Exploration of an Adaptable Just Intonation System

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ABSTRACT

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In this paper, I describe my recent work, which is primarily focused around a dynamic tuning system, and the construction of new electro-acoustic instruments using this system. I provide an overview of my aesthetic and theoretical influences, in order to give some idea of the path that led me to my current project. I then explain the tuning system itself, which is a type of dynamically tuned just intonation, realized through electronics. The third section of this paper gives details on the design and construction of the instruments I have invented for my own compositional purposes. The final section of this paper gives an analysis of the first large-scale piece to be written for my instruments using my tuning system, *Concerning the Nature of Things*.

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I. Why Adaptable Just Intonation on Invented Instruments?

This paper has three main goals: to explain the tuning system which I call Adaptable Just Intonation, to examine the instruments I have built to realize this tuning system and my music, and to analyze a particular composition I have written for my instruments using this tuning system. To make clear the reasoning behind the choices I have made in my work, the initial section will explore the prior art that has influenced my work most significantly. At the end of the first chapter, I will describe some of my earlier artistic works, to more accurately show the course of development toward the current state of my music and instruments.

1.1 - Influences

1.1.1 - Inspiration from Medieval and Renaissance music

For a long time, I have found the art music of the late medieval period and the Renaissance period in European history to be particularly fascinating. I am attracted to the complicated melismatic lines of the Ars Subtilior composers, the strange false relations in British keyboard music in the 16th century, and the gradual transition of harmonic and melodic thinking from a modal and horizontal mindset toward a more tonal and vertical one. I also find the mysterious nature of many of the less-documented features of this music intriguing, such as the practice of *musica ficta* and some of the instruments which only survive as visual representations in paintings, not to mention the more subtle details of performance practice which have been lost to time. For many years I have found myself continually seeking out recordings of music made with historical instruments tuned to historical temperaments like ¼-comma meantone or one of the many unequal well-temperaments of the Baroque period. These interests have inspired me to conceive of a musical sound-world that imagines improbable or impossible answers to the more mysterious aspects of this music. In some ways, I view my current art as a kind of “alternate universe” Early music, in which electricity was discovered before tonality.

1.1.2 - Inspiration from Harry Partch

Ever since I became aware of the work of Harry Partch, I have been in awe of his accomplishments. At the age of twenty, I first read *Genesis of a Music*; it influenced my thinking greatly in the years to follow. I was studying music composition at the University of Wisconsin-Madison, where Partch had briefly settled in the mid-1940s while he completed the manuscript for the book. While his music was stylistically very removed from the aesthetics I was pursuing at the time, I found his individualism and inventiveness extremely stimulating. The fact that he had imagined an entirely original genre of music, influenced by diverse sources like Ancient Greek music theory and hobo songs, and then almost single-handedly managed to build an entire ensemble of instruments for its performance was incredibly impressive. The fact that his music had a theatrical and visual element as well was equally interesting. I found both the strange sounds and the beautiful visual designs of the instruments to be extremely compelling.

In Partch, I saw an admirable model of a composer finding his own path in music, without being restricted by the conventions of his contemporaries. I hoped to someday be able to forge my own artistic path as well, and I recognized that part of Partch's freedom from limited musical attitudes came from his creation of his own original instruments. Because the instruments themselves had no tradition outside of his own invention, there was no way to argue that his use of them was inappropriate or unsuitable. The instruments formed something of a blank slate for his musical ideas, where he didn't have to grapple with the history of Western Art Music or the machinations of the popular music world. My interesting in building my own instruments and forging my own pitch theory derives primarily from the work of Partch.

1.1.3 - Inspiration from American country music

Another source of inspiration for my aesthetic direction has been my love of American country music. I am particularly interested in the work of artists in the "hard country" or honky-tonk genre from the 1950s through the early 1970s. I find the stark, close vocal harmonies - usually delivered without vibrato in exceptionally agile voices - to be very emotionally moving.

The crying sound of the pedal steel is an unusually mechanical and electronic instrument for such an acoustic genre. The fiddle playing is filled with nimble intonational slides and aggressive non-vibrato double-stops. The deceptively simple harmonic and rhythmic structures lend the genre a form that encourages subtlety; the strong force of expectation allows striking changes to result from small twists of compositional wit. I have become particularly interested in discovering how the internal harmonic and melodic language of the music functions - what unspoken rules the composers and performers follow to allow the genre to be distinguishable and to maintain a “country” sound. After performing for several years in a country band, I have been increasingly interesting in discovering a way to capture the power of that music within my concert music practice. I will discuss some of the direct influences on my writing in the fourth chapter of this paper.

1.2 - Tuning Systems

1.2.1 - Why just?

Another research interest of mine, and one that intersects with my musical and aesthetic goals, is tuning theory. I will attempt here to briefly explain why I have chosen to explore the particular kind of tuning theory I use in my music.

First, some background on the possibilities is needed. When considering pitch systems, there are basically three kinds of pitch systems available.

1.2.1.1 – Non-prescriptive pitch systems

The first is non-prescriptive - where the pitches are not organized by a rational or arithmetic system. According to most current research on the tuning of Indonesian gamelan instruments, this is the way that instruments of a gamelan are tuned - the tuner has tuned the inharmonic instruments by ear and they do not conform to an organized mathematical system (Perlman, 26).

1.2.1.2 - Just pitch systems

The second kind of pitch system is a tuning in just intonation. The general definition of this style of pitch organization is that the frequencies of the pitches are related to one another by whole number ratios.

For instance, a pitch with a frequency of 3 times another pitch would be considered to relate to that pitch by a “just” interval. This ratio can be expressed as a relationship of 3:1. By convention, just intonation theory tends to put the ratios in simplest form, and also to reduce the fraction to express an interval within the octave. In terms of frequency ratios, an octave is the ratio 2:1, so 3:1 is greater than an octave, and would therefore be reduced in notation to 3:2, which is the same pitch an octave lower. The decimal equivalent of 3:2 is 1.5, which is between 1 (1:1) and 2 (2:1), so it is within the octave, and 3:2 is the notation that should be used for this interval. This makes sense for traditional theory, as we would consider 3:1 (a twelfth, or an octave plus a perfect fifth) as being the same interval class as 3:2 (a perfect fifth).

The number of possible tunings that would fit under this broad definition is theoretically infinite; even a very complex ratio can still be made up of whole numbers, although they may be very high numbers. Usually, the designers of just intonation pitch systems are mostly interested in ratios that use relatively low whole numbers.

Theoretically, just intonation defines only relations between pitches, not the pitches themselves. Therefore, in order to turn the pitch described by the ratio 5/4 into a performable note, one needs to first know the frequency of 1/1. Once 1/1 is a known frequency, the frequency of 5/4 can be calculated. In this paper, I will follow a convention used by David Doty in his *Just Intonation Primer* (Doty, 25), of using “slash” notation when describing specific pitches (for instance: the three pitches in a traditional just major chord are 1/1, 5/4, and 3/2) and using “colon” notation when describing the ratios between pitches (for instance: the ratio between the pitches 5/4 and 3/2 is 6:5).

1.2.1.3 - Tempered pitch systems

The third kind of pitch system is a temperament. This category could include systems that have either equal or unequal step sizes. The distinguishing feature of temperaments is that, while they are organized by a clear system, they use intervals that are not exclusively whole number ratios. Often, this is done so that a single pitch can serve where multiple pitches would be necessary in a just tuning. For instance, while a strict just intonation system based on the standard 12 pitch classes used in Western music would require two different versions of the pitch class D (9/8 and 10/9) to act as both the fifth above G (3/2 X 3:2) and the fourth above A (5/3 X 4:3), one could choose to use a single D pitch which is somewhere between those two ratios. This would mean that neither the G-D fifth, nor the D-A fifth would be in tune, but they would both be acceptable. This is the type of solution used in meantone temperaments, which were popular in Renaissance-era Europe (Lindley, 43). In ¼-comma meantone, a meantone temperament first described mathematically by Zarlino in the mid-16th century (Donahue, 110), the whole-tone size is exactly half the size of a just major third (5:4). This comes about by flatting the fifth from the ideal 3:2 ratio so that four tempered fifths equal the ratio 5:1, or a just major third plus 2 octaves. This means that the amount of flattening is one quarter of the interval called a syntonic comma (81:80) which is a name for the difference between four just fifths and a just major third plus two octaves. Another example of a temperament would be twelve-tone equal temperament, often abbreviated 12-TET. This is the familiar temperament that provides the theoretical basis for most modern orchestral instruments. In 12-TET, the fifths are all altered slightly, so that twelve tempered fifths will equal seven true octaves. This results in twelve pitches that are equidistant from each other, making this an equal temperament (unlike meantone tuning). In 12-TET, the twelve pitch classes serve to approximate several different just intervals. The E pitch class can be perceived as a slightly flat fifth (about 2 cents) above the A pitch class, or as a significantly sharp major third (about 14 cents) above the C pitch class. This accomplishes a considerable reduction in the number of discrete pitches necessary to perform music on a fixed-pitch instrument, with the tradeoff that all the intervals (except the octave) are of tune.

1.2.1.4 - Rationale for choice of just tunings

All of the above-mentioned pitch system types are interesting, and each has its uses. However, upon considering the options, I have chosen to pursue a system of Just intonation over the other options. My reasoning for this choice follows.

1.2.1.4.1 - Consideration of non-prescriptive tunings

Non-prescriptive tunings are appealing and I have experimented with them in several ways, but it is hard to justify the use of a particular non-prescriptive tuning for a large body of work. In Indonesia, each gamelan has its own tuning (within a certain range of variation) and that tuning is generally unique to that particular group of instruments (Sethares, 173). However, this type of approach seems theoretically unsuited to my needs. It seems to me that non-prescriptive tunings might be nicely applicable to a single piece or instrument – and these are the situations in which I have used them successfully – but not to a whole group of pieces. In recent years, I have been looking for a system that I can apply to an entire body of work, which will be flexible enough for several types of music. In my opinion, using a non-prescriptive tuning for this type of goal would be difficult to justify.

1.2.1.4.2 - Consideration of 12-tone equal temperament

The practicality and convenience of certain temperaments cannot be ignored. 12-TET, for instance, has an enormous collection of instruments intended for its use, and a significant body of musical theory - most of the theory of the 20th century, in fact – in which its use is taken for granted. It is extremely compatible with the Western system of musical notation, and presents a low cardinality of pitches for the performer to navigate. However, it is an equal temperament, and I find all equal temperaments problematic for my purposes. The fact that the only perfect interval is the octave seems like too large an artistic compromise for the simplicity it brings. Also, the bland quality of sameness that the interval classes exude in equal temperament has never excited me. Every minor third is the same kind of mistuned minor third. Many sonorities that the ear can readily comprehend as consonances - such as the 7th harmonic, or 7:4 - are poorly represented by the pitches available. These drawbacks are enough to convince me that exploration of alternative systems is warranted.

1.2.1.4.3 - Consideration of non-twelve equal temperaments

One alternative to 12-TET that is popular among composers experimenting with tunings is to employ equal temperaments that divide the octave into more or fewer equally spaced pitches. If the goal is to approximate just intervals in the way that 12-TET is able to do, there are several equal temperaments that line up well with simple consonances. 19-TET is a popular choice, since it has a close fit to the major and minor third ratios of 5:4 and 6:5, although the perfect fifth is a poorer fit (Loy, 73). 31-TET is another important equal temperament, in that it closely approximates many ratios involving 7 and 11, something that neither 12-TET nor 19-TET do well. In fact, both of these equal temperaments are very closely related to meantone tunings, and their early description can be traced to Renaissance theory (Benson, 228). Another well-known type of equal temperament is 24-TET, or quarter-tone tuning, which was theoretically introduced in the 19th century and has been in common use among 20th-century composers since at least Charles Ives. Quarter-tone tuning allows an acceptable approximation of the 7:4 and 11:8 intervals. In addition to these popular temperaments, there are an arbitrary number of equal temperaments that can be created, some of which have no clear approximations of just ratios outside of the octave. Many composers have explored these unusual temperaments, looking for sounds that are alien to the ear or move in unexpected ways. While these alternative equal temperaments are interesting and provide much room for experimentation, I find them to suffer from the same lack of intervallic variety exhibited by 12-TET. All of the intervals except for the octave are still “not quite right”, and they have the additional deficit of requiring a new notation system for their use.

1.2.1.4.4 - Consideration of unequal temperaments

I find unequal temperaments very attractive. Listening to British harpsichord music of the Renaissance performed in quarter-comma meantone is an ear-opening experience, where the forays into harmonically distant territory become even more bizarre, but the home-key thirds still ring out pure. There is something melodically advantageous in unequal temperaments, where the horizontal direction of the music can be afforded additional propulsion through the motion of the distinctive intervals. Also, there are many possible unequal temperaments that share the same number of pitches as the current standard, twelve, making them practically useful. Well temperaments are another interesting option, where adjustments are made to tune certain chords more correctly than others, but all triads are acceptable. These temperaments tend to converge toward 12-TET, but their subtly unique qualities give them each their own character. The most commonly used of the well temperaments are probably the Werckmeister’s “correct” temperament, or the temperament known as Kirnberger III (Donahue, 26). Both of these have tempered out the “wolf” fifth that occurs in meantone tunings, and both of these contain several different intervals that share the same interval class. The irregularity of these scales helps them avoid the bland grayness of equal temperaments, but they still suffer from the fact that few of their intervals correspond exactly to the ideal ratios they represent.

1.2.1.4.5 - Consideration of just tuning systems

If one finds non-prescriptive tunings systems to be too unstructured, and temperaments to be too much of a compromise, then just tunings appear to be the remaining option. I find the smooth, perfectly tuned consonances to have a powerful effect not achievable by other means. The bold dissonances that are achievable with just tunings can also lend a strong flavor to a chord. Unfortunately, these gains come at a price; there are many difficulties inherent in systems that are restricted to whole-number ratios that have historically prevented their adoption for performance by fixed-pitch instruments. The difficulties encountered when dealing with just intonation come from two main problems. The first problem is the existence of what are called "anomalies". As David Doty writes in the Just Intonation Primer:

> Anomalies are small discrepancies resulting from sequences of intervals that, in equal temperament, arrive at identical destinations, but that, in Just intonation, arrive at microtonally distinct pitches. (Doty, 33)

An example of this phenomenon was mentioned above, in the discussion of the syntonic comma in the section on meantone temperaments. A sequence of four perfect 3:2 intervals arrives at a note that is very close to 5:4 plus two octaves. The difference between the two intervals is called the syntonic comma, and there are several other examples of similar "commas" in just intonation theory. This problem is closely related to the other problem of just intonation, the fact that it is not a closed system. Any sequence of simple intervals will only produce a more complex interval. For instance, while in 12-TET, twelve fifths will produce a note that is equivalent to seven octaves, in just intonation, twelve perfect fifths will only produce a relatively dissonant interval which is uncomfortably close to seven octaves[1]. This process, applied to any interval in just intonation, could continue into infinity, producing a system with an unlimited number of pitches. Negotiating such a system is problematic from a practical standpoint, although theoretically the endless resources of the system could be seen as advantageous. Without question, they make harmonically flexible music difficult to execute on a just-tuned fixed-pitch instrument with a limited number of pitches. This difficulty accounts for the relatively rare usage of just intonation systems in modern music. Most music written or performed in just intonation is harmonically static, like La Monte Young's *Dream House*, or Hindustani classical music[2]. Much of the remaining music written in just intonation at present is essentially "tape" music, without a performance component. An overview of the vast majority of composers who actively pursue composition in just intonation will find an unusually high number of artists who render the final versions of their pieces with MIDI hardware; there is no intention of live performance whatsoever. Both of those scenarios are antithetical to my compositional aesthetic, but I find the potential of just tunings too interesting to dismiss the possibility of a harmonically active, practically performable employment of just intonation.

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[1] $(((3/2)^{12}) / 2^{7}) = 531441 : 524288$. This interval is known as the Pythagorean comma.

[2] Whether Indian classical music is actually conceptually in Just intonation is debatable, but some research suggests that it approaches Just intonation in practice. This is practical because it uses an unchanging drone fundamental, and the focus of the music is melodic.

1.2.2 – The developments of Harry Partch

The best-known composer of music in just intonation in the twentieth century is undoubtedly Harry Partch (1901-1974). He is generally credited with the rejuvenation of the concept of just tunings among American composers, although the work of the nineteenth-century German physicist Hermann Helmholtz was possibly as influential from a theoretical standpoint. Partch drew inspiration from the writings of Helmholtz, alongside intriguing – but somewhat misguided – theories about ancient Greek tunings proposed by Kathleen Schlesinger, to create a new system of pitch organization. By the time *Genesis of a Music* was first published, he had developed a pitch system that had a gamut of 43 tones per octave, all of which were based on whole-number ratios.

1.2.2.1 – Partch's 43-tone scale

The 43-tone scale developed by Partch starts with the collection of all ratios within the octave with odd factors up to and include the number 11. This produces the set {1/1, 12/11, 11/10, 10/9, 9/8, 8/7, 7/6, 6/5, 11/9, 5/4, 14/11, 9/7, 4/3, 11/8, 7/5, 10/7, 16/11, 3/2, 14/9, 11/7, 8/5, 18/11, 5/3, 12/7, 7/4, 16/9, 9/5, 20/11, 11/6}, twenty-nine pitches in all. For every interval that is included in the scale, its inversion is also present, so the scale forms a mirror structure from the center point. While this scale includes many of the familiar intervals of western music, it also includes many intervals that are exotic or unusual, mostly those involving the prime number 11. A graph to these 29 pitches, represented in cents value, is reproduced below.

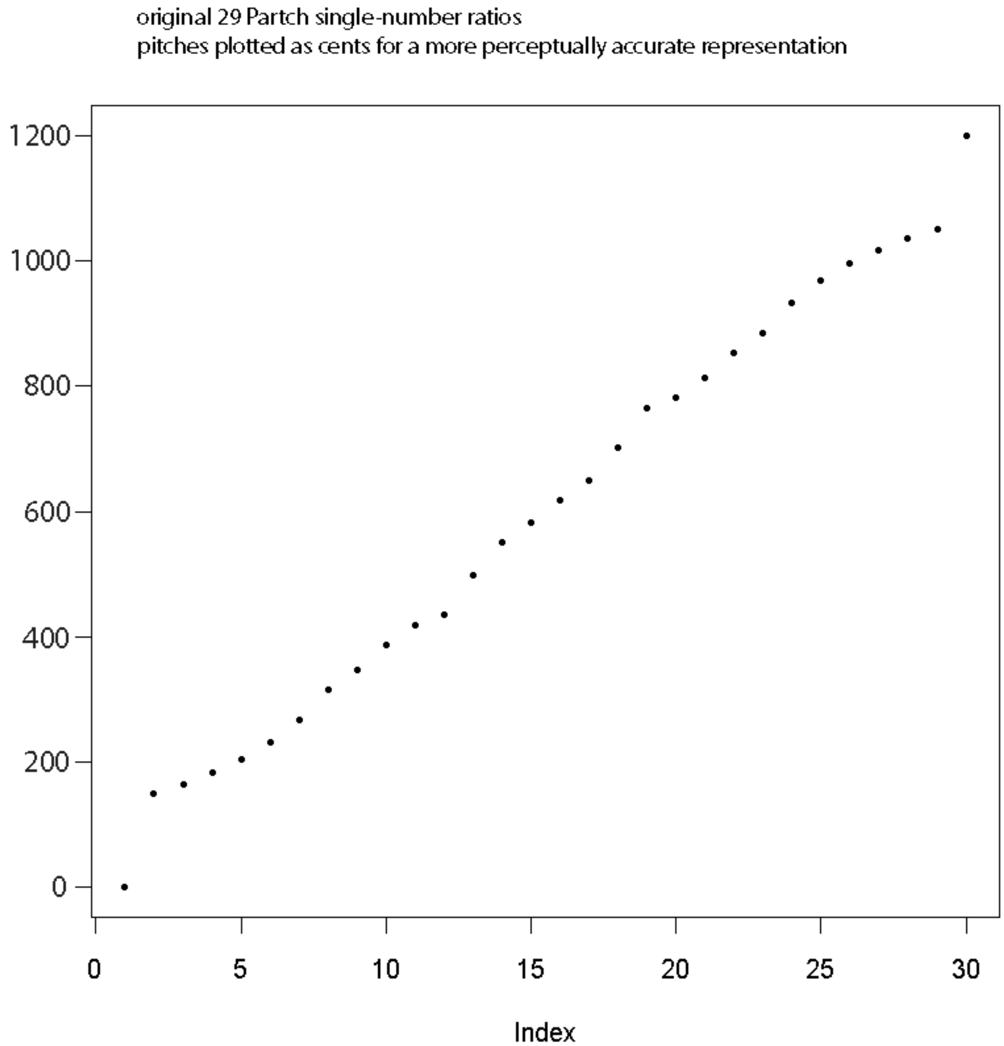

Figure 1: The original 29 single-number ratios for Partch's 43-tone scale

The graph shows clearly why this scale has certain failings. The most salient problem is the existence of large gaps in the scale, which could hamper the construction of melodic material. The most obvious gaps are at the beginning and end of the scale (2/1 is included in the graph so that to make these gaps more clear). There are other, smaller gaps around 4/3 and 3/2, and between the minor third (6/5) and the "septimal minor third" (7/6), as well as their sixth-sized inversions (5/3, 12/7). Partch has elected to fill these gaps with what he calls *multiple-number ratios,* meaning that they are created through the multiplication of two simpler ratios. These additional ratios – {81/80, 33/32, 21/20, 16/15, 32/27, 21/16, 27/20, 40/27, 32/21, 27/16, 15/8, 40/21, 64/33, 160/81} - complete the tuning system described in Genesis of a Music, and bring the total number of pitches to 43. The figure below shows how these ratios succeed in filling the gaps in the original 29-note scale; the *multiple-number* ratios are shown as diamonds against the filled circles of the original ratios.

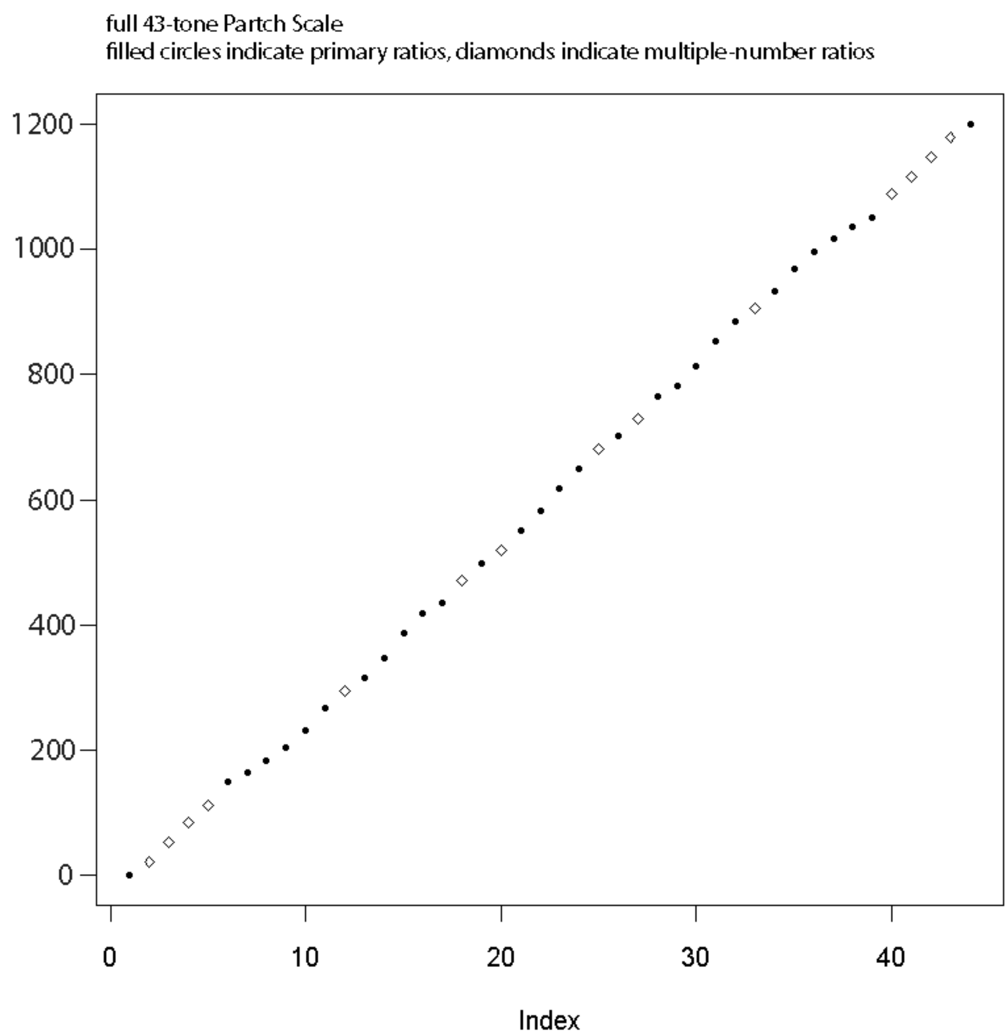

Figure 2: the full 43-tone scale, as designed by Partch – including the multiple-number ratios

The other effect of the addition of these multiple-number ratios is that more possibilities for modulation are opened up, since simple ratios now exist between more pitches of the scale.

1.2.2.1 – Partch's otonality and utonality

Another concept that Partch introduced is the idea of *otonalities* and *utonalities*. In Partch's terms, an *otonality* is a sonority in which the number factorable by the higher number is in the numerator of the fraction. For instance, 5/3 is an *otonal* ratio, because 5 is a higher odd number than 3. 8/11 is not an *otonal* ratio because 8 is factorable by 2, while 11 is a higher odd number and is in the denominator. Fractions in which the denominator is factorable by the higher odd number are considered *utonal*. The two terms are rough contractions of overtone and undertone, and imply that the intervals are native to either the harmonic (or "overtone") series or the subharmonic (or "undertone") series, respectively. A chord created using *otonal* ratios is considered an *otonal* chord, or *otonality*, and one created using *utonal* ratios is considered an *utonal* chord, or *utonality*.

1.2.2.2 – Consideration of Partch's system

Partch introduced the concept of a *limit*, which is a number that determines the maximum complexity of the ratios used in a system. According to Partch, his 43-tone scale would be considered an 11-limit system, because 11 is the highest odd number used in the generation of the ratios. Later work by other authors has added some complexity to this concept, so that instead of "odd limit" values, just intonation systems can also be thought of in terms of “prime limit” values. The first noticeable difference between the “odd limit” and the “prime limit” occurs in intervals involving the number 9. The ratio 9:8 would be considered a 9-limit number in Partch’s conception, but would be considered a 3-limit number in a “prime limit” framework, since 9 is divisible by 3, and is therefore not a prime number. When designing scales or pitch collections, the use of prime numbers as limits tends to make sense, since it makes the limits more independent in a certain way. If one imagines the intervals of a system arranged as points in space on a multi-dimensional lattice, like those designed by Adrian Fokker or Ben Johnston (Gilmore, 481), each interval that includes a new prime limit will require a new dimension. The addition of intervals involving 9 will not require a new dimension on the lattice, since they are already present as multiple-number ratios of the 3-limit. On the other hand, the ninth harmonic is higher up in the harmonic series than the seventh harmonic, so in that sense it could be considered to be more dissonant. Also, in comparing the ratios 243:128 and 5:4, the former is a much more dissonant interval, even though the later uses a higher prime limit (the prime limit of 243:128 is 3). Often, when writing about perceptual consonance of chords, theorists use the odd limit, and when writing about the complexity of a pitch system or scale, theorists use the prime limit. I will generally use the concept of the prime limit in this paper, and consider consonance and dissonance in more general terms – the size of the numbers involved in the ratio, and the interval’s proximity to other, simpler ratios. I will also consider *otonality* and *utonality* to involve the higher *prime* factor in the numerator or denominator, respectively, rather than Partch’s implied meaning of the higher *odd* number.

In the scale designed by Partch, most of the intervals are very closely related to the interval 1/1. This limits modulation somewhat to a small area around 1/1. While Partch never actually conceived of the scale as a completely fixed system, and occasionally used ratios outside the 43-tone scale in practice, his system is of relatively limited utility for highly modulatory music. Because Partch was building acoustic instruments which could not be easily re-tuned during performance, he needed to set practical limits on his pitch space, and this tradeoff was acceptable to him.

Another problem with Partch's system is the question of notation. In earlier manuscripts, Partch proposed several possible notation systems, all of which were relatively difficult to read and interpret. In practice, he eventually resorted to individualized tablature for each of his invented instruments. This makes his music performable, but it sacrifices the power of symbolic notation – in which the symbols used have specific meaning for the musical language, not just the instrument involved. It also creates difficulties in analyzing the music from the score, since it provides no standardized system that is applied across all the instruments.

