for solo string bass* (1976), in which the performer must recite a running philosophical commentary while attempting to play the piece (which eventually becomes impossible, hence the title). Other recent examples include sonifications or sonic illustrations in radio shows and podcasts, such as Radiolab's 2015 episode "Antibodies Part 1: CRISPR [24].

## 5. SYMBOLIC SOUND

As we approach the abstract, symbolic end of the continuum shown in Figure 1, we encounter musical analogues to Morse code: generalized, more or less arbitrary sonic symbols that can convey any desired meaning (of course, this description also applies to spoken language). Perhaps the most well known of these is musical cryptography, in which musical notes stand for letters of the alphabet or other symbols. Examples include BACH (B-flat, A, C, B-natural), and Dmitri Shostakovich's signature motive DSCB (D, E-flat, C, B-natural). Gematria, the mystical practice of assigning numbers to letters of the alphabet (e.g. 666, the number of the beast in the Book of Revelation), has also long been practiced by composers, including Bach.

Messiaen's "communicable language" provides a more recent example. Instead of single pitches, he uses pungent chords to form a sonic alphabet, spelling out messages from the Hebrew Bible [25]. One criticism of Messiaen's system is that, like language, its meaning depends on the arbitrary assignment of meaning to different sounds. Unless you know Messiaen's system (or you have access to the score, where he

labels each chord with its corresponding alphabet letter), there is no way to discern the sacred texts. Julian Anderson pushes back against this criticism: "Any alert listener, even if unaware of the composer's detailed intentions, will not fail to register in Messiaen's most characteristic pieces the repeated impression of vivid musical signals being given forth as declaimed utterances one after the other, usually grouped into the distinct juxtaposed blocks so typical of his mature work" (p. 257). In this way, perhaps, Messiaen is using his invented alphabet as a spur to his creative impulse, a new means of creating music in his own style; not so different than Berg's use of serialism, manipulating tone rows for his own expressive, tonal, emotional goals; or perhaps Stockhausen, tracing the Alps to get new ideas for orchestral timbre.

This idea of an arbitrary conveyor of meaning, dependent on a kind of translation from music to language, recalls the sonification of data. Barras [26] describes an aesthetic continuum, or teeter-totter, similar to Figure 1, but with music at one end and sonification at the other: "The intention to produce a musical experience does not necessarily include the intention to reveal explicit information about the sources of composition. However, when the composer does intend the listener to understand extra-musical information, the work then enters the realm of sonification." (p. 146).

This is an intriguing idea, to pit the musical material (derived from data or an algorithm) against the musical experience, to decide whether something is sonification or music. It makes sense, if we think back to the "unmusical", choppy form of the Marais kidney-stone piece; here the data is the narrative of the surgery. This kind of formal choppiness is part of what people find cheap about cartoonish musical caricatures: it is as if the music is subservient to an outside driver, rather than following its own abstract, non-representational course. (An important exception to this dichotomy, though, would be the minimal music of Steve Reich (e.g. *Piano Phase*, 1967), in which the self-referential, canonic algorithm revealing itself is the musical experience.) *Narayana's Cows* seems to perch exactly on the tipping point between music and sonification; it could go either way, depending on how you listen.

## 6. BIO-MUSICOLOGY AND SONIFICATION

Returning to bio-musicology, if musicality is innate, then there could exist intuitive (or at least, not completely arbitrary) ways of representing even abstract data. Some of these possibilities are suggested by Kofi Agawu [18] in a series of oppositions: "...the so-called binary classification, in which the relationships between phenomena are perceived as oppositions, may also be seen in the metaphors that we apply to various dimensional behaviors: pitch and register are conceptualized within a high-low axis, rhythm and duration on a long-short axis, timbre on a dark-bright axis, texture on a thick-thin axis, and so on." By applying these metaphors (and others) to extra-musical information, we can find ways of representing complex data that listeners can understand more intuitively. Fitch [1] describes these metaphors as "a comparative approach, which seeks and investigates animal homologues or analogues of specific components of musicality, wherever they can be found." (Nettl [6] cautions us to "be careful in transferring the labels of human taxonomies—of Western taxonomies, actually—too readily to other species.")

This kind of metaphorical thinking is closely related to Grond and Berger's work on Parameter Mapping Sonification [20]. As they admit, "the lack of standards and ubiquity in mapping strategies often makes sonification research akin to working on the tower of Babel" (p. 387). But at the same time, "Effective sonification must be intuitive and easily learned" (p. 388). By applying some long-held ideas from composers working with program music, as well as principles of bio-musicology, researchers can meet these challenges, and perhaps arrive at some standards for mapping sound to data. These are simple and intuitive: high/low, long/short, near/far, etc. Much of the subtlety of rhythm and harmony—what Barrass calls the "musical experience"—might get lost. The goal is to keep the basic dimensions simple and recognizable, while using musical aspects like rhythmic and harmonic subtlety to heighten the aesthetic quality of the sonification (although there may be ways to use these subtleties in a parameter mapping). Graphical analogies can be found in works like Edward Tufte's *The visual display of quantitative information* [27].

