CALIFORNIA INSTITUTE OF THE ARTS

The Scale Navigator

A Synesthetic Interface for Manipulating Harmony in Composition, Performance and Installation

by

Nathan Turczan

A thesis submitted in partial fulfillment for the degree of Master of Fine Arts

in the

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Music Technology: Interaction, Intelligence and Design

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Declaration of Authorship

I, NATHAN TURCZAN, declare that this thesis titled, 'THE SCALE NAVIGATOR: A SYNESTHETIC INTERFACE FOR MANIPULATING HARMONY IN COMPOSITION, PERFORMANCE AND INSTALLATION' and the work presented in it are my own. I confirm that:

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- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
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'It is needless to say that one who attacks the problem of modern harmony with the intention of rationalizing it will perhaps be considered presumptuous."

Horace Alden Miller

CALIFORNIA INSTITUTE OF THE ARTS

Abstract

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This thesis is about the Scale Navigator: a graphical interface implementation of Dmitri Tymoczko's scale network for audiences, performers and composers to interact with multi-media art. It is was also designed to help generate algorithmic harmony and harmonically synchronize performers in a laptop or electro-acoustic orchestra. The user manipulates the Scale Navigator to direct harmony on a chord-to-chord level and on a scale-to-scale level. In a live performance setting, the interface broadcasts control data, MIDI, and real-time notation to an ensemble of live electronic performers, sight-reading improvisers, and musical generative algorithms. ...

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Chapter 1

Introduction

In the search for new ways to express ourselves we extend existing artistic techniques and systems. Computer programs are tools well-suited to this endeavor, allowing artists to mathematically map out all possibilities within their chosen system of expression. Brute force computation is sometimes necessary to see how far the set of rules that constitute a given artistic language can go, and to predict the most likely points where these rules can be bent or broken. The next step is to search for commonalities and intersections between two or more sets of rules, thus deriving works that satisfy the criteria of multiple grammars of art.

This thesis is an attempt to extend musical harmony using software methods, specifically the author's "Scale Navigator" web application, detailing the development of these methods and their applications in performance, composition, and audience participation. First, though, some context and clarification is needed. Borrowing from Wikipedia, music is defined here as "the art form and cultural activity whose medium is sound organized in time" [1]. From this definition, we infer that sound and duration are the two most basic materials that comprise music, and that all other higher-level elements of music such as harmony, formal structure, rhythm, tempo, texture, timbre, orchestration, or dynamics are categorizations for dealing with sound, duration, or the inter-relationship of the two. Harmony deals with the simultaneous occurrence of more than one sound to create chords, or many chords arranged in time.

Stravinsky said, "The more constraints one imposes, the more one frees one's self. And the arbitrariness of the constraint serves only to obtain precision of execution" [2]. Harmonic constraints of the past, such as Tonality or Serialism, are communicatively useful for their emotional and cultural associations. Therefore, our way forward harmonically must include extending old patterns of harmony to their breaking points, following each pattern's internal logic until we begin to find points of connection among them. In this

way we can construct music that can literally say different things to different audiences at the same time. We can delineate roadmaps of modulation not only between musical keys, but between modes, ragas, chords, or any other combination of tones in any number of tunings. In the same way that English is an amalgamation of several languages, so too will our harmony of the future encompass many harmonic dialects.

Any given harmonic language is a set of rules for organizing notes sounding simultaneously, but ultimately this language is a means of expression and therefore plastic, moldable to the will of the composer. Harmonic languages must be given a chance to morph to better convey the composer's thoughts and feelings to an ever changing culture, giving rise to new idioms. As the field of harmony extends to encompass more languages, systems, and algorithms, tools become more and more necessary to the composer in their search for new idioms. Geometry and graph theory and other methods for visualizing harmony can be of invaluable assistance: after all, tonality is built around the circle of fifths. This simple circle is a gentle introduction to geometric representations of musical relationships and the idea of "pitch space." What sort of models of pitch space become necessary in a musical culture that has moved beyond tonality, beyond the circle of fifths, or beyond 12-notes per octave into microtonality?

1.1 The Synesthetic Interface

The concept of pitch space—defined here as visual representation of sonic relationships—is synesthetic, conflating dimension with frequency. To quote Bacchius, an ancient Greek music theorist: "And what is a diagram? A representation of a musical system. And we use a diagram so that, for students of the subject, matters which are hard to grasp with the hearing may appear before their eyes" [3].

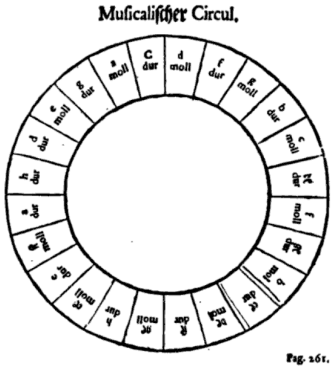


FIGURE 1.1: Heinichen's musical circle

Various models of pitch space in any number of dimensions have been proposed: lattices, circles (Figure 1.1), helices, networks, orbifolds, Tonnetze, Venn diagrams (Figure 1.2),

Möbius strips. Color, shapes, position, and texture are possible parameters for synesthetic mapping that may be integrated into the pitch space model. It is logical that the usefulness of these models increases when they are made interactive, and so the next step is the creation of synesthetic interfaces for manipulating harmony—perhaps elevating the model from learning tool to expressive instrument.

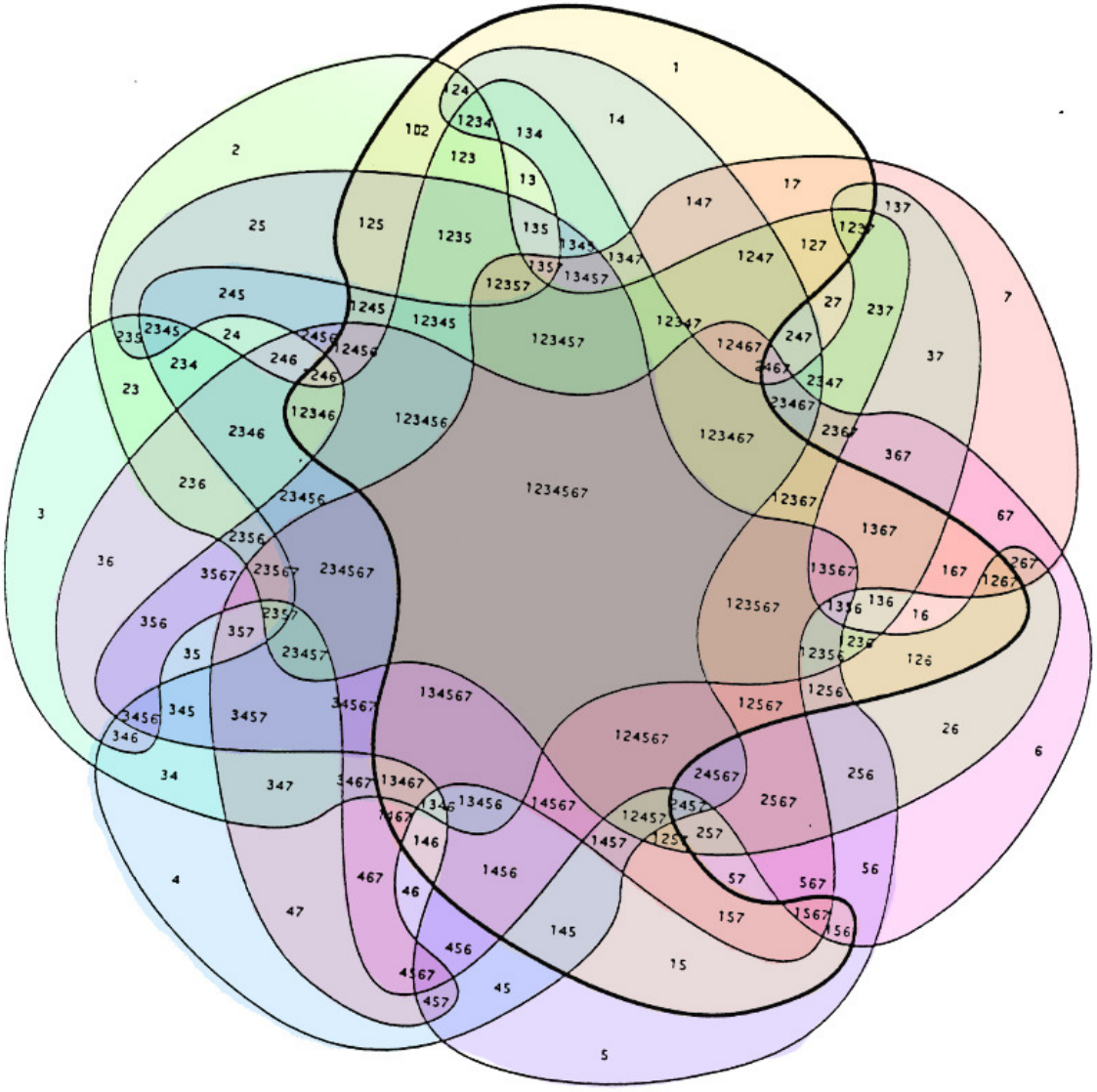


FIGURE 1.2: 7-way venn diagram

Ian Jones defines synesthetic interfaces as "interfaces that enact a sensory substitution by translating information normally accessed through one sense modality into the phenomenal forms associated with another" [4]. Interfaces such as these are well suited to the analysis and creation of information-dense media such as music.

FIGURE 1.3: Synesthetic interface in The Legend of Zelda: Twilight Princess in which scent is represented visually, as a trail

1.2 Thesis Outline

The writing that follows details the authors attempts at integration of the design of a synesthetic software harmony interface—called the Scale Navigator–with his artistic practice. Chapter 2 is a record of the author's influences in the field of harmony, form, and networked music, listing several composers and describing their respective harmonic languages or approaches to musical form and their impact on the design of the Scale Navigator. This chapter also includes a section discussing an existing body of works and research in the field of networked music as pertaining to the realtime score, or "screen score," and how these have influences the design of the Scale Navigator as a tool for harmonically synchronizing ensembles. Chapter 3 documents the design of the Scale Navigator, it's parent network the Scale Navigator Live Performance Network, and it's sibling Client Page. This chapter also explains the Scale Navigator's functionality for chord progression generation. Chapter 4 is a deep dive into composing with the Scale Navigator, using the author's vocal work *Network Impressions* and its subsequent iteration *Heptagrams* to highlight advantages and flaws in the interface. Chapter 5 showcases the author's ensemble piece for the CalArts Machine Orchestra *INTERSTICES* and the pivotal role of the Scale Navigator in harmonically synchronizing the group. Chapter 6 is a discussion of the Scale Navigator as an interface for audience participation in two of the authors audiovisual installations, *Modal Intersections* and *Thought Loops*. Chapter 7 concludes this thesis with some possible future directions for the Scale Navigator.

Chapter 2

Influences

The first section of this chapter takes a look at the various composers whose harmonic language has influenced the author in the creation of the Scale Navigator. Following this section on harmony is a section detailing the composers who influenced the author's software methods for guiding musical form, followed by a catalog of influences regarding networked delivery systems for digital musical scores.

2.1 Harmonic Language

What constitutes a composer's harmonic language? The author's attempt at answering this question is undoubtedly biased by a fascination with the expansion of western tonality, presupposing that a harmonic language can only be defined by its relationship with "Common Practice", or the major-minor functional tonality shared by much of the western canon after 1600. In Yuri Kholopov's words—as translated into English by Philip Ewel—a harmonic system or language is defined by "those fundamental principles, the totality of which encompasses the composer's entire harmonic thinking in its most important forms" [5]. The following is an attempt by the author to list these "fundamental principals":

- chord progressions / sequences
- harmonic rhythm
- variety and quality of chords / simultaneities commonly used
- chord extensions / alterations
- chord voicings

- chord functionality
- non-normative sonorites, non-chord tones
- modulations
- use of passing chords, secondary dominants, modal mixture
- use of modes / scales
- use of non-tonal methods, such as set theory, serialist techniques, or other miscellaneous and possibly intuitive means

Before the early 20th century, there was no expectation that a composer would have a coherent, distinct, individual, or consistent harmonic language apart from tonality. A composer's approach to the harmonic procedures listed above would have fallen within the imitations of Common Practice, leaving only style and execution to differentiate the composer from their peers.