For a composer considering employing Partch's 43-tone scale, there is another issue – more of a conceptual problem. Partch didn't design the scale with the goal of creating a new standard to which others would comply. The very nature of just intonation lies in the fact that it is an infinite system, and that one may select pitches from this infinite fabric that serve the purposes of a particular body of work. Partch titled his book *Genesis of a Music*, meaning that he was describing how a particular body of work – his music – came to be. For one who wishes to preserve his tradition for future generations (a daunting task, given the individualistic nature of his instruments and performance practices[3]), adhering to his theoretical writings would be the ideal path. However, for one taking inspiration from Partch's iconoclastic example, it would seem unimaginative to accept the system Partch proposed as set in stone. His proselytizing extended only to the use of ratios as the organizing principle for pitch systems, not to the specific use of the scale he developed for his own music.

1.2.3 – The developments of Ben Johnston

Ben Johnston (b. 1926) is a composer who studied with Harry Partch in 1950, and subsequently developed his own system of just intonation. Johnston's compositional goals differ considerably from those of Partch. While Partch was concerned with creating his own music independent of the concert art tradition, Johnston has a strong aesthetic connection to Western art music. He has endeavored to reconcile the theoretical concepts of Partch with 20th century concert art music techniques and practices – not an easy undertaking, when the concert music tradition's deep indoctrination of 12-TET is taken into account. This desire led Johnston to develop several distinctive differences from Partch's implementation of just intonation, two of which are particularly relevant to my own research: his use of traditional instruments and his notation system.

[3] In my estimation, an incredibly important one – and especially necessary given the visual and performative nature of his work. Dean Drummond has been devoted to this goal, and the results are spectacular.

1.2.3.1 – Johnston's use of traditional instruments

Johnston had no interest in instrument building, and he had limited access to the electronic resources that were beginning to become available at the time[4]. These reasons, combined with his love for the Western art music tradition, led him to compose music in just intonation for performance on traditional instruments. His work employed both fixed-pitch instruments, such as the piano, retuned to his own tunings, as well as continuous-pitch instruments, like the violin. In practice, the fixed-pitch implementation could be considered much more practical. While re-tuning an entire piano for a single piece in a concert is not as practical as writing for a normally tuned piano, it is still not an insurmountable obstacle to performance. When writing for continuous-pitch instruments like the violin, significant practical difficulties are encountered. On this type of instrument, the performers are in complete control of the tuning of each pitch. However, those same performers have spent a lifetime learning to play in tune with a piano accompaniment, and usually have a very general sense of the twelve pitch classes used in classical music. Given the complexities of an unfamiliar – and theoretically infinitely expandable – tuning system, most performers would be ill equipped to execute the musical ideas described by the composer with any degree of precision. This is the essential problem Johnston

[4] Interestingly, Heidi von Gunden's biography of Johnston mentions that the composer received a Guggenheim grant in 1959 to work at the Columbia-Princeton Electronic Music Center, hoping to realize his tuning ideas electronically there. For unspecified reasons, he was turned away upon arrival – and this is given as the impetus for his productive studies with John Cage, who was in New York City at the time. While aesthetic differences can't be ruled out, my research into the RCA Mark II synthesizer (which is what was available for use at the time at the Columbia-Princeton Center) suggests that it would not have been suitable for his purposes. It was designed with a limitation to 12-TET built in, with the exception of a separate oscillator bank which was unfortunately not under the same powerful digital control as the main oscillators. I found this information interesting, since my research has been undertaken in the very same institution (now the Columbia University Computer Music Center), around 50 years later.

has encountered – performers of his music for string instruments have historically been unable to accurately realize the tuning directions he had given them. As an example, his 7th String Quartet was written in 1984, and remains unperformed at present, twenty-six years later. Anecdotal evidence from the performances of his pieces throughout his life suggest that this impracticality was a constant stumbling block: when his sixth string quartet was due for a premiere at the hands of the New World String Quartet, it was delayed for a year when the quartet found that it was too difficult to perform at the scheduled concert. Recently, the Kepler Quartet, a Wisconsin-based group, have released two CDs in their quest to record all of Johnston's string quartets, and the effort has so far produced some incredible recorded music. In response to a letter of congratulations I sent to the group, the violist wrote back with the following thoughts:

> The demands of recording Ben Johnston's string quartets are astounding. We've been doing this for six years, and we still find it to be overwhelming…
> In essence, Ben's stuff is unperformable. He wrote for instruments and humans that don't exist yet ... a hybrid of acoustic strings with real-time electronic/digital feedback of some sort and people with brains the size of HumVees… In rehearsal, we use microtuners and contact mics to let us know where on the dial we're playing -- X number of cents above or below tempered 'in tune'. (This is after we have laboriously translated Ben's notation into tempered-speak values -- his scores and parts as offered by his publisher are only half ready to be of any use because they're not written in a language anybody understands.) But in performance, darting the eye down to the tuner and back up to the page isn't going to work.

1.2.3.2 – Johnston's notation system

The other relevant development of Johnston's is his notation system. Unlike Partch, Johnston chose to keep his system of just intonation conceptually unlimited. Rather than selecting a subset of the infinite possibilities that just intonation allows, Johnston worked to find a way to express specific pitches within that continuum in a flexible way, so that one could compositionally navigate the just intonation pitch space without predefined limitations. Johnston developed a notation system by which a potentially infinite number of pitches could be expressed, and he worked to make this notation system as similar as possible to conventional Western notation.

The essential nature of Johnston's notation system is as follows: the diatonic pitches are given specific tuning ratio values, and then microtonal inflections by the commas of just intonation are assigned various accidentals which may be applied to these uninflected diatonic pitches in any combination. The original diatonic scale used is a simple 5-limit scale originally proposed by Ptolemy, known as the syntonon diatonic. The ratios for this scale are shown below:

C= 1/1	**D = 9/8**	**E = 5/4**	**F = 4/3**	**G = 3/2**	**A = 5/3**	**B = 15/8**

This scale is chosen because it produces three pure triads with the ratios {1:1, 5:4, 3:2} on the tonic, dominant, and subdominant scale degrees. To this simple system, accidentals are added, which allow for various combinations of just intervals. The accidentals used by Johnston in much of his work are listed in the chart below (Gilmore, 480):

raise	lower	ratio	cents	amount by which. . . .	exceeds
♯	♭	25/24	71	5/4	6/5
+	−	81/80	22	9/8	10/9
ㄥ	7	36/35	49	9/5	7/4
↑	↓	33/32	53	11/8	4/3
13	ƐI	65/64	27	13/8	8/5
17	ㄥI	51/50	34	17/16	25/24
6I	19	96/95	18	6/5	19/16

Figure 3: the notational symbols used as accidentals by Ben Johnston

This notation system is technically precise. If one wishes to calculate the exact frequency of a given notated pitch, it is relatively trivial to do so. One simply multiplies together the ratios implied by the accidentals, multiplies them by the ratio used for the uninflected pitch, and then multiplies that final ratio by the reference pitch for the tuning system, which is C = 261.26 Hz in Johnston’s case. From the perspective of someone analyzing the score, this is a clear way to go about notation – although I have found that writing a computer program to aid in auditory comprehension of the resulting intervals is something of a necessity. For a performer of a continuous pitch instrument, however, this notation system is extremely confusing. It has redefined the “white-notes” in what may be a counter-intuitive fashion, and has introduced a host of new interval classes that the performer using relative pitch to navigate the music must now internalize. The difficulties encountered by a performer approaching a Johnston score are not those difficulties for which their training has prepared them.

Another conceptual problem arising from this notation is that the placement of the comma shifts is relatively arbitrary. Since the basic diatonic system in Johnston's system uses both 3-limit and 5-limit values, not all perfect fifths (a 3-limit interval) will be uninflected by accidentals, even when they involve only the diatonic pitches. For instance, a perfect fifth written as an uninflected D and A would actually sound as the interval 27:40, rather than the interval 3:2 that a performer might expect from the notation. Adding a minus-sign accidental to the D would correct the interval to 3:2, but would possibly cause the performer to think they should play that note flatter than a pure fifth. A possible solution to this problem would be the use of a Pythagorean 3-limit scale for the diatonic notes (such as that employed by Easley Blackwood, and also Ellis/Helmholtz). This solution creates other problems, among them the necessitation of a comma sign for intervals of a major and minor third (for instance, the major third between C and E would be spelled {C, E-} in order to be a pure 5:4 ratio). These problems are discussed in depth in Paul Rappaport's article *Just Inton(ot)ation* (Rappaport, 12), but I have mentioned them here only to illustrate that that a completely intuitive use of standard notation in just intonation systems is an elusive goal.

Practical performance problems would seem to be more easily sidestepped in Johnston's writing for fixed-pitch instruments, like the piano. It would seem logical that, when writing a microtonal piece for the piano, one could simply notate the pitches that the piano player needs to play, while giving tuning directions in a preface to control the actual pitches that are sounded. This would be somewhat similar to the technique employed by John Cage in the notation of his prepared piano pieces, and it amounts to something of a tablature notation, but is a relatively expedient solution to a difficult problem. Strangely, Johnston chooses to follow a more purist notation in his piano works, where he notates the actual sounding pitch using his notation system, rather than the key to be played by the pianist. To me, this seems useful as a study-score, but detrimental as a performance score, since often a notated pitch with many accidental inflections will actually be played by striking a key that isn't even the same pitch class as the notated pitch.

1.2.4 – Other tuning theory research

The theory of just intonation has enjoyed a considerable revival since Partch, and many theorists have proposed interesting suggestions for its use and interpretation.

Ervin Wilson, a friend of Partch's, has explored physical keyboard layouts for just intonation and other microtonal systems, a line of research that interests me greatly, but which I have not yet employed in my own work.

Harold Waage has proposed a theory of electronically controlled dynamic tuning that is similar to my own, with some important differences that I will explain in section II of this paper (Waage, 1). Larry Polansky has also explored this concept compositionally, with what he calls *paratactical tunings*, in which a computer dynamically tunes passages "on-the-fly" rather than adhering to a strict scale of just intonation pitches (Polansky, 61). Although both of these theorists developed these concepts well before me, I was not aware of their work until after my system had been designed – and I was therefore unable to consider their findings in my employment of the idea.

The Journal of the Just Intonation Network, *1/1*, which was published from 1986-2006 and edited by David Doty, has collected an impressive amount of recent research into the possibilities of just intonation, and many of the articles published therein have influenced my thinking on tuning concepts.

Compositionally, in addition to the works of Partch and Johnston, I have been influenced by the music of the American composers La Monte Young, James Tenney, and Larry Polansky.

Additionally, I have been intrigued for many years by the various graphical representations of pitch space employed by composers and theorists involved in just intonation, and the use of these types of visualizations is particularly helpful in gaining a comprehension of the complex systems at work in tuning. Bob Gilmore's article in Perspectives of New Music, *Changing the Metaphor: Ratio Models of Musical Pitch in the Work of Harry Partch, Ben Johnston, and James Tenney*, provides an informative comparison of various approaches to these types of visualizations (Gilmore, 458). However, this research is less relevant to the actual development of my own tuning system and compositional work, since I have not yet conceived of a graphic representation of my own pitch space that makes it more intelligible in a meaningful way.

1.3 - Invented instruments

The influence of Harry Partch and my interest in exploring unusual tuning systems converged into my desire to build my own instruments for the performance of music in just intonation. Below I will briefly describe some of the early experiments that led to my current work, and then outline the goals these experiments led me to formulate.

1.3.1 – Early experimentation

1.3.1.1 – The Anolé

In 2002, in collaboration with visual artist Don Miller[5], I developed an acoustic string instrument for the performance of music in just intonation. The instrument was called the Anolé, after the color-changing lizard. The name was in reference to the fact that the instrument was conceived as an adaptable instrument which could change to suit diverse performance needs.

[5] http://drmstudio.com/

Figure 4: The Anolé, with septimal scale fretboard and without resonator.

The core of the instrument was a pair of aluminum tubes, welded together with some cross bracing to form a stiff body/neck structure for strings. A third aluminum tube was added to part of the body to make a support for the thumb of the left hand. At the tip of the neck-end of the instrument, I affixed a headstock made from cocobolo wood, which held 12 tuning machines. Aside from this core construction, everything else about the instrument was intended to be changeable: the number of strings, the scale length, the type of bridge, the fretboard or fingerboard, the resonator or pickup, and anything else I could imagine that would fit the physical constraints of the instrument. I carved several bridges out of maple, some curved for bowing, some flat for plucking, some stepped for kora-style performance. These could be slipped underneath the strings, and fit onto the aluminum tubing with specially cut notches in the bridge. I also designed and built (with the assistance of Don Miller) several resonators to change the sound of the instrument; one was made from spruce and maple, another from a large hollowed-out gourd.

At the time, the part of the instrument that I was most interested in making variable was the left-hand fretboard. I initially designed two different fretboards. The first was a simple, standard fretboard for implementing 12-TET. The second was a complex fretboard, which made possible performance in a peculiar "septimal" just intonation system I had designed. This pitch system used only "septimal" intervals, including only those pitches that were added in the 7-limit, without the intervals that were included in the 3 and 5 limit. I was influenced to experiment with this type of tuning by some articles suggesting that Indonesian Gamelan tunings were based on 7-limit intervals (Dudon, 1; Polansky, 64). I designed this fretboard to be used with 5 melody strings and 7 sympathetic strings, which would be routed under the fretboard in the style of a hardanger fiddle or sitar. I also designed the fretboard to be curved so that performance with a bow would be possible. Since I wanted to tune each melody string to a different pitch, I needed to have a different arrangement of frets under each string, so I built the fretboard with small mini-frets for each pitch, laboriously hammering them in one by one. The two fretboards could be used interchangeably, and were held in place by threaded bolts and nuts at the headstock and neck joint. I composed several short solo pieces for the instrument and performed them around Madison, Wisconsin and the Chicago area.

1.3.1.1.1 – Advantages of the Anolé

The Anolé made possible music that I wouldn't have been able to create otherwise. I especially found the interchangeable resonators to be inspiring. The core body of the instrument was also useful for experimentation with Glenn Branca's harmonic guitar idea, in which a bridge is placed in the middle of the string length and an electromagnetic pickup is placed "behind the bridge" to pick up only sympathetic vibrations at the harmonics of plucked pitches (Hopkin, 12). I have always found the sound of bowed, fretted instruments – like the viol family – appealing. The curved fretboards and bridges I made for the instrument allowed me to get an unusual variation on that sound quality. Also, the slight flexibility of the aluminum tubing gave me the option of a strange vibrato from shaking the instrument while playing. The aluminum tubing also added an interesting acoustic effect that I didn't expect, imparting a metallic shimmer to the overtones of the strings.

1.3.1.1.2 – Disadvantages of the Anolé

Despite these charms, the instrument suffered from several design faults that limited its usefulness. I had used special machine heads for the tuners, in hopes of getting exceptional tuning accuracy, but they turned out to be inordinately heavy, making the instrument unbalanced and unwieldy. While the flexibility of the aluminum did allow for an interesting vibrato effect, it also served to destroy any tuning accuracy I had hoped to achieve. Most disappointing was the difficulty in utilizing the interchangeability of the fretboards. The bolts that held the fretboards on were not captive, and therefore easily lost. Also, the strings had to be removed to change fretboards, which was time consuming and impractical in performance. I have since read about much more effective systems of removable fretboards, such as those designed by Mark Rankin, which employ magnets to enable the fretboard to slide into place under the strings. To further complicate things, I soon found the septimal scale I had designed to be uninspiring for the type of music I was composing at the time. There were large gaps in the scale (I had not filled it in with multiple-number ratios like Partch), and it included no strong consonances. However, the construction of a new microtonal fretboard was so labor-intensive that I never managed to create another one. My dissatisfaction with the limited tuning system I had designed was particularly irking, since I had no simple way to change it and put the instrument to good use. Eventually, I found myself abandoning the instrument and focusing on other things.

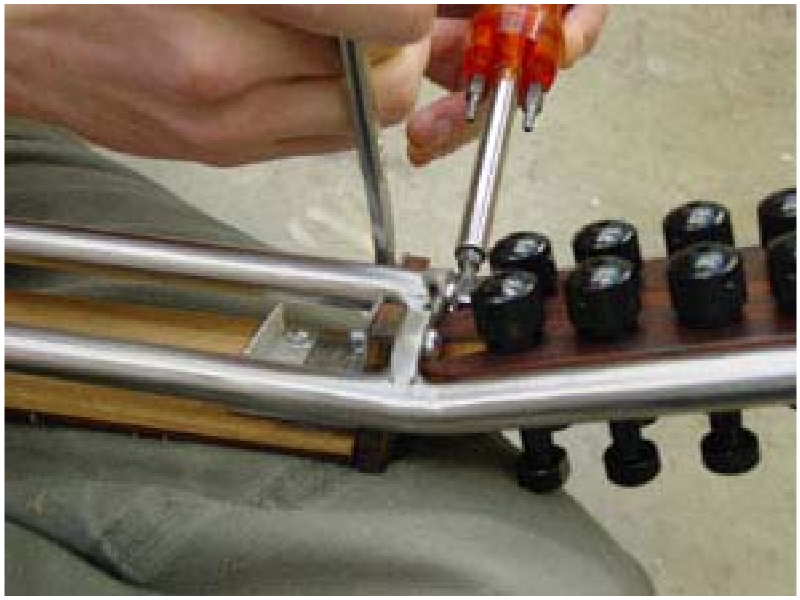

Figure 5: Removing the Anolé fretboard.

1.3.1.2 – Computer-controlled cymbals

Later on, I began exploring ways to make electronic sounds more acoustic. I was excited by the very different sounds I had gotten from the different resonators on the Anolé, and I wanted to be able to apply the idea of different resonators to the electronic sounds that I was then using. I took inspiration from the work of David Tudor's *Rainforest IV*, where electronic and recorded sounds were transformed by their transduction through a variety of resonant materials.

My first successful experiment in this area was a piece called *Percussion*. It was a concert work in which two cymbals are positioned on a stage. An electromagnetic transducer is affixed to each cymbal, fed by sine waves produced electronically by a computer. A microphone is placed near each cymbal, and feeds the acoustic sound of the cymbal into the computer for analysis. With this system, I was able to find resonant frequencies of the cymbal and excite them precisely. The sound produced is similar to the effect of bowing a cymbal, but with much more control and the ability to pick a particular resonant frequency. If the cymbal is vibrated with a tone that does not match a resonant frequency of the cymbal, it will make no sound. If the tone matches a resonant frequency, it will cause the cymbal to respond. The response, however, is not linear, and often a single sine wave input will produce a complex sonic output – akin to saxophone multiphonics or a tam-tam wash.

In *Percussion*, I was able to give up a certain amount of control over pitch material. I collected data through acoustic analysis that would create a table of resonant frequencies of a specific cymbal. Since cymbals produce a mix of harmonic and inharmonic partials, this table of frequencies could be quite idiosyncratic, and would be unique to each cymbal. In essence, the type of tuning system used in the piece is an example of an "non-prescriptive" pitch system, as described earlier in this paper. There is no specific theoretical system used to generate the pitches; they are simply whatever pitches a certain piece of metal forged in a certain shape happens to contain as its spectral content. The music is generated algorithmically, based on properties of this pitch set that the computer has been able to deduce.

I made several pieces based on this concept, including a 2008 work for string orchestra and computer-controlled cymbals, in which I based all of the pitch material for the string writing on the peculiarities of the particular cymbals I was using. I continue to find this method of working conceptually interesting and aesthetically rewarding, but I find the relatively haphazard nature of the pitch material somewhat troubling. While working with these pieces, I developed a desire to have a more systematic, controlled approach to pitch, in which I could make decisions based more on theoretical foundations than acoustic happenstance.

However, I couldn't help but find the particular acoustic qualities of these pieces enchanting. Something about the use of those resonant cymbals made the electronic sounds come alive and feel much more real than sounds emerging from speakers. It also introduced an element of imperfection and unpredictability that I enjoyed. There was another quality to the sound, though – a certain mysterious quality brought about by the uneasy mix of electronic and acoustic. While the sound was clearly acoustic, it didn't correspond to any familiar instrument, and the amplitude envelopes and gestures had a distinctly electronic feel. Whenever I play recordings of the *Percussion* pieces for people, they always ask whether it is electronic or acoustic music, because the music seems ambiguous in this regard and defies categorization to some degree. I found that quality very attractive, and I wanted to explore it more, but in a way that would allow for increased compositional control.

1.3.2 – Intentions for new instruments

The experiences outlined above eventually led me to my current compositional work. I realized that I needed to build an ensemble of instruments to explore just intonation systems compositionally, and that these instruments should have certain features. Performing solo on the Anolé was not particularly satisfying, because I couldn't use any timbral relationships between instruments, and because I was limited to my own performance abilities. The inflexibility of the tuning on the acoustic instrument convinced me that I needed to use electronics to make the tuning system dynamically adjustable. My experiments with the computer-controlled cymbals persuaded me that acoustic resonators, as the output for electronically generated sound, would create an attractive sound world. Therefore, I decided on the following features for my new instruments:

1. The instruments should be designed for the purpose of performance by humans. This is because I was interested in imparting human expression into electronic sound, and because I value the nature of a live performance.
2. The instruments should have a flexible tuning system that allows for on-the-fly electronic alteration of the pitches themselves.
3. The instruments should use acoustic resonators with electromagnetic transducers, so that while the sound is generated electronically, it still has an acoustic quality.
4. The instruments should belong to different “families”, to provide visual variety, and allow for interesting timbral differences.

I also developed some ideas about what properties a tuning system designed for these instruments should have.

1. The tuning system should use symbolic notation, not tablature, so that the score is understandable.
2. The tuning system should be designed for practical application by musicians trained in the Western concert music tradition. This would

allow me to use some of the skills already present in the excellent musicians of the New York City area.

3. The tuning system should be consistent across the instruments, and generalized as a theoretical system, rather than a group of instrument-specific tunings. It was important to make the instruments designed for combination into an ensemble, not simply a collection of individual instruments.

With these concepts in mind, I began to work toward the goal of an ensemble of new instruments for just intonation performance.

II. The Pitch System

2.1 General features of the pitch system

Compared to precedents I discussed earlier, such as those of Partch and Johnston, the system of Adaptable Just Intonation that I've developed has several distinctive features. Perhaps its most important feature is that only twelve pitch classes are available to the performer at any given time. These twelve pitch classes relate roughly to the standard chromatic scale developed through the history of Western music, allowing me to utilize standard notation in composition. It is possible to notate any pitch available in my system through the usual twelve pitch classes on a 5-line staff, without resorting to the use of any additional unfamiliar accidentals. The system described by the notation, then, presents a low cardinality (number of pitches) to the performer. But although it utilizes a manageable number of pitch classes for performance purposes, the actual cardinality of the underlying available pitch system is extremely high. 168 unique pitches exist within the octave, although only certain 12-note subsets of this collection are available to the performer at a given time on a given instrument. It is also worth noting that each of these 12-note subsets includes one representative of each of the twelve standard pitch classes. **Appendix A** is a table of all 168 pitches in the octave, and which 12-note subsets include each interval. **Appendix B** is the table of every 12-note subset, organized by ratio scale and reference pitch. Sections 2.2 and 2.3 explain how the 168 pitches are derived from a combination of three ratio scales and twelve reference pitches.

2.2 The 12-note ratio scales

2.2.1 - The normal scale

The system is structured as a set of three possible 12-note scales, each of which can be re-tuned to relate more directly to any of twelve possible fundamentals. The basic building block is what I refer to in my system as the *normal scale*. This is the most common representation of the Western 12-note chromatic scale in just intonation, sometimes referred to as the *Ellis duodene* (Ellis, 3). The scale would be described as 5-limit, meaning that all ratios represented in the scale involve no prime numbers higher than 5. Advantages of this scale include pure triads on the tonic, the dominant and the subdominant, as well as several other diatonic triads. However, the use of 9/8 for the second diatonic scale degree (which is done in order to make the 3:2 ratio of the dominant triad pure) results in what is known as the supertonic problem, in which the supertonic triad is out of tune. Using 10/9 for the supertonic pitch would only result in the dominant triad being out of tune. As I regard triads related by fifths as being more harmonically related, the 9/8 version is more appropriate for my purposes. I've made the somewhat arbitrary choice to tune F# as 5:4 above D and 3:2 above B, rather than 5:4 below Bb and 3:2 below C#, which would have made the interval 64/45. Both options are harmonically the same distance from C on a lattice showing the factors of 3 and 5, but I've chosen to privilege the more otonal version of F#.

1/1	16/15	9/8	6/5	5/4	4/3	45/32	3/2	8/5	5/3	16/9	15/8
C	C#	D	E*b*	E	F	F#	G	A*b*	A	B*b*	B

Figure 6: the Normal Scale

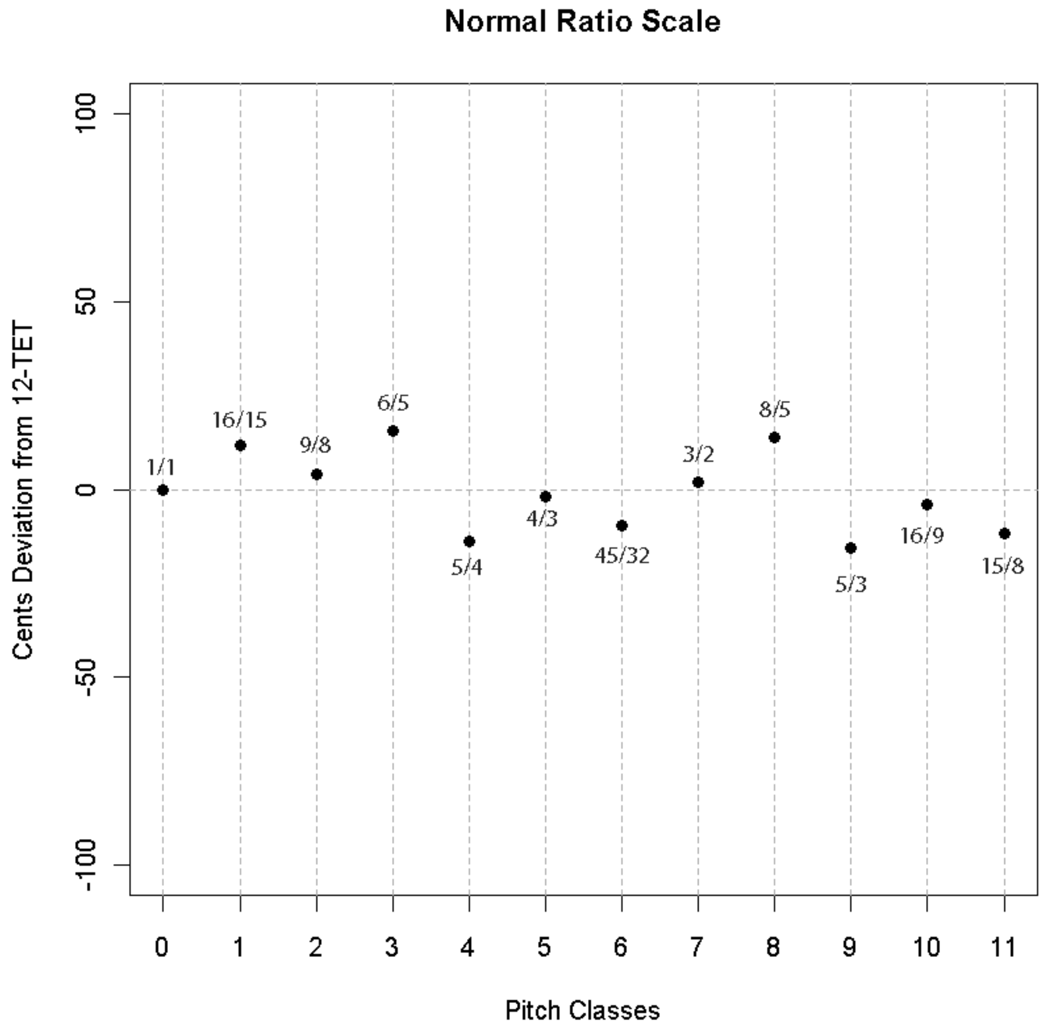

Figure 7: The Normal Scale, cents deviation from equal temperament

2.2.2 - The otonal scale

The second 12-note scale represented in my system is what I call the *otonal scale*. This scale is somewhat more restricted than the conventional meaning of otonal described by Partch, in which the ratios involved need only have the number factorable by the higher prime (or odd number in Partch's actual writing) in the numerator. In my *otonal scale*, ratios are further limited to include only powers of two in the denominator. This makes the scale into an approximation of the harmonic series, allowing for the use of chords constructed from relatively high portions of the overtone series.

