

GENERALIZED MULTIPLE ORDER-NUMBER FUNCTION ARRAYS

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To my family

ACKNOWLEDGMENTS

Acknowledgments go here.

TABLE OF CONTENTS

	<u>page</u>
ACKNOWLEDGMENTS	4
LIST OF TABLES	7
LIST OF FIGURES	8
CHAPTER	
ABSTRACT	9
1 INTRODUCTION	10
1.1 Basic Derivation Theory	11
1.1.1 Aggregate Realizations	15
1.1.2 Row Segments	23
1.2 A Survey of Derivation Techniques	27
1.2.1 Folded Derivation	30
1.2.2 Shifted Derivation	32
1.2.3 Self-Derivation	33
1.2.4 Derivation from Aggregate Realizations	38
1.3 The Mallalieu Property	45
1.4 Final Remarks	49
2 LITERATURE REVIEW	52
2.1 Discovering Derivation	52
3 THEORETICAL FRAMEWORK	56
3.1 Group Actions	56
3.2 Polya's Enumeration Formula	60
4 THEORETICAL FRAMEWORK	66
4.1 Defining an algorithm to compute a row class	66
4.1.1 The canonical form of a row	67
4.1.2 Storing a row class in memory	73
4.2 Defining an algorithm to compute semi-magical squares	78
4.2.1 Computing the partitions of an integer	79
4.2.2 Combining partition rows into squares	84
4.3 Computing all possible combination matrices for a row	89
4.3.1 Computing the side and top rows of a combination matrix	90
4.3.2 Writing a solution as text	92
4.3.3 Computing all possible solutions for a given combination matrix	94
4.4 Creating work data for use in concurrent threads	97
4.5 Defining a top-level procedure for computing all solutions for a given row class	101

4.5.1	Directions for the future	103
APPENDIX		
A	104
A.1	ELEMENTARY TWELVE-TONE THEORY	104
B	ELEMENTARY GROUP THEORY	105
BIOGRAPHICAL SKETCH		108

LIST OF TABLES

<u>Table</u>	<u>page</u>
1-1 Rahn's Common Tones Under Inversion	25
1-2 Derivation Involving the Retrograde and an Arbitrary Operation	28
1-3 Folded Derivation Involving the Retrograde	30
1-4 Shifted Derivation Involving the Retrograde	32
1-5 Self-Derivation Involving the Retrograde	34
2-1 Martino's Source Hexachords	52

LIST OF FIGURES

<u>Figure</u>	<u>page</u>
1-1 Berg's <i>Lulu</i>	10
1-2 Derived Row in Berg's <i>Lulu</i>	11
1-3 Bars 1–7 in Webern's Op. 27	16
1-4 Aggregate Realization of Bars 1–7 in Webern's Op. 27	17
1-5 Another Aggregate Realization of Bars 1–7 in Webern's Op. 27	17
1-6 Bars 8–10 in Webern's Op. 27	18
1-7 An Aggregate Realization of Bars 8–10 in Webern's Op. 27	18
1-8 Bars 19–23 in Webern's Op. 27	19
1-9 An Aggregate Realization of Bars 19–23 in Webern's Op. 27	19
1-10 Intersecting Bars 1–7 with Bars 8–10 in Webern's Op. 27	20
1-11 Intersecting Bars 1–7 with Bars 19–23 in Webern's Op. 27	20
1-12 Intersecting Bars 8–10 with Bars 19–23 in Webern's Op. 27	20
1-13 The intersection of Bars 1–7, 8–10, and 19–23 in Webern's Op. 27	21
1-14 Self-derived row in Scotto's <i>Tetralogy</i>	35
1-15 Folded derivation in Scotto's <i>Tetralogy</i>	36
1-16 Schenkerian middle-ground structure in Scotto's <i>Tetralogy</i>	36
1-17 Musical realization of the middle-ground in Scotto's <i>Tetralogy</i>	37
1-18 Prolongation of the middle-ground structure in Scotto's <i>Tetralogy</i>	37
1-19 Musical realization of the prolonged middle-ground in Scotto's <i>Tetralogy</i>	37
1-20 Self-derivation in Damiani's <i>Stingray</i>	45

Abstract of Dissertation Presented to the Graduate School
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The purpose of the present study is the application of self-derivation matrices to the algorithmic composition of acoustic and electroacoustic music. It departs from the seminal work of Daniel Starr in the field of twelve-tone theory, published by Perspectives of New Music in 1984, generalizing it to arbitrary equal-temperament systems. A solid mathematical foundation that describes the derivation of multiple order-number function arrays is a major contribution to the fields of music composition and music theory, as well as a requirement for the implementation of non-brute-force algorithms. We confront our findings with those of David Kowalski, and verify the latter for accuracy. The results of this research include a complete classification of rows that support self-derivation in matrices of all sizes, as well as a complete classification of the algebraic operations that afford such procedures. In addition, several general-purpose and non-brute-force algorithms are provided that implement our findings in the programming languages that pertain to musicians the most. A myriad of musical compositions are specially devised with the intent of illustrating the real-life use of such algorithms, and to provide criticism as to where such compositional practices situate within the realm of 21st-century music composition.