Wagner's radical tonal expansion is seen as the spark that eventually led to Schoenberg's elimination of tonality, opening the floodgates for composers to experiment with establishing other harmonic systems: Bartók's axis system [6], Hindemith's unique system of overtone-derived consonance hierarchies [7], Joseph Schillinger's Kaleidophonic system of musical composition, Milhaud's polytonality [8], Messiaen's symmetrical approach to scales [9], or Stravinsky's outright rejection of harmony in favor of counterpoint, which he believed to represent "the true constructive material" of music [5].

At some point, harmonic language became culturally loaded. Associations began to attach themselves to certain harmonic languages, and genres organically began to grow around these (e.g. Blues growing from the twelve-bar blues progression). Composers began to mix and match different systems of harmony as a way to communicate with an audience through a language of associations. Alfred Schnittke embraced this aesthetic and called it "Polystylism," applying wildly contrasting harmonic and compositional techniques within a single piece: traditional functional harmonies evoking Bach one moment, serialism or aleatory in the style of Cage or Stockhausen in the next moment [10]. Daniel Lopatin, aka Oneohtrix Point Never, weighs in on polystylism in his 2014 Reddit AMA: "there's a lot i guess but it boils down to dealing w/ genre in a material way...manipulating the affects themselves, instead of being used by them, to reinforce their stereotypes, histories, etc" [11].

While future synesthetic interfaces for manipulating harmony will include methods for navigating the other harmonic languages listed above, perhaps giving the user the ability to polystilistically modulate from language to language, this thesis is limited in its scope

to a harmonic interface firmly rooted in 2019: The Scale Navigator. The following sections detail the various harmonic languages that influenced the Scale Navigator's design, chiefly Dmitri Tymoczko's scale network concept and the chordal vocabulary of Bill Boyd's *Jazz Chord Progressions*. A lot more software is required to fully emulate the harmonic language of some of the other composers mentioned in this chapter, and so these are listed as stylistic influences on the kinds of music that the Scale Navigator can create when integrated with software modules for form, melody, texture, etc.

2.1.1 Scale Networks and Tymoczko

Dmitri Tymoczko's 2004 paper *Scale Networks and Debussy* is all about "depicting an abstract, precompositional space within which Debussy's music moves" [12]. The Scale Navigator is the author's attempt to turn that abstract, precompositional space into a playground where anyone can explore. Tymoczko writes of "maximally intersecting" scalar relationships: scales maximally intersect if they share 6 notes in common, and if the odd note out differs by only a half step. This is how Diatonic scales are connected to each other in the familiar circle of fifths, and this pattern also reveals relationships to other similarly triadic scales: Acoustic, Harmonic Major, and Harmonic Minor (Figure 2.1). A more in depth explanation and discussion of the relationship of this harmonic language to the Scale Navigator can be found in Section 3.2.1: Scale Navigator Interface.

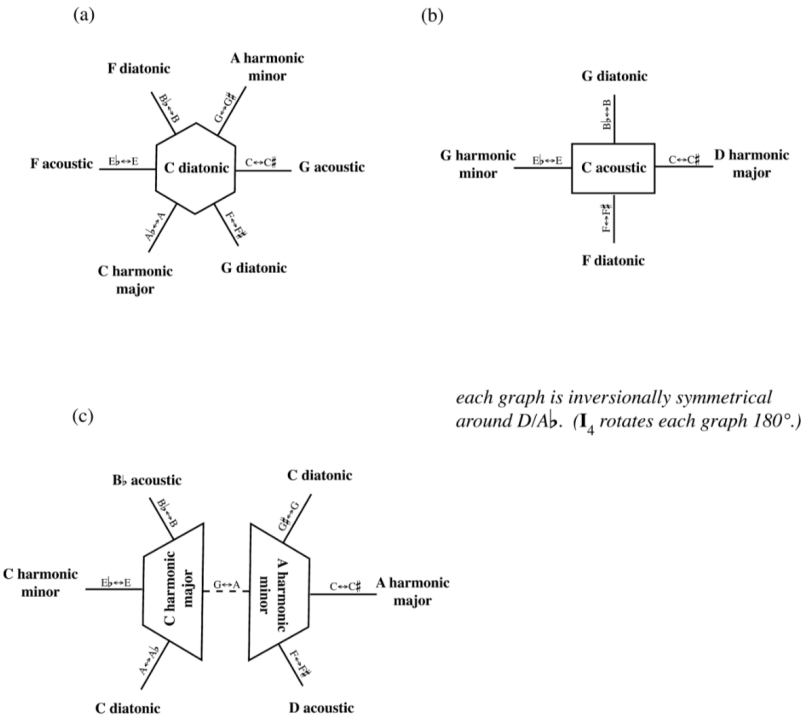


FIGURE 2.1: seven-note Pressing scales and their maximally intersecting neighbors

The scale network framework has found a lot of application for analysis in the realms of impressionism and jazz. Keith Waters applies a scale network to analyze the use of modes, scales, and modulation in the music of Herbie Hancock [13]. Steven Strunk also uses this method to analyze Wayne Shorter's approach to scales and modes [14].

Much of Tymoczko's research is about how harmony and counterpoint can be described as efficient movements in higher dimensional space. His 2006 book *The Geometry of Musical Chords*, for example, explores how chord relationships can be represented in three-dimensional cubic lattices [15].

2.1.2 Bill Boyd's Jazz Lexicon

The Scale Navigator's chord generator draws from a vocabulary of one hundred and thirteen distinct jazz chord voicings (and their twelve transpositions) catalogued in Bill Boyd's *Jazz Chord Progressions* [16]. All of these chords are triads with extensions or alterations, and exist as subsets of scales such as Diatonic, Acoustic, etc. A more in depth explanation of how the Scale Navigator generates progressions with these chords can be found Section 3.2.2: Chord Generator.

Part of Boyd's taxonomy of jazz chords includes a "Position" designation for each chord, of which there are two: Position 1, with the third of the chord as the bottom note in the right hand (Figure 2.2):

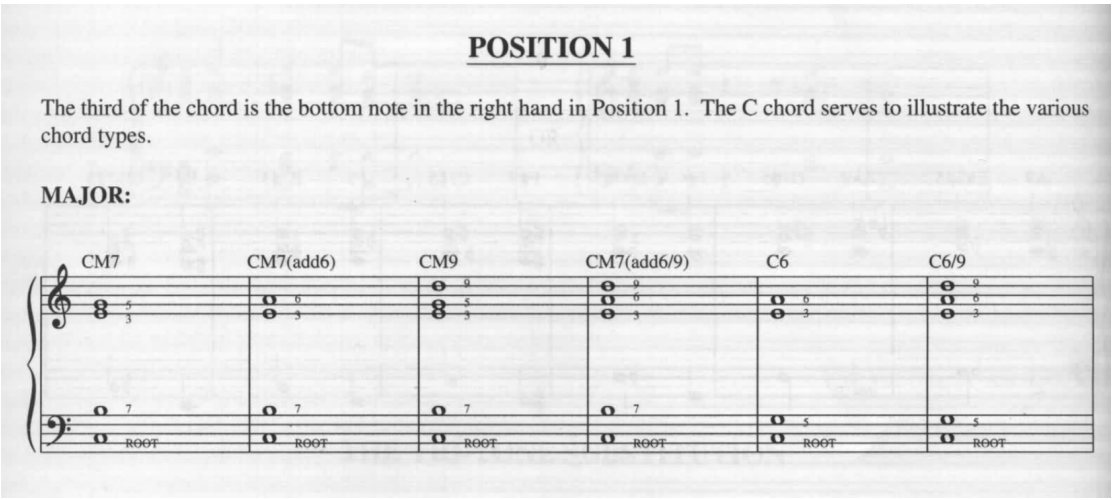


FIGURE 2.2: excerpt from *Jazz Chord Progressions* with examples illustrating Position 1

and Position 2, which has the seventh of the chord as the bottom of the right hand (Figure 2.3):

Boyd gives instructions as to how to arrange these sonorities in a progression (Figure 2.4)

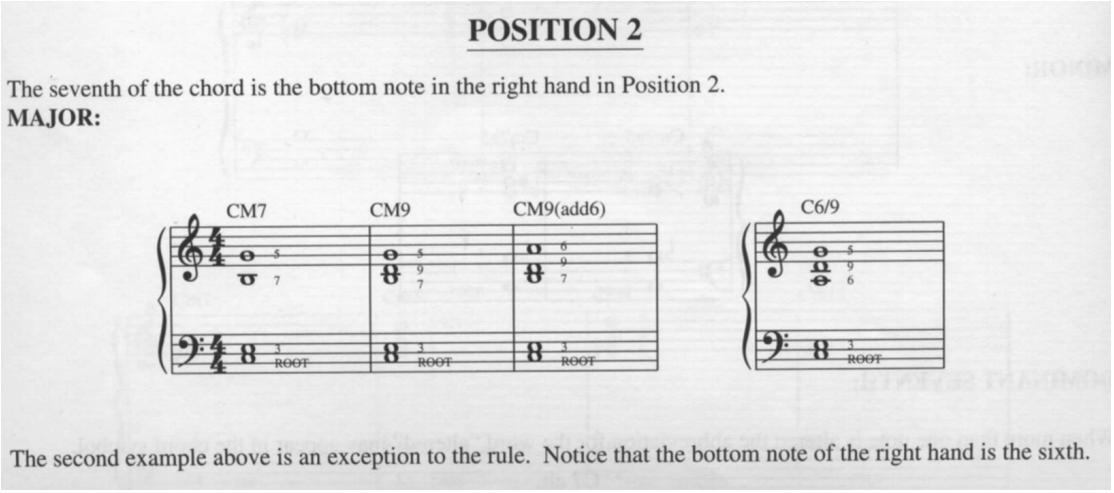


FIGURE 2.3: excerpt from *Jazz Chord Progressions* with examples illustrating Position 2

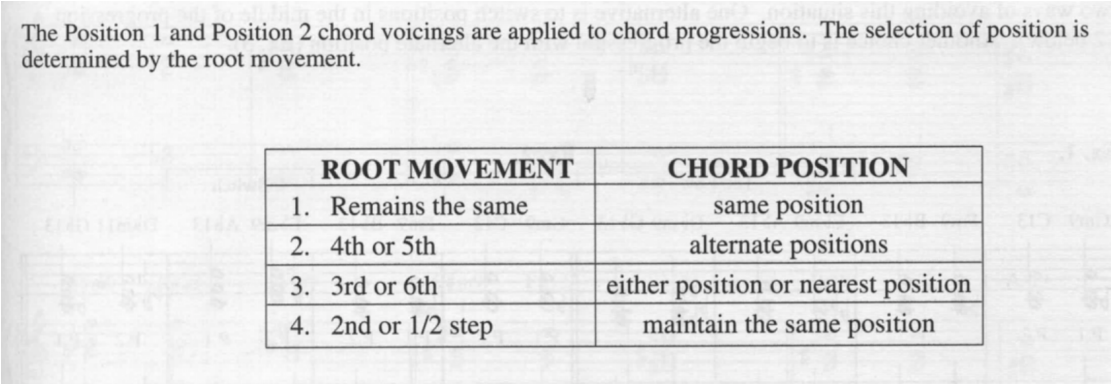


FIGURE 2.4: table from *Jazz Chord Progressions* showing rules for chord choice based on root movement

2.1.3 Claude Debussy

As previously stated, The Scale Navigator is a synesthetic interface for manipulating harmony that borrows from Tymoczko's representation of Debussy's "abstract, precompositional" harmonic method. This section addresses Debussy's harmonic and compositional methods.