1/1	17/16	9/8	19/16	5/4	21/16	11/8	3/2	13/8	27/16	7/4	15/8
C	C#	D	E*b*	E	F	F#	G	A*b*	A	B*b*	B

Figure 8: the Otonal Scale

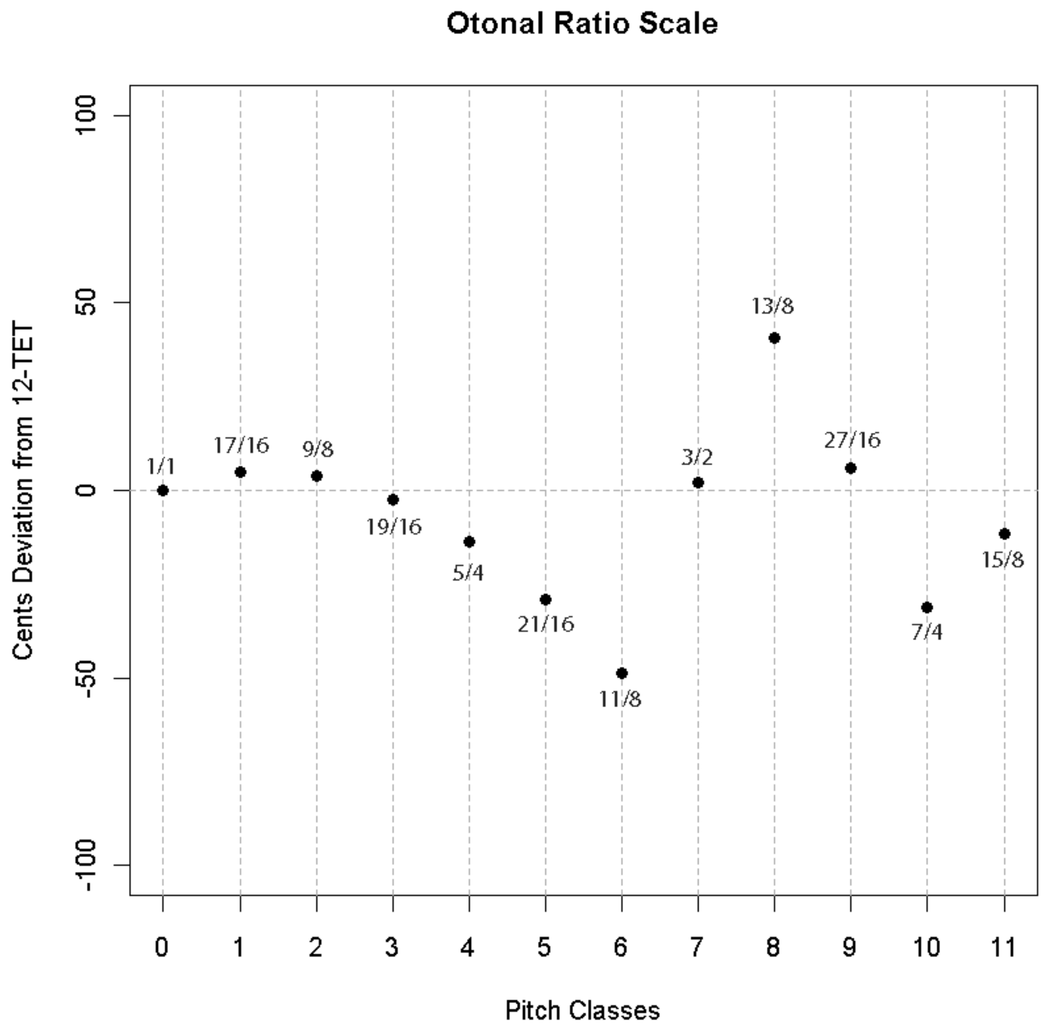

Figure 9: the Otonal Scale, and its cents deviation from equal temperament

2.2.3 - The utonal scale

The third 12-note scale is given the name the *utonal scale*. It is the subharmonic mirror of the *otonal scale*. An example of this mirroring is that the last pitch of the otonal scale, 15/8, becomes the first pitch of the utonal scale, but inverted, so it is now 8/15, which becomes 16/15 when multiplied by two to place it within the octave. If one is aiming for harmonies with tonal reference, it is important to note that the utonal triad in the subharmonic series (which is generally analogous to the minor triad) occurs on what would normally be considered the fourth scale degree. For instance, the pure minor triad {1:1, 6:5, 3:2} occurs in the pitches F-Ab-C when the utonal scale is tuned to reference pitch C. Therefore, the utonal triad will be expressed in this paper in the form {4:3, 8:5, 1:1} - as it is viewed from the perspective of the subharmonic generator. One way to understand this is to think of the utonal triad as an inversion of the otonal triad, so the ratios {1:1, 3:2, 5:4} become {1:1, 2:3, 4:5}. Octave transposition to bring these ratios between 1:1 and 2:1 produces the set {1:1, 4:3, 8:5}.

1/1	16/15	8/7	32/27	16/13	4/3	16/11	32/21	8/5	32/19	16/9	32/17
C	C#	D	E*b*	E	F	F#	G	A*b*	A	B*b*	B

Figure 10: the Utonal Scale

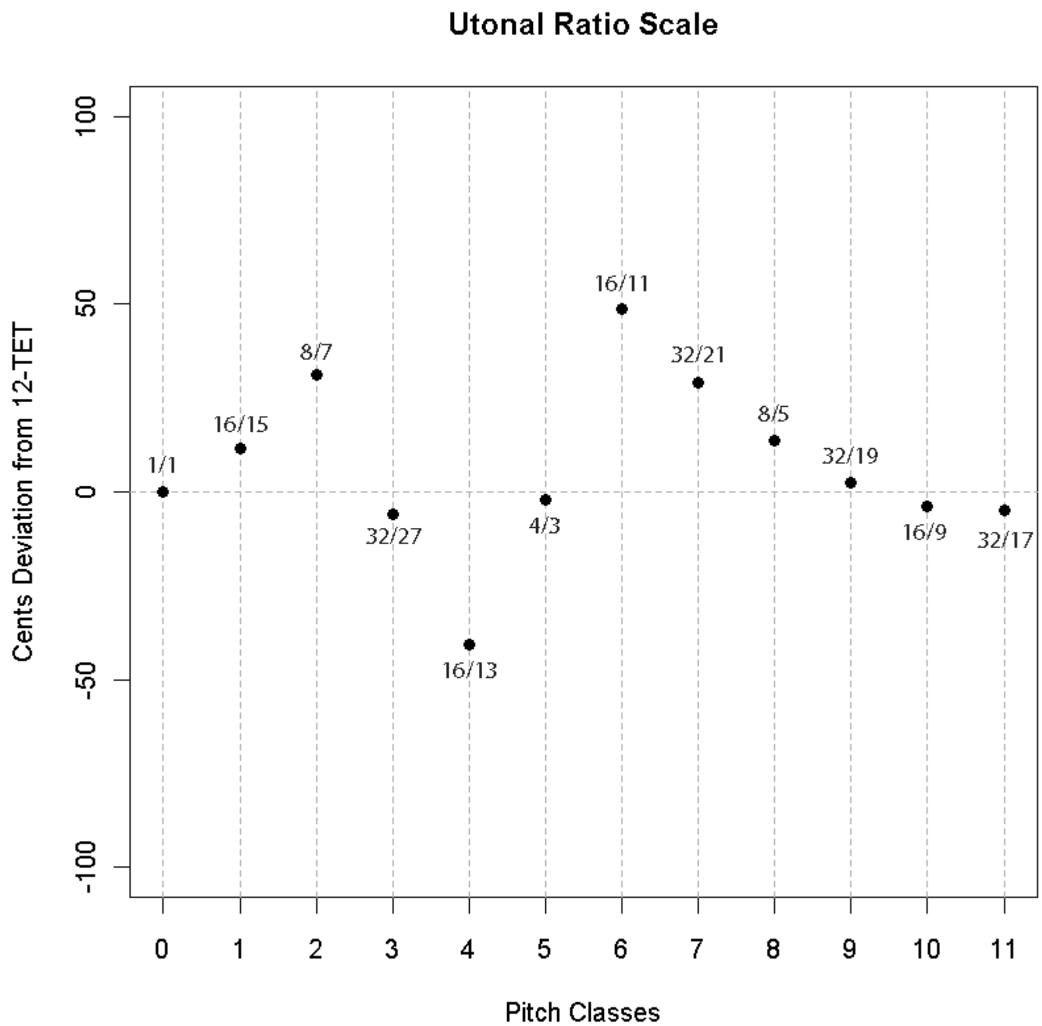

Figure 11: the Utonal Scale, and its cents deviation from equal temperament

2.2.4 - Relationships between the ratio scales

Some of the interesting relationships between the three ratio scales may be readily observed in an overplot of the scales. In figure 12, you can clearly see that the *otonal* and *utonal* scales are retrograde inversions of each other (upside down and backwards). It's easier to perceive this if you cover the first pitch class with your hand, or imagine a 2/1 pitch at the end of the graph. Another visible relationship between the scales is that many ratios in the *otonal* and *utonal* scales are shared with the *normal* scale. There are only three ratios in the *normal* scale that are not shared by either the *otonal* or *utonal* ratio scales. These exceptions occur on the third, sixth and ninth scale degrees. The exception on the sixth scale degree occurs because the *otonal* scale uses the 11^{th} harmonic, and the *utonal* scale uses the 11^{th} subharmonic. The *normal* scale is a five-limit construction, so it uses 45/32 for the F# position. The other exceptions occur because I have limited the *otonal* and *utonal* scales to only include ratios with a power of two in the denominator or numerator, respectively. This excludes 5/3 from the *otonal* scale, and 6/5 from the *utonal* scale, replacing them instead with the higher-number ratios of 27/16 and 32/27.

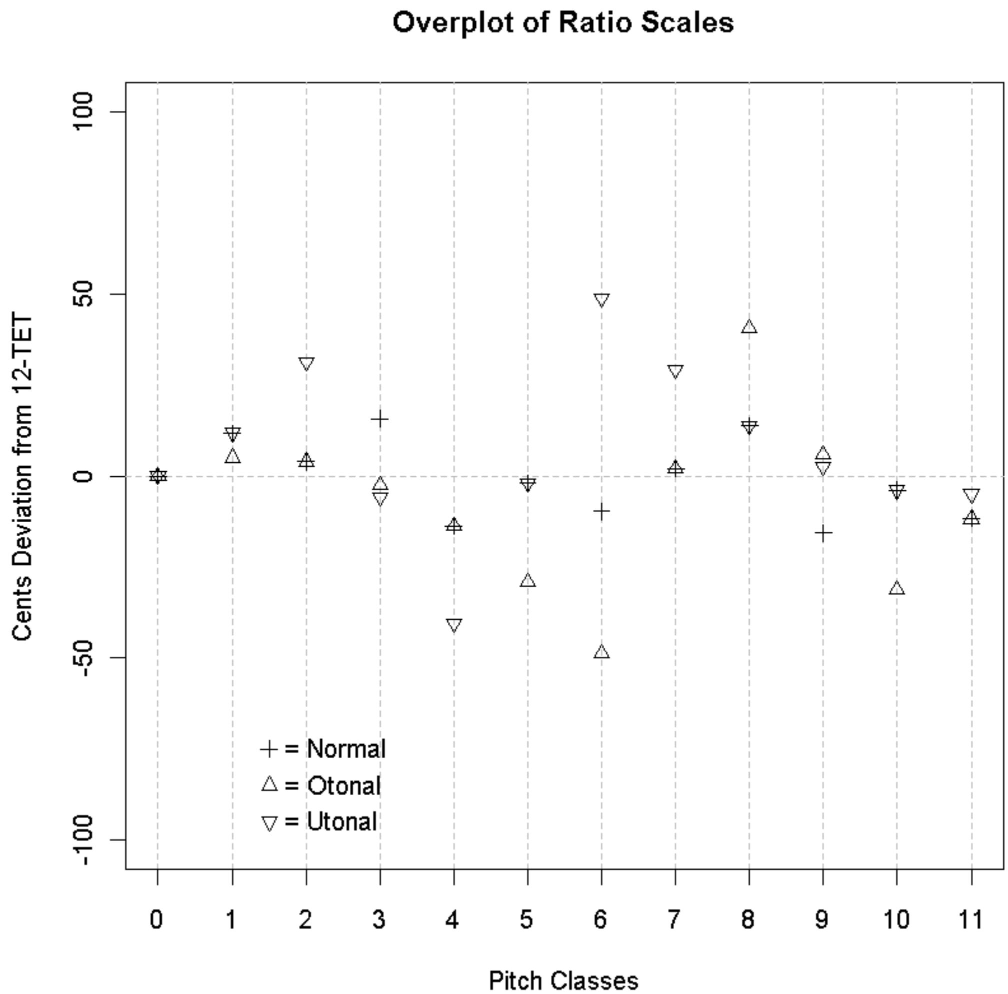

Figure 12: Overplot of the normal, otonal and utonal scales to show their relationships

2.3 Movable reference pitches

These three ratio scales can be applied to any of 12 fundamentals. The 12 fundamentals that are available for this purpose are calculated from the 12 ratios of the *normal scale* applied to C=261.626 Hz. So, the *normal scale* on C generates the fundamentals that are available for modulation, which I refer to as *reference pitches*. This may seem to privilege the key of C in tonal contexts. While this predisposition is obviously present to some degree in this system, I consider its effect in practice to be minimal.

2.3.1 - Objections to a fixed reference pitch

An example of a tonal problem caused by the choice of a single generator reference for all possible modulations is the case in which a piece in the key of A modulates to the subdominant. In my system, where all reference pitches are tuned to the C *normal scale*, the following situation can occur: if one starts tuned to the reference pitch A, this is an A that has been tuned to C (5/3). The D tuned from the A-tuned-to-C (4:3 X 5/3) would be 10/9 (in relation to C). So, while playing within the normal scale on A, the D that is available is 10/9. However, if when modulating to D, one wishes to retune so that the primary chords in the key of D are consonant, D must be selected as the reference pitch. The new "D" is the D of the C *normal scale*, so it is 9/8. In the process of modulation, the pitch class of D has moved the interval of 81:80. The difference between these two flavors of D is 21.5 cents, which is an interval large enough to be audible as a significant difference. I tend to think of this as a kind of counterpoint challenge, which must be worked around compositionally. I have found the problems described above to be the most acceptable outcome among several alternatives that were less satisfactory for my musical purposes; I will describe some other possibilities and their shortcomings below.

2.3.2 - Objection to a wide range of reference pitches

One could also allow for a much wider range of reference pitches, but this would complicate the scenario of selecting a fundamental in performance. A low number of reference pitches allows for a simpler and more effective selection system. In a situation where the greatest freedom of compositional choice was the most important factor, and where there were no performance factors to consider, this option would be a useful concept to employ.

2.3.3 - Objection to the use of equal-tempered pitches as reference pitches

Another option would be to base the fundamentals for modulation on equal-tempered pitches. I have experimented with this option, and while it allows some modulations to have less dramatic comma shifts, it also greatly reduces the full number of ratio-related pitches in the system. Keeping the modulation fundamentals limited to ratio-related pitches ensures a large collection of pitches, all of which are related by whole number ratios (although some of these relationships may be quite complex). This gives the composer many more possibilities for simultaneous performance by two instruments that are tuned to different reference pitches, since all intervals will still be related by just intonation. This would not be possible in a system that used equal-tempered divisions for the reference pitches.

However, systems in which just-intonation inflections must maintain a close relationship to instruments which are tuned to equal temperament may find this option useful. For an implementation of a dynamic tuning system using this premise, see Harold Waage (Waage, 1), or observe the dynamic intonation script employed in Kontakt, a software sampler by Native Instruments.

2.3.4 - Objections to dynamic or automatically-configured reference pitches

Another possible solution would be to dynamically change the actual ratio of the reference pitches to fit the current context – in the case of the above example in modulating from A to D, the new set of performance pitches would be calculated from the reference pitch of 10/9, based on the currently selected ratio scale. This would allow for smoother transitions between modulations, and could be an excellent solution for solo performance. However, my system is designed for performance by multiple instruments at once, and a dynamic system of moving reference pitches would be unwieldy in that situation. All of the instruments need to be able to play in tune together. Therefore, selecting a reference pitch of D on a certain ratio scale needs to produce the same tuning result on all of the instruments, regardless of musical context.

2.3.5 - Justification for the use of the *normal scale* as a generator for the reference pitches

As for the selection of the C *normal scale* as the generator for the collection of reference pitches, the choice reflects the precedents of historical tuning systems. Many well temperaments were designed to put keys with fewer sharps or flats in the most comfortable tuning. One significant downside of choosing to use only the normal scale as a generator for reference pitches is that the *normal scale* only includes 5-limit ratios, and the otonal and utonal scales only include ratios where a higher prime number is paired with a multiple of two. Because of this, ratios combining two primes higher than 5 cannot occur in my system, which accounts for the only two pitches in the 43-tone Partch scale that are absent from my scale, 14/11 and 11/7. All other pitches in the Partch scale are available in at least one 12-note performance subset of my scale, and are therefore considered part of the 168-note gamut of my scale. I find the limitation of reference pitches to the *normal scale* ratios to be an acceptable tradeoff for the simplicity it affords the performer. Since there is only one option, there are no unnecessary complications in selecting one of the three ratio scales from which to draw the reference pitches.

The graph below shows how some pitches occur in more 12-note subsets than others. The most frequently used pitches are the normal scale on C, due to the use of this scale as the generator for the reference pitches.

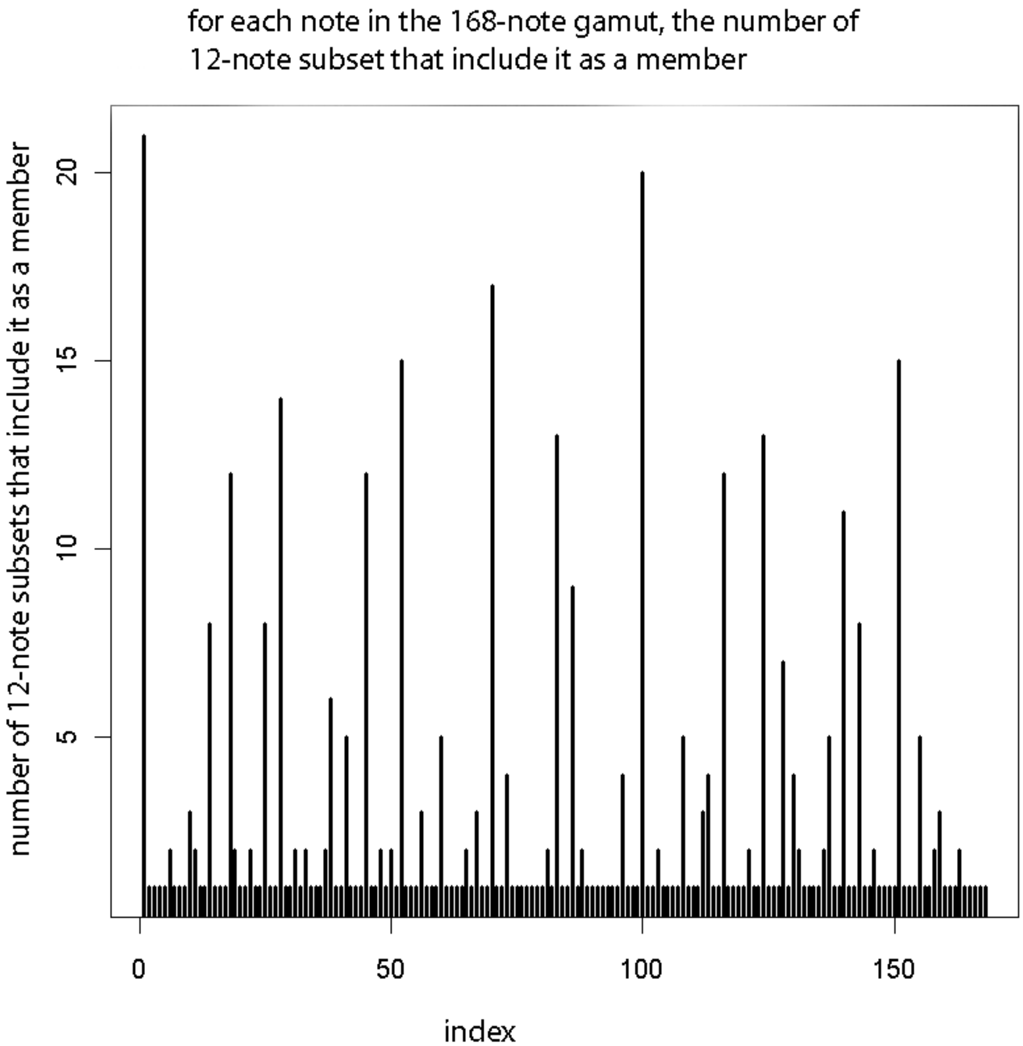

Figure 13:The variation in how many 12-note subsets have each pitch of the gamut as a member

2.3.6 - Avoidance of gaps in the full gamut

One useful feature of the full 168-note gamut of my scale is that it presents a relatively even distribution of pitches over the span of the octave. Because many of the ratios are what Partch would call *multiple-number ratios* (meaning that they are created by multiplying two simpler *successive number ratios* together), this gamut eliminates the gaps that often occur between 1/1 and the first scale degree, and 2/1 and the penultimate scale degree in just intonation systems.

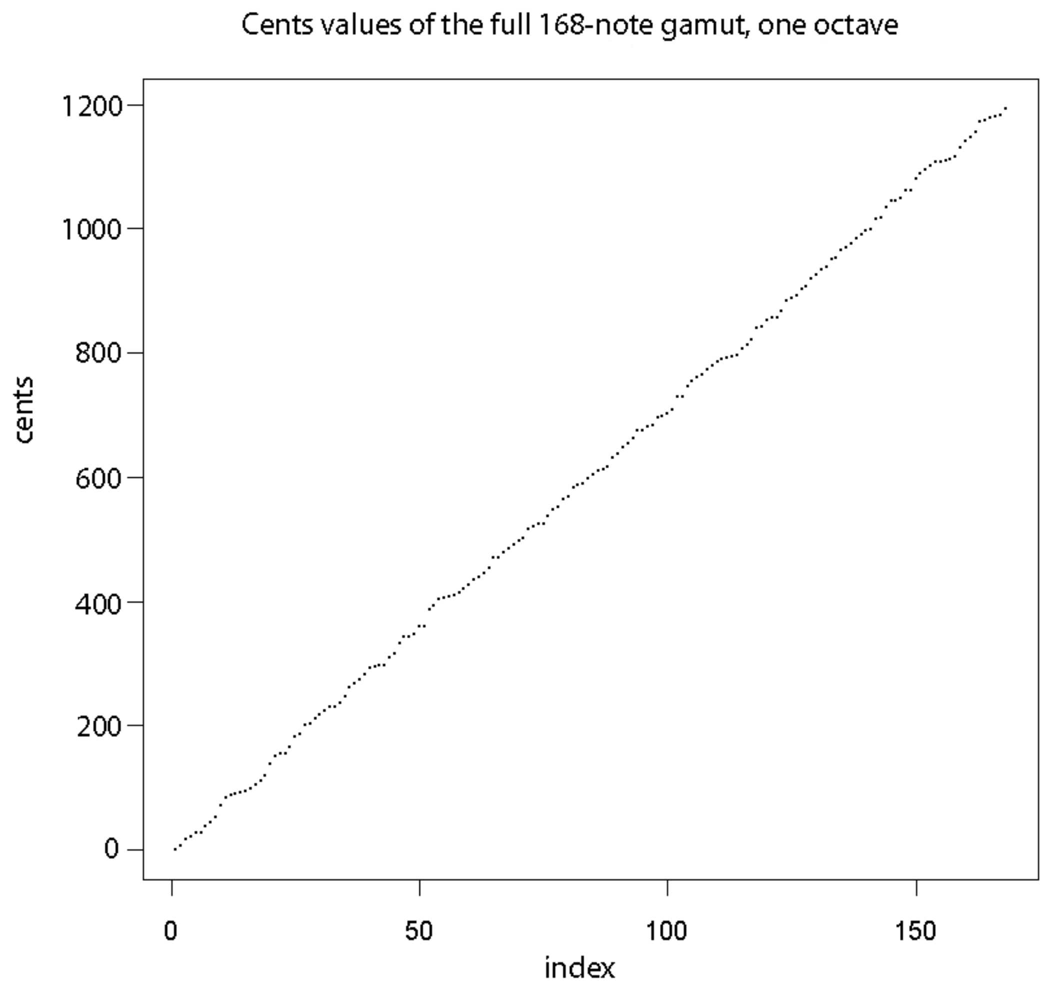

Figure 14: Cents values of the full 168-note gamut

2.4 Performer navigation through the scale system

Thus, the system can be conceived as a set of 12 *performance pitches*, which change their specific tuning based on a selection of one of 12 possible *reference pitches*, and a selection of one of three possible *ratio scales*. Having the number of reference pitches and the number of available performance pitches restricted to the same value (12, in this case) enables a simple system for selecting a reference pitch.

2.4.1 - Selection of the reference pitch

The performer has a single *tune* button. The performer presses this *tune* button, while holding down a performance pitch, and all of the 12 performance pitches are retuned in relation to the reference pitch in the same pitch class. In effect, the performance pitches double as reference pitch selectors when the tuning button is held down. This is especially useful in the design of instruments for which pitch selection is decoupled from the actual sounding of pitches. An example of this is a guitar-style interface, where the left hand chooses a pitch on the fretboard, but the note is not sounded until the right hand plucks the string. In this instrumental context, the performer can tune to a new reference pitch very quickly without making a sound. I use variations on this reference pitch selection scheme in several of my instruments, including the *Contravielles*, which is based on a string instrument design and the *Birls*, based on a wind instrument design. But for instruments where the selection of a pitch immediately sounds that pitch – as in the case of touch-sensitive keyboard instrument, such as the *Mantas* – it is often desirable to have this ability to switch reference pitches without playing the note of the new reference pitch. In order to surmount this problem in the design of the *Mantas*, I have provided them with 12 dedicated reference pitch selection buttons, which allow the performer to silently adjust the reference pitch.

2.4.2 - Selection of the ratio scale

Besides selecting a reference pitch, the only remaining distinction required of the performer is the selection of a ratio scale that will be used for the calculation of the actual pitches. This selection has been implemented in two different ways, depending on the style of instrument. For some instruments, a latching button action has been employed with three dedicated buttons that represent *normal*, *otonal* and *utonal* ratio scales; whichever button was pressed last selects the current scale. While this is the most flexible system, on some other instruments, I have simplified the playing action by reducing the number of dedicated buttons to two. In this design, the *normal scale* the default mode of operation unless one of two momentary switches selects either *otonal* or *utonal*. Although this method privileges the *normal* ratio scale, it is an effective solution for instruments for which the holding down of one additional button while playing presents little additional difficulty.

2.4.3 - Notation of tuning adjustments

This interface for tuning adjustment enables a large variety of intervals to become accessible with minimal changes to traditional notation. In addition, the performer is not required to internalize and understand more unfamiliar ratios or intervals. The notation requires the performer to become familiar with only two additional types of symbols. The first is "tune <reference pitch>", for example "tune C". The second is an "N", "O" or "U" above the staff to show changes in the currently selected ratio scale. These symbols correspond directly to specific actions that are relatively simple to remember and minimize distractions of physical movement and mental attention.

III. The Instruments

3.1 General features of all the instruments

For the creation of my music, I have developed five unique instruments, which can be roughly classified in three types of performance interface: keyboard instruments (the Mantas), string instruments (the Contravielles) and wind instruments (the Birls).

3.1.1 - Electronic or acoustic?

These instruments are all designed to allow performers access to the full range of pitches in my Adaptable Just Intonation system. All of the instruments are, at their core, electronic. In contrast with the inflexibility of acoustic systems, this method of sound production makes practical the dynamic method of pitch selection I have devised. However, each instrument has an acoustic resonating body, which is electro-magnetically driven, imparting a distinctive character of physical resonance to the electronic tone.

3.1.2 - Electronic made acoustic

This acoustic character results primarily from the combination of air resonance, determined by the shape and volume of the instrument's body, and a filtering effect, determined by the properties of the material driven by the electromagnet. The technique of using an electromagnetic driver on an acoustic body achieves two goals: firstly, it creates an unusual semi-acoustic sound quality, and secondly, it achieves a natural spatial blending of the instruments as an ensemble in space. This latter effect is a desirable alternative to the beam-like projection effected by typical speaker-cone transmissions of electronic sound commonly found in electro-acoustic performance contexts. Other approaches to this problem include the use of arrays of traditional speakers set at varying angles to create a more natural projection of the sound. For instance, Perry Cook and Dan Trueman have worked for several years on the employment of spherical and hemispherical speaker arrays to provide a localized sound source (Trueman, Bahn, Cook, 1).

3.1.3 - Traditional interface models

I made the decision to model these interfaces after common instruments of Western art music in order to more immediately encourage their adoption by musicians trained in this tradition. Given a choice between interfaces that will be familiar to a Western musician and interfaces that will be unfamiliar, I have generally selected the former. While it is true that a new system may suggest a new approach to performer interface, there are several advantages to adopting familiar interfaces. The music I write tends to require skills that are generally possessed by performers of what is often termed “new music”. These skills include the ability to read and comprehend complex rhythmic notation and the ability to perform relatively fast passages with ease. My music often requires a conductor, so the performer needs to be able to direct his or her visual attention away from the instrument while playing. These concerns led me to design the instruments with existing pitch layouts and fingering systems whenever possible. For instance, the Birl, fashioned after a traditional wind instrument model, uses a fingering system derived from the recorder, which would be relatively familiar to anyone who plays the flute or a similar woodwind.