CHAPTER 1 INTRODUCTION

Music has become an almost arbitrary matter, and composers will no longer be bound by laws and rules, but avoid the names of School and Law as they would Death itself...

– Johann Joseph Fux

Auftakt - - Comodo^{)}*

Gesang

Wenn sich die Men - schen um mei - net-wil-len

Piano

p *Vibraphon* *N^r* *poco f* *7* *p* *Str.* *Mit Ped.* *mf espr.* *Vlc.* *Bkl.*

schwebend *rit. - - a tempo*

um-ge-bracht ha-ben, so setzt das mei-nen Wert nicht herab.

rit. - - a tempo *Sax. espr.* *p* *Kb. Klav.* *Rubato -*

The image displays a musical score for Alban Berg's opera Lulu. It features a vocal line (Gesang) and a piano accompaniment (Piano). The vocal line begins with the instruction 'Auftakt - - Comodo*)' and the lyrics 'Wenn sich die Men - schen um mei - net-wil-len'. The piano accompaniment includes various instruments: Vibraphon, Hr. (Horn), Str. (Strings), Vlc. (Violoncello), Bkl. (Bassoon), and Kb. Klav. (Klavier). Performance instructions such as 'p' (piano), 'poco f' (poco forte), 'mf espr.' (mezzo-forte espressivo), 'Mit Ped.' (with Pedal), 'rit.' (ritardando), 'a tempo', and 'Rubato -' are present. The score is written in 3/4 time and includes dynamic markings like 'p', 'poco f', 'mf', and 'p'.

Figure 1-1. Alban Berg's *Lulu* [1, 182].

1.1 Basic Derivation Theory

Derivation is the process of extracting ordered segments from rows in order to generate new compositional materials. It is a technique that dates back to the Second Viennese School. In its most incipient form, a composer may simply extract these segments from a row, and combine them to form another, as we see in Berg's *Lulu*. The basic row used by Berg is $S = \{10, 2, 3, 0, 5, 7, 4, 6, 9, 8, 1, 11\}$. In the Prologue, however, one is greeted with the row $\{10, 3, 4, 9, 2, 7, 8, 1, 0, 5, 6, 11\}$, as depicted in Fig. 1-2. It is clear that the segments that constitute the Prologue's row are ordered segments in the basic row form, and the fact that one row cannot be obtained from another via row operations is here irrelevant.

The image shows a musical score for the Prologue of Alban Berg's *Lulu*. The score is for five instruments: 1. 2. Horn in F o. D., 3. 4. Horn in F o. D., 2. Trompete in C o. D., 1. 2. Posaune o. D., and Tambourin. The key signature is one flat (B-flat), and the time signature is 3/4. The music is in 3/4 time. The Horn parts (1. 2. and 3. 4.) play a melody that is a derived row, starting with a forte (f) dynamic and a 'legatissimo' marking. The Trompete and Posaune parts play a similar melody, also starting with a forte (f) dynamic and a 'schmetternd.' (staccato) marking. The Tambourin part plays a simple rhythmic pattern. The score includes various musical notations such as notes, rests, and dynamic markings.

Figure 1-2. Derived row in the *Prologue* of Alban Berg's *Lulu* [1, 182].

Less naive approaches to derivation often involve a derived row that will have more structure. In them, one will usually see a combination matrix where derived and original rows are matched with some twelve-tone or order operation of themselves, or both. This is illustrated in Ex. 1.1.1.