Debussy was absolutely a musical innovator, especially in the field of harmony. Building upon Wagner's progressive harmonic language, Debussy forged ahead with a tonality without "the fixed need for chordal or intervallic resolution ... resulting in the free play of any chromatic interval above a root." [17]. Debussy's mature style, Matthew Aucoin writes, "bears the stamp of an unmistakable sensibility: sensual, tender, alternately delicate and lush, it reveals a wizardly gift for draining familiar tonal harmonies of their usual stability and suspending them gorgeously in midair" [18].

Nahre Sol agrees with this sentiment in her excellent 2018 YouTube video *How to Sound Like Debussy*, noting that frequent use of unstable—though still tertian—chords in a non-functional way is one of Debussy's hallmarks. She goes on to note a few other compositional techniques that distinguish his style [19]:

- Frequent use of harp-like arpeggiated cascades supported by resonant basslines, often in fifths.
- Tasteful application of space, emptiness, and silence. Debussy was a master of ambience and mood.
- Use of subtle and tonal centers that are often ambiguous, modulating among them non-functionally.
- An inclination toward plagal chordal movement, generally eschewing the typical V-I cadence.
- Use of tremolos and rhythmic variation in general with an aim at de-stabilizing a sense of pulse.
- An affinity for "exotic" (at least in Debussy's time) modes and scales. In Tymoczko's words, "He makes most frequent use of just four scales—diatonic, pentatonic, acoustic, and whole-tone. Other scales, such as the octatonic, harmonic major, and harmonic minor, appear much less frequently. (Debussy almost never used the hexatonic scale.)" [12]
- Gestures evoking the resonant tolling of bells.
- Frequent use of the technique of harmonic planing, or as Tymoczko puts it: "his harmonies frequently move in parallel within a scale."

As discussed in Section 2.1.1, Tymoczko's *Scale Networks and Debussy* paper endeavors to create a framework describing Debussy's approach to modulation, pointing out his ever present exploitation of maximally-intersecting, voice-leading and common-tone relationships among Pressing scales. For example, Tymoczko's diagrammatic analysis of "Le vent dans la plaine" (Figure 2.5) clearly depicts the piece's various islands of tonality and the efficient means by which Debussy voyages from one to the other. On the French composer's scalar harmonic rhythm, i.e. the length of time spent at each island of tonality before sailing on to the next, Tymoczko writes, "Debussy tends to change scales reasonably slowly. One often hears several measures of music conforming to a single scalar collection, in which all of the scale's pitches appear" [12].

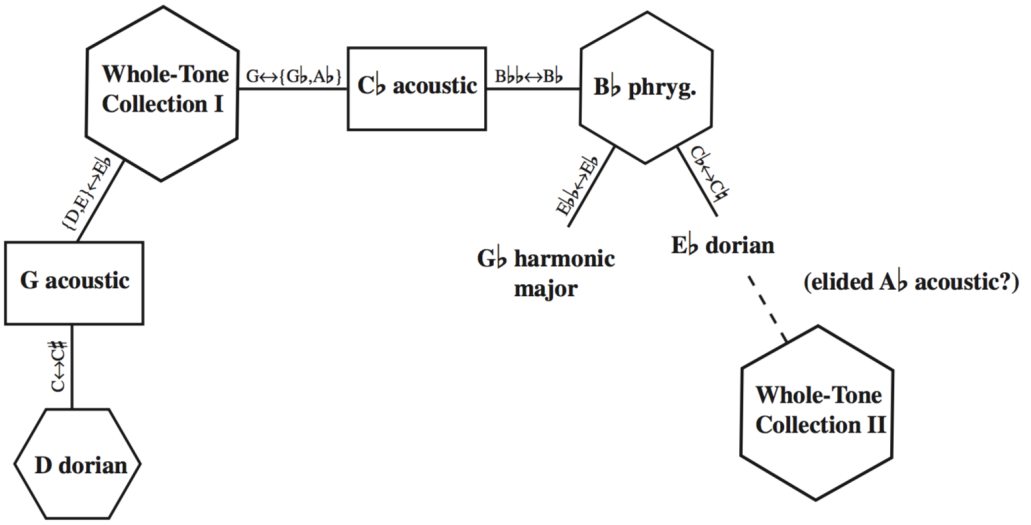


FIGURE 2.5: scale map in Debussy's *Le vent dans la plaine*

Musicologists have long suspected that Debussy's approach to formal structure involved a conscious application ofφ, also called the Golden Ratio: the length of certain passages, when compared to each other in the context of the length of the piece, certainly seem to approximate this mathematical relationship. A deeper discussion of musical form as it relates to φ can be found in Section 2.2.2 Bartók and φ.

2.1.4 Nicolas Slonimsky and Pandiatonicism

The author first came across the term "Pandiatonicism" in Nicolas Slonimsky's 1947 work *Thesaurus of Scales and Melodic Patterns* [20]. Woodward defines Pandiatonicism on a basic level as "free use of the pitches of a diatonic scale," further explaining it as a system for "creating melodic tonality through a hierarchy and tendency tones of a diatonic scale, and creating harmony that fluctuates between dissonance and consonance while using only the notes of a diatonic scale thus avoiding the use of traditional triadic harmony" [21].

It should be noted that Richard Grayson—American composer, pianist, and educator—writes at length about pandiatonicism in his 2014 short instructional handbook *Improvising at the Keyboard* [22], defining the term as "the use of diatonic (7-note) scales without reference to conventional chords or tonality" and providing several illustrative examples in eight different keys, showing how a pandiatonic doesn't have to emphasize triads or chord-tones (Figure 2.6).

The author's *INTERSTICES* for electro-acoustic orchestra is pandiatonic in the sense that any performer may freely play the pitches of whichever seven-note scale is currently selected by the conductor. A more in depth explanation of *INTERSTICES*, pandiatonicism and the Scale Navigator can be found in Section 6: *INTERSTICES*.

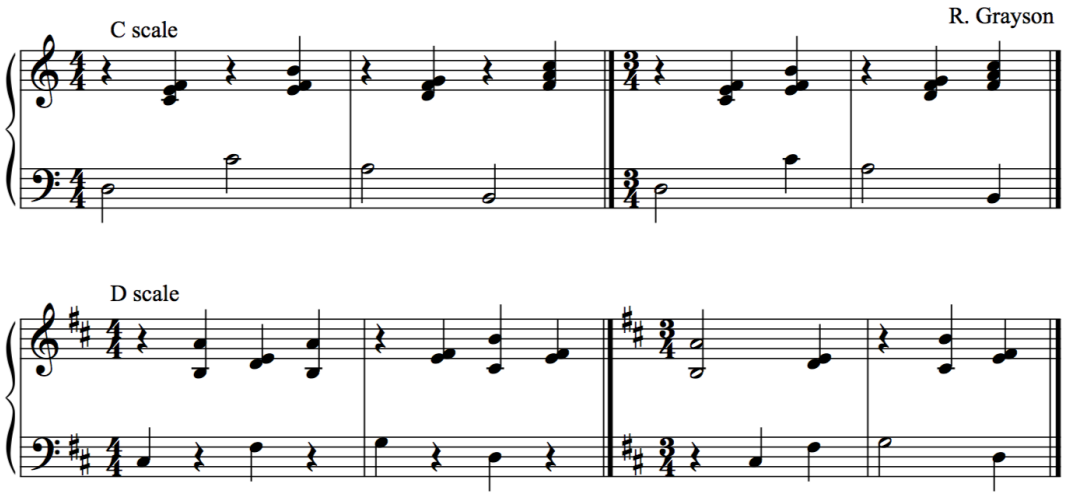


FIGURE 2.6: excerpt from *Improvising at the Keyboard* with two pandiatonic examples in two time signatures

2.2 Formal Structure

Harmony does not exist in a vacuum. It springs out of the silent void, existing suddenly where there was none before. For a while it flows, changes, and progresses, and then ceases. This is the beginning, middle, and end that comprises the formal structure of music.

The form of a musical work, whether it be meticulously planned out as a composition or improvised in the moment of performance, can be discerned by paying attention to the controlled repetition, temporization and development of musical materials in the piece: phythm, melody, texture, orchestration, etc. Harmony is another parameter that contributes to articulation of form, e.g. the first section introduces a theme in one key and the second section presents a new theme in a contrasting key.

All of this is to say that the Scale Navigator needs an accompanying system for wrangling the harmony it creates into a beginning, middle and end for the resultant music to be called a piece of music and not a scalar exercise. This section is a discussion of the formal techniques of Bela Bartók and Brian Eno that have influenced the author's approach to musical structure.

2.2.1 Bartók and φ

Hungarian musicologist Ernö Lendvai was the first to point out the influence of the Golden Ratio on aspects of Bartók's music: the structure of pieces, where climaxes occur, and phrasing (Figure 2.7). Lendvai defined the Golden Ratio as "...the division of a distance in such a way that the proportion of the whole length to the larger part corresponds geometrically to the proportion of the larger part to the smaller part, i.e. the larger part is the *geometric mean* of the whole length and the smaller part" [6].

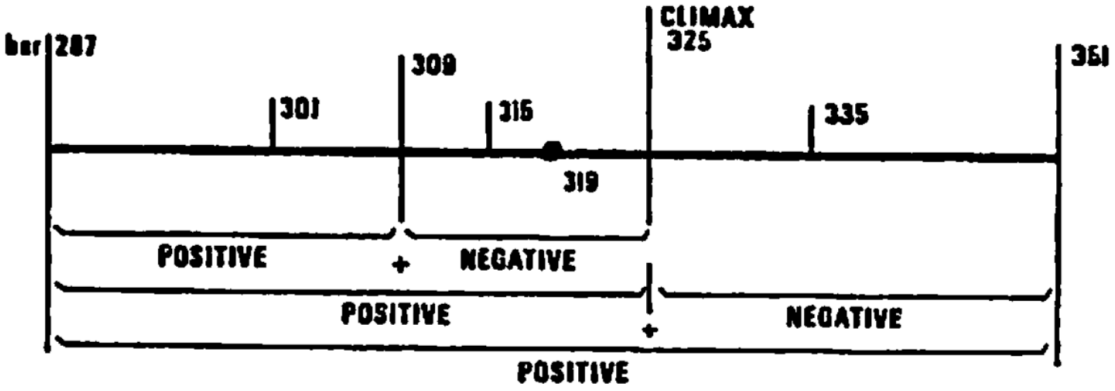


FIGURE 2.7: lendvais analysis of golden mean form, each section can be broken up into positive and negative sections

Other than Lendvai's analyses, there is only anecdotal evidence to back up the claim that Bartók used φ consciously to organize his music, though Bartók did have a love for nature, and a deep fascination for insects, minerals, and plants—particularly sunflowers and fir-cones (famous for their growth patterns' correlation to φ). Bartók wrote on the relationship between the natural and the musical in his 1925 essay *At the Sources of Folk Music* [23]:

> We follow nature in composition ... folk music is a phenomenon of nature. Its formations developed as spontaneously as other living natural organisms: the flowers, animals, etc.

Lendvai's structural diagrams of Bartók's music was hugely influential on the way the author constructed the form of electro-acoustic orchestral piece *INTERSTICES*. The author first determined the length of the piece, then divided the piece up into sections according to the Golden Ratio. See Figure 2.7 for how the length of each section—and each successive subsection—was calculated.

```
180 => int length; //the length of the piece
(1 + Math.sqrt(5))/2 => float phi; //define phi

length/phi => float A; //the length of the piece divided by phi gives the length of the larger "positive" part,
length - A => float B; //the lenth of the piece minus the larger part gives the length of the smaller "negative" part

A/phi => float AA; //further subdivisions of the subdivisions by the same process
A - AA => float AB;

B/phi => float BA;
B - BA => float BB;

AA/phi => float AAA;
AA - AAA => float AAB;

AB/phi => float ABA;
AB - ABA => float ABB;

BB/phi => float BAA;
BB - BAA => float BAB;
```

FIGURE 2.8: using the ChucK language to calculate the sections of a given length according to the golden ratio

2.2.2 Brian Eno

Site-specific interactive installations that feature music as a prominent component pose a structural challenge to composers: what's the best way to structure this music when 1. the installation is up for a long period of time (in the case of *Modal Intersections* and *Thought Loops*, one week each), 2. the audience members decide how much time they spend in the space, and 3. there is an opportunity for the music to feature interaction and unpredictability? What kind of form can reinforce the music's relationship "to a sense of place - landscape, environment..." [24]?