3.1.4 - Instruments vs. controllers

While the instruments are electronic in nature, they are conceived as true instruments, not as mere controllers. By this, I mean that each has a defined sound that is unique to the particular instrument type. A rough guiding rule that I use to define the distinction between an instrument and a controller is that in the case of an instrument, the listener can identify the instrument by the sound alone. It is my intention that the instruments that make up my ensemble are all identifiable by their unique sound. These sounds could be seen as the product of three things:

1. the articulation details imparted by the physicality of the performer interface,
2. style of electrical tone generation, and
3. the acoustical properties of the resonator through which the electronic sound is radiated and made acoustic.

The instruments are all designed with these concerns in mind.

3.1.5 - Traditional design aesthetics

Another important feature of the instruments is that they should be visually attractive objects, designed to have an identifiable look. I am often disappointed by the assumption that electronic musical instruments must be built using plastic and metal with a simple, utilitarian design aesthetic. I am drawn to the individualized qualities of wood as a material, especially the traditional tone woods, such as spruce and maple. In situations where my acoustic purposes would be served by a simple circular sound-hole, I prefer to design a lute rose to decorate the construction detail. While this aesthetic has no effect on the actual sound of the music produced on the instruments, I believe that it adds significantly to visual aspect of the performance, and also that it improves the performer’s relationship to the instrument as an object. I believe that it’s easier to enter the mental state necessary for the production of beautiful music when performing on an attractive instrument. Generally, visual design goals must be balanced with ergonomic goals, in the pursuit of a comfortable and handsome instrument for performance.

3.1.6 - Continuous control over amplitude

One relatively unusual goal of my instruments is that all the instruments allow the performer continuous control over amplitude. In my search for greater expression in electronic music, I have found that continuous control of amplitude makes important gains toward avoiding mechanical gestures. This could be contrasted with the traditional model of an envelope generator to control amplitude, begun by a key-press and completed by a key-release. This performance interface model has been standard for electronic sound production since the application of the organ keyboard to the synthesizer by Robert Moog in the mid-1960s. There have always been alternatives that allow continuous amplitude control, from the Theremin, to Donald Buchla’s touch keyboards (models 217, 218, and 219, for instance), to Nyle Steiner’s EVI and EWI controllers (which served in some ways as a model for the Birl, my wind-controlled instrument). All of my instruments allow for continuous manual shaping of the amplitude envelope.

3.1.7 - Acoustic construction techniques

As I discussed earlier, another characteristic feature of my instruments is that they are designed to be semi-acoustic, in that they each have their own acoustic resonator, which is electromagnetically driven into a vibratory mode. In this way, I avoid the beam-like nature of speaker-cone sound diffusion, while simultaneously imparting each instrument with a unique and identifiable tone quality. No two instruments can sound exactly alike, since the materials being vibrated are irregular (the grain pattern of the top-plate wood will affect the tone). Generally, the instruments take their resonator inspiration from traditional string instrument construction. A simplified description of the mechanism would be as follows: a thin board made from a softer wood with a high density-to-weight ratio (like spruce) is glued to a body enclosure made from a harder wood (like maple). Taking my nomenclature from the violin family and acoustic guitars, I refer to the softer wood as the “top” and the harder wood as the “sides and back”. A stiff bridge, usually made from maple, makes firm contact with the softer “top” and drives it with oscillatory motion, causing the top to resonate, which forms the major portion of the audible sound. This top resonance filters the oscillatory input waveform from the bridge, attenuating certain frequencies and amplifying others, depending on several factors such as the grain of the wood, the varying thicknesses in different locations on the top, and the outline of the top. The sides and back form an enclosed space, primarily functioning as a Helmholtz resonator, adding a low-frequency boost generally called the “air resonance”. The combination of the top resonance and the air resonance creates the particular sound of the resonator. In my instruments, rather than having a vibrating string produce the oscillations of the bridge, I use an electromagnetic transducer (specifically the Rolen Star brand audio transducers) [6] to transfer an oscillation that was produced electronically. This method of construction evolved through my own experimentation, combined with research into traditional string instrument construction techniques (such as those employed on the violin, harpsichord, and guitar). The use of audio transducers rather than speakers for the playback of electronic sounds is not a new idea – perhaps the highest profile use of this technique for artistic purposes would be David Tudor’s Rainforest. The quote below indicates that Tudor’s intention was very similar to my own. Based on photographs of various versions of Rainforest, it appears that he also used the same transducers.

My piece, "Rainforest IV", was developed from ideas I had as early as 1965. The basic notion, which is a technical one, was the idea that the loudspeaker should have a voice which was unique and not just an instrument of reproduction, but as an instrument unto itself.

-David Tudor, from An Interview with David Tudor by Teddy Hultberg in Dusseldorf, May 17-18, 1988.

[6] http://www.lederers.com/products/soundmasking/index.php

It is important to note that the goal of this type of acoustic resonator system is not to produce an accurate reproduction of the input signal. The intention is to provide the electronic sound with a unique mechanical filter, giving it an individual voice.

3.2 Individual instruments: design, construction and performer interface

3.2.1 - The Bass Manta and the Resophonic Manta

3.2.1.1 - The Manta keyboard

The keyboard instrument of my ensemble is the Manta. The keys are touch sensors that use the technique of capacitive sensing, specifically an algorithm using a sigma-delta modulator[7] to measure the capacitance change caused by the placement of a human finger on the sensor surface.

[7] http://en.wikipedia.org/wiki/Delta-sigma_modulation

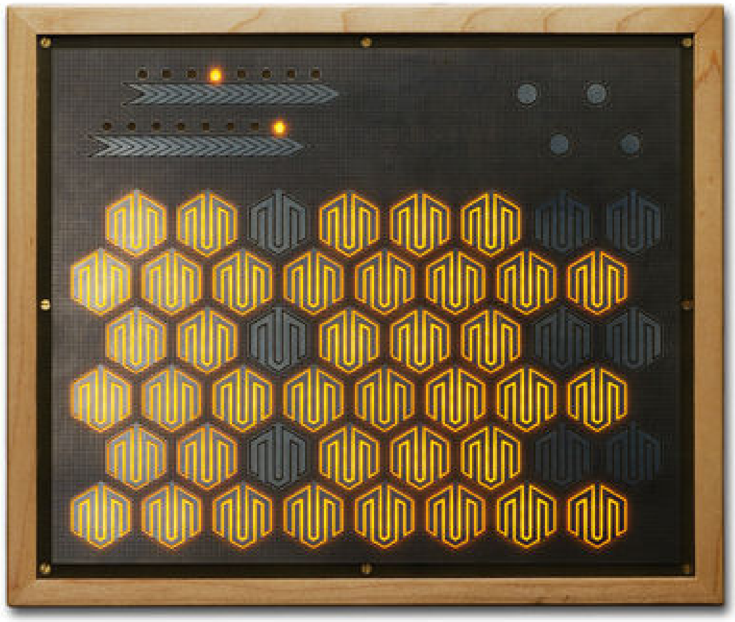

Figure 15: The Manta Keyboard

3.2.1.1.1 - Capacitive touch sensing

The initial inspiration for utilizing capacitive touch sensing for my keyboard instrument was derived from Don Buchla's touch keyboards from the 1960s, two of which are owned by the Columbia University Computer Music Center. I found the response of Buchla's touch keyboard very natural and expressive, and I wanted a more powerful, expanded, and modern version of the controller. Other commercial products to use the capacitive touch-sensing technique include the EDP Wasp synthesizer (1978), and newer digital hand-held devices like the iPod. The current trend toward the use of touch-screens on portable devices has led semiconductor manufacturers to develop libraries that simplify the addition of touch sensing to new designs. I was able to implement capacitive touch sensing for the Manta using a very low part count, since the sigma-delta method avoids the two-step procedure of converting the capacitance change to an analog voltage and then digitizing the voltage; the method itself creates a direct digital sensor reading. [8]

3.2.1.1.2 - Keyboard layout

The keyboard of the Manta is a grid of regular hexagons. The layout was somewhat inspired by the generalized keyboard designs of Ervin Wilson, who was in turn inspired by earlier generalized keyboards of the 19th Century, like the keyboard designed by Robert Bosanquet in the 1870s (Keislar, 19). However, the Manta does not actually have enough keys to take advantage of the main benefits of regularized keyboard layouts, since redundant notes are generally considered important for such systems. I prefer to have as many pitches as possible presented to the player, making redundant keys a hindrance. The grid on each Manta panel is 8X6, providing 48 hexagonal keys, and what I refer to as the "concert version" of the instrument uses two Manta panels, for a total of 96 hexagonal keys. Each panel also includes four assignable function buttons, and two sliders. I use the function buttons on the right-hand panel to select between ratio scales, and the function buttons on the left hand side to select the octave range of the instrument, essentially transposing the keyboard up two octaves or down one from the original pitch. The sliders on the right-hand panel allow the user to select between "arco" and "pizz." performance methods, which are described below. The top slider on the left-hand panel cross-fades between a triangle wave oscillator and a sawtooth wave oscillator, while the bottom slider adjusts the cutoff frequency for a lowpass filter applied to the audio output.

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[8] http://electronicdesign.com/Articles/ArticleID/10185/10185.html

3.2.1.1.3 - Manta performance methods

The two different performance methods for the Manta are “arco, and “pizz.”. “Arco” routes the continuous data of each hexagon sensor (which is a measure of the surface area on the sensor covered by the finger), to control the amplitude of a note assigned to that hexagon. This allows for the performance of expressive fades, and complex envelopes like sfortzandos or tremolos. “Pizz.” mode mimics the envelope of a plucked string, with a short attack and a long decay (the decay being decreased linearly for higher pitches to simulate the more rapid decay of a shorter string). In “pizz.” mode, the only information collected from the sensor is the first two positive samples (which come in at a rate of about 4ms), from which an attack velocity is calculated. This is a difficult task, since there is no physical motion to measure, as in the case of a mechanical keyboard with moving keys. Instead, the changes in sequential surface area readings are used to estimate an attack velocity. The attack velocity algorithm was developed by Angie Hugeback, a statistician at the University of Washington, and is based on training data I provided by repeatedly touching the hexagons with varying levels of attack velocity and characterizing the intended velocity output. An algorithm was trained on this data set, and a reliable predictive equation was found.

3.2.1.1.4 - Computer interface for the Manta

The Manta touch keyboards serve as controllers for a computer running Max/MSP, an audio software environment. Communication is handled over USB, and the Manta conforms to the Human Interface Device class, so that special drivers are not necessary. A custom “Manta” object, developed with Brad Garton, collects the USB data from the operating system and presents it to the Max/MSP environment in a usable form. The Max patch allows for full polyphony, in that all hexagonal sensors could be sounding individual notes at once, and the surface area covered on each sensor can independently control the amplitude of its associated pitch.

3.2.1.1.5 - Tuning procedure for the Manta

Not all hexagonal sensors are used as active keys for the triggering of notes. While the bottom four rows on each panel are used for this purpose, the top two rows on each panel are used to select the reference pitch, and therefore alter the 12-note subset of the scale without actually sounding any pitches. This is different from the method used by my other instruments. It was necessary because, in either performance mode on the Mantas, the act of touching a key produces a sound. Selection of reference pitch should be possible without the creation of a sound, so that it can be done quickly within a rest in the musical texture. Pressing a hexagon associated with a reference pitch on either Manta panel immediately recalculates the 12-note scale to refer to that pitch on both Manta panels, and lights the selected hexagon with an LED backlight to indicate the new selection. This visual feedback makes fast assessment of the current scale subset possible for the performer.

3.2.1.1.6 - Pitch mapping on the Manta

The pattern of the pitch layout on the Mantas is borrowed from the standard Western musical keyboard. The hexagons are arranged so that the closest packing is along the horizontal axis, meaning that the flat sides of the hexagons touch on the horizontal axis, rather than on a diagonal. Since the hexagon grid is 8X6, there are eight sensors in each row, and the rows are offset at diagonals from each other. This layout makes it easy to envision the bottom row as naturals, and the row directly above the bottom row as sharps/flats, since the diagonal relationship places the upper hexagons between the lower ones. However, while 8 hexagons in a row can work intuitively as a full octave of naturals, the row above them has more hexagons than we need to complete the collection of sharps/flats. I deal with this by simply not using the hexagons that sit between E and F, or B and C. This, in effect, forces an irregular layout onto a regularized keyboard, which could seem counterintuitive or possibly pointless; I will concede that it's not an ideal layout. It does not take advantage of some possibilities of a regularized keyboard, such as a layout based on an interval lattice or identical fingerings for different scales. However, it does make the instrument simple to play for a keyboardist trained in the Western art music tradition, which is useful for my purposes. Note that the hexagonal sensors can be backlit in any arbitrary pattern through software, and I use this feature to make the pitch layout more immediately visible.

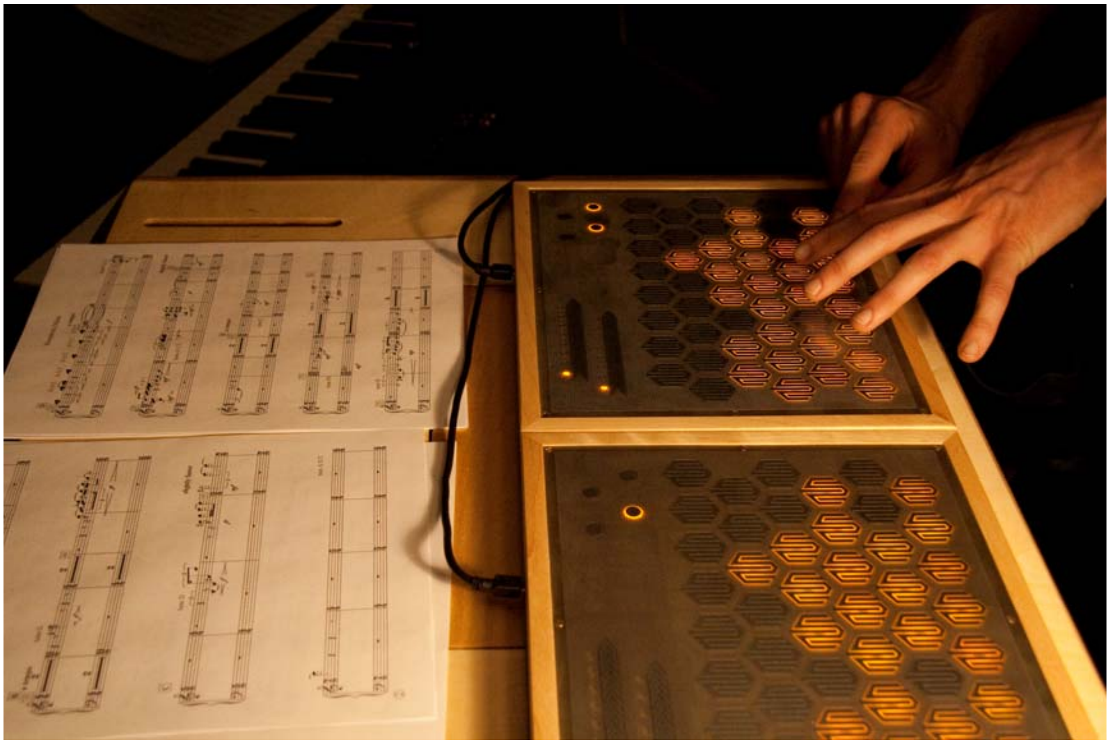

Figure 16: The Manta keyboard in its standard concert layout – two Mantas side by side with a traditional keyboard pattern for the sensors.

3.2.1.2 - The resonators for the Manta keyboard

The Bass Manta and the Resophonic Manta are identical in their performer interface; they both use two Manta keyboard panels side-by-side, with the same control configuration and the same Max patch handling the audio synthesis. However, they differ in the acoustic properties of their resonator bodies. The resonators serve a dual function: they provide a stable stand to put the Manta keyboards into comfortable playing position for a standing performer, and they radiate the sound of the audio synthesis through the coupling of electromagnetic transducers to their resonator bodies.

3.2.1.2.1 - The Bass Manta

The Bass Manta is inspired by construction of the double bass, the lowest-pitched bowed string instrument in the Western orchestra. It consists of a sitka spruce top coupled to a maple back through a maple sound-post. If I had followed the double bass model more accurately, the sides would be maple. However, because they are of less importance acoustically, I've used birch plywood for more affordable construction. While I have designed the volume of the air enclosed in the Bass Manta resonator to produce a Helmholtz frequency[9] in the 65Hz range (Askenfelt, 158), in pursuit of acoustic properties similar to a double bass, the actual shape of the resonator differs from a double bass significantly. The orchestral double bass shape takes its design primarily from the necessity of the instrument's mechanics. For instance, the waist is cut into the sides to avoid obstructing the bow, and the fingerboard extends in a straight line to hold the strings tightly. Without strings or a bow to force these design features onto me, I opted for a simpler construction, which is based on a rectangular box shape. The top is carved in a pattern to give strength where it is needed to withstand the forces of the electromagnetic driver, and the sound-hole is cut in a size that will place the Helmholtz frequency within the desired range. The Manta keyboard rests on a lectern-like surface, which is slanted slightly toward the player to make the wrists more comfortable. The size of the resonator as a whole was a design tradeoff between the desired Helmholtz main air resonance, the availability of large pieces of spruce, and the functional goal of the resonator as a platform to support the Manta keyboard at a comfortable height for the performer.

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[9] Helmholtz resonance is the phenomenon of air resonance in a cavity, and the Helmholtz frequency is the predominant frequency of this resonance.

A separate, smaller resonator, which I call the *midrange pulpit*, rests on the top of the bass resonator, and serves as the surface for the two Manta keyboards. This smaller resonator uses a less conventional construction technique, where all of the sides are plywood, except for the vibrating top plate, which is minimally braced. This leaves the top plate relatively free to vibrate, and produces some strong resonances that can lend a distorted bite to the tone of the instrument. I generally put the audio input to the midrange pulpit through a volume pedal controlled by the performer, so that it is an optional coloration, rather than a primary tone color. I have found the tone quality of the Bass Manta resonator to be very successful. It is capable of producing a very full, attractive sound, which is somewhere in between a pipe organ and a string section to my ears. Bass frequencies are heftily reinforced, while the treble tones are given a pleasant smoothing, and the addition of the midrange pulpit provides a dramatic punch when necessary.

Figure 17: The Bass Manta Resonator

3.2.1.2.2 - The Resophonic Manta

The Resophonic Manta is another instrument based on the same Manta keyboard, but with a different resonator. This resonator is inspired by the spun aluminum cone resonator system developed by John Dopyera in the 1920s to make the acoustic guitar louder (Martin, 99). In this construction, the bridge of the instrument touches an aluminum cone, which is set into a box-style resonator (like a flat-top guitar) made from either aluminum or wood. For my implementation of this system in the Resophonic Manta, an aluminum cone (purchased from Beard,[10] a manufacturer that supplies makers of resophonic guitars) is set into a spruce resonator front. The top, sides, and bottom of the resonator are made from .5" plywood, and the back is from solid maple, planed to around 0.1" and supported with spruce bracing. This is similar to Dobro guitar construction, except for the shape and total volume of the enclosed air space. In the Resophonic Manta, the enclosed air space is relatively large to support a wide frequency range. The actual sound production is identical to the Bass Manta, with the Manta keyboard sending data to a laptop computer, which produces lowpass-filtered sawtooth waves at amplitudes based on finger pseudo-pressure (actually the surface area touched on each sensor). However, the resulting sound is very distinctive, once the laptop audio is sent through the Resophonic Manta resonator. There is strong support for upper partials of the sound for all input levels, and higher amplitude levels cause a subtle metallic overdrive to be heard. The character of this overdrive changes based on the particular orientation of the spider-bridge, an aluminum structure which transmits the vibration of the driver transducer to the outer edges of the aluminum cone, so I often manually rearrange the

[10] http://www.beardguitars.com/guitarbeardmain.html

spider bridge after transporting the instrument to achieve the most interesting sound. The bottom of the Resophonic Manta case has three tone-holes, with three decorative lute roses, meant to imitate both triple rose designs on early lutes and the triple-cone resonators of early Dobro guitars. I haven’t experimentally determined how these tone-holes effect the sound of the resonator, but the intention was for them to allow the air resonance to escape, since the aluminum cone has an unbroken surface and therefore does not serve to allow air from the inside of the resonator to escape.

Figure 18: The Resophonic Manta resonator

Figure 19: The Resophonic Manta resonator – detail of the aluminum cone

3.2.2 - The Contravielles

The Contravielle is an electronic instrument based on a string instrument interface. It has a set of buttons, actuated by the left hand, that function like the frets or fingerboard on a guitar or violin. The buttons are arranged in four rows of 16 (or 14 in the case of the Treble Contravielle). These four rows represent the virtual strings of the instrument, and pressing a button “higher up on the neck” on a given row will set that row to report a higher pitch to the processor. The right hand controls the amplitude of these virtual strings, using four actual strings. The strings are wired as capacitive sensors, so that by touching them a performer can send a message to the processor to raise the amplitude of the virtual string the performer is indicating. This interface is most closely related to instruments like the nyckelharpa or hurdy-gurdy, in which strings are activated by a bow or rosin-coated wheel, and the string lengths are changed by button-like key systems, rather than actuated directly by the fingers of the performer.

Figure 20: The Contravielles

3.2.2.1 Contravielle visual and structural design features

The visual design of the instrument is also somewhat inspired by the above-mentioned keyed fiddles. The keying system is integrated into the resonating body, rather than on a separate neck attachment. Most other aspects of the visual design are functional, like a small curve under the right hand for the instrument to rest on a leg. The sound hole is an *f*-hole, although the proportions of the *f* are not quite those of a violin. Purely for visual reasons, the hole is modeled after the *f*-holes on Sören Åhker's Nyckelharpas,[11] which are coincidentally similar to early hollow-bodied electric guitars, in that they are less angular than those of a traditional violin. I experimented with several body shapes, mostly in an effort to avoid shapes that referenced existing instruments too obviously. The final shape of the Contravielles most closely resembles a sewing machine to my eye. In terms of construction, it is similar to a classical guitar, in that it has a spruce top-plate with internal bracing, but no sound-post or bass-bar, which would be present in a member of the violin family. Unlike any acoustic string instrument of which I am aware, the back of the instrument is vibrationally decoupled from the top and sides with a gasket of silicone rubber. This is necessary to effect an air-seal for the enclosed air resonance, without making the internal electronics inaccessible for repair, as would be the case with a traditional glued back. I have not experimented with a sound-post between the top-plate and this acoustically decoupled back, although that may be a sonically advantageous system.

3.2.2.2 - Contravielle left hand buttons

The left-hand keying system used on the Contravielles is made up of small momentary pushbuttons.[12] I have replaced the standard plastic caps on the pushbuttons with wooden caps, made from modified wood plugs intended for screw holes. This improves the feel of the left hand actuation for the player, and helps me achieve a more traditional visual aesthetic. Early versions of the instrument arranged the button rows in an equally spaced grid, while later Contravielles adjusted this grid

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[11] http://www.sorenahker.com/
[12] C&K brand, model TP11

to match the more logarithmic spacing of pitches along a string instrument neck. This was an improvement on the treble instrument, but the larger Tenor Contravielle suffers from this change, as it creates large gaps in the lower register of the keying system, since the size of the buttons remains constant. This could be improved by the use of different sized wooden keycaps for each "fret", or column of buttons, compensating for the stretch, but I have not yet made this alteration, and it seems to me to require a different approach to the mechanical system, since the center of the finger force may be relatively distant from the location of the small pushbutton actuator. There are several things that I like about the use of these mechanical pushbuttons as virtual strings. The slight noise of their activation produces an acoustic quality that reflects the effort involved in performance, and adds a pleasant sound to the attacks of pitches. I liken it to the subtle noise portions of acoustic instrument attacks, much like the sound of harpsichord keys touching the keybed, or the key-clicks on a wind instrument. However, the direct coupling of the buttons to the resonator (they are screwed into the spruce top directly) makes it impractical to use snap-action pushbuttons like the C&K 8020 series. In my experiments, this added snap was amplified beyond acceptable levels by the acoustic resonator, to the point of being a nuisance. This is unfortunate, since the current, non-snap-action pushbuttons give little feedback to the performer regarding their current state. I find the visual look of the wooden button array to be delightfully unusual and to suggest both mechanical and acoustic instruments, without directly referencing modern electronics.

In terms of performer interaction, though, the button system is somewhat flawed, and I am currently designing a replacement system for the left-hand portion of the instrument. One performer-interface issue regarded how the open strings were represented. There are two reasonable possibilities: either the leftmost button column represents the open string, or the open string is represented by a lack of any button press. My first prototype used the former system, so that the performers needed to press a particular button to get the pitch they expected from an open string. The performers found two problems with this – firstly that they were not used to having to use their left hand to play open strings, and secondly that the existence of this “zero-fret” caused confusion regarding the positions of pitches in the rest of the button array. Due to these concerns, I adopted the latter method, where a lack of button actuation signals an open string state. This caused a new problem, in that it became very difficult to avoid sounding the open string note while switching between pitches on the same virtual string. This difficulty arises because in a real acoustic string instrument, when the player lifts his or her finger from a given stopped note to move to another stopped note, the finger remains in contact with the string, effectively damping it. This produces a third state of actuation for the left hand on a string—between *open* and *stopped* there exists *muted*. With a simple digital button control, the Contravielle is not able to sense this third state, and therefore the performer had to be especially careful to avoid these unintentional open string soundings either by making sure to hold down the initial note until the second note is completely pressed, or by cautious use of the right hand amplitude controls.

Additionally, all performers who have worked to learn the instrument have expressed difficulty in determining the position of the left hand on the button array without looking. This seems to be due to the haptic similarity of the button surfaces of each row – there is no reliable way of telling where your fingers are without visual feedback. In early performances, this led the performers to play the instruments on their laps, like steel guitars, a playing position that made them feel less blind. I discouraged this practice in later performances, because it decreases the visual impact of the instrument by making it significantly less visible. The performers, mostly coming from violin or guitar backgrounds, also expressed a desire to be able to slide or glissando into new positions, which is impossible on the button array. My new prototypes (designed to address these issues) use a group of linear position sensors pressed by real physical strings suspended above the fingerboard. This affords the player a familiar interface, while still allowing me the configurable, discrete pitch system I need for my tunings; I simply quantize the analog input into the closest 12-note location, and then tune as necessary. The major drawback to this new system is the lack of the subtle actuation noise that I find particularly charming about the sound of the current Contravielle models, but I think the advantages for performance expression outweigh the loss.

3.2.2.3 - Contravielle right hand controls

The right hand controls of the Contravielle evolved from a more Manta-like touch surface to their current state as real physical strings acting as capacitance sensors. In the original implementation, I was conceiving of the Contravielle as a monophonic melodic instrument capable of playing only one pitch at a time. This mostly derived from the fact that my early prototypes used analog synthesis as the sound generation, so polyphony becomes expensive – requiring additional hardware modules. Therefore, I used whichever button was most recently pressed on the left hand for pitch control, and I used the right hand for parametric timbral control. I designed the original Contravielles with four sensors, one for each non-thumb digit of the right hand. I envisioned this layout as providing theoretically powerful control possibilities, but in practice instrumentalists trained on traditional string instruments found the independent functioning of the four fingers representing different timbral controls to be unwieldy and confusing. For instance, the index finger controlled amplitude; the middle finger modulated the cutoff frequency of a low-pass filter; the ring finger could frequency modulate the oscillator with noise; and the little finger could frequency modulate the oscillator with the sonic output of the other Contravielle. This last option was particularly unusual and interesting – I used it extensively in the composition of my concerto for Contravielles and acoustic chamber ensemble, *Vox In Vitro* (premiered in April of 2008 by the International Contemporary Ensemble). When I made the choice to convert the Contravielle to a polyphonic instrument, I originally kept the layout of the right hand system, simply changing the function of the sensors to be the amplitude control for the different strings. I realized after some experimentation that this layout – designed to fit the hand placed in a natural position on the instrument, was not ideal for the new task. On a traditional plucked string instrument, multiple fingers may pluck the same string one after the other, allowing for a faster plucking rate, and avoiding the exhaustion of a single finger. My layout of the sensors, with each sensor extending down vertically from the top of the instrument and a significant tactile distinction between finger areas, made the use of multiple fingers on the same sensor uncomfortable. I decided to turn the sensors horizontally and remove the wooden separation between them. This change brought them closer to the normal configuration of strings on an instrument, but it had the disadvantage of a lack of tactile feedback. There was no way to tell where your right hand was without looking. This led me to the system now in use for the right hand of the Contravielle, in which four strings of varying thicknesses protrude through the top plate and are positioned by two bridges. The capacitive sensing of the surface area touched on the strings serves to provide an adequate control of amplitude to mimic something of an arco performance style. I am currently working to implement an electromagnetic pickup system to sense plucking as well, so that a pizzicato mode may be implemented. It has so far proved very promising, the only issue being the miniaturization of the envelope detection electronics to avoid an obstruction of the interior acoustic space.