My final example, an attempt at using multiple dimensions of sound simultaneously to represent corresponding data dimensions, is a 30-second video of protein folding (screenshot, Figure 8). The goal is to present dimensions of data, sonically, that are orthogonal to the animated computer model on the right.

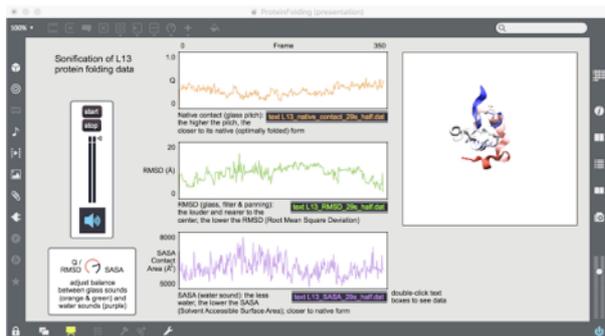


Figure 8. Sonification of protein folding by the author, made with Max; video and download links can be found at [www.stephenandrewtaylor.net/genetics.html](http://www.stephenandrewtaylor.net/genetics.html). A 30-second animation of the rapidly shifting protein plays on the right (video animation courtesy of Martin Gruebele). In the middle are shown three orthogonal data dimensions, explained in the text.

In the middle are shown three graphs representing different dimensions of data which cannot be portrayed by the video animation. The orange line at top represents native contact, or how close the protein is to its optimal shape; the green line below it shows RMSD (root mean square deviation), or how far away the protein is from its native form; the purple line at bottom shows SASA (solvent accessible surface area, or "leakiness"). Each is sonified in a different way, using a different dimension (or axis in Agawu's words). The orange line is played by a percussive glass sound, where pitch height is on the y-axis; the higher the pitch, the closer to the protein's ideal form (since the folding data are sampled at a constant speed, rhythm is constant). The green line (deviation from ideal form) *modulates* the orange line: the higher the green line, the more the glass sound is filtered and panned; this makes it sound farther away, both in distance and in the stereo field. When the glass sound (the orange line) sounds

very close and centered, then the deviation is low. By combining these data dimensions with the video animation on the right, it is possible to hear the data with caption-like visual reinforcement (the three graphs in the middle). By focusing visually on the protein animation while listening, one can simultaneously perceive multiple data streams.

One note on the aesthetics of the glass sound: in my previous sonification attempts, I have been frustrated by the artificial quality of MIDI and synthesis. So for this example, I recorded several different percussive wine glass sounds (gently striking the glass with a chopstick). For each glass sound (all coming very fast, 12 notes per second, with 24 video frames per second), a Max patch randomly selects one of the wineglass sounds. The result sounds more like someone actually playing an instrument, which contributes to the aesthetic quality (I tried various synthesis options as well, but at least to my ears none of them sounded as good as using recordings).

Finally, the purple line, showing the "leakiness" of the protein, is represented by water droplet sounds (also chosen randomly from about a dozen samples, all coming very fast). The higher the line, the louder the droplet. A rain sound is also constantly present, representing a smoothed version of the purple graph. Because the "amount" of rain depends on the y-axis, I cannot use an existing recording of rain; so it is synthesized, following techniques outlined by Andy Farnell [28].

By using musical sound (or iconic *musique concrète* in the case of the water drops and rain sounds) to represent three data dimensions in addition to the video animation, the presentation is more informative, and arguably more effective. The sonification technique uses both icon (water) and index (the up-down axis and the near-far axis). The glass percussion sound is a symbolic representation of the protein's shape as it rapidly changes. Each of these dimensions, of course, requires a caption to make sense to the listener, no different than Marais or Berlioz. It can interpreted either as music or sonification, as Barrass points out [26], depending on whether the listener focuses on the "musical experience" or the "extra-musical information", although I have designed it more on the sonification end of the continuum (if anything, it sounds a little like Rimsky-Korsakov's "Flight of the bumblebee", itself an evocative, buzzing portrait, hovering between index and icon).

## 7. CONCLUSION

As a composer I have long been inspired by science, and written many works of "program music" inspired by scientific phenomena. Over the past several years I have grown dissatisfied with this approach. Just as Messiaen's birds are much more faithful to reality [14] than Beethoven's, composers are finding it is possible to create a new kind of program music that is actually built on extramusical information, not just inspired by it. Data itself is inspiring. And as we learn more about the origins of music and language, and the nature of human and animal musicality, we can learn to portray this data more effectively, more intuitively.

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