The author use technology to assist with the real-time improvisation aspects of *Modal Intersections* and *Thought Loops*, including the Scale Navigator interface in the installations through which the audience participated in the generation and development of music and visuals. The author was heavily influenced in this approach by Brian Eno's essay *Generating and Organizing Variety in the Arts*, in that the piece was governed by a generative system: set it up, lock in formal constraints, define parameters and cosmological constants and the audience plays in this multimedia playground–or, if there are no people present, it plays itself.

This kind of experience is drastically different from recorded media—that is, arrangements of sound, visuals, or combinations thereof frozen in time that remain unchanged. The author's installations mentioned above were constantly changing: while some aspects did recur, there were large-scale formal consequences to every interaction an audience member had with the system.

The author believes strongly that the future of music is generative and interactive; recorded media already beginning to share market space with software that governs dynamic multi-media systems offering unparalleled new levels of abstraction/ expression

to art, opening up exciting possibilities for real time interaction and personalization (Brian Eno and Peter Chilvers' application for iOS and Android 'Bloom: 10 Worlds' comes to mind).

2.3 Network Music, Screen Scores

The web browser is a fantastic platform for music performance. JavaScript has a multitude of libraries available for communication, building interfaces, synthesizing or sampling audio, or networking groups of people so that they might collaborate on a project [25].

Designers of musical systems might take advantage of the internet "to connect physical spaces or instruments" or to integrate the physical with "virtual environments, or ... virtual instruments" [26]. These designers could use "the Internet to enable collaborative composition or performance," delivering this music to audiences via the internet "with varying degrees of user interactivity" [26].

All of these tools can be integrated with a digital musical score, giving performers unprecedented ways of collaborating musically. This technology affords the possibility for the score to be animated, or to change, transform, or otherwise communicate with its sight readers in real time. Lindsay Vickery calls this the "Screen Score" [27].

Quintet.net is an interactive networked performance environment that involves a screen score and all the other capabilities afforded by the web browser previously listed in this section. In the words of its inventor, Georg Hajdu [28]:

> It enables up to five performers to play music over the Internet under the control of a "conductor." The environment, which was programmed with the graphical programming language Max/MSP consists of four components: the Server, the Client, the Conductor and the Listener. In addition, there is a Viewer add-on for the Client and Listener components .... In addition, a sixth performer, the conductor, can control the musical outcome by changing settings remotely and sending streams of parameter values either manually or by utilizing a timeline ... Quintet.net's notation layer allows for better interaction and control on a symbolical level: The performers see the music that the participants produce on screen in "space" notation on five grand staves. The conductor can also send musical parts, which are displayed on screen and played back by the performers–all in real time.

Chapter 3

The Scale Navigator

3.1 Introduction

Dmitri Tymoczko describes a system of interconnected "Pressing scales" inclusive of all twelve transpositions of the Diatonic [024579e], Acoustic [024679t], Harmonic Major [024578e], and Harmonic Minor [023578e] scale classes, both transpositions of the Whole-tone [02468t] scale class, all three transpositions of the Octatonic [0134679t] scale class, and all four transpositions of the Hexatonic [014589] scale class [12]. Pressing scales meet both NCS and DT requirements, defined as follows:

- NCS: No consecutive semitones: no scale may contain two consecutive semitones between scale steps
- DT: Diatonic thirds — any notes two scale steps apart must be either a minor third or major third

Tymoczko organizes all the possible transpositions of these Pressing scale classes—numbering fifty-seven—as nodes in a network (Figure 3.1). Two scales are connected if one can be transformed to the other by altering one note by a single semitone. As an example, C Diatonic has six notes in common with G Diatonic, differing by only the semi-tone between the F and the F♯, respectively. Diatonic scales have six neighbors, and the other three scale classes all have four (see Figure 2.1 in Section 2.1.1). Tymoczko calls this relationship "maximally intersecting voice leading." This concept is closely related to the idea of "parsimony," discussed in Section 7.3.

The author chose to limit the Scale Navigator's network to only the the seven-note pressing scales classes, of which there are four (with twelve transpositions each, numbering

forty-eight in total): Diatonic, Acoustic, Harmonic Major and Harmonic Minor. For the purposes of this paper, the "scale network" (Figure 3.2) will apply only to this limited network of forty-eight scales.

Much like the circle of fifths, the described scale network is a geometric visualization of scalar relationships. The circle of fifths is in fact one possible Diatonic-only pathway through the scale network, though the structure also contains connections to Acoustic, Harmonic Major and Harmonic Minor. These "synthetic scales" differ from the Diatonic scale class by only one note; they are still highly triadic and familiar.

Tymoczko's scale network is a framework for diverse approaches to harmony. It can be used to analyze and create tonal works because it encompasses the circle of fifths. If one ignores harmonic functionality, one can use the scale network to find connections to scales that would be impossible to modulate to under the restrictions of tonality. If one dispenses with triads, the scale network can be used in conjunction with diatonic set technique or pandiatonicism to find exciting new chordal possibilities.

For an electro-acoustic orchestra or laptop ensemble to perform the kind of post-tonal diatonic music described above, there needs to be a system in place for harmonic synchronization of players over a Local and/or Wide Area Network. The system must also

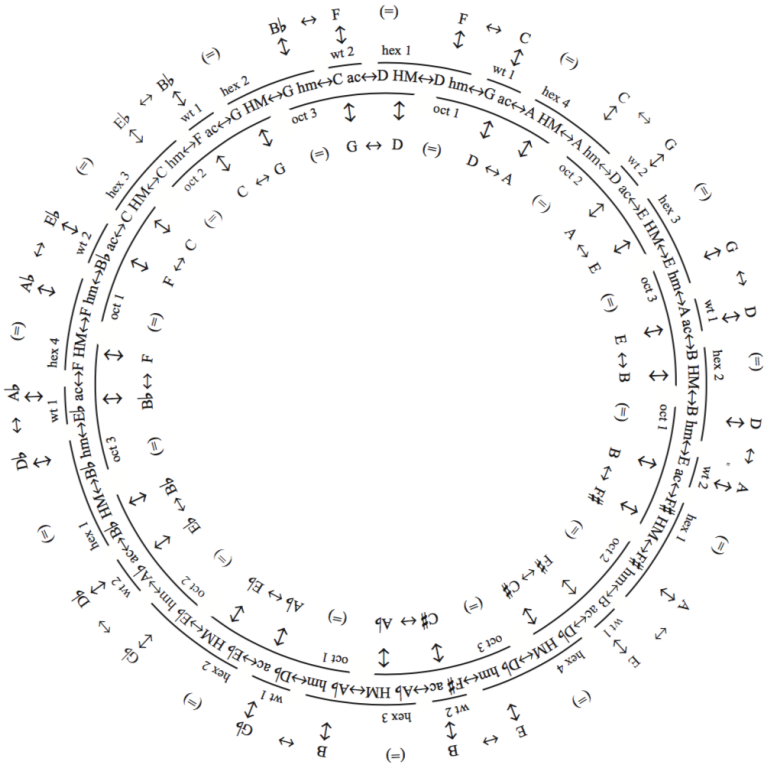


FIGURE 3.1: fully inclusive Pressing scale circle diagram

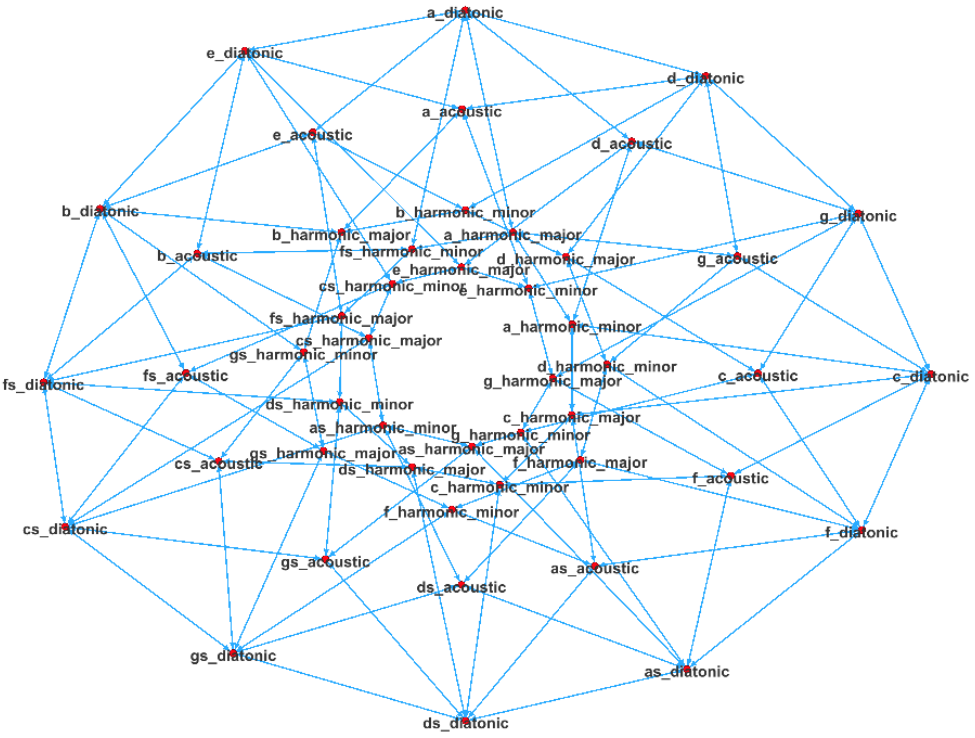


FIGURE 3.2: the torus of the 48 scale nodes

feature a way to deliver realtime scores to sight-reading instrumentalists. In this context, the realtime score is "any notation, either traditional or graphic, which is created or transformed during an actual musical performance" [29]. As these are inevitably read on a laptop, iPad, television or projector screen, we will for the purposes of this paper refer to them as "screen scores." Lindsay Vickery divides the screen score into four types: Scrolling[1], Permutative, Transformative, and Generative [27]. As the Scale Navigator does not emphasize rhythmic synchronization, its interface makes use of the transformative only.

Other systems for networked computer music performances designed around the screen score include Georg Hajdu's Quintet.net [28], Gerhard Winkler's Realtime-Score [31], and Rob Canning's NodeScore [32]. These systems do not focus on harmony as an all-important global parameter, and instead emphasize remote collaboration, graphic and non-traditional notation, and interactivity.

Thus far there has been little emphasis placed on harmonic synchronization, and the kinds of harmonic languages listed above have not been explicitly explored in a laptop

[1]Rob Canning's Parallax Score Server, which coordinates musicians playing at different tempos to enable "Liqetiesque polyrhythmic ensemble textures" [30], employs a scrolling screen score model.

ensemble context, hence the need for the Scale Navigator and its Live Performance Network.

In the following sections we discuss the Scale Navigator's design, detailing the methods it uses to modulate scales, generate chords, and network with other musicians as well as its overall UI. We also describe three ways the Scale Navigator was employed in three pieces by author Nathan Turczan, and recount their varying levels of success.