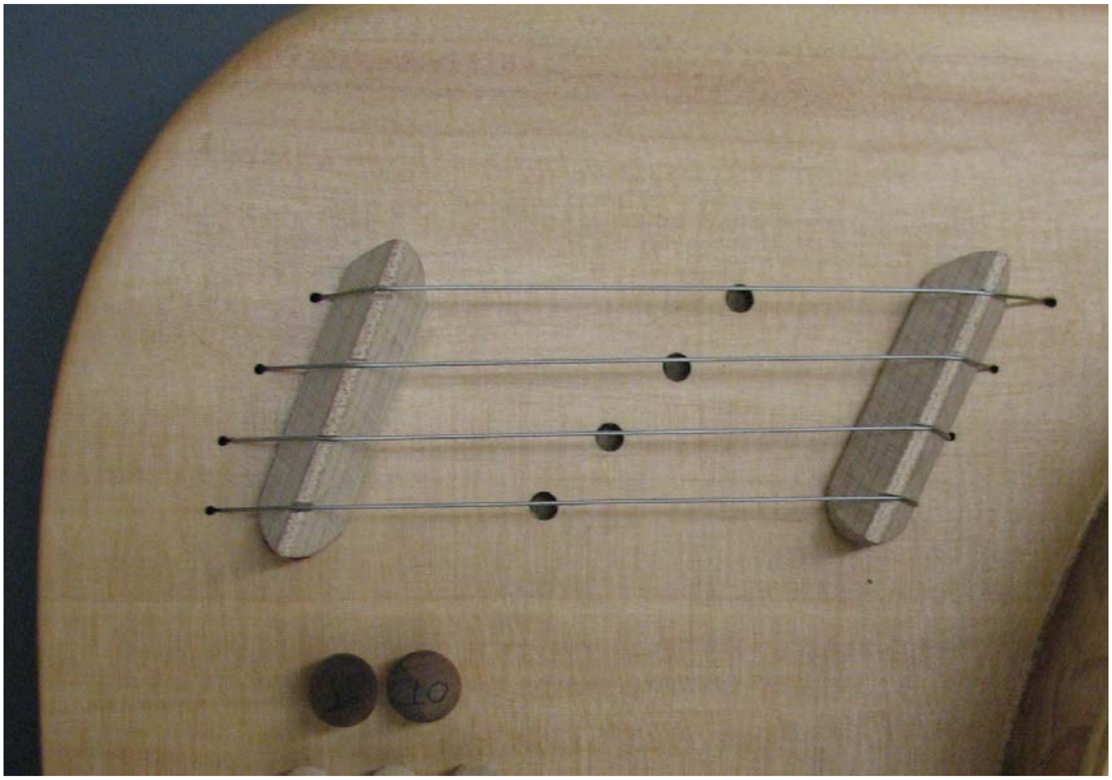

Figure 21: Contravielle right hand controls

In addition to the right hand capacitive strings for amplitude control, the right hand is also responsible for all additional electronic selection duties, mostly for tuning purposes. The current Contravielle models use 6 right hand momentary buttons for this role. My original system, still in use during the composition of *Vox In Vitro*, was to have two rotary switches. One was a twelve-position switch, selecting the *reference pitch* for the tuning system, the other was a three-position switch selecting whether the ratio scale used was *normal*, *otonal*, or *utonal*. The use of these rotary switches turned out to be a poor choice, from a performer interaction perspective. I had many comments after the performance that one of the most noteworthy aspects of the concert was the distress on the faces of the performers as they tried to find the correct settings for the switches between phrases. The rotary switch system was not viable for tuning changes that had to occur quickly. This led me to the current system, in which a single momentary *tune* button is combined with two momentary *otonal* and *utonal* buttons. To reset the reference pitch, the performer simply has to press the pitch class of the desired reference pitch, in any octave, on the left-hand key array, and hold it down while pressing the *tune* button. This allows me to simply notate reference pitch changes in the score, where I use parenthetic noteheads, combined with the "tune" direction. The fact that pressing a button on the left hand does not produce sound unless the right hand is touching a capacitance-sensing string makes this system possible. I have also simplified things by having the *normal* scale be the default state, making the *otonal* and *utonal* scales alternate possibilities active only while their respective momentary switches are depressed. This necessitates the placement of these switches to be near enough to the capacitive strings that their activation is not particularly distracting from the usual performance position of the right hand. I may eventually move this job to a pedal system for the feet, since freedom from these buttons could allow for more a more expressive right hand playing style. The remaining three buttons control the octave range of the instrument, with the middle button being the normal range for the comparable string instrument (such as the violin for the Treble Contravielle) and the buttons to either side moving the pitch of the instrument one octave higher or lower. In notation, I found that the most comfortable way to notate these octave differences was to simply write the note at sounding pitch, and then let the player choose which octave settings were most comfortable for a given passage. So, the only additional notation necessary to indicate the right hand buttons are the "tune" indication, and an O or U for *otonal* and *utonal* buttons with a line showing the duration of the button press. I built a seventh button onto the instrument, which does not currently serve a purpose, but is simply there for future expansion of the possibilities of the instrument.

3.2.2.4 - Treble and Tenor Contravielles

There are at present two Contravielles, although I plan to eventually expand the instrument family into a full five-voice consort to mirror the viol family. The smaller of the two is the Treble Contravielle. In function and performer interface they are identical, except that the Treble Contravielle has only 14 rows of buttons instead of 16, due to the lack of room on the face of the instrument. The main difference between the two instruments is the size and shape of the top plate, and the overall volume of the enclosed air space. In the Treble Contravielle, these are both relatively small, giving the instrument a dramatically reduced bass response and a strong acoustical focus on the reproduction of higher frequencies. The Tenor Contravielle has a much larger top-plate surface, and a much larger enclosed air space, leading to a much lower primary Helmholtz air resonance, and an ability of the top-plate to reproduce frequencies in the low-mid range. The focus of the resonance of this instrument is not nearly as low as the Bass Manta, however. The Treble Contravielle was designed first, and the shape of the Tenor Contravielle was an alteration of this model to better suit its larger size. A treble instrument scaled up to a tenor size would have resulted in a rather bulky instrument, so I changed some aspects of the shape to accommodate the size change. I also simplified some visual aspects of the design – removing the cutoff angle above the f-hole, and the rounded right-hand support – in an attempt to make the construction less time consuming. While these changes did make the construction less complicated, I will probably reintroduce these visual details when building future generations of the instrument; I find the tenor instrument, outside of its almost theorbo-esque size, to be slightly lacking in visual style. Additionally, in the construction of the Tenor Contravielle, I improved on a mistake I had made with the treble instrument. In the Treble Contravielle, the left hand buttons are placed directly on the front of the resonator, without a cutaway behind them to allow for an efficient action of the opposable thumb to support the fingers pressing the buttons. I eventually altered the instrument by adding a small thumb support that runs along the edge of the instrument, but this doesn't quite solve the problem, since while it decreases the total reach required of the fingers, it doesn't put the thumb in the most advantageous position – directly behind the fingers. On the Tenor Contravielle, I introduced a cutaway behind the buttons, which allows the left hand to have a more comfortable position, at the expense of internal air volume. I intend to rebuild the Treble Contravielle at some point with this same adjustment, since the players who have spent time with it generally find it tiring for the left hand.

Figure 22: Treble Contravielle

Figure 23: Tenor Contravielle

3.2.3 The Birl

The Birl is styled as the wind instrument of the ensemble, although once again it is mainly electronic in nature. However, unlike the other instruments, the sound of the Birl is produced electromechanically by a spinning motor, instead of digitally by a computer outputting a waveform. This rotational source of oscillation is the instrument's namesake, as *Birl* is a verb usually defined as "to spin with a whirring sound". I am also attracted to the word by the fact that *Birling* is the name for the lumberjack sport in which woodsmen stand on a rolling log in the water.

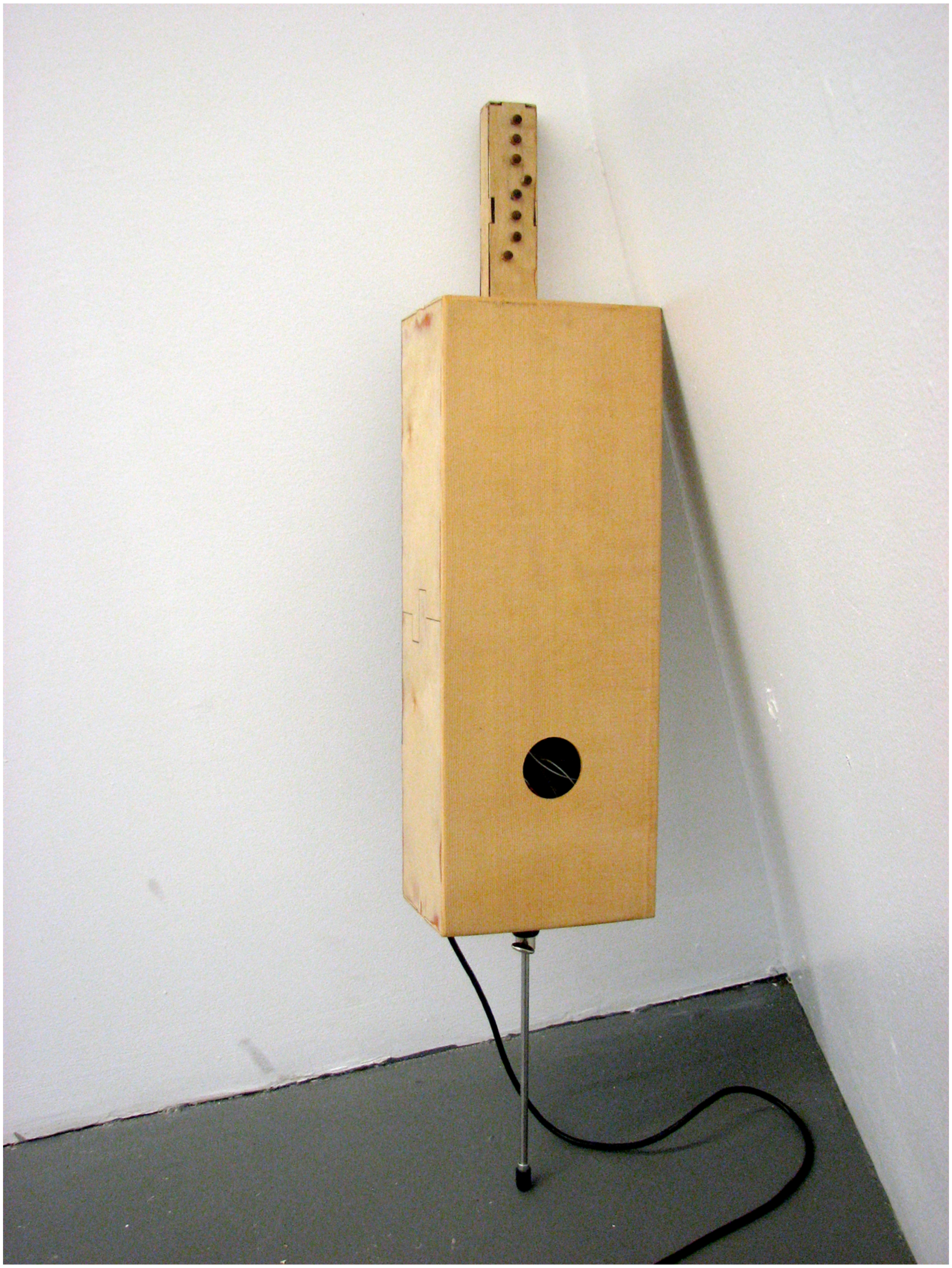

Figure 24: The Birl

3.2.3.1 - The Birl Controller

The performance controller for the Birl is a combination of a breath sensor and a keying system. The keying system determines the pitch of the sound, and the breath sensor determines the amplitude. This is a rough approximation of how most real wind instruments work, but without the subtleties of embouchure control of pitch and timbre, or overblowing for octave or twelfth register changes. While overblowing appears to be prohibitively difficult to implement electronically, current experimentation for future versions of the Birl involves the incorporation of embouchure sensing systems.

3.2.3.1.1 - The Birl controller keying system

The keying system is based on that of the recorder, because it is a familiar pattern easily recognizable by flautists, clarinetists, and saxophonists. C&K 8021 switches are used for the keys, with wooden keycaps similar to those used for the Contravielles substituted for the commercially available plastic ones. These snap-action switches give a satisfying tactile feedback to their actuation, although I consider the actuation force required to be undesirably high for the application. Performers learning the Birl had to adapt to using an unusual amount of pressure on their fingers in selecting a fingering, a feature of the instrument that I hope to remedy in future revisions. My current experiments involve capacitive sensors, much like Nyle Steiner's EWI. Unlike the EWI, however, they are inset to better simulate covering open holes. The pattern of the main pitch keys is four for each hand on the front, with the pinky keys offset slightly to allow for a comfortable hand position, and a thumb key on the left hand. Earlier versions had more keys, but when performers tested these, they found them confusing and hard to navigate. I have ignored the traditional use of extra pinky keys – perhaps foolishly – and instead concocted separate fingerings for the notes below middle D. The concert version of the instrument used in the performance of *Concerning the Nature of Things* had a range of two octaves plus a major second, from C4 (middle C) to D6. The lower octave used the recorder fingerings from D4 to C#5. These fingerings were repeated for the second octave, but with the addition of a second thumb key in the left hand, above the normal thumb key. For fingerings that already involved the thumb key, both left hand thumb keys had to be held down. This was made simpler by the close proximity of the two left hand thumb keys.

There are three additional thumb keys used for tuning purposes. One is an additional key for the left hand, positioned below the normal thumb key, and with a distinctive concave shape that made its tactile profile different from the others. This key is the *tune* key, and its action is analogous to the *tune* key in the Contravielles. When the player wishes to set a new *reference pitch*, he or she fingers the desired note (in the lower octave) and presses the *tune* key. It is not physically possible to press down all three left hand thumb keys at once, but this is also never necessary, since the top thumb key only selects a higher octave, and octave doesn't matter when selecting the pitch class of the new *reference pitch*. There are also two right hand thumb keys, which serve to select the *otonal* and *utonal* ratio scales. These switches only affect the instrument for the duration that they are held down, and when they are released the instrument's tuning returns to the *normal* scale, a system that recalls the tuning implementation of the Contravielles, and contrasts the latching action of the ratio scale selection on the two Manta instruments.

3.2.3.1.2 - The Birl controller breath sensor

The breath sensor is relatively conventional; it converts breath pressure in the mouthpiece to a voltage, which is sensed by a microcontroller. I experimented with building a custom breath sensor using a hall sensor and a magnet glued to a rubber diaphragm, but found the results unpredictable, and wound up using a commercially available Yamaha breath controller attachment[13] instead for the performance of *Concerning the Nature of Things*. Interestingly, I later opened up the Yamaha module to find what appears to be a more successful implementation of the system I had attempted earlier. The current version of the Birl uses a simpler custom solution, with a DIP-mounted pressure sensor from Honeywell[14] inside a small wooden box, which is fed by a clarinet mouthpiece. I decided to go with the clarinet mouthpiece because it was an easily available part that could be removed and washed, while the addition of a plastic reed allowed for a simple control of the amount of air the performer wants to allow to escape. A major drawback of many breath controller systems is that, unlike in a normal wind instrument, the amount of air escaping from the instrument is very small, so the effect on the performer is like attempting to blow up a balloon. I encountered this problem while working on my breath controller input, and I found that using a larger cavity for the enclosed air space, while also allowing the performer access to a physical adjustment for air escapement, helped

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[13] Yamaha BC-1
[14] Honeywell part# ASDXAVX001PGAA5

immensely. However, the more air that is allowed to escape, the lower the pressure difference was, and therefore the lower the noise floor of the sensing system needed to be, so I found myself putting quite a bit of effort into designing a noise-free circuit for the sensing technology.

3.2.3.2 - The electromechanical oscillator

The sound of the Birl is produced by the rotation of a stepper motor. The inspiration for this technique came while I was altering a pen plotter for musical performance. My duo with Víctor Adán, the Draftmasters, performs with X-Y pen plotters from the 1980s, controlled to draw specific lines and shapes, while the electromagnetic fields generated by the motors are amplified through an electromagnetic pickup.[15] While I was installing a pickup inside a plotter, I happened to move the drawing arm, thereby mechanically turning the rotor of the stepper motor without any electricity applied. The audio produced by the pickup from this action was very different from the sound we were used to in the Draftmasters, which has a very bright, aggressive, noisy quality, since it is dominated by the electrical noise of the control input square waves. When the motor was driven mechanically, the tone of the oscillation was very pure, similar to a sine wave. I decided to develop a system that would turn a passive motor at precise rates to achieve specific pitches, in hopes of controlling that intriguing sound. The similarity of the sound to the tone of a recorder immediately made me consider using the technique as a tone generator for a wind-style instrument.

[15] http://vimeo.com/4611451

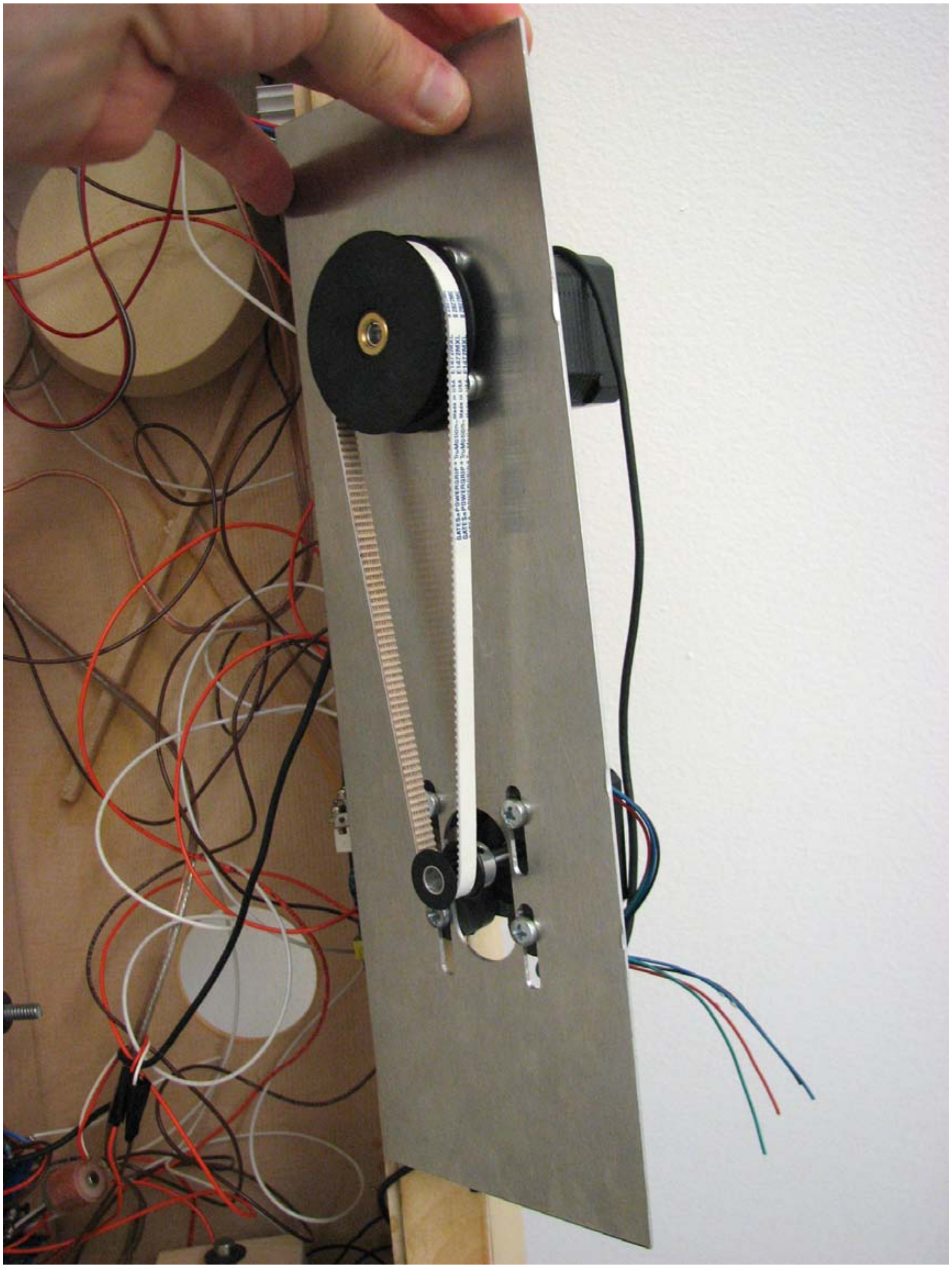

Figure 25: The Birl electromechanical oscillator

The system used in the Birl is made up of two stepper motors, which I will call the *drive* motor and the *audio* motor. The *drive* motor is driven by a microcontroller and a stepper motor controller IC to turn at a precise frequency. This rotation is transmitted to the *audio* motor by means of a pulley system. The electrical leads for the *audio* motor (intended by the manufacturer as inputs to the driver coils) are used as output for the voltage produced by the rotation of the rotor around the internal magnets. Stepper motors lose torque at higher speeds, so I achieve a speed increase to the second motor through a 4:1 gear ratio in the pulley system. This allows me to control the *drive* motor at a frequency two octaves below the intended audio output frequency, which is much more practical for the level of torque required for reliable rotation. I use NEMA17 size motors, and I've found that specifically selecting the second stepper for a low rotor inertia specification helps in the successful application of this concept by making the rotor easier for the first motor to turn. I experimented with different types of belts, and found that timing belts, while reproducing pitch very accurately, allow a little too much of the graininess of the initial drive steps to enter the sound. The timbre of the timing belt version is interesting, but it's not what I was looking for. Also, timing belts require additional tensioning, since they do not stretch, and the tensioning required changes depending on the frequency the motor is turning at. This is problematic in a system with a wide and dynamic frequency range, and necessitates a spring loaded tensioning pulley, which I found to introduce more unwanted acoustical noise than I could accept. I tried both 1/16" and 1/8" round urethane belts (which are self-tensioning), and found the thicker of the two to be an excellent choice for the application. The thinner belt allowed for too much stretching, introducing vibrato and pitch overshoot on frequency changes. The 1/8" belt seemed to be an ideal choice for the system, and was able to run with very little acoustical noise. Another experiment involved direct gearing, which was very promising. I was able to achieve an 8:1 gear ratio with stock parts, allowing for much greater torque, but the acoustic noise of the gear backlash was overpowering. However, I think the direct gearing system may be an excellent choice in a recording situation where only the electrical output was used. For my purposes, I needed to reduce the unwanted acoustic noise of the system, since the motor system would be on stage during a performance, and acoustical isolation would be difficult. Some colleagues who heard the acoustically noisy systems asked why I was concerned with eliminating the noise, since it occurred at frequencies that are harmonically related to the desired audio output, and I am trying for a more acoustic sound. My reasons for not being able to use the acoustic noise of the motor system directly derive from the fact that there is no simple way to effect amplitude control. The electrical signal of the *audio* motor can easily be attenuated by a voltage controlled amplifier, but the acoustic noise of the motor system is either on or off – the only parameter that can be changed in the system is the speed of rotation. The constant noise of the motors in early prototypes rendered the amplitude control offered by the breath sensor of the Birl useless, so I needed to concentrate my efforts on reducing this noise to acceptable levels.

The pitch accuracy of the motor is surprisingly good. I am able to get stable tuning within about a 3-octave range using the current system. The pitch resolution on the digital side is limited only by the resolution of the microcontroller's frequency division. Since it operates by division of a master clock in 16-bit integers, the resolution increases in lower pitch registers, so on the lowest few pitches I'm achieving around 0.05 cents resolution, while on the highest pitches I achieve a resolution of around 0.4 cents. This range is still much better than the tuning resolution of most MIDI gear, which is rarely below 3 cents. The actual tuning resolution of the physical system is difficult to measure, but it's clear that I'm getting acceptable results, while definitely not approaching in practice the theoretical resolutions the digital microcontroller is capable of. In the physical system, the low register of the instrument begins to lose tuning resolution due to the inertia of the motor; the individual pulses get slow enough that the motor stops between pulses, rather than remaining in constant rotation, deforming the waveform and introducing some tuning instability. Another interesting feature of the physical system is that higher frequencies of rotation on the *audio* motor produce higher amplitudes of output voltage. Early prototypes of the instrument, including the version used for the premiere of *Concerning the Nature of Things*, provided no compensation for this tendency, requiring the performer to compensate for this discrepancy manually by reducing breath pressure on higher pitches. More recent versions of the Birl have included a digital potentiometer at the *audio* motor output to dynamically attenuate the voltage of the higher frequency pitches, while allowing lower pitches to pass through with less attenuation.

Between the voltage output of the *audio* motor and the magnetic driver transducer that turns the electrical signal into physical vibrations, there is an analog Voltage Controlled Amplifier in the signal path. I'm currently using a Blackmer

VCA IC from THAT Corporation for this purpose, controlled by a passively filtered voltage from a 12-bit DAC. Originally, this path was entirely analog, which was a natural choice since I receive an analog signal from the breath sensor I use. However, I have found that the control afforded by an ADC/DAC stage allows me for more control options, including external control from MIDI during compositional experimentation, that hard-wired analog control doesn’t allow. This VCA allows for amplitude control only – there is no timbral modification available in the current state of the instrument. This makes the timbre very dark and without harmonics — the recorder-like tone which fits my aesthetic direction well.

3.2.3.3 - The Birl resonator

The concert version of the Birl used in the premiere of *Concerning the Nature of Things* was, with the exception of the audio power amplifier, a self-contained instrument. The keying system is built into a rectangular wooden projection from the top of a box-shaped resonator. The complete structure sits on a ‘cello endpin, to relieve the player of the need to support the weight of the relatively heavy components (motors, motor mounting plate, power supply, and driver transducer) inside the resonator. The principle of the resonator is very similar to that of the Contravielles: an electromagnetic driver transducer is screwed into a maple “bridge”, which is glued to the inside of a spruce top. The sides and back are made from birch plywood, and screwed on through threaded inserts to be easily removable. The back is acoustically decoupled from the rest of the instrument by a silicone gasket. I have used a simple cross-bracing pattern inside the spruce top, and a round sound hole, which will eventually be decorated with a lute rose, but is presently unadorned. The uncomplicated rectangular shape of the resonator and the cello pin construction is partially inspired by modern contrabass recorders made by Paetzold or Dolmetsch[16]. My design is significantly wider that these instruments, however. Since the actual acoustic mechanism of the resonator is much more closely related to a classical guitar than to an actual wind instrument, I need to maximize surface area of the top and have a large enough enclosed air volume to produce a Helmholtz resonance capable of reinforcing at least a C4, preferably a C3.