3.2 Design

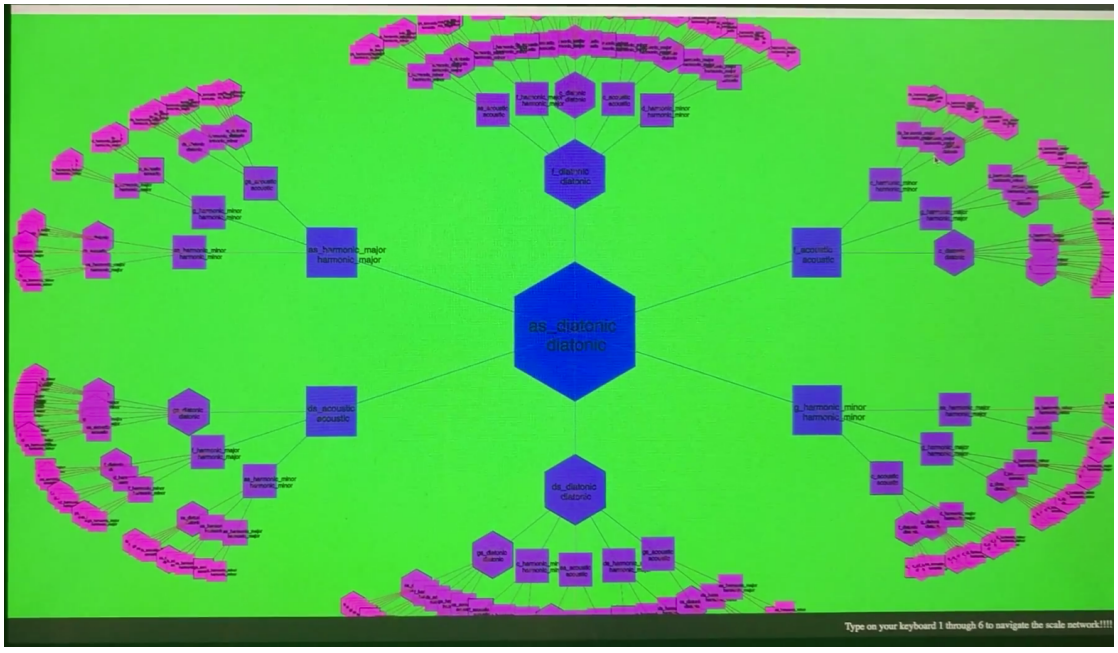


FIGURE 3.3: an early version of the Scale Navigator user interface, showing 4 generations of children

This section details the Scale Navigator as a web based application for composing, producing, and performing from a user interface design standpoint. It also describes the network infrastructure by which the Scale Navigator harmonically synchronizes screen scores distributed throughout the network.

3.2.1 Scale Navigator Interface

The Scale Navigator has a web interface that presents the scale network in visual format. Publicly available on author Nathan Turczan's website[2], it features sliders, checkboxes, clickable shapes, and clickable text to control harmony (Figure 3.4).

[2]https://www.nathanturczan.com/visualizer/index.html

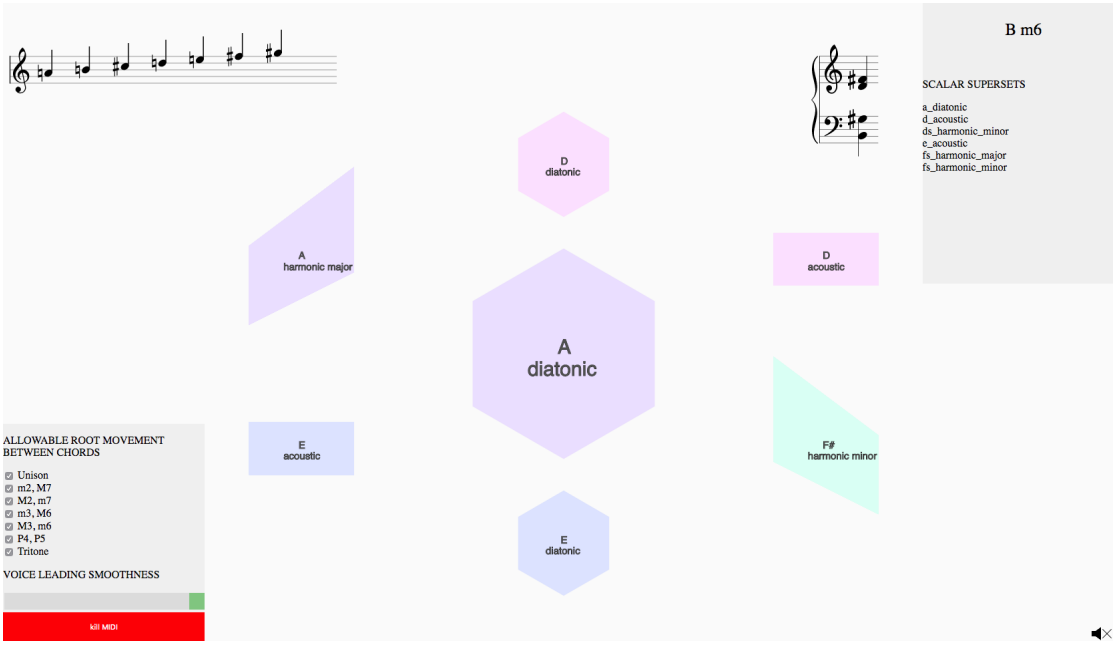


FIGURE 3.4: Scale Navigator user interface

Its functionality as a framework for smooth modulation between scales assists the composer's decision-making on a scale-to-scale level. The selected scale is in the center of the interface, radially surrounded by adjacent neighbor scales. Clicking on an adjacent scale (or scalar superset) selects a new scale and a new chord from that scale (this chord generation process is detailed in section 2.2).

Each scale in the Scale Navigator is represented by a clickable polygonal-shaped node. The scale's number of adjacent neighbors determines the number of sides its shape has. The hexagon represents Diatonic scales because they have six locally adjacent scale neighbors. Similarly, we chose the rectangle to represent four-neighbored Acoustic scales for its four sides. We assigned one shape—the parallelogram—to symbolize the Harmonic scales because of their shared diminished aural character: a right-leaning parallelogram for Harmonic Major scales and a symmetrical, left-leaning parallelogram for Harmonic Minor. The root of each scale determines its node's color. We selected these hues by mapping the color wheel to the twelve notes of the chromatic scale arranged in fifths.

A display in the upper left corner shows the seven notes of the selected scale in ascending order on a treble clef, starting at the root of the scale. In the upper right, a chord from the selected scale is notated on a grand staff. These elements of the Scale Navigator comprise the interface's screen score, which transforms with each new selection of scale or chord.

3.2.2 Chord Generator

integration between hierarchies (scale/key and chord) seems rather loose. On the one hand you have a very general method (for scales) and on the other end you have a rather style-dependent method (for chords). Why not adopt Tymoczko diagrams for all spaces?

This section details the Scale Navigator's functionality for chord progression generation. The selected chord is immediately audible in the browser window thanks to Tone.js. This feature can be muted, and the user can instead choose to route the chord to Ableton Live (or similar DAW) via virtual MIDI bus for further customization of the chords duration, velocity, arpeggiation, and sound design.

The Scale Navigator's chord generator draws from a vocabulary of jazz chord voicings catalogued in Bill Boyd's Jazz Chord Progressions [16]. To generate a new chord, the user clicks on the currently selected scale, one of its adjacent scale neighbors, or one of a list of "scalar supersets" found in the upper right of the interface). The chord generated will be a subset of the scale clicked.

Part of Boyd's taxonomy of jazz chords includes a "Position" designation for each chord, of which there are two: "the third of the chord is the bottom note in the right hand in Position 1," and "the seventh of the chord is the bottom of the right hand in Position 2" [16]. The authors implement Boyd's algorithm for chord choice based on root movement: If the root movement remains the same, or moves by step either higher or lower, choose a chord that has the same position as the current chord. If the root moves by fourth or fifth in either direction, choose a chord with a position alternate to the current chord. If the root moves by third or sixth in either direction, choose a chord in any position. Boyd did not mention what to do in the case of root movement by tritone, and so the authors allow for selection of a chord in any position in this case. The user can select allowable root movements using the checkboxes in the bottom left corner of the interface.

Boyd's algorithm leaves us with a list of allowable next-chord candidates, which we further hone using a voice-leading algorithm that ranks the list of candidates according to a fitness function describing the smoothness of voice leading from current chord to next chord. Chords are given a higher fitness score if the next chord has many notes in common with the current chord, or if the next chord has many notes that are stepwise to the notes of the current chord. A slider in the bottom left corner of the screen dictates which candidates get selected: when the slider is all the way to the right at 100%, only the highest ranked chords are chosen. At 0%, the chord generator picks at random from the list of chord candidates regardless of their ranking.

The Scale Navigator displays the current chord as notation on a grand staff in the upper right area of the interface. To the left of this notated chord is a text box with the chord's name: root note followed by chord quality. Depending on the chord, this name may also include the number of an interval (e.g. 7), whether or not the fifth is altered(e.g. ♯5), added chord-tones, and alterations (e.g. (add♯11)). Included in this chord display is the option to 'jump' in the network to the selected chord's scalar supersets: other, possibly non-adjacent scales that also contain the pitches of the chord. This enables pivot chord modulations to distant parts of the graph.

3.2.3 Network Infrastructure

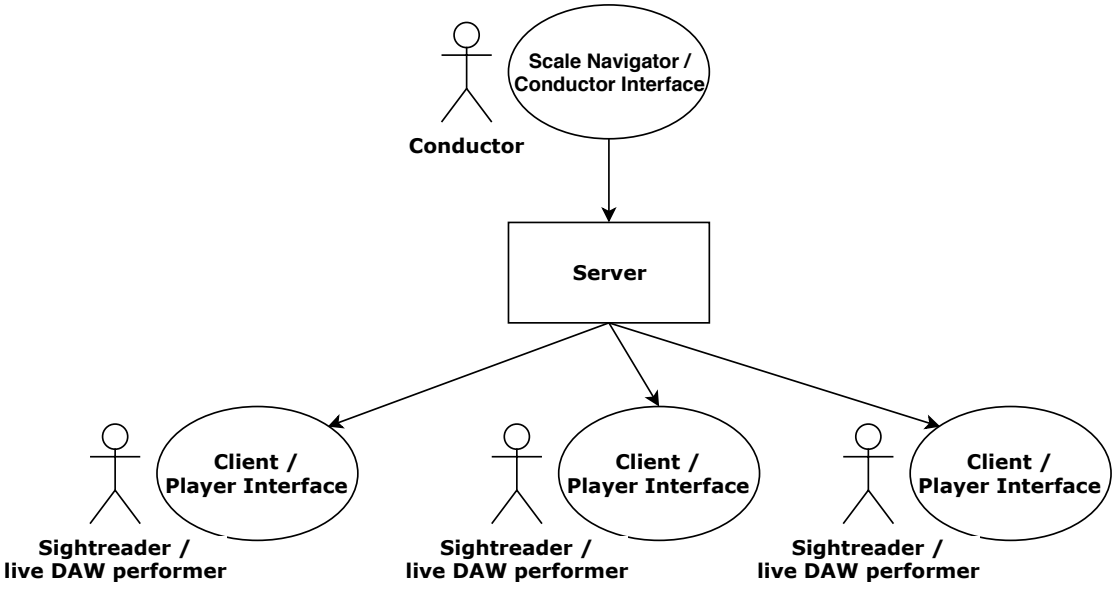


FIGURE 3.5: Signal flow of the Scale Navigator Live Performance Network

The Conductor component[3], Client component, and Server component make up the Scale Navigator Live Performance Network (SNLPN). This infrastructure is loosely modeled on Georg Hajdu's interactive network performance environment Quintet.net, comprised of Conductor, Server, Client, Listener, and Viewer components.[4] Unlike Hajdu, Freeman [33], and Canning [30], the Scale Navigator's network infrastructure is hierarchical and unidirectional in the traditional Western conductor-musician configuration (Figure 3.5): the Conductor module sends messages to the Server (scale and chord

[3]In a networked music performance context, the Scale Navigator interface becomes the Conductor component.

[4]Unlike Hajdu, the authors chose to forgo integrating Listener and Viewer components to the SNLPN, favoring instead commonly-used video platforms such as YouTube, Ustream, or Twitch to live stream performances to remote audiences.

information) which automatically pushes this data to a Client page (Figure 3.6), open in the performers' browser windows and displaying notation describing the current scale as selected by the Conductor.

Because the Client page is intended for use by both sight-readers and electronic improvisers, it also has a button for mapping various streams of incoming control data to parameters in Ableton Live (or similar DAW).

The SNLPN was built with open-source web-standard technologies: Javascript, HTML5, CSS3, Node.js, Web Sockets, P5.js, VexFlow, and Tone.js. It uses socket.io to communicate unidirectionally across a multi-nodal server network. All of these components are publicly available for use online, and can run on a LAN or WAN.

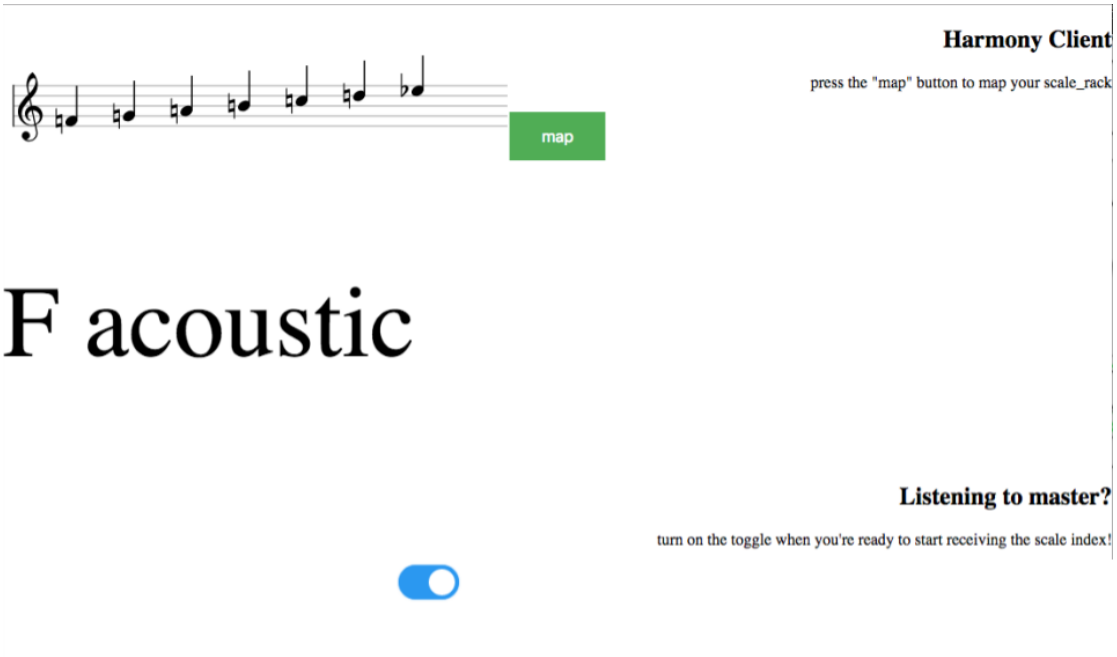


FIGURE 3.6: Client component of the Scale Navigator Live Performance Network

Chapter 4

Composition

4.1 Introduction

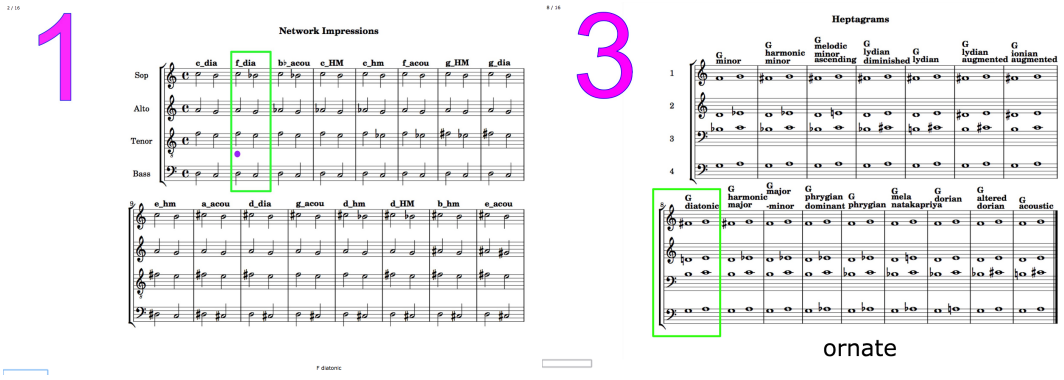
This chapter details the author's use of the Scale Navigator as an aid to the precompositional phase of writing music, charting the development of the author's piece *Network Impressions* for Chordas Collective.

4.2 Composing Screen Score Works for Chordas Vocal Ensemble

Chordas Collective is a group of vocalists, composers, and technologists creating vocal-electronic art. Founded by Tanner Pfeiffer in 2018 at CalArts, the author is an original member, creating a role for himself as Chief Technology Officer.

4.2.1 *Network Impressions* to *Heptagrams*

The piece is an electro-acoustic improvisational chorale for the Chordas vocal ensemble (SATB), live electronics, and interactive score that premiered December 1st 2018 at CalArts. It begins in C Diatonic, with each of the four singers responsible for improvising melody using only two notes of the scale. The author used the Scale Navigator to determine the next fifteen measures that comprise the form of the piece.



(a) *Network Impressions* (b) *Heptagrams*

FIGURE 4.1: *Network Impressions* to *Heptagrams*

The author created a transformative screen score to cue singers and assist them with each modulation.[1] This screen score is controlled by a conductor, who presses a "Next Measure" button that highlights the current measure and triggers electronic and recorded sounds in a concurrently running Ableton session.

The author re-titled the piece *Heptagrams* after changing the harmonic structure of the piece.

4.3 Challenges

The Scale Navigator presents the user with several challenges and limitations. In its capacity as a composing tool, the constraints that determine the structure of the scale network may also limit the composer relying completely on the Scale Navigator for ideas, and they may not be aware of methods for modulation to more distant, less-related scales.

4.3.1 Qualified User Survey: Feedback from Composers who have used the Scale Navigator

This section is a compendium of feedback from various people who have used the Scale Navigator to compose music.

> Place the notes front and center on the Client Page and include a piano roll for further reference. My eyes were immediately drawn to 'F Acoustic,' which many musicians that work with electronics may not understand. Also, it might be helpful to include a description or a tutorial of some kind on the

[1] http://www.nathanturczan.com/impressions/index.html

> Scale Navigator Interface page. At a glance, it is not immediately clear what the shapes or colors mean or what the relationship is between the center node and the surrounding nodes. What do the supersets do? Do they constrain the Scale Network library so only certain choices are available? Depending on your desired audience, all of this might be fine but I'm not convinced that a random musician or composer searching the internet for musical resources will immediately know what to do with your tool, how to use it, or how to make it produce sound.

Users wanted more control of the quality of the chords produced.

> Maybe the user could select the number of notes to use in the chord. You could also add suspended chords to the mix, or inversions...

Users had some suggestions as to where certain elements of the interface were displayed.

> I would place the two chord-related panels together. It would be nice to display the scale degree transformation that is required to go from one scale to its relatives, with labeled arrows or something like that. I'd try to use a different color scheme, sometimes there's not enough contrast between the shapes and the background. I'd probably remove the natural symbols at the score.

Chapter 5

Performance

5.1 Introduction

This chapter discusses the Scale Navigator's use as an instrument for live performance, specifically as it is used to harmonically synchronize an electro-acoustic ensemble in the author's *INTERSTICES*.

5.2 *INTERSTICES*

INTERSTICES is an improvisational piece of networked music composed for the CalArts Machine Orchestra that premiered December 6th, 2018. Inspired by Terry Reilly's In C, the piece is based around the idea of synchronizing a large ensemble of improvisers over changing scales as controlled by a conductor.

FIGURE 5.1: rehearsal of INTERSTICES

INTERSTICES makes use of the SNLPN to stay in harmonic sync, with a player directing modulation on a global scale using the Scale Navigator in its Conductor capacity. Other members of the ensemble—playing acoustic instruments or performing with a

Ableton Live—are updated of scale changes via the Client component, whose screen score transforms to describe the current selected scale for the acoustic players to sight read and interpret.[1] If the player is performing with an Ableton session, the Client also sends an index number identifying the current scale to a "Scale Rack" object, controlling every MIDI track within the session and filtering out notes that are foreign to the current scale. The form of the piece is determined by an animated scrolling score that plays on a projector screen (Figure 5.2). This score also contained indications for rehearsal number, tempo, dynamics, density, color, and other miscellaneous expressive instructions.

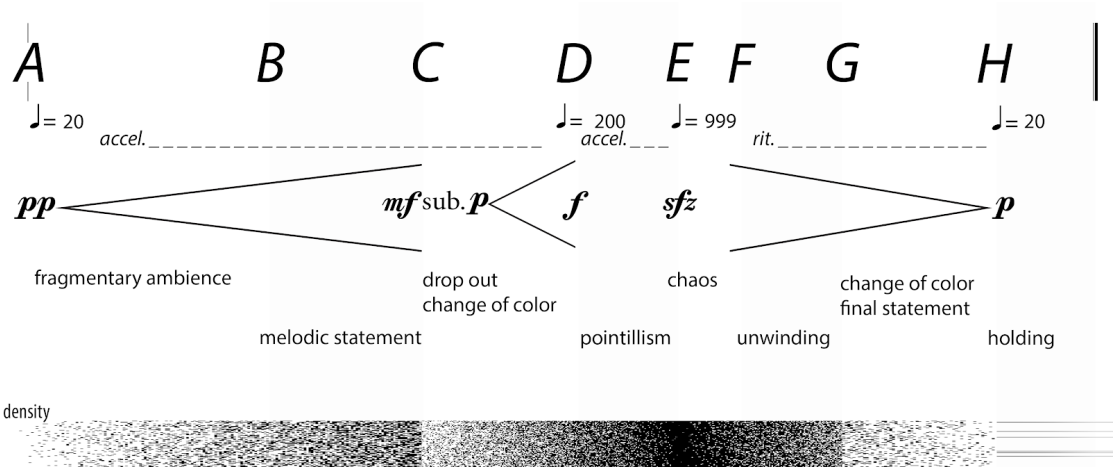


FIGURE 5.2: *INTERSTICES*' animated scrolling score

5.3 Challenges

If one were to perform with the Scale Navigator as it currently exists on the author's website circa 2019 without routing the MIDI to Ableton or similar DAW for further textural manipulation and orchestration, both the audience and the performer would have a great deal to complain about. Disregarding the Scale Navigator's in-browser sound design that uses only the most rudimentary synthesis Tone.js has to offer, the interface's present algorithm for selecting chords does not account for function or resolution. The resultant progressions often sound unsatisfying to those expecting that resolution.

The Scale Navigator functions in *INTERSTICES* as a way to harmonically synchronize improvisers, therefore the conductor leaves the Navigator's chord generation capacity of the equation. This process of synchronization comes with its own particular set of challenges: if, for instance, the conductor were to repeatedly changes scales in the Navigator so quickly that no human can possibly keep up with it, this behavior would

[1] https://www.youtube.com/w1Bs_j3KwBY

greatly diminish the improvisers' trust in the system. An empathetic ear is required for the conductor to fulfill their role in a way that makes musical sense. By this same token, the improvisers must follow the current scalar indication as chosen by the conductor. Moreover, acoustic performers are required to sight read from the SNLPN's screen score. As the screen score is transformative, the performer must pay close attention so as not to miss a change, which might be as small as the alteration of one accidental.

As a general failing, *INTERSTICES* pulls the performers' attention in many different directions. They have to sight read from the screen score, they have to heed the conductor's occasional hand-waiving or other expressive gestures, and they are also expected to follow indications for rehearsal number, tempo, dynamics, density, and color on a scrolling score playing on a large screen at the front of the room. In rehearsal and in performance, results tend to be less than cohesive. The following section is a discussion of *INTERSTICES* from the perspective of the performers that took part in its 2018 debut.

5.3.1 feedback from Musicians who have performed in works employing the Scale Navigator

As expected, the performers' feedback focused overwhelmingly on the many aspects of the piece that required their attention, especially sight reading:

> Difficult to sightread especially if the conductor is moving scales quickly. Since only one pitch class is changed at a time, a highlight indicating which note has changed would be helpful.

When asked how they thought the Scale Navigator Live Performance Network contributed to the cohesion of the ensemble:

> It certainly organized the melodic and harmonic content of the ensemble by dictating our available note choices. This might be a very useful tool in some situations and a hindrance in others.