[16] http://www.dolmetsch.com/millennium.htm and http://www.contrabass.com/pages/big-recorders.html

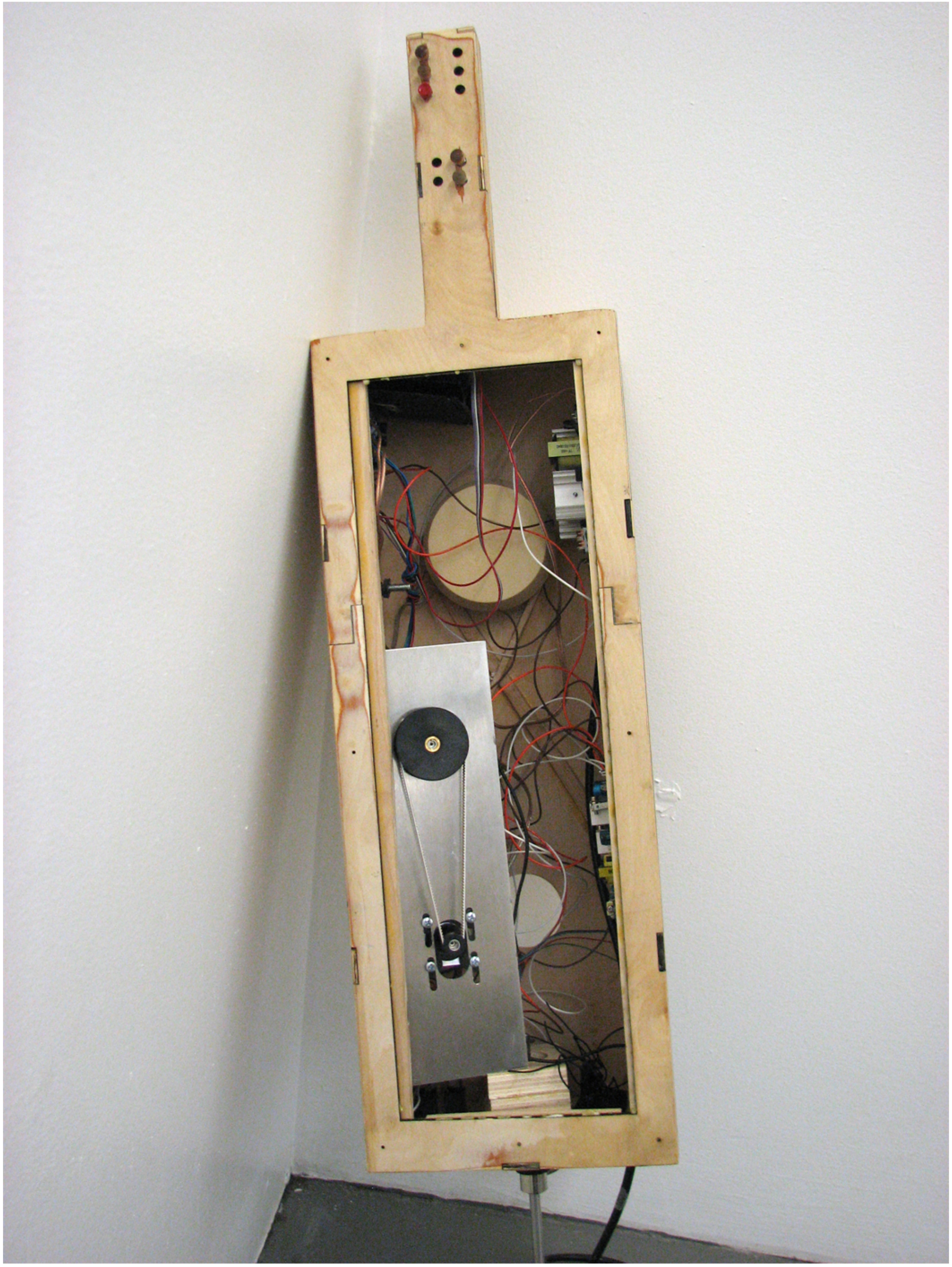

Figure 26: Internal back view of the Birl

3.2.3.4 - Future development of the Birl

Future development of the Birl is focused on two things: improving the layout and response of the keying and breath control systems, and integrating the electromechanical oscillator with more compact circuitry and increased timbral options. In pursuit of the first goal, I am exploring new ways to orient the mouthpiece using my current clarinet-styled breath sensor, and the addition of capacitive sensors above and below the mouthpiece to sense upper and lower lip embouchure. I am also working on a more comfortable keying system using capacitive touch sensors to simulate open holes. Cleverly deployed, this arrangement could possibly allow for controlled bending between pitches, which would be an asset to expressive playing. Additionally, I plan to add at least a C# and C right hand pinky key to the keying system. Because the instrument is now capable of reliably producing pitches an octave below my original design (the current range for the oscillator is C3-D6), I am working on devising a new system for octave shifts. The current system is only usable for an instrument in which there are two octave possibilities, and I now have three. I am considering having the right hand take over octave duties, necessitating a re-purposing of the *otonal* and *utonal* keys into 8va and 15ma keys. This would require additional controls for the *otonal* and *utonal* tuning adjustments, which could perhaps be done by momentary foot pedals. My work toward the goal of a more compact and more powerful oscillator system is currently focused on the design of a digitally controlled analog signal processing chain. Since the oscillator output is close to a sine wave, I have added an analog wave-shaper circuit that folds the wave at the peaks in a variety of ways to create a richer harmonic spectrum. I intend to modulate the amount of shaping applied to the signal through the use of the upper lip embouchure sensor. After the wave-shaper stage, the audio passes through a Low Pass Gate, a timbral shaper based on the Buchla model 292 module. The lower lip embouchure sensor, or perhaps the bite sensor, will modulate the cutoff frequency of this signal processing stage. Finally, the signal will be attenuated by a VCA stage, which is controlled (as on the present version) by the breath sensor. Right now, I'm experimenting with moving the oscillator system (motors, motor mount, analog processing, power supply) to an external box, and simply controlling it with serial data from the Birl controller. This configuration allows for more careful acoustic isolation of the unavoidable motor noise, reduces the weight of the instrument held by the player, and leaves the internal enclosed air space of the resonator cavity significantly less cluttered. The downside of this change is a weaker perception of the instrument as a self-contained entity, turning it more into a multi-purpose controller controlling a multi-purpose audio generator, which then sends its sound back into the resonator. My recent thinking is that the advantages of the external oscillator box configuration probably outweigh the reduction in psychological completeness that the instrument conveys.

IV. The Composition

4.1 - Structure of *Concerning the Nature of Things*

Concerning the Nature of Things is a single continuous work written for mezzo-soprano, tenor, and a six-piece instrumental chamber group. The chamber group is formed exclusively from instruments of my own design and construction, and is drawn from the group of instruments described above: two Birls, Bass Manta, Resophonic Manta, Treble Contravielle, and Tenor Contravielle.

4.1.1 - Origin of the text, and reasons for its selection

The piece is structured in three parts, and uses a different text by the same author for each section. The texts are taken from the works of Auroleus Phillipus Theostratus Bombastus von Hohenheim, generally known by the name Paracelsus. Paracelsus was a 16th century physician/alchemist/occultist/philosopher who is often credited with the concept that illnesses were caused by outside agents, rather than an imbalance in the four humours. I was drawn to these texts because I was interested in the period in European history when science, religion, and magic were not clearly delineated from each other. I find the history of science fascinating, and I am especially intrigued by the gradual shift toward rational thought from magical thinking in the Renaissance – the slow change from alchemy to chemistry, and astrology to astronomy. I find Paracelsus interesting as an example of this transitional period, since his works often combine significant advances in chemistry and medical science with bizarre occult techniques and practices.[17] I was also interested in his synthesis of ancient Greek worldviews with those of the Middle Ages and early Renaissance, such as his connection of Aristotle's four elements (Air, Fire, Water, and Earth) to his own three spiritual substances (Mercury, Sulfur, and Salt). Upon reading his *Philosophia Ad Athienses*, I was surprised to find a description of a fairly pantheistic worldview that mirrors my own beliefs in several respects. I chose to select two portions of text from this work that reflect my own belief in a self-sufficient and all-encompassing natural order – a picture of the entirety of Nature as an organism in itself. These two texts, both from *Philosophia Ad Athienses*, are supplemented by a third, more alchemical text excerpt from *De Natura Rerum*. I have inserted the third text as a middle section between the sections from *Philosophia Ad Athienses*.

Unlike most European writers of the Renaissance, Paracelsus wrote in the vernacular, in his case German. When I began looking for texts for this piece, I was assuming I would be using Latin, an idea that appealed to me due to its style references and religious connotations. I decided that it would not be too much of a

[17] In his 1572 book *De Natura Rerum*, Paracelsus gives the following recipe to create a homunculus- *"Let the semen of a man putrefy by itself in a sealed cucurbite with the highest putrefaction of venter equinus for forty days, or until it begins at last to live, move, and be agitated, which can easily be seen. At this time it will be in some degree like a human being, but, nevertheless, transparent and without a body. If now, after this, it be every day nourished and fed cautiously with the arcanum of human blood, and kept for forty weeks in the perpetual and equal heat of venter equinus, it becomes thence-fold a true living infant, having all the members of a child that is born from a woman, but much smaller. This we call a homunculus; and it should be afterwards educated with the greatest care and zeal, until it grows up and starts to display intelligence. Now, this is one of the greatest secrets which God has revealed to mortal and fallible man. It is a miracle and a marvel of God, an arcanum above all arcana, and deserves to be kept secret until the last of times, when there shall be nothing hidden, but all things shall be manifest. And although up to this time it has not been known to men, it was, nevertheless, known to the wood-sprites and nymphs and giants long ago, because they themselves were sprung from this source; since from such homunculi when they come to manhood are produced giants, pygmies,and other marvelous people, who get great victories over their enemies, and know all secrets and hidden matters."*

stretch to use Latin versions of the texts by Paracelsus, since most of his works were translated into Latin for the international community during his lifetime. Finding a contemporary translation of the specific texts I needed turned out to be more difficult than I expected. After much searching, I eventually found a contemporary translation into Latin of some parts of *De Natura Rerum* in the Rare Book collection at the New York Academy of Medicine. This translation focused only on what the author deemed to be practical advice, mainly covering the more routine chemical descriptions of medicines. Curiously, while much of the original text is divided into "the life in things" and "the death in things", the author of the translation skips the section marked "the death in things", with an explanation that the material in this section has dangerous uses, and should be of no concern to a physician. The portion of the text that is skipped in the translation includes an assertion that it is definitely possible to bring the dead back to life, which I may use in a future piece. Unfortunately, the *Philosophia Ad Athienses* turned out to be unobtainable in a Latin translation, so I had my friend Amara Magloughlin, an art historian, undertake a translation of the needed portions from the English translation.

4.1.2 - Large scale formal divisions of the piece

Once I had arranged the texts in an order that suited my needs, I structured the piece around the form of the text. The large-scale structure of the piece is a kind of rounded binary, with the A and A' sections bearing similar musical features without actual literal repetition. The B section acts as a contrast to the A and A' sections, by introducing different text setting textures, instrumental roles, and musical material. I have aligned the A and A’ sections with the texts from *Philosophia Ad Athienses*, and the B section with the inserted text from *De Natura Rerum*.

Concerning the Nature of Things: Text by Paracelsus

Ea est res vivens in qua omnia naturalia sunt in harmonia et misericordia inter se.

It is an organism in which all natural things harmonize and sympathize with each other.

Natura, qua universum est, una est, origineque potest solum esse una unitas aeterna.

Nature, being the Universe, is one, and its origin can only be one eternal Unity.

Makro kosmos est.

It is a Macrocosm.

Omnia fructus unae conationis communis sollertis est.

Everything is the product of one universal creative effort.

Makro kosmos est hominesque mikro kosmos est et sunt unus.

The Macrocosm and man (the Microcosm) are one.

Sunt unum sidus, una impulsio, unus spiritus, una harmonia, una aetas, unum metallum, unum malum.

They are one constellation, one influence, one breath, one harmony, one time, one metal, one fruit.

- -

vita postrema hominis videlicet, est astrale balsamus, impressiobal famica, coelestis et invisibilis ignis, inclusus aer, et spiritus salis tincus.

the life of all men is none other than a certain astral balsam, a balsamic impression, a celestial and invisible fire, and included air, and a spirit of salt which tinges.

vita compositorum elementorum ut aquae, est eius fluxio, quasi destituatur, est auqa mortua.

the life of water is flowing, and when it no longer flows, it is dead.

vita quidem ignis, est aer, qui per seipsum vivit, aliisque rebus elementatis vitam tribuit.

the life of fire is air, which lives of itself and gives life to all other things.

terra vero per seipsum est mortua, sed eius elementum, invisibilis est, et occulta sua vita: quae singula bene consideranda sunt.

the earth, however, is of itself dead, but its own element is its invisible and occult life: each of these are to be considered well.

- -

Nihil est corporalis qui non vim latam possidet.

There is nothing corporeal which does not possess a soul hidden in it.

Nihil exsistit in quo non principia vitae celata sunt.

There exists nothing in which is not a hidden principle of life.

Neque solum res quae movent, sicut hominesque animalia, vermes mundi, et aves aerique pisces in aqua, sed etiam omnis res corporales et essentiae vitam habent.

Not only the things that move, such as men and animals, the worms of the Earth, and the birds of the air and the fishes in the water, but all corporeal and essential things have life.

4.2 - Vocal writing in *Concerning the Nature of Things*

The vocal writing in *Concerning the Nature of Things* is influenced by a variety of traditions and time periods. The most prominent influences, and those which were most consciously guiding my creative choices, are from Western Art Music between 1350 and 1700, and American country music. Because the theoretical rules governing modal counterpoint are more familiar to a scholarly audience, I'll devote more space here to an argument for what the underlying guiding principles of American country music vocal harmony might be, since I have been strongly influenced by my interpretation of these theoretical rules. I should note that these rules are ideas I have derived for my own use.

4.2.1 - American country music vocal harmony rules

The specific subset of country music I am focusing on is the type of harmony exemplified by "brother duets" in bluegrass music, or that sung by two males in honky-tonk music (such as the back-up parts by Don Rich to Buck Owens lead, or Johnny Paycheck's harmony singing on early 1960s George Jones songs). These rules are also followed by most male/female duets of the 1960s and 1970s, such as Dolly Parton and Porter Wagoner, or Conway Twitty and Loretta Lynn. Although the full breadth of country music includes many other styles, for simplicity's sake I will use the term American country music to denote these genre subsets.

I would characterize the general rules of American country music vocal harmony as follows:

1. One voice is the lead voice, and the second voice or additional voices are supportive of this melody.
2. The second voice should accompany the lead voice with the closet chord tone on strong beats, and follow the trajectory of the melody on weaker beats. Intervals should generally not be further apart than a sixth.
3. Contrary motion is avoided. Oblique motion and parallel motion are both acceptable, but parallel motion is preferred.
4. Strict homophony is generally observed, except where an unusual effect is intended.

4.2.1.1 - Hierarchy of voices

The first rule comes from the fact that country music is primarily a melodic tradition, and a "song" is generally considered to consist of a melody with or without accompanying chords. Unlike genres of music where vocal polyphony is the emphasis (such as Renaissance church music), independence of voices is not particularly valued. Rather, the intention is to create a quasi-unanimous action that supports and reinforces the melody. A similar goal is achieved by very comparable means in the saxophone section of a big band ensemble. One could also liken the goal to that of French spectral music, in that the harmony singers should fuse as much as possible into one sound (usually using harmonies that correspond with the 3-4-5 identities of the harmonic series). Outside of the lack of value placed on individuality of voices, there is another notable difference between country vocal harmony and the standard rules of Western Art Music since the Renaissance: the lead voice (therefore the melody) is rarely placed in the highest voice. For instance, in “brother duets”, a common genre of American country music from which a standard of country music vocal harmony developed, the lower voice is usually termed the “lead” and takes the melody, while the upper voice sings the “tenor”, which is the harmony part. This arrangement allows for the final cadences of phrases to end on the dyad of a third, since the melody will always end on the tonic, and the harmony part will usually land on the third above it. No other arrangement allows for a closer harmony pitch (according to rule #2) as the final sonority of a song. Of course, this type of ending means that a “perfect authentic cadence” by the standards of common-practice Western Art Music harmony almost never occurs in country music. The only situation in which the upper voice takes the melody more frequently is in duets between male and female singers, where often the difference between the voice ranges prevents the usual 1-3 relationship on cadences. In this case, the third would generally be too low for the woman if the man takes the tonic, so the woman takes the melody voice, landing on the tonic, and the man can take either the third scale degree below her (producing a relatively close sixth) or the fifth scale degree (producing a fourth).

4.2.1.2 - “Close” harmony

This brings us to the second rule, which states that the harmony part should be the closest available chord tone on strong beats, and follow the melodic trajectory if possible on weaker beats. This, combined with rule 3, will tend to regularly produce “hidden fifths”, or perfect intervals approached by parallel motion. In country music vocal harmony, this motion is completely acceptable, since the major argument against it – that it weakens the independence of the voices – is not significant for this genre. In fact, fully parallel fifths or fourths are relatively common, and unavoidable if the aforementioned rules are followed in a three-voice texture. This rule is somewhat explicit in country music circles, as the style of singing is often termed “close harmony”.

4.2.1.3 - Avoidance of contrary motion

The third rule states that contrary motion is to be avoided. This is the easiest rule to see in effect by surveying a sample of the genre, since exceptions are rare. In my own experimentation, altering a country music vocal duet to include an instance of contrary motion often alters the character of the music to the point where it sounds unnaturally “classical”. The predominant texture is of parallel motion, but oblique motion is acceptable and provides a welcome contrast in some instances.

4.2.1.4 - Voices should be in rhythmic unison, or homophony

The fourth rule states that homophony is the textural norm. This rule is in keeping with the others, in that it tends to reinforce the concept of the harmony voices being dependent on the melody, and to suggest the effect of a single enhanced voice.

4.2.1.5 - Examples of American country music theory in practice

To elaborate on these points, I will refer to some examples from the repertoire of country music. The first example I will point to is “I Wish It Had Been a Dream”, by the Louvin Brothers.

Figure 27: “I Wish It Had Been a Dream”, by the Louvin Brothers (m.1-16)

This is an example of a “brother duet” typical of the 40s and 50s, and similar in style to what might be recorded by the Delmore Brothers, the Monroe Brothers, or the Stanley Brothers. It is clear that all the harmony rules I’ve enumerated are followed closely. The lower voice is the lead, with the upper voice providing the harmony. The harmonic intervals are always very close, and contrary motion never occurs. Similar motion dominates the texture, to the point that long strings of parallel fourths are allowed to occur in order to avoid jumping to a wider interval or losing the momentum of the parallel motion. Also, there is no break in the rhythmic homophony, until a solo voice begins to sing the “bridge” or “verse” depending on how you interpret the structure (I have omitted this section). This example follows the harmony rules I have described without exception.

Another illustrative example would be “Afraid”, a Fred Rose song that I have transcribed from a 1960s duet album by George Jones and Melba Montgomery.

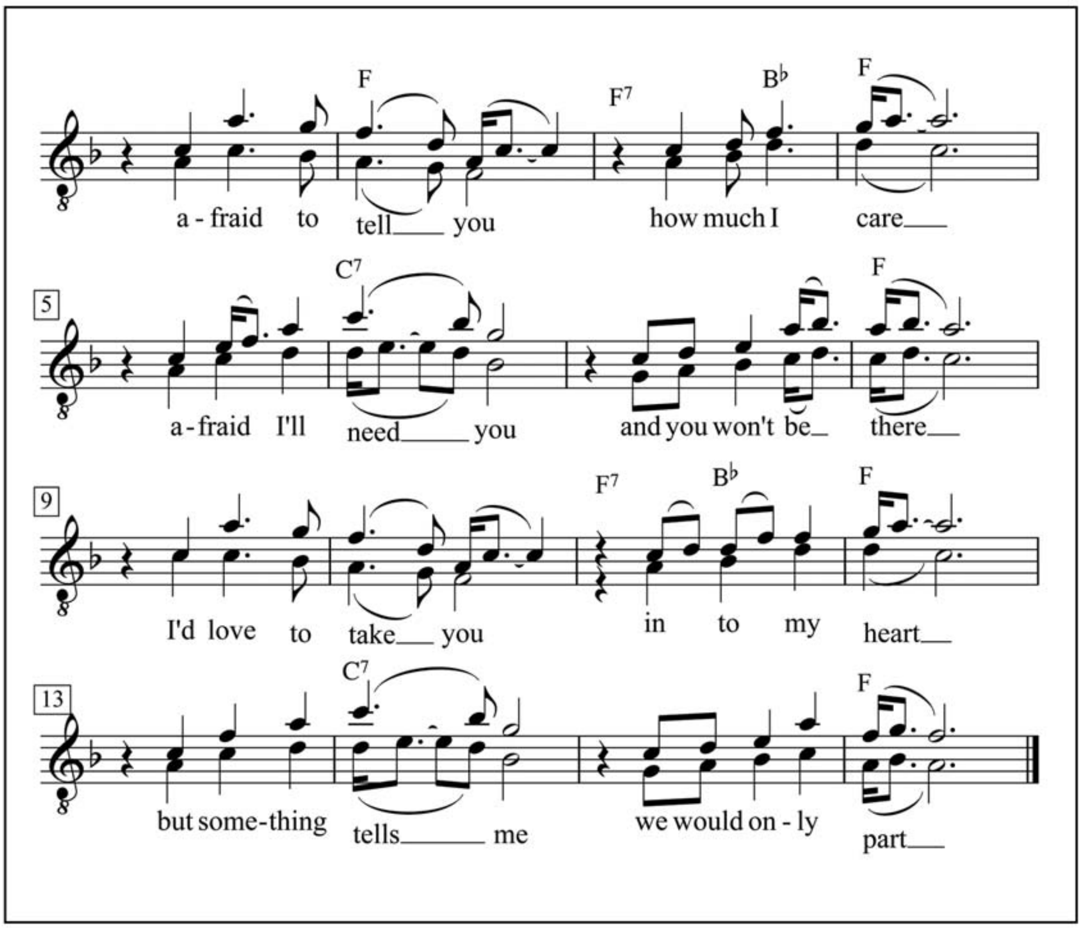

Figure 28: “Afraid”, by Fred Rose (m.1-16). Performance by George Jones and Melba Montgomery.

The original song is not intended as a duet, and only the melody appears in the published music; the harmony is probably improvised by the performer (in this case, George Jones on the lower part). The performance shows a strong adherence to the rules I have suggested. Typical examples of harmonic choices that would be unacceptable in traditional Western voice leading are the parallel fourths in measures 7 and 15, both leading to an improperly resolved tritone, and the subtly obscured parallel fifths in measures 2 and 10. The almost grace-note figure sung by the upper voice in measure 2 is an example of a somewhat common way to avoid parallel fifths, which - unlike parallel fourths - often show evidence of avoidance in country music harmony. Exceptions to my "closest intervals" rule occur at several points in the piece, but never in a way that would make the interval wider than a sixth. Interestingly, the jump from thirds to sixths in the first measure appears to me to be a rare avoidance of parallel fourths. The closer option for the lower voice would be to leap to the tonic, then drop through the 6th scale degree to the 5th, and on through the 4th to the 3rd. This would avoid the 7th scale degree (a common occurrence, to produce a more pentatonic melody line over the tonic triad), and would still place the chord tones on each strong beat. However, it would produce perfect fourths from the D to the C, after which it would collapse into thirds. Another possible reason for the wider interval is that a high F would be the highest note in the song, and would possibly sound too strained in Jones's voice (although a strained vocal sound is desirable in the genre). A third explanation for this choice, and possibly the most convincing one, would be that it avoids the phenomenon known in traditional Western music voice leading as "voice overlap", in which two voices move in the same direction, but the lower voice leaps above where the upper voice was.

This song is also an example of the common country vocal arrangement in which the upper voice ends the chorus on the tonic, while the lower voice takes the third a sixth below. An interesting characteristic of this piece is the fact that the duet is between a relatively high-voiced male and an unusually low-voiced female. The highest note for Melba Montgomery in the song is a tenor C, which sounds very high for her vocal range. This type of pairing is relatively common in male/female country vocal duets, probably because it allows for the type of close harmony that a pairing between a bass and a soprano would not. Jones's later pairing with Tammy Wynette is another example, as are the pairings of Merle Haggard and Bonnie Owens, Carl and Pearl Butler, and Conway Twitty and Loretta Lynn. In *Concerning the Nature of Things*, I wanted to explore this type of vocal tessitura - where a lower female voice sings close harmony with a higher male voice. For instance, my setting of the first few lines of text, from m.19 to m.40, never exceeds the interval of a sixth (except for a brief passage in measure 26). I also follow the other three rules of American country music vocal harmony that I derived, especially the complete homophony and avoidance of contrary motion.

4.2.2 - Use of false relations

Influences in the piece also derive from Concert Art Music sources, mostly from the periods commonly grouped together as "early music", and sometimes from musical phenomenons that I also find in country music. One of my favorite occurrences in the music of the medieval and Renaissance periods is the effect of a "false relation" – also called a "cross relation" – in which one voice sings one inflection of a diatonic pitch, which another sings a contrasting inflection shortly thereafter. This phenomena in the music of the Renaissance usually occurs as a result of the use of different diatonic modes for ascending and descending lines. A typical example can be seen in the 16th Century organ setting of the Aeterne Rerum Conditor by John Blitheman (Lowinsky, 536).

Figure 29: mm.15-16 of *Aeterne Rerum Conditor* by John Blitheman.

The excerpt shows mm.15-16 of the piece. In m.15, the C-natural in the soprano line is placed against a C# in the alto line, producing a striking false relation. A similar type of phenomenon occurs often in Country music, although usually for different musical reasons. Often, a minor pentatonic scale is sung by the lead voice over a major key chord background (in the other instruments), while the harmony singer also sings a strictly major key accompaniment. This practice is probably derived at least in part from the blues tradition, and it seems to have passed into the Country music canon through its use by blues-influenced musicians like Bill Monroe and Jimmie Rodgers. In the case of Bill Monroe, the third of the chord is often intentionally ambiguous in the lead voice - either always bending upward from minor to major, or holding obstinately at a pitch between the two (perhaps an approximation of one of the possible just intonation neutral thirds?). A commonly heard phrase in country music is the figure in which the lead melody moves minor 3-2-1 while the upper harmony voice moves 5-4-major3. This could be seen as a country music equivalent of the Picardy Third, but the prevalence of the major third in the chordal instruments throughout seems to confound that interpretation. The most obvious example of my use of the false relation occurs in the passage from m.174 to m.181. In these bars, the upper voice sings in a firm D Ionian mode, while the lower voice sings parallel motion in D Aeolian. There is a brief section of agreement in m.179 when the upper voice sings a C natural, but the split returns when the C# and F# appear in the upper voice in the next measure against a C natural and F natural in the lower voice. Due to the nature of the parallel tenths in the passage, these conflicting pitches are never heard simultaneously, so the difference is much more subtle than it would be if they presented a simultaneous augmented or diminished octave. A more acidic false relation happens in m.165, when the upper voice holds on to a G# while the lower voice reaches up to a high G natural in falsetto. This discrepancy is mirrored in the conflict between the G# in the Resophonic Manta part and the G natural in the Contravielle. The tension is resolved ambiguously in the following bar, when the phrase lands on an open fifth on E (although the brief added G natural in the Resophonic Manta before the resolution seems to suggest that it is E minor/B utonal). That moment is one of my favorites in the piece, and I intend to further explore that type of writing in the future - where clearly diatonic individual lines come into more aggressive confrontation, while still retaining enough tonal suggestion to have harmonic subtlety.

4.2.3 - Complex melismas

Another thread that I find to be common between Early Music and American country music is the use of long, florid melismas in vocal parts, often with unusual or perceptually obscure rhythmic divisions. The obvious exemplary genre in the Concert Music tradition is the Ars Nova movement of the late 14th century, or more specifically its Ars Subtilior subgenre. A typical example of such a phrase occurs in Senleches's ballade, *En Attendant*, mm.41-45.

Figure 30: mm.41-45 of *En Attendant*, by Jacob Senleches (discantus part)

There are several possible explanations for the use of this type of figuration in the Ars Nova repertoire. One likely reason is that they were excited about experimenting with the newfound technique of notating complex rhythmic divisions and their subsequent freedom from the strict compound-duple "rhythmic modes". Another possible reason is that clear declamation of a text through "naturalistic" rhythmic setting was not yet a priority before the Renaissance; complex and winding melismas that obscured the syllabic content were not a problem. Another possible reason is that these passages allowed for the performer to show off their virtuosity. Phrases like this are, to a lesser extreme, found in the country music repertoire, but once again the reasons for their use in American country music are very different than the reasons for their use by Ars Nova composers. The chorus to George Jones's *Mr. Fool* is an excellent example of this type of melodic writing.

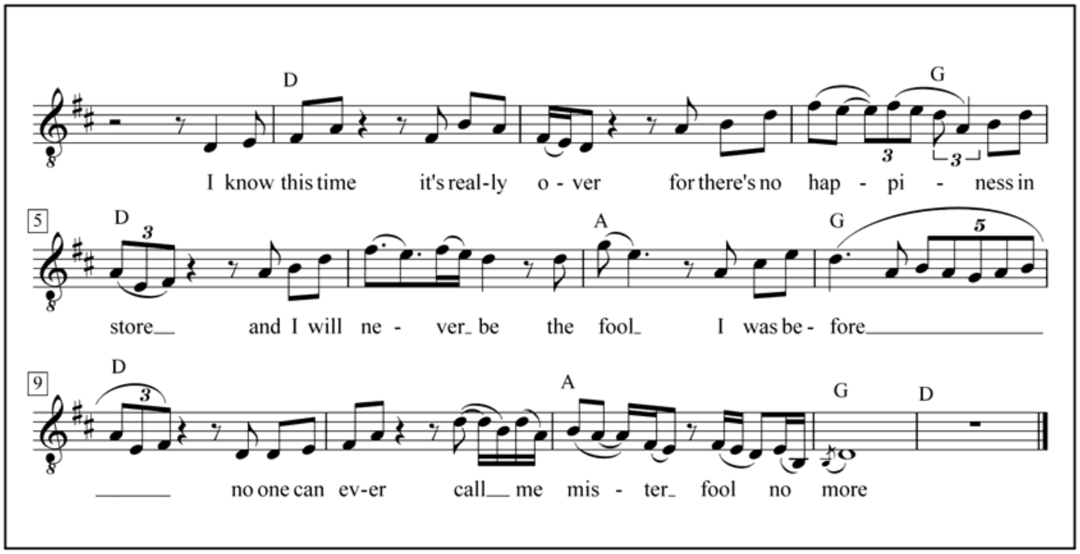

Figure 31: "Mr. Fool" by George Jones (chorus only)

Notice the ten-note melisma on the last syllable of "before". One might argue that this melisma (which I transcribed as closely as I could, but which is somewhat rhythmically ambiguous) could simply be an improvised embellishment. However, the phrase is repeated exactly the same each time the chorus occurs, and it is difficult to imagine what the melody would be without the embellishment. I would argue that the melisma is actually the melody itself. What are the reasons for the occurrence of these types of phrases in country music? I think there would be a strong argument that virtuosic display is part of the impetus. Another likely motivating factor would be that this is part of Country music's large body of techniques for stylizing weeping, or for encoding the act of the singer being overcome with emotion. My reasons for using similar figures in my music draw from all of these possibilities. I find them particularly expressive, and the auditory reference to late Medieval music helps me to set the reverential mood I'm seeking. In mm.178-180, another traditional text-setting technique is in use. The fluttering of birds in the sky and the agile swimming of fish in the sea are depicted in the fast, melismatic runs in the vocal parts of this section – a kind of word-painting. I also think of the completely coordinated motion of the two parts as mimicking the way that birds flock and fish school. Measures 61 and 62 show examples of more independent fast melismas in the vocal parts, and show a situation where word-painting is not the objective.