There was consensus among performers that *INTERSTICES* felt "more like a scale exercise" than a fully realized musical work. As one respondent put it:

> The instructions that the composer gave to the ensemble outside of the broadcasted harmonic data were too ambiguous due to a lack of clear vision in

arrangement, sound design, and thematic development. It was the ONLY cohesive element in a piece that had no other cohesion.

Chapter 6

User-directed experience

6.1 Introduction

All of the Scale Navigator's functionality thus described has painted a picture of a musical tool that is only for musicians. This section details the author's attempt to integrate the Scale Navigator into an interactive installation as an interface for a potential non-musician participant to direct their own experience.

6.2 Modal Intersections

Modal Intersections was a 2018 interactive audiovisual installation for the CalArts WaveCave centered around the Scale Navigator as an interface for interaction, giving the experience of conductor to a user. The Scale Navigator—running on Chrome—was open on an iPad embedded in a podium in the middle of the space (Figure 6.1) for participants to interact with, triggering melodies and arpeggios in the selected scale on two opposing Yamaha DisKlaviers. Software patches for arpeggiation and melody were designed entirely in Ableton using some precomposed MIDI files and a lot of MIDI effects: the Max4Live MIDI Echo effect was particularly useful for repeating chords, melodies, and other musical figures morph and mold to fit the selected scale.

Each scale was accompanied by its own looping video of roadway intersections in Los Angeles; scale selection in the Scale Navigator (routed via MIDI to TouchDesigner) triggered the footage. This piece exploited the structure of the scale network to create a non-linear film experience. The way each scale was paired with its own video loop was an

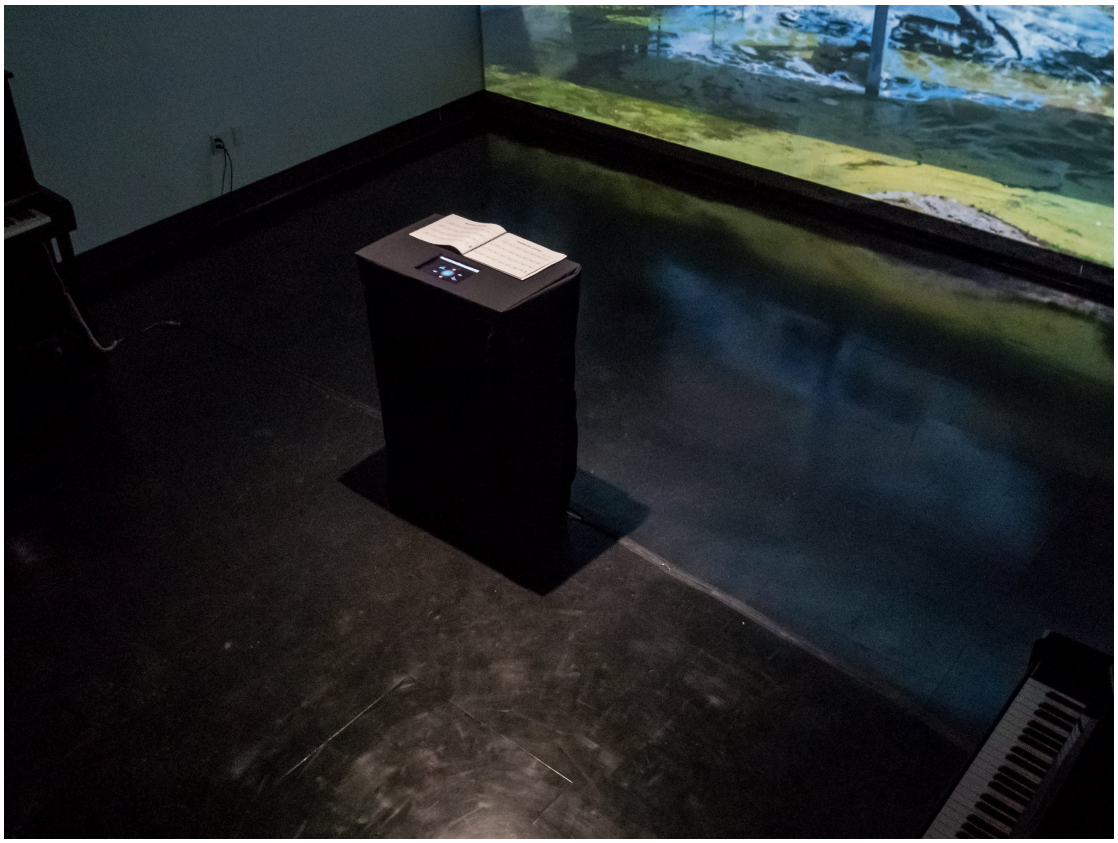


FIGURE 6.1: view of *Modal Intersections* from above

attempt to synesthetically associate parallel sensory phenomena: a highway intersection for each harmonic intersection [1].

The author submits that synesthesia differs from metaphor only in that it is a more persistent association between two or more sensations. No two synesthedes agree on which sensory input gets associated with what. The synesthesia underlying *Modal Intersections* is therefore arbitrary: only in the CalArts WaveCave for one week in October is F Harmonic Major so closely married to footage of a pillar by the 101 freeway.

The Scale Navigator interface was accompanied on the podium by a book entitled *Modal Intersections: Network Etudes* and a pen. The first three etudes in this book were already completed by the author, and after these came a written suggestion:

> Please feel free to write your own Network Etudes in the following pages!
>
> - Nathan

These scores all contained a shape indicating what kind of scale to begin with followed by directional arrows pointing where to navigate next. Rather than continue in this

[1] https://youtu.be/dmfJexDdbV0

template, audience members got creative with their Network Etudes compositions (Figure 6.2).

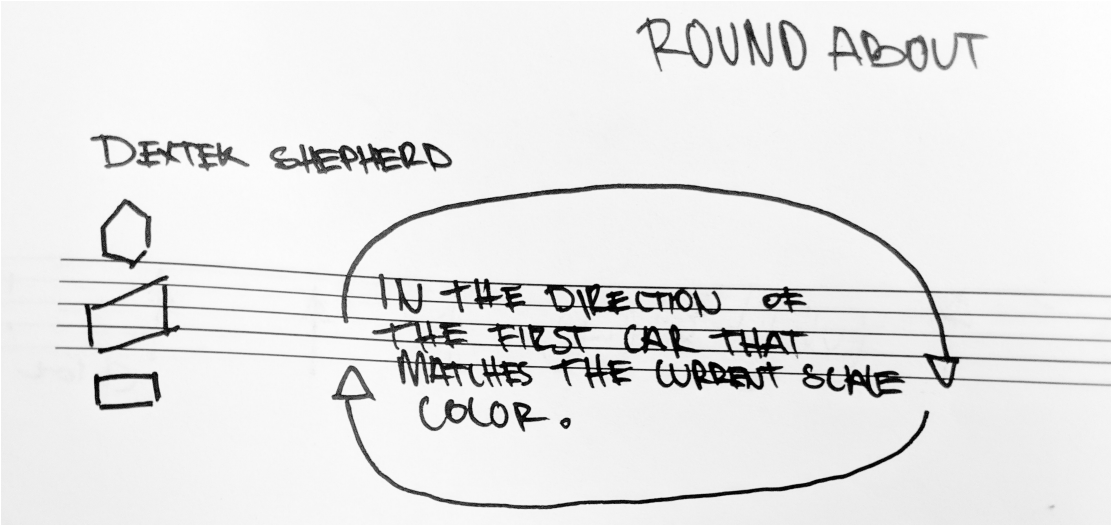


FIGURE 6.2: Dexter Shepherd's *ROUNDABOUT*, Network Etude number 5

The following is an assessment from an anonymous critic who reviewed documentation of *Modal Intersections* but did not experience it in person:

> ...the link between the visuals and the music is tenuous, hanging only on a superficial pun (the fact that both can be described as "intersections"). The music produced, while pleasing, is also not particularly impressive, in that it seems to completely forgo any notion of voice-leading or continuity when the user elects to modulate to a new scale. This greatly limits any sense of development or coherence that the scale network idea may have provided in the first place.

6.3 Thought Loops

Thought Loops was a non linear poem for voice and accompaniment that lived in the CalArts WaveCave for one week in January 2019. The author spent many hours with frequent collaborator Tanner Pfeiffer in the CalArts Radio Station—where there are some decent microphones—recording each others voices across a range of over an octave, inclusive of four vowel types and three dynamics to create a library of vocal samples to create the sound world for *Thought Loops*. Much like *Modal Intersections*, users interacted with the Scale Navigator open in an iPad on a podium in the center of the room to navigate through scales, though unlike *Modal Intersections*, the chord generator

remained an integral part of the piece. The Navigator was significantly altered to display no text information whatsoever, and its colors were inverted.

Each scale was synesthetically associated with one line of a non-linear poem (Figure 6.3), projected on one wall of the WaveCave. The notated scale was projected onto an adjacent wall for musicians to sight-read. Documentation of live sight-reading experiments within *Thought Loops* can be found on the author's website.

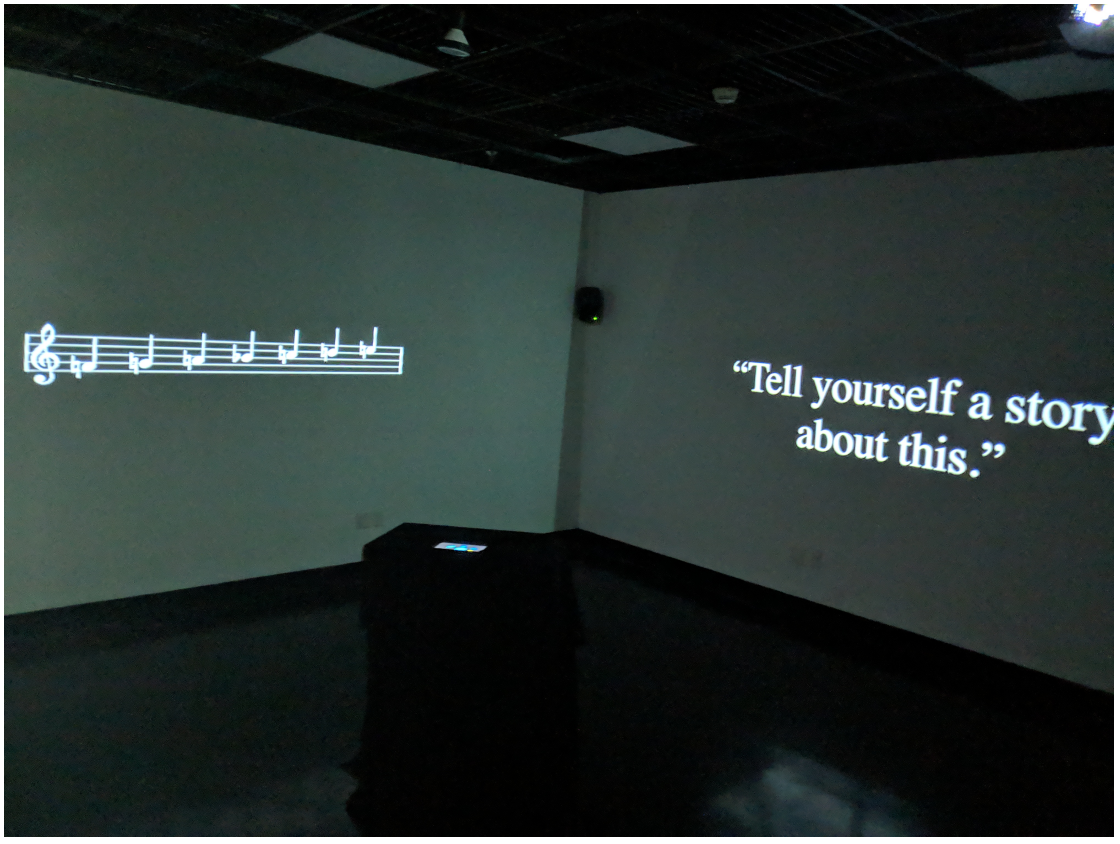


FIGURE 6.3: wide angle shot of the interior of *Thought Loops*

6.4 Challenges

In *Modal Intersections*, the Scale Navigator interface had text information attached to each scale shape. The author chose to do without this for *Thought Loops*, aiming for a more mysterious aesthetic. The following section is a discussion of the Scale Navigator from the perspective of the its users in an installation setting.

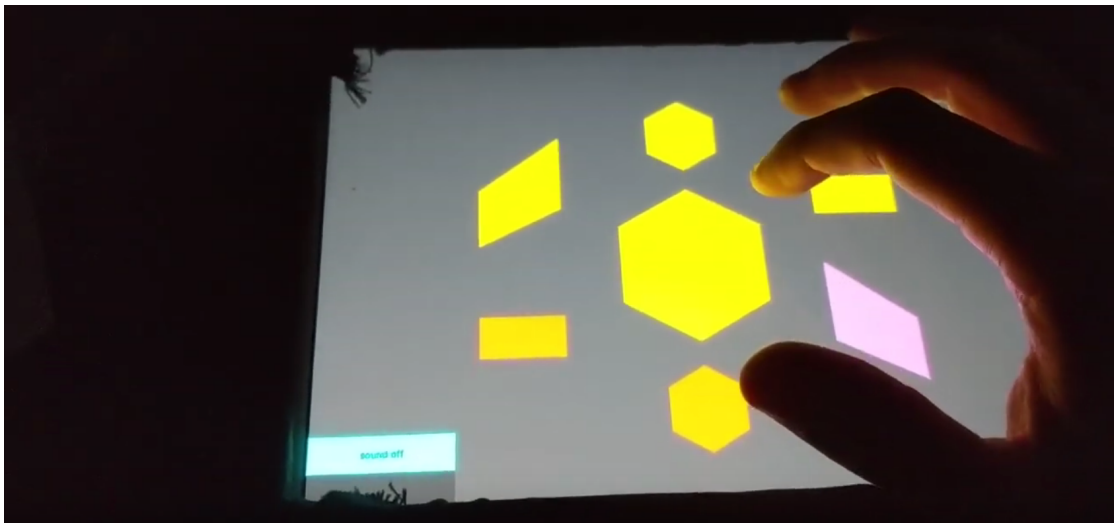


FIGURE 6.4: Custom Scale Navigator without text for *Thought Loops*

6.4.1 Qualified User Survey: Feedback from Users who have Directed their own Experience

Users noted the clear sense of audience control in both *Modal Intersections* and *Thought Loops*, with some lamenting that this control was too obvious. In the words of one respondent:

> To me the Scale Navigator felt like the driving force. I like the idea of giving control of an installation space to the user, I do however wonder if these installations could have been made better using a less direct interface. I understand that in part the installation was probably meant to showcase the Scale Navigator as a tool. But I'm more interested in it as a sort of glue logic to add organization and musicality to the chaotic signals that you often get from raw sensor data. I'm imagining distance sensors and accelerometers being used as the form of navigation through the scales.

One common complaint was that the Scale Navigator suffered from off-putting latency in response to tapping on polygons.

As one reviewer said of *Modal Intersections*:

> Love the concept, and it's something I would use regularly in my music making practice. I really liked how I was able to turn my music theory brain off and just play with it and be surprised by the output. I wasn't completely clear on whether the differing geometry had symbolic meaning within the scales, but definitely enjoyed it. With Modal Intersections, I found

> the pairing of the DisKlaviers and the projection to be really on point and I think that pairing elevated it from something that might feel like a product presentation to something that definitely belonged in a gallery space.

Regarding the visual design of the Scale Network interface:

> I would love to see the entire scale network appear on the iPad as a three dimensional object. I would also love to see animation and lines connecting the nodes.

One last comment to conclude this chapter:

> Pleasant! I enjoyed the tactile interface and hearing the resulting sounds. It was moderately mysterious, but I enjoyed that aspect of it.

Chapter 7

Conclusion

The Scale Navigator has proven a successful composition tool, helping composers write chords and modulations. As an instrument for improvising these modulations and chords in a live context, it produces pleasing harmonic progressions. When connected to Client modules over the SNLPN, it achieves its aim of keeping diverse performers in the same tonality. The following sections details ways in which the Scale Navigator's functionality and usefulness might be improved or expanded upon.

7.1 Network Configuration

Future changes to the network infrastructure could include client chat rooms for each instrument, or group of players. The network could also be distributed non hierarchically for bi-directional communication between components, allowing for distributed and democratic harmonic decisions. The network could also feature a component for audience participation, encouraging collaborative feedback loops à la Jason Freeman [33]. Spectral analysis might also be introduced into the feedback loop, so that timbre might influence harmony, voicing, or instrumentation.

7.2 Modular Vocabularies

Future harmonic applications of the Scale Navigator interface could include seeing how Tymoczko's scale network concept might work as a musical grammar to govern progressions of chord types other than those listed by Boyd. The author is interested in incorporating such unusual sonorities as:

- Stravinsky's Petrushka chord and Psalms chord
- Wagner's Tristan chord
- Slonimsky's Mother Chord and Grandmother chord and Pyramid chord
- Scriabins Prometheus / Mystic chord
- Strauss' Elektra chord
- Ernst Krenek's Northern Lights chord
- Schoenberg's Farben chord and One-to-Napoleon Hexachord
- Miles Davis' So What chord

Future iterations of the Scale Navigator might include an interface to switch between entire datasets of chords, or a way for the user to input their own chord constructions. Morton Feldmans intuitive chordal lexicon, Henry Cowell's clusters, or Milhaud's vocabulary of polychords are all viable chordal dataset candidates that would contrast satisfyingly with the Boyd chord library.

Polychords are of particular interest: their construction suggests two independent streams of harmony (as they can be analyzed as a combination of two independent chords), but they are can also be evaluated as on collection of pitches sounding simultaneously. Ravel has been suspected of playing with this kind of tonal ambiguity in his music [34] as has Hugo Wolf [35], though this is analytical speculation. Darius Milhaud, on the other hand, has written extensively about his system for creating polychordal sonorities (Figure 7.1) and has used them explicitly in his work.

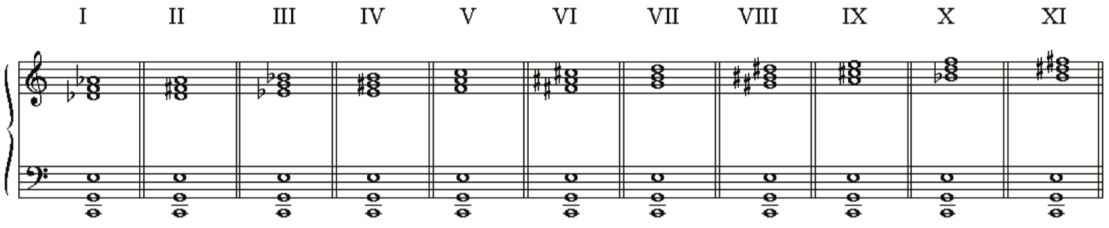


FIGURE 7.1: harmonic combinations that arise from the superposition of two major triads

Certain kinds of polychordal or atonal chord construction will require scales classes other than those currently in the Scale Navigator's network. The next section discusses the possibility of incorporating more scale types into the network.

7.3 Olivier Messiaen, Modes of Limited Transposition, and Every Possible Combination of Notes

If a harmonic interface's main objective is to have a most inclusive and varied compositional tool, perhaps a bigger network of all possible combinations of the twelve chromatic notes is preferable. Why then does the Scale Navigator contain only four scale classes? If the main objective is to create an interactive representation of Debussy's harmonic language, why doesn't the Scale Navigator include that favorite of Debussy's, the Whole-tone scale?

The author's had two motivations for constraining this iteration of the Scale Navigator to include only the Diatonic, Acoustic, Harmonic Major and Harmonic Minor scales: 1. as these are the only Pressing scales with seven notes, the author believed that this would have more pleasing results when altering diatonic melodies, and 2. these are the most triadic of the Pressing scales.

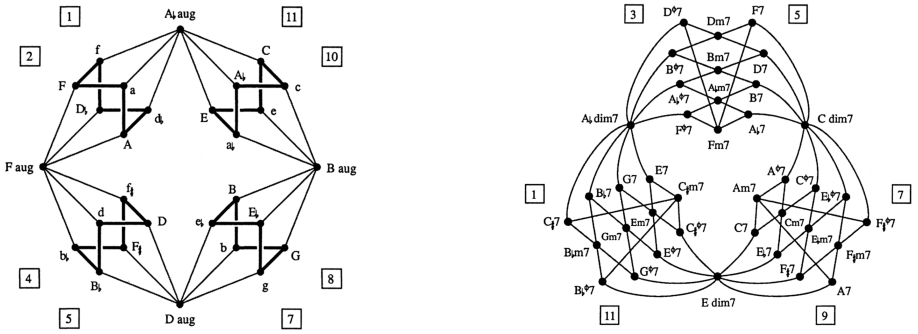
Future iterations of the Scale Navigator will absolutely include the Whole-tone scale in its network, as well as Octatonic, and Hexatonic. In fact, the network could be expanded to incorporate all of the modes of limited transposition[1]; this would allow for new exciting harmonic approaches that exploit symmetries inherent in equal temperament such as the musical language of Olivier Messiaen [9].

In Tymoczko's words, these particular modes of limited transposition, (he calls them "locally diatonic") "...allow composers to obtain a wealth of nontraditional sounds while continuing to compose in fairly traditional ways. They therefore constitute an attractive set of tools for composers seeking to expand, rather than replace, the vocabulary of traditional tonality" [12].

One particularly rich resource for melodic studies of all of the modes of limited transposition—not just the locally diatonic ones—is Guy Lacour's *Twenty-Eight Etudes* for saxophone [36]. The author fully intends to make use the material found in this book in the near future.

The modes of limited transposition can also be related via maximally intersecting (also called "parsimonious") voice leading: in their paper *Parsimonious Graphs: A Study in Parsimony, Contextual Transformations, and Modes of Limited Transposition*, Jack Douthett and Peter Steinbachand present a number of interesting network graphs can be derived from these modes, from seventh chords, and from triads [37]. For example, Figure **??** depicts how triads are related to one another by a difference of one note, and Figure **??** shows a similar relationship among seventh chords.

[1] modes of limited transposition are defined here as scales that have fewer than twelve transpositions



(a) *parsimonious voice leading among triads* (b) *parsimonious voice leading among seventh chords*

FIGURE 7.2: network of chords in *Parsimonious Graphs: A Study in Parsimony, Contextual Transformations, and Modes of Limited Transposition*

7.4 Microtonality

As discussed in the previous section, a harmonic interface for navigating a network of all possible combinations of the twelve chromatic notes would be a very exciting tool. But why stop there? There are scales that contain a single note that is a quartertone flat or sharp; these would maximally intersect with some of the scalar objects previously mentioned in this thesis, and might provide a way for the scale navigator to explore the entire gamut of quartertone music, emulating the harmonic language of Ivan Wyschnegradsky [38]. But if we didn't stop at twelve notes per octave, why should we stop at twenty-four? Easley Blackwood has made a systematic study of all equal divisions of the octave from twelve to twenty-four [39], and Georg Hajdu has written extensively on the seventeen-notes-per-octave chromatic scale [40], perhaps these might be connected to the network already proposed.

7.5 Other Models of Pitch Space

The scale network works well for modeling Debussy's harmonic language, but perhaps other models of pitch space are better suited to representing certain harmonic languages. The expansion of the Scale Network previously discussed in this chapter points toward a possible future suite of harmony software modules, each with a different visualizations of harmonic space: Bergomi's orbifolds [41], Gollin's three dimensional tonnetz [42], Tymoczko's spiral array [15], or Cannas' seventh chord tonnetz [43].

7.6 Integration with other softwares

Further integration with industry standard DAW software is a possible future direction for the Scale Navigator: Ableton, Logic, Pro Tools, etc. For this to happen, the Scale Navigator needs to be re-written as a JUCE plugin. The Scale Navigator dataset could also become an API, or a library for languages such as Supercollider or Abjad to reference.

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