4.2.4 - Phrases in text setting, and acceptable cadential consonances

I am following basic Renaissance rules of text setting in *Concerning the Nature of Things*. As Zarlino suggests in his treatise on text setting from 1558 (Zarlino, iv. 33), I organize the musical material to follow the form of the text phrases. Commas receive short moments of rest, while periods coincide with extended sections of instrumental music to break up the stanzas. I also adhere to restrictions on acceptable consonances for cadences. All of the complete clauses end on consonances within the vocal parts. Within the A and A' sections, there is a general progression toward more perfect consonances. The first phrase in both A and A' is a 5-related ratio, 5/3 (a major sixth) in the case of m.29 ("inter se"), and 6/5 (a minor third) in the case of m.162 ("possidet"). The middle phrases in each section end with 3-related ratios (fourths and fifths), with the exception of m.49, because I opted for a unison to emphasize the text "unity eternal". The final phrase of each section (m.99, m.194) resolves to a 2/1 interval (an octave). This technique helps to make the form of the text clearer, even though the language is foreign to anyone living in the modern era.

4.2.5 - Middle section hocket

The B section, which uses text from *De Natura Rerum*, is written in a contrasting style to the A and A' sections. Inspired by the country western tradition, I decided that the contrasting section in a male/female duet should involve a solo voice. However, taking influence from Medieval music, I chose to set this "solo" section as a hocket. This way, a single vocal line involves both singers, and produces an interesting effect. This section spans mm.101-158. I chose to make the hocket emphasize the accented syllables of the text. I had my Latin translator read the text using a typical modern pronunciation style. This gave me an idea of which syllables should be accented in a standard reading. Because the female voice is higher in pitch, I set the accented syllables in the female voice part, and the unaccented syllables in the lower male voice. Some exceptions to this technique are on the words *aer* and *fluxio*, which I emphasize through harmonization.

4.2.6 - Rhythmic language of the vocal writing

4.2.6.1 - Speech rhythms and even declamation

The rhythmic language for the vocal writing is heavily influenced by speech rhythms. I have attempted to lean toward a stylized representation of the natural rhythm suggested by normal pronunciation of the text. An example is found in m.45, on the text "origina que potest sollum", in which the rhythms of the syllables change from word to word to reflect a natural speaking style. I balance this more flexible rhythmic notation with occasional breaks of even declamation, which is useful to make more forceful musical statements. An example of this more even style is found on the text "hominesque" across mm.75-76, or on the word "misericordia" in mm.27-28. When a composer chooses to use more complex rhythmic phrasing such as I have in *Concerning the Nature of Things*, he or she must choose between several methods of notation. The most obvious choices are the following three:

1. Reflect the rhythmic independence of the parts by not enforcing an overall metric structure with common barlines the are consistent between the parts. This is the technique used by the Ars Nova and Ars Subtilior composers (mostly because our modern concept of meter didn't yet exist), but it creates difficulties for a conducted ensemble, and requires very exact execution by the performers to avoid synchronization problems.
2. Write with an unchanging meter, and simply set up rhythmic differences with different tuplets and complex subdivisions. This type of writing is familiar from the works of Georgy Ligeti in the 60s and 70s (such as *Lux Aeterna*, from 1966). It provides for easy synchronization with a conductor, but lends no natural cues for accent pattern, and tends to enforce limits on the composition if the composer wishes to avoid tuplets over barlines.
3. Write with a changing meter and tempo to follow the changing rhythm closely. This allows for conductor-oriented synchronization, but necessitates more effort than option 2, and requires more active visual contact with the conductor. However, it provides for intuitive accents in the music (since

downbeats can be meaningful) and allows for the avoidance of tuplets across a barline.

I have chosen to use the third option, mostly so that the metrically strong beats could easily correspond with text accents, and to avoid complex tuplets over barlines. I found that this type of metrical writing helped me achieve the text declamation I intended, but it did cause problems. The performers were all relatively unfamiliar with their instruments, since those instruments were not the standard orchestral instruments they were trained on. This necessitated the use of more visual feedback with the instrument than usual; they needed to watch their hands to make sure they were in the correct position to play a particular passage, for instance. The use of quickly changing, irregular meters was problematic in this context, because the performers had to negotiate a difficult balance between watching the conductor and watching their hands. I think in the future, I will aim for a compromise between these two rhythmic notation styles, by only changing meter when absolutely necessary, and avoiding meters that divide the 16th note, as in mm.70-75.

4.2.6.2 - Rational metric divisions

Besides the goal of approximating speech rhythms, there is another reason for my use of relatively rapid changes of beat divisions and tempos. For instance, the two main tempos for the A and A’ sections are 60 and 72, which have a 6/5 relationship with one another (similar to a minor third if the periodic ratio were applied on a pitch time-scale). In order to set the third section apart more dramatically, the tempo is set at 92, which bears a 23/15 relationship with the original tempo of 60, or 23/18 to the preceding tempo of 72, and feels very foreign. From moment to moment, the small scale rhythmic figures often change from dotted rhythms to tuplets of 3 or 5, producing varying rhythmic relationships related to the numbers 2, 3, and 5. The simple change between 8th-note tuplets and straight 8th-notes represents a rhythmic ratio of 3/2, equivalent to a fifth on a pitch time-scale. I chose to use this type of ratio-related rhythmic alteration to mirror the types of ratios I am using in the pitch language, since the roots of the harmonic structures tend to be moving by simple ratios using factors of 2, 3, or 5. Equating pitch relationships with rhythmic ratios is an idea that goes back at least to Henry Cowell, and was later explored by Stockhausen. As an example of how I use these types of relationships in my piece, take the vocal parts in mm.158-162. The rhythmic unit changes from the quarter-note, to the eighth note, to the dotted eighth note, to the quarter-note triplet, back to the eighth-note. In terms of rhythmic relationships, the first change, from quarter to eighth, is a ratio of 2 to 1. If we liken the first pulse to C3, the new pulse would be equivalent to C4, an octave above. The next pulse is a change from eighth-notes to dotted eighth-notes. This change is equivalent to a ratio of 3:4. Seen another way, this new pulse is 4/3 above the original tempo. On a pitch time-scale, this new pulse would be F3. The next pulse is the quarter-note triplet, which would represent a ratio of 3/2 above the original quarter note, or G3. This pulse then speeds back up 4:3 to C4, 2/1 of the original tempo. So, in the course of five measures, the vocal parts have rhythmically simulated a I-IV-V-I progression. Seen in terms of just intonation, this progression represents an exploration of the three most simply related intervals, the octave, the fifth, and the fourth. This interpretation of the kind of rhythmic writing I am employing coincides neatly with how I tend to hear actual speech rhythm, so I find that this rhythmic technique satisfies both goals. While I don't believe that we perceive exact ratio relationships in the speed of our syllables in normal speech, this ratio-based rhythmic technique does, to my ear, mimic the ebb and flow of syllabic rhythm in speech. It also makes sense perceptually, as higher ratios in rhythmic relationships are harder to hear.

4.2.7 - Last line repetition

There is another aspect of the piece which is clearly related to the American country music tradition. I have chosen to repeat the final line of text, to give extra closure to the ending of the piece. This is an incredibly common device in country music, and is especially associated with the honky-tonk genre from which I am borrowing many of my musical ideas.

4.3 - Instrumental writing in *Concerning the Nature of Things*

The instrumental writing in *Concerning the Nature of Things* is organized through the application of certain roles to each instrument. These roles change between what I call the A/A' and the B sections of the piece, so when discussing each instrument, I will describe the role the instrument takes in each part of the piece.

4.3.1 - The role of the Bass Manta

The Bass Manta is the core of the ensemble in *Concerning the Nature of Things.* I conceived of the Bass Manta part as being the equivalent of a basso continuo of the Baroque era. The Bass Manta performs almost continuously through the piece, and is the only instrument entrusted with a clear presentation of the harmonic progressions. More specifically, in light of the pseudo-religious connotations of the piece, I see the Bass Manta as a kind of pipe organ for the ensemble, and the timbre I've chosen for the tone generation tends to support this aural identification. While the range of the Bass Manta is the same as that of the Resophonic Manta, I have chosen to give the fundamental pitches of most chords to the Bass Manta part, since the tone color of its resonator is more suited to a full bass response. The general figuration allotted to the Bass Manta part involves long bass notes, often colored by relatively sparse chordal constructions above. The only change to this pattern occurs in the B section, where the Bass Manta joins the Resophonic Manta is a type of overlapping instrumental half-hocket. During this section, the two Manta instruments interact in an unusual way. Both Mantas are playing arpeggios of otonal and utonal harmonies (always the same harmony), but the rhythmic presentation of the pitches varies between being independent, or hocket-like, and being in rhythmic unison. For the duration of the B section, the two Manta parts always play downward arpeggios, except for a brief passage from m.139 to m.141, where the Bass Manta plays an upward arpeggio against the downward arpeggio in the Resophonic Manta. This unusual event serves to introduce the interruptive instrumental melody by the first Birl and the Treble Contravielle from m.142 to m.145. The Bass Manta returns to its original role as the basso continuo of the ensemble for the A' section at m.158, and retains this role until the end of the piece.

4.3.2 - The role of the Resophonic Manta

The role of the Resophonic Manta is as a coloristic instrument. The country-western equivalent would be the pedal steel guitar, which generally provides harmonic and melodic fills between vocal phrases. I use the Resophonic Manta for a very similar purpose, in that it tends to take the forefront only when the vocal parts have a rest. Also, the pedal steel guitar tends to be the only instrument in Country music that is allowed to play more extended harmonies, including 7th and 9th chords, or major chords with added sixths.[18] I take this role a step further with the Resophonic Manta. Generally, if I would like to give a harmonic structure a more complex character, using more complicated pitch ratios, I will give these added pitches to the Resophonic Manta. Additionally, in *Concerning the Nature of Things*, the Resophonic Manta is the only instrument that switches between different tunings of the same chordal material for coloristic purposes, as in mm.50-51. I have chosen this role for the instrument because the timbre of the aluminum resonator cone seemed to fit nicely with more metallic and dissonant sonorities. Also, the buzzing of the cone suggests a "multiphonic" character, which tends to fuse the complex just chords together nicely into one instrumental voice. The volume swells that are characteristic of the

[18] Interestingly, the pedal steel is the instrument in the country western ensemble that has the strongest relation to just intonation. Since the left-hand slide transposes all pitches of a chord equally, the performer can choose to tune the instrument to a just-tuned chord, and will then be able to play that chord on any base pitch without tuning difficulty. Tuning this way is called "tuning sweet" by steel players, and many steel guitar websites make explicit reference to the use of just intonation on the pedal steel.

Resophonic Manta part serve two purposes – on one hand, they suggest the similar volume swells traditionally executed on a pedal steel with a volume pedal – on the other hand, they emphasize the acoustic and physical nature of the instrument. I have found the resophonic cone system to have a non-linear response to amplitude changes, in which the tone distorts or breaks up in the cone when a certain amplitude threshold is reached on resonant frequencies. The volume swells written into the part bring this uneven amplitude response to the foreground and provide an unequivocally acoustic sound quality to the electronic instrument.

4.3.3 - The role of the Contravielles and the Birls

The Contravielles serve as the string instruments of my invented orchestra, and the Birls are the winds. I see the Treble Contravielle as a treble viol, violin, or fiddle in the ensemble, the Tenor Contravielle as a viola da gamba or cello, and the Birls as a pair of recorders. In the A and A' material, the Treble Contravielle or the 1st Birl take the melodic foreground whenever the voices rest due to a phrase break, trading off occasionally to provide timbral contrast. The lower instrument in each family fulfills a supporting role, generally playing harmony to the upper instrument, and occasionally playing a more complex melodic line while the first instrument holds a static tone. The effect of these instrumental roles is the sense that there are two independent pairs of instrument types, each of which always performs as a family group.

In the B section, the roles of these instruments change. The two upper instruments, the 1st Birl and the Treble Contravielle, become a melodic pair. The instrumental writing in this section is more typical of Renaissance counterpoint – it allows for contrary motion, and aims for the effect of two independent melodies working together. In the first part of the B section, the Tenor Contravielle drops out of the texture, and the 2nd Birl plays only sparsely. In the second part of the B section, the Tenor Contravielle plays sparse accompaniment while the 2nd Birl is absent. In mm.142-144, there is a striking section where the 1st Birl and the Treble Contravielle play a melodic line together in even sixteenth-notes, doubled in octaves. This is the only appearance of this type of texture in the piece so far, and it is intended to provide for a relief from the prevailing texture of rhythmic and harmonic ambiguity in the B section. A similar, but more rhythmically disjunct octave-doubled melody appears at m.155 to signal the end of the B section, and the return to the original roles in A'. However, the treatment of the instruments is much sparser in A', to focus attention on the vocal harmonies. There is also the occasional rhythmic unison between the 1st Birl and the Treble Contravielle, as in mm.178-180, suggesting the texture of the B section. At the end of the A' section, the instruments embark upon a coda that is harmonically static within the Ionian mode on G. The coda exclusively features even sixteenth-notes doubled in octaves by the 1st Birl and Treble Contravielle, a figuration that was hinted at in the doubled melody in the B section. This coda is intended to provide a period of repose after the length of the piece, and to give sufficient closure to the material. It is inspired in part by the ending measures of many Bach chorale preludes for organ, where the different melodic voices gradually settle down into a chord while a pedal tone holds the static bass pitch (such as BWV 656, *O Lamm Gottes unschuldig,* or BWV 663, *Allein Gott in der Höh' sei Ehr'*).

4.4 - Adaptable Just Intonation in *Concerning the Nature of Things*

4.4.1 - Large-scale harmonic progression

The harmonic structures and progressions in *Concerning the Nature of Things* could be analyzed in many ways. The material is clearly formed from diatonic scale fragments and triadic vertical harmonies. This might suggest a tonal interpretation of the materials, such that exceptions to regular tonal rules would be considered unusual. I admit some tonal reference in the composition of the piece; for instance, the piece begins on a major triad in C and ends on a major triad in G: essentially creating one long plagal cadence, which was perhaps a playful reference to the religious undertones of the piece. However, I think the most useful way to view the musical language of the piece is through the intersection of modal counterpoint and just intonation. These two systems of musical organization are reconciled somewhat through the application of my Adaptable Just Intonation system, which allows for flexible diatonic scale subsets of the vast just intonation pitch spectrum.

Harmonic areas in the piece tend to progress from one stable triadic structure to another, sometimes traveling through more ambiguous sonorities on the way. Often, the root notes of successive triads are related by intervals of a fifth, fourth or third. This phenomenon would easily lead one to attempt a “Roman numeral” analysis of the harmonic progressions, in which a tonal center for each section of music is determined and subsequent chords are related to this center by hierarchical relationships. While this procedure might produce interesting and relevant results, it would not reveal the internal process by which the piece functions. When composing the piece, I was trying to use the concepts behind just intonation as a guiding force. For instance, rather than thinking of triads built on I, IV and V, I am starting from a perspective that the simplest harmonic motion involves fundamental movement by small-number ratios of a small-number prime-limit. This would tend to produce similar results, as the simplest whole-number ratios using small-number prime-limits are 3/2 and 4/3, the fourth and fifth respectively. Combine this with the simplest chord structure utilizing low whole number ratios, and you get a chord which resembles a major triad. However, extending this practice further, tonal harmony and just-intonation-derived harmony begin to diverge, and I am consistently thinking of the harmony in this piece from a just-intonation perspective.

As an example of the type of harmonic progressions used in the piece, I will examine the first 18 bars of music, the instrumental introduction before the vocals enter. The harmonic basis of the first two and a half bars is an otonal structure based on C. At the onset of the chord, the 1/1, 3/2, 5/4 triad is presented, along with 11/8, corresponding to the 11th harmonic, in the Bass Manta. The second note onset occurs on the fourth eighth-note of the measure, when the Resophonic Manta and 1st Birl simultaneously introduce 9/8, a major second above the tonic. Later in the measure, the 2nd Birl supports the 11/8 interval melodically, and the Treble Contravielle adds the 7/4 interval melodically. The only real deviation from a straightforward otonal harmonic presentation is the melodic introduction of 6/5 (an Eb) in the Treble Contravielle as a grace note in the second measure. This forms a brief cross relation with the sustained 5/4 in the 2nd Birl, but it makes sense from a modal counterpoint perspective as a kind of *musica ficta*.

The third beat of the third measure introduces a new harmony, an utonal triad on B. Related to C, the notes are 6/5, 3/2, 15/8 (this is what would normally be recognized as an E-minor chord - note that in utonal harmony the pitch that would be traditionally considered the 5th of the chord is actually the root). Related to the utonal root of 15/8, the pitches could be seen as 4:3, 8:5, 1:1. While not as stable as the first chord (since utonal ratios are not directly supported by the overtone series), this is still a very consonant chord. At the downbeat of the next measure this consonance is disturbed by the melodic figuration in the Contravielles, which introduce pitch ratios that are relatively complex and somewhat dissonant to the ear. The new pitches act as neighbor notes, introducing 11/8 and 5/3 to the chord. When compared against the current utonal root of 15/8, these new pitches represent the intervals of 22:15 and 9:8, both of which are otonal intervals and the first of which is an unusual interval. The 11/8 is 22:15 (a wide tritone of 663 cents) away from the 15/8 identity, and 55:48 away from the aurally perceived root of 6/5 (a wide whole tone of 236 cents). In the second half of the fourth measure, the C# in the 1st Birl adds the interval 16/15, which is 64:57 when measured against the utonal root of 15/8. As a vertical sonority, the chord heard on the fourth beat of the fourth measure would be, calculated from C: {6/5, 4/3, 15/8, 16/15, 11/8}. Calculated from the current context of an utonal root on 15/8, this chord is actually {1:1, 6:5, 64:57, 4:3, 22:15} - a mixed utonal/otonal structure with some very juicy dissonances.

This chord resolves to an otonal triad on D in the middle of measure 5. The only disagreement with this stable sonority is a subtle melodic neighbor note motion in the 2nd Birl, which uses the utonal 4:3 above 9/8 (3/2 when considered with relation to

C). This stability is undermined in the second beat of measure 6, when the Bass Manta reinforces this 4:3 relationship, and adds a 5:3 above it (3/2 and 35/24 when related to C). Also at this point, the stable 3:2 above the D (27/16 related to C) disappears, lending support to the possibility of G as a new fundamental, although the lowest pitch is still a D. Denying stability to the new chord is an altered F# in the Bass Manta and Tenor Contravielle. This F# is slightly lower than the previous F#, since it is 11/8 (related to C) as opposed to 45/32, a significant difference of around 40 cents. This note doesn't really support either possible fundamental well, since it forms a wide minor seventh with G (11:6) and a wide minor third above D (11:9) so the harmony is truly ambiguous.

The ambiguity continues into mm.7-8. The Birls perform a foregrounded melodic part which lands on a 3:2 interval from A to E, suggesting either A otonal or E utonal. The Resophonic Manta enters with a triadic sonority which suggests A utonal, subverting either of those possibilities. To further obfuscate things, the actual tuning of the pitches in the Manta part is rough, since the instrument is tuned at that point to the E utonal scale, producing a triad with the pitches {5/4, 64/45, 64/35} when referred to C, and {1:1, 32:27, 32:21} when referred to E. Both the G and the B are uncomfortably close to more consonant ratios (6:5 and 3:2 respectively). The last beat of measure 7 introduces another harmonically complex pitch, with an added 10/7 (the F# in the Resophonic Manta part). In the second half of measure 8, the Bass Manta enters, and plays a chord which suggests E utonal, supporting the Birls, and in the second half of measure 9, the Resophonic Manta acquiesces and allows the E utonal harmony to dominate.

At the downbeat of measure 10, a very stable F otonal chord takes over the texture forcefully with a forte attack. While it may appear from the notation that there is a disagreement between the treble and Tenor Contravielle parts in the subsequent two measures, this is not actually the case. While the Treble Contravielle is tuned to a reference pitch of F and the Tenor Contravielle is tuned to a reference pitch of C, all of the pitches played in the passage are actually the same in both tunings. The reason for the difference is practical; there is no rest for the instruments to retune, so I have them retune while playing (by touching the “tune” button while playing a note) and the pitch the Treble Contravielle is playing at the beginning of the passage is an F.

Near the end of measure 12, the harmony moves to C otonal. The two Birls play a melodic figure in close dyads, with a slightly unusual false relation in the 2nd Birl part as a 45/32 F# neighbor note in measure 12 becomes a 4/3 F-natural in the following measure, and a 16/9 Bb suggests a possible move back to F. The Resophonic Manta quietly adds some unusual color to the simple harmony, including the 7th, 11th, 13th, 19th and 21st partials, but spaced in a closed position to add some beating.

Midway through measure 14, the F otonal sonority returns. This time, it is slightly colored with a major seventh in the chord, the E in the Treble Contravielle. This pitch is 5/4 tuned to C, but is 15:8 above the 4/3 root. Melodically, other ratios are introduced, including a 27:32 relationship with the F in the D played by both Contravielles.

The final sound in the instrumental opening is a pure fifth (3:2) played in the Contravielles alone. The voicing is the same as the first pitches they played on the introduction of the F otonal harmony (when the E was 15:8 over the F) but now, played alone, it readjusts the harmonic connotation since the F in the Mantas is gone. While the 5th is ambiguous, the sonic memory of the C-natural played recently tends to suggest an E utonal harmony. This implication is made explicit when the voices enter in m.19 and use the pitches A, B, C, and D natural.

4.4.2 - Beatless consonances

The concept of a "beatless" interval is problematic. In practice, interval type alone is not enough to determine whether the acoustic phenomenon known as "beating" (which involves a perceptible amplitude modulation below the rate of audio) will occur. Even very simple ratios will produce beating effects when played in very low registers, or with sounds that have stretched partials. Very complex intervals, which one would assume should create beating patterns, will not produce the effect when played using timbres with few overtones as long as the overtones are outside the critical band.

Despite these caveats, there is a certain smoothness associated with simple just intervals, and often that is the effect I am going for in *Concerning the Nature of Things*. This can be explained somewhat by the psychoacoustic concept of *smoothness* and *roughness*. Compared with a major triad played on a piano, a {1:1, 5:4, 3:2} sonority played with precise tuning on a Manta is a very smooth, attractive sound. I have chosen to use a rich timbre (a slightly filtered sawtooth wave oscillator) as the sound source for both the Mantas and the Contravielles in order to accentuate the special quality of just consonances, and to make more dramatic the roughness of just dissonances.

In most circumstances, when a perfect interval or a consonance occurs in the music, I am using the adjustments of Adaptable Just Intonation to make the intervals correspond to the simplest ratios in that interval family. While truly tempered intervals are not actually possible, there are several flavors of each pitch class, and some are comma-shifted in ways that would produce dissonant just intervals (mostly due to their proximity to simpler ratios). For instance, in m.48, the A pitch class occurring in the Bass Manta part is 27/16, because it is tuned to the normal scale on reference pitch D. If tuned to reference pitch C, without Adaptable Just Intonation, this pitch class would be 5/3. Against the root of D = 9/8, the 5/3 pitch would be the interval of 40:27, a very rough type of fifth. Therefore, in this case, the retuning of the instruments to reference pitch D at that point in the score avoids a dissonance that would probably cause the impression of mistuning, and instead produces a purely consonant 3:2 interval.

4.4.3 - Unusual harmonic resources

Sometimes in the piece, I take advantage of the unusual harmonic resources that are available in Adaptable Just Intonation. As an example, I will examine the passage from m.55 to m.56.

Superficially, it is a phrase that passes from an otonal triad on Bb, through an otonal triad on F, to an utonal triad on A (in a progression that is similar to Bb-F-Dm in traditional harmony). However, the unusual harmonies that occur during the progression are interesting. Since the initial F in the 1st Birl is tuned to A, it is 4/3. Since the D in the 2nd Birl is tuned to the reference pitch A as well, it is a 10/9. The Bb in the Bass Manta is also tuned to A, so it is 80/45. Because the structure sounds to the ear like an otonal triad on Bb, we shall look at the intervals from the bass note: 10/9 divided by 80/45 is in fact 5:4, and 4/3 divided by 80/45 is in fact 3:2, so this is a properly tuned Bb otonal triad based on the 80/45 flavor of the Bb pitch class.

In the Treble Contravielle part, an Eb, C and A are used melodically in addition to the aforementioned pitches. In a standard just diatonic scale (like the Ellis duodene used for the *normal* ratio scale in my system), these should be tuned as 4:3, 9:8 and 15:8 above 80/45, respectively. These ratios would work out to be 32/27, 1/1, and 5/3. However, the actual pitches used by the Treble Contravielle are 40/33, 160/81, and 5/3, because it is tuned to the utonal ratio scale on the A reference pitch. These pitches set up an unusual mode over the Bb otonal triad, causing it to be less stable than it would be otherwise.

The following chord has the appearance of an F otonal triad, since the Bass Manta moves down to an F, and the 2nd Birl changes from a D to a C. The F in the Bass Manta and the F in the 1st Birl are both 4/3, and the C in the 2nd Birl is 1/1 (a different C from what was just sounded in the Treble Contravielle). The Treble Contravielle has moved to an A, which is 5/3. So, the intervals from the 4/3 root are the consonant triad {1:1, 5:4, 3:2}. However, the Resophonic Manta performs a cluster chord in A utonal tuning, adding another C, a C#, a D, and an E to the mix. These ratios work out to be {160/81, 40/39, 10/9, and 80/63}, which are - when compared against the current fundamental of F = 4/3, {120:81, 20:13, 5:3, and

120:63}. All of these intervals, except for 5:3 (a consonant minor sixth), are complex and relatively dissonant intervals when sounding against the F. The 160/81 pitch clashes aggressively as a mistuned unison with the 1/1 in the 2nd Birl. The other two pitches give a clear indication that the sonority is unstable. Additionally, the melodic false relation in the Tenor Contravielle part between a 40/21 B-natural and a 16/9 B-flat adds to the harmonic instability.

The instability is resolved when we receive a perfect fifth on D in the following bar, which seems to reinforce the A-utonal harmonic extensions happening over the previous chords. In the second half of the bar, a cadential phrase in the Resophonic Manta uneasily confirms this: the bass voice moves from F to D while the upper voices spread out from Eb and Gb to D and A. The common-tone G that is held through both chords prevents a completely solid triadic harmony, it pits a 4:3 fourth and a 3:2 fifth against the same note, the low D, in a kind of quartal harmony.

A brief foray into an otonal version of A in m.58 makes a vertically stable but horizontally confusing statement, including the harmonically complex A-otonal flavors of D, F and B in the Treble Contravielle (suggestive of a kind of mistuned polytonal harmony).

Eventually, the melodic false relation in the 2nd Birl in the second half of the bar returns us to the A-utonal realm with a final stable A-utonal triad of {10/9, 4/3, 5/3}, or, spelled as intervals from the root of A, {4:3, 8:5, 1:1}. This A-utonal soundworld continues after the brief rest, since it is the first harmony sounded after the rest by the instruments and voices together. I would argue that from m.56 until m.60, the A-utonal harmony is continually hinted and prepared. Just before it is reached, the surprising A-otonal harmony interrupts, but the momentum of A-utonal wins the struggle. This preparation allows for some complex and unusual inflections in the intervening measures, and also aids in creating a satisfying resolution at m.60 when the fully A-utonal texture arrives.

4.4.4 - Just intonation false relations

I have already discussed my interest in the musical phenomenon of the false relation, in which different inflections of the same diatonic pitch occur simultaneously or in rapid succession, creating a conflict of modes. In just intonation, there is the possibility for a special type of micro-false-relation, in which – rather than being between F sharp and F natural, for instance – the conflict can be between different flavors of F natural. These type of phenomena are readily available in my Adaptable Just Intonation system, and I have used them throughout the piece to a unique effect. As an example, I will examine the passage in mm.50-51.

At the outset of measure 50, the Bass Manta begins to sustain a low octave on A. This is immediately supported by an upper harmonic cluster of G, A and B, tuned to A-otonal, in the Resophonic Manta. Because the selected ratio scale is otonal, and the *reference pitch* is A, the three-note chord is (in pitch names related to C) {35/24, 5/3, 15/8}. In ratios to the bass pitch, this chord is {7:4, 1:1, 9:8}, which reinforces the seventh and ninth partial of the fundament. After a short rest, the same three pitch classes are sounded again by the Resophonic alManta, but the *reference pitch* has been changed to D. Now, seen from C, these pitches would be spelled {189/128, 27/16, 243/128}. Against the A in the Bass Manta, the new intervals are {640:567, 160:81, 729:640}. All of these are dissonant intervals, including a syntonic comma of 21.5 cents between the low A and the higher A. I alternate back and forth between these two flavors of the cluster chord, and after a subtle change of the original chord to include an F that is the 13th harmonic of the A, a new sonority is introduced.

This new chord is a cluster of A, B, and C with a G below. I have tuned this harmony to *reference pitch* D, so the pitches are {189/128, 27/16, 243/128, 63/32}. However, the pitch in the Bass Manta changes at this point to a low 9/8 D, so these pitches are now a lush overtone series with the ratios {21:16, 3:2, 27:16, 7:4}. While the 21st and 27th harmonics are relatively dissonant, and the 21st harmonic is a little too close to the more consonant 4:3 ratio, the chord still supports the D tonality. In this case, I have used a microtonal false relation to create a subtle color effect, while also preparing a shift in fundamental by introducing pitches that belong to the new tonality before it appears. In this way, the pitches that were “wrong” in their original presentation become “right” when the bass note is changed. Other clear examples of this technique occur at mm.24-25, m.34, and m.85.

4.4.6 - Intonation and the voice parts

It may seems strange that after going to all this trouble to enable precise tunings on all of the instruments, I have then written a piece in which the focal point of the music is the human voice. Obviously, it would be impractical to use the same notation technique I use for the instruments on the vocal parts. A direction to “tune E utonal” before singing a phrase starting on an F# would be meaningless to a singer, and would not reliably produce a pitch with a frequency ratio of 10/7 in relation to C =

261.6125Hz. One option would be to try to approximate the microtonal inflections with quarter-tone or eighth-tone notation. I consider that option unusable in this context, since singers tend to perceive these types of accidentals as alterations of a pitch, but without a reference from the instruments, they don't know where they are inflecting the pitch from. Also, this complicates the notation greatly, and leads to an anxiety-inducing score for the performer to read from, not much removed from the difficulties encountered by a performer on a flexible-pitch instrument attempting to read a part from a Ben Johnston piece.

The solution I have chosen is to avoid notational complication and allow the singers to use their ears. In order to make this feasible, I have opted to limit my vocal writing to relatively familiar intervals, and save the more exotic resources of Adaptable Just Intonation for the instruments. Since the pitch references are often changing, I have been careful to introduce pitches before they are sung by the vocalists. The most obvious example is the first vocal entrance, in which the two pitches are played in isolation, and in the correct register by the Contravielles prior to the vocal entrance. I have found that -- with good singers -- this choice was a successful one. Given a simultaneous dyad of a perfect fifth, or a third or sixth, skilled singers will naturally tune to a just interval. Added support from the instruments gives them additional feedback when necessary.

4.4.7 - Resources for further exploration

Concerning the Nature of Things is the first piece I have written for this grouping of my instruments, and the second piece I have written in my Adaptable Just

Intonation system (the first was *Vox in Vitro*). There are many aspects of the instruments and of the tuning system that I have yet to explore. One would be a more systematic use of relatively exotic intervals through the juxtaposition of instruments performing simultaneous material tuned to contrasting *reference pitches*. Another idea is to write lines which modulate through reference pitches much more frequently than these earlier pieces. Since composing *Concerning the Nature of Things*, I have completed a computer algorithm that computed every *reference pitch / ratio scale* combination that includes a specific pitch. This new algorithm has produced a table that makes finding routes to a particular ratio a simple exercise, thereby making elegant use of common tones in my system much easier, and allowing for particularly fluid tuning modulation (presented as **Appendix A**). At present I am inspired by both the tuning system and the instruments I have built to realize it. I look forward to writing a substantial body of work that will develop these ideas further.

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Appendix A

pitch	pitch in cents	pitch class	available routes to pitch
1/1	0.000	C	(C:n) (C#:n) (D:n) (Eb:n) (E:n) (F:n) (G:n) (Ab:n) (A:n) (Bb:n) (B:n) (C:o) (C#:o) (F:o) (Ab:o) (Bb:o) (C:u) (D:u) (E:u) (G:u) (B:u)
256/255	6.776	C	(C#:u)
96/95	18.128	C	(Eb:u)
81/80	21.506	C	(Eb:o)
65/64	26.841	C	(E:o)
64/63	27.264	C	(F:u) (Bb:u)
45/44	38.906	C	(F#:u)
40/39	43.831	C#	(A:u)
33/32	53.273	C#	(G:o)
25/24	70.672	C#	(E:n) (A:n) (A:o)
21/20	84.467	C#	(Eb:o) (Ab:o)
20/19	88.801	C#	(E:u)
256/243	90.225	C#	(Bb:u)
135/128	92.179	C#	(D:n) (F#:n) (G:n) (B:n) (D:o) (E:o) (F#:o) (B:o)
19/18	93.603	C#	(Bb:o)
18/17	98.955	C#	(D:u)
17/16	104.955	C#	(C:o)
16/15	111.731	C#	(C:n) (C#:n) (Eb:n) (F:n) (Ab:n) (Bb:n) (C#:o) (C:u) (C#:u) (Eb:u) (F:u) (Ab:u)
15/14	119.443	C#	(F#:u) (B:u)
13/12	138.573	C#	(F:o)
12/11	150.637	C#	(G:u)
35/32	155.140	D	(E:o) (A:o)
128/117	155.562	D	(Bb:u)
11/10	165.004	D	(Ab:o)
10/9	182.404	D	(E:n) (F:n) (A:n) (Bb:n) (Bb:o) (E:u) (A:u) (B:u)
285/256	185.782	D	(B:o)
64/57	200.532	D	(F:u)
9/8	203.910	D	(C:n) (D:n) (Eb:n) (F#:n) (G:n) (Ab:n) (B:n) (C:o) (D:o) (Eb:o) (F:o) (G:o) (D:u) (F#:u)
96/85	210.686	D	(Eb:u)
17/15	216.687	D	(C#:o)
256/225	223.463	D	(C#:n) (C#:u)
585/512	230.751	D	(F#:o)
8/7	231.174	D	(C:u) (G:u)
55/48	235.677	Eb	(A:o)
15/13	247.741	Eb	(B:u)
64/55	262.368	D	(Ab:u)
7/6	266.871	Eb	(F:o) (Bb:o)
75/64	274.582	Eb	(E:n) (F#:n) (A:n) (B:n) (E:o) (B:o)
20/17	281.358	Eb	(E:u)
45/38	292.711	Eb	(F#:u)
32/27	294.135	Eb	(F:n) (Bb:n) (C:u) (F:u) (Bb:u)
1215/1024	296.089	Eb	(F#:o)
19/16	297.513	Eb	(C:o)
153/128	308.865	Eb	(D:o)
6/5	315.641	Eb	(C:n) (C#:n) (D:n) (Eb:n) (G:n) (Ab:n) (C#:o) (Eb:o) (Ab:o) (D:u) (Eb:u) (G:u)

40/33	333.041	Eb	(A:u)
39/32	342.483	Eb	(G:o)
128/105	342.905	Eb	(C#:u) (Ab:u)
11/9	347.408	E	(Bb:o)
315/256	359.050	E	(F#:o) (B:o)
16/13	359.472	E	(C:u)
5/4	386.314	E	(C:n) (E:n) (F:n) (F#:n) (G:n) (A:n) (Bb:n) (B:n) (C:o) (E:o) (F:o) (A:o) (E:u) (F#:u) (B:u)
64/51	393.090	E	(F:u)
24/19	404.442	E	(G:u)
512/405	405.866	E	(C#:u)
81/64	407.820	E	(D:n) (D:o) (G:o)
19/15	409.244	E	(C#:o)
80/63	413.578	E	(A:u)
51/40	420.597	E	(Eb:o)
32/25	427.373	E	(C#:n) (Eb:n) (Ab:n) (Eb:u) (Ab:u)
9/7	435.084	E	(D:u)
165/128	439.587	F	(B:o)
128/99	444.772	E	(Bb:u)
13/10	454.214	E	(Ab:o)
21/16	470.781	F	(C:o) (G:o)
256/195	471.204	F	(C#:u)
675/512	478.492	F	(F#:n) (B:n) (F#:o)
45/34	485.268	F	(F#:u)
85/64	491.269	F	(E:o)
4/3	498.045	F	(C:n) (C#:n) (E:n) (F:n) (G:n) (Ab:n) (A:n) (Bb:n) (C#:o) (F:o) (Bb:o) (C:u) (D:u) (E:u) (F:u) (G:u) (A:u)
171/128	501.423	F	(D:o)
128/95	516.173	F	(Ab:u)
27/20	519.551	F	(D:n) (Eb:n) (Eb:o) (Ab:o)
65/48	524.886	F	(A:o)
256/189	525.309	F	(Bb:u)
15/11	536.951	F	(B:u)
48/35	546.815	F	(Eb:u)
11/8	551.318	F#	(C:o)
18/13	563.382	F#	(D:u)
25/18	568.717	F#	(A:n)
7/5	582.512	F#	(C#:o) (Ab:o)
80/57	586.846	F#	(A:u)
45/32	590.224	F#	(C:n) (D:n) (E:n) (F#:n) (G:n) (B:n) (D:o) (E:o) (F#:o) (G:o) (A:o) (B:o) (F#:u)
24/17	597.000	F#	(G:u)
17/12	603.000	F#	(F:o)
64/45	609.776	F#	(C#:n) (F:n) (Ab:n) (Bb:n) (C#:u) (Eb:u) (F:u) (Ab:u) (Bb:u)
57/40	613.154	F#	(Eb:o)
10/7	617.488	F#	(E:u) (B:u)
36/25	631.283	F#	(Eb:n)
13/9	636.618	F#	(Bb:o)
16/11	648.682	F#	(C:u)

35/24	653.185	G	(A:o)
22/15	663.049	G	(C#:o)
189/128	674.691	G	(D:o)
96/65	675.114	G	(Eb:u)
40/27	680.449	G	(A:n) (Bb:n) (E:u) (A:u)
95/64	683.827	G	(E:o)
765/512	695.179	G	(F#:o)
256/171	698.577	G	(Bb:u)
3/2	701.955	G	(C:n) (C#:n) (D:n) (Eb:n) (E:n) (F:n) (F#:n) (G:n) (Ab:n) (B:n) (C:o) (Eb:o) (F:o) (G:o) (Ab:o) (Bb:o) (D:u) (F#:u) (G:u) (B:u)
128/85	708.731	G	(Ab:u)
195/128	728.796	G	(B:o)
32/21	729.219	G	(C:u) (F:u)
20/13	745.786	Ab	(E:u)
99/64	755.228	Ab	(D:o)
256/165	760.413	G	(C#:u)
14/9	764.916	Ab	(Bb:o)
25/16	772.627	Ab	(E:n) (A:n) (B:n) (E:o) (A:o)
80/51	779.403	Ab	(A:u)
63/40	786.422	Ab	(Eb:o)
30/19	790.756	Ab	(B:u)
128/81	792.180	Ab	(Bb:n) (F:u) (Bb:u)
405/256	794.134	Ab	(D:n) (F#:n) (F#:o) (B:o)
19/12	795.558	Ab	(F:o)
51/32	806.910	Ab	(G:o)
8/5	813.686	Ab	(C:n) (C#:n) (Eb:n) (F:n) (G:n) (Ab:n) (C#:o) (Ab:o) (C:u) (Eb:u) (G:u) (Ab:u)
45/28	821.398	Ab	(F#:u)
13/8	840.528	Ab	(C:o)
512/315	840.950	Ab	(C#:u)
18/11	852.592	Ab	(D:u)
105/64	857.095	A	(E:o) (B:o)
64/39	857.517	A	(F:u)
33/20	866.959	A	(Eb:o)
5/3	884.359	A	(C:n) (E:n) (F:n) (A:n) (Bb:n) (B:n) (F:o) (A:o) (Bb:o) (E:u) (F#:u) (A:u) (B:u)
855/512	887.737	A	(F#:o)
256/153	891.135	A	(Bb:u)
32/19	902.487	A	(C:u)
27/16	905.865	A	(D:n) (Eb:n) (F#:n) (G:n) (C:o) (D:o) (G:o)
17/10	918.642	A	(Ab:o)
128/75	925.418	A	(C#:n) (Ab:n) (C#:u) (Ab:u)
12/7	933.129	A	(D:u) (G:u)
55/32	937.632	Bb	(E:o)
45/26	949.696	Bb	(F#:u)
26/15	952.259	A	(C#:o)
96/55	964.323	A	(Eb:u)
7/4	968.826	Bb	(C:o) (F:o)
225/128	976.537	Bb	(E:n) (F#:n) (B:n) (F#:o) (B:o)

30/17	983.313	Bb	(B:u)
85/48	989.314	Bb	(A:o)
16/9	996.090	Bb	(C:n) (C#:n) (F:n) (A:n) (Bb:n) (Bb:o) (C:u) (F:u) (G:u) (A:u) (Bb:u)
57/32	999.468	Bb	(G:o)
512/285	1014.218	Bb	(C#:u)
9/5	1017.596	Bb	(D:n) (Eb:n) (G:n) (Ab:n) (C#:o) (Eb:o) (Ab:o) (D:u)
20/11	1034.996	Bb	(E:u)
117/64	1044.438	Bb	(D:o)
64/35	1044.860	Bb	(Eb:u) (Ab:u)
11/6	1049.363	B	(F:o)
945/512	1061.005	B	(F#:o)
24/13	1061.427	B	(G:u)
28/15	1080.557	B	(C#:o)
15/8	1088.269	B	(C:n) (D:n) (E:n) (F:n) (F#:n) (G:n) (A:n) (B:n) (C:o) (E:o) (G:o) (A:o) (B:o) (F#:u) (B:u)
32/17	1095.045	B	(C:u)
17/9	1101.045	B	(Bb:o)
36/19	1106.397	B	(D:u)
256/135	1107.821	B	(C#:n) (Bb:n) (C#:u) (Ab:u) (Bb:u)
243/128	1109.775	B	(D:o)
19/10	1111.199	B	(Ab:o)
40/21	1115.533	B	(E:u) (A:u)
48/25	1129.328	B	(Eb:n) (Ab:n) (Eb:u)
495/256	1141.542	C	(F#:o)
64/33	1146.727	B	(F:u)
39/20	1156.169	B	(Eb:o)
63/32	1172.736	C	(D:o) (G:o)
128/65	1173.159	C	(Ab:u)
160/81	1178.494	C	(A:u)
2025/1024	1180.447	C	(F#:n)
95/48	1181.872	C	(A:o)
255/128	1193.224	C	(B:o)

Appendix B

Normal Scales												
	scale degree											
reference pitch	C	C#	D	Eb	E	F	F#	G	Ab	A	Bb	B
C	1/1	16/15	9/8	6/5	5/4	4/3	45/32	3/2	8/5	5/3	16/9	15/8
C#	1/1	16/15	256/225	6/5	32/25	4/3	64/45	3/2	8/5	128/75	16/9	256/135
D	1/1	135/128	9/8	6/5	81/64	27/20	45/32	3/2	405/256	27/16	9/5	15/8
Eb	1/1	16/15	9/8	6/5	32/25	27/20	36/25	3/2	8/5	27/16	9/5	48/25
E	1/1	25/24	10/9	75/64	5/4	4/3	45/32	3/2	25/16	5/3	225/128	15/8
F	1/1	16/15	10/9	32/27	5/4	4/3	64/45	3/2	8/5	5/3	16/9	15/8
F#	2025/1024	135/128	9/8	75/64	5/4	675/512	45/32	3/2	405/256	27/16	225/128	15/8
G	1/1	135/128	9/8	6/5	5/4	4/3	45/32	3/2	8/5	27/16	9/5	15/8
Ab	1/1	16/15	9/8	6/5	32/25	4/3	64/45	3/2	8/5	128/75	9/5	48/25
A	1/1	25/24	10/9	75/64	5/4	4/3	25/18	40/27	25/16	5/3	16/9	15/8
Bb	1/1	16/15	10/9	32/27	5/4	4/3	64/45	40/27	128/81	5/3	16/9	256/135
B	1/1	135/128	9/8	75/64	5/4	675/512	45/32	3/2	25/16	5/3	225/128	15/8

Otonal Scales												
	scale degree											
reference pitch	C	C#	D	Eb	E	F	F#	G	Ab	A	Bb	B
C	1/1	17/16	9/8	19/16	5/4	21/16	11/8	3/2	13/8	27/16	7/4	15/8
C#	1/1	16/15	17/15	6/5	19/15	4/3	7/5	22/15	8/5	26/15	9/5	28/15
D	63/32	135/128	9/8	153/128	81/64	171/128	45/32	189/128	99/64	27/16	117/64	243/128
Eb	81/80	21/20	9/8	6/5	51/40	27/20	57/40	3/2	63/40	33/20	9/5	39/20
E	65/64	135/128	35/32	75/64	5/4	85/64	45/32	95/64	25/16	105/64	55/32	15/8
F	1/1	13/12	9/8	7/6	5/4	4/3	17/12	3/2	19/12	5/3	7/4	11/6
F#	495/256	135/128	585/512	1215/1024	315/256	675/512	45/32	765/512	405/256	855/512	225/128	945/512
G	63/32	33/32	9/8	39/32	81/64	21/16	45/32	3/2	51/32	27/16	57/32	15/8
Ab	1/1	21/20	11/10	6/5	13/10	27/20	7/5	3/2	8/5	17/10	9/5	19/10
A	95/48	25/24	35/32	55/48	5/4	65/48	45/32	35/24	25/16	5/3	85/48	15/8
Bb	1/1	19/18	10/9	7/6	11/9	4/3	13/9	3/2	14/9	5/3	16/9	17/9
B	255/128	135/128	285/256	75/64	315/256	165/128	45/32	195/128	405/256	105/64	225/128	15/8

Utonal Scales												
	scale degree											
reference pitch	C	C#	D	Eb	E	F	F#	G	Ab	A	Bb	B
C	1/1	16/15	8/7	32/27	16/13	4/3	16/11	32/21	8/5	32/19	16/9	32/17
C#	256/255	16/15	256/225	128/105	512/405	256/195	64/45	256/165	512/315	128/75	512/285	256/135
D	1/1	18/17	9/8	6/5	9/7	4/3	18/13	3/2	18/11	12/7	9/5	36/19
Eb	96/95	16/15	96/85	6/5	32/25	48/35	64/45	96/65	8/5	96/55	64/35	48/25
E	1/1	20/19	10/9	20/17	5/4	4/3	10/7	40/27	20/13	5/3	20/11	40/21
F	64/63	16/15	64/57	32/27	64/51	4/3	64/45	32/21	128/81	64/39	16/9	64/33
F#	45/44	15/14	9/8	45/38	5/4	45/34	45/32	3/2	45/28	5/3	45/26	15/8
G	1/1	12/11	8/7	6/5	24/19	4/3	24/17	3/2	8/5	12/7	16/9	24/13
Ab	128/65	16/15	64/55	128/105	32/25	128/95	64/45	128/85	8/5	128/75	64/35	256/135
A	160/81	40/39	10/9	40/33	80/63	4/3	80/57	40/27	80/51	5/3	16/9	40/21
Bb	64/63	256/243	128/117	32/27	128/99	256/189	64/45	256/171	128/81	256/153	16/9	256/135
B	1/1	15/14	10/9	15/13	5/4	15/11	10/7	3/2	30/19	5/3	30/17	15/8

Concerning the Nature of Things

text by Paracelsus

Jeff Snyder


10
15
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
O
tune C
tune F (while playing)
tune C (while playing)

A
20
♩=72
♩=60
25
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
U
O
U
E - a est res vi - vens in qua om - ni - a na - tu - ra - li - a sunt in har- mo - ni - a et
E - a est res vi - vens in qua om - ni - a na - tu - ra - li - a sunt in har- mo - ni - a et
tune C
8ve 1
8ve 2

♩=72
30
35
B
♩=60
bl. I
bl. II
res. m.
tune D
O
tune A tune E
bs. m.
tune G
S.
mi - se - ri - cor - di - a
in ter__ se,
na - tu - ra___
T.
mi - se - ri - cor - di - a
in ter__ se,
na - tu - ra___
treb. c.v.
ten. c.v.
8ve 1

C
40
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune G
tune D
qua u - ni - ver - sum est,
u - na u - na est
8ve 3

45
♩=72
50
D
♩=60
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune D
tune D
O
tune A
D
A
D
A
D
or-i-gi-na que po-test so-lum es-se_ u-na u-ni-tas_ ae-ter-na.
or-i-gi-na que po-test so-lum es-se_ u-na u-ni-tas_ ae-ter-na.
(8ve 3)
8ve 1

bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
55
tune F
tune A
O
U
8ve 1
8ve 2
8ve 3


E
F
60
65
♩=72
♩=60
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune E
tune C
8ve 1
ma-kro kos - mos est,
om - ni - a fruc - tus


70
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune F#
tune A
u - nae co-na-ti - o-nis com mu-nis sol - ler - tis est.
u - nae co-na-ti - o-nis com mu-nis sol - ler - tis est.
8ve 2
8ve 1


G
H
75
80
bl. I
bl. II
res. m.
tune B
bs. m.
S.
T.
ma kro - kos - mos est ho - mi - nes-que mik ro - kos - mos est et sunt un - us
treb. c.v.
ten. c.v.
8ve 3


bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
85
90
I
tune F
tune A
tune D
tune E
♩=72
(8ve 3)
sunt u-num si-dus u-na im-pul-si-o u-nus spi-ri-tus
sunt u-num si-dus u-na im-pul-si-o u-nus spi-ri-tus


95
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
u - na har - mon-i - a u - na ae - tas u - num me tal - lum u - num mal lum


J ♩ = 92
100
105
K
110
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune G
U
tune Bb
O
tune C
"pizz." tune G
accents ad lib
tune C
U
tune G.
vit strem hom lis stral sam pres bal - sam les
ta pos ma mi - nis vi-de cet est ast le bal mus im si - o mi - ca co - el


L
115
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
O
si
ae - r(e)
spir
tin
stis et in vis bi lis ig - nis
in-clu-sus ae - r(e)
et ri-tus sa-lis cus
mp
p
mf
8vb


M
♩= 72
120
N
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
mf
p
p < mf
mf
tor tor a flux a
vi-ta_ com-pos-i - rum el-e-ment rum_ ut quae est e-i-us flux - i - o qua-si des-ti-tu tur


125
130
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune D
O
tune D
tune D
mort
est a-quae
tu - a
tune D
O
tune D
tune C
tune C
tune C
mp
f
p
mp
f
p
mp
f
p


O
♩ = 96
135
♩ = 84
140
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune C
tune C
qui ae si-ep vi is re ta tri
vi-ta dem ig-nis est ae-r(e) qui per sum vit a-li sque bus el-e-ment tis vi-tam bu-it.
switch to low octave
8ve 1
switch to normal octave

P
Q ♩= 96
145
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune Eb
ver
mort
ter - ra
ro
per
si-ep sum
est
tu - a


tune Eb
♩= 84
150
O
R
♩= 96
tune B
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
men si cul vi sing ben rand
sed ei - us el - e tum in vis bi-lis est et oc lta su - a ta qua gu - la ne con - si - der da sunt
8ve 2
p

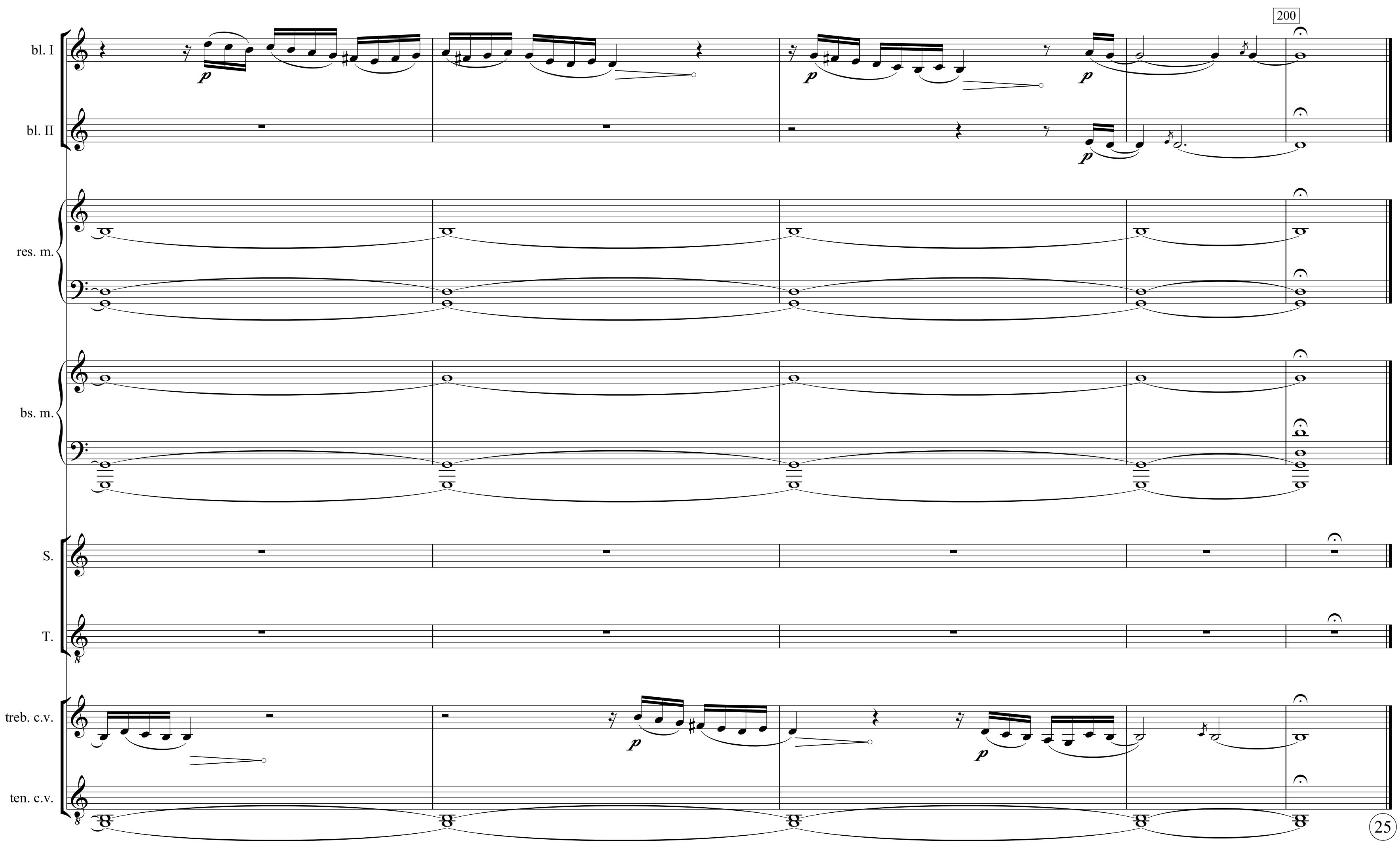

155
S ♩ = 60
160
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
arco
arco
mf
f
p
ni - hil est cor - por - a - lis qui non vim la ten pos - si - det ni - hil ex - sis - tit
ni - hil est cor - por - a - lis qui non vim la ten pos - si - det ni - hil ex - sis - tit
S ♩ = 60


T
♩=72
165
170
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune F#
tune D
in quo prin - ci - pi - a vi - tae ce - la - ta sunt
Ne - que sol - lum res quae mo - vent si - cut hom in - es que


♩=60
tune D
175
tune C
180
tune F
O
tune D
tune C
tune A O
tune C
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
an - i - mal - i - a ver - mes mun - di et a - ves aer - i - que pis - ces in a - qua
an - i - mal - i - a ver - mes mun - di et a - ves aer - i - que pis - ces in a - qua


U ♩=72
tune G 185
♩=60
V
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune G
subito
sed e - ti - am_ om - nis res cor - por - al - es et es - sen - ti - ae vi - tam_ ha - bent sed e - ti - am_ om -
tune G (8ve 2)

slightly slower
♩=60
190
195
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.
tune F
O
tune G
nis res cor-por-a-les et es sent-i-ae vi-tam ha-bent
nis res cor-por-a-les et es sent-i-ae vi-tam ha-bent
(8ve 2)


200
bl. I
bl. II
res. m.
bs. m.
S.
T.
treb. c.v.
ten. c.v.