Example 1.1.1. We may use the basic row in *Lulu* as motivation for a basic derivation procedure. The first step is to create a 2×24 array where the first row is S followed by $R(S)$,

and the second row is initially undefined.

$$\left[\begin{array}{cccccccccccc|cccccccccccc} 10 & 2 & 3 & 0 & 5 & 7 & 4 & 6 & 9 & 8 & 1 & 11 & 11 & 1 & 8 & 9 & 6 & 4 & 7 & 5 & 0 & 3 & 2 & 10 \\ \cdot & \cdot \end{array} \right] \quad (1-1)$$

Next, one chooses an arbitrary segment, and separates it from the the top row by placing in in the bottom row:

$$\left[\begin{array}{cccccccccccc|cccccccccccc} \cdot & 2 & 3 & \cdot & \cdot & \cdot & 4 & 6 & 9 & 8 & 1 & 11 & \cdot & \cdot & \cdot & \cdot & \cdot & 7 & 5 & 0 & \cdot & \cdot & 10 \\ 10 & \cdot & \cdot & 0 & 5 & 7 & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & 11 & 1 & 8 & 9 & 6 & 4 & \cdot & \cdot & \cdot & 3 & 2 & \cdot \end{array} \right] \quad (1-2)$$

Let $V = \{2, 3, 4, 6, 9, 8, 1, 11, 7, 5, 0, 10\}$. Then V is a row derived from S . In particular, the ordered segment $\{10, 0, 5, 7\}$ in S is preserved by $R(V)$, and a counterpoint that combines S vertically with V horizontally is possible by construction.

It is of interest to note at this point that, in this kind of construction, the choice of a particular segment is already an important compositional decision. This choice bears relevance in that it establishes motivic material, that is, the segment itself. It also potentially introduces complementary harmonic regions, one given by the segment, the other given by its set complement. Moreover, and perhaps more importantly, it presents an opportunity for exploring syntax. There are a multitude of ways in which a composer may obtain syntax from a simple derivation procedure such as the one given in the example above. One way would be to find an operation that makes the chosen segment invariant. In particular, it is easily checked that $S_1 = \{10, 0, 5, 7\} = RT_5 I(S_1)$. One can then extend Ex. 1.1.1 into the combination array $[S \mid R(S) \mid RT_5 I(S) \mid T_5 I(S_1)]$. In the extended array, the segment S_1 would be preserved, but the row derived from $RT_5 I(S)$ would not be a transform of V . If the set complement of S_1 in V were parsed to produce more than one harmonic region, then the complement of S_1 under this new derived row would produce different harmonic regions. This can be very pertinent compositionally, as one would be capable of producing contrasting harmonic regions while maintaining motivic coherence under the S_1 segment.

Yet another way of generating syntax from derivation would be to follow S with V itself. One would then derive a new row from V , say Q , and eventually follow V with Q . Repeating this procedure *ad libitum* could generate many contrasting harmonic regions. In particular, this type of derivation is seen in Donald Martino's *Notturmo* of 1974, a composition that won the Pulitzer Prize in the following year [1, 181]. If, by compositional choice, the chain of derived rows picked always the same order numbers, then a potential for rhythmic and agogic coherence could also be explored.

In one of the seminal academic works in the field of twelve-tone theory, [1] utilizes a mostly set-theoretic framework to understand and categorize rows and procedures involved in producing derivation, polyphony, and self-derived combination matrices. The main objective is similar to ours, in it has a bias toward unveiling self-derivation, which unfortunately still remains a somewhat obscure topic. The set-theoretic approach revolves around the idea of looking at collections from the standpoint of their order constraints: a totally constrained set with no precedence contradictions is a twelve-tone row; a completely unconstrained set of twelve tones represents the free aggregate; a maximally constrained one is what the author calls the simultaneous aggregate, that is, a twelve-tone cluster. Sets that live in-between can often be projected in the middle and background of a composition, fact that amounts to a Schenkerian-flavored view of the whole process.

Mathematically, the ideas in [1] translate into considering the set U of all ordered pairs of pitch classes. There are twelve choices for the first position, and twelve choices for the second position. As both choices are independent, this set has cardinality $12^2 = 144$. An element of U is called an order constraint, and a subset C of U is called a pitch-class relation. The latter can be viewed as a 12×12 matrix where the entry c_{ij} is equal to one whenever $\{i, j\} \in C$, and zero otherwise. One can then apply bitwise operations to these matrices in a very computationally efficient manner: bitwise *and* and *or* correspond respectively to set intersection and union. For any pair of pitch classes x and y , we define a relation $x \sim y$ on the power set of U by the set inclusion of the element $\{x, y\}$. A subset C will then be reflexive

if, whenever an element of C (which is a set) contains the pitch class x , then $\{x, x\} \in C$. In words, reflexivity means that if a reflexive collection C of notes contains an element x , then x precedes (and follows) itself in C . The free aggregate is a minimal reflexive subset of U that contains all twelve tones. The relation \sim will be symmetric if $\{x, y\} \in C$ implies $\{y, x\} \in C$, and antisymmetric whenever $\{x, y\} \in C$ implies $\{y, x\} \notin C$, for $x \neq y \in \mathbb{Z}/12\mathbb{Z}$. Similarly, transitivity is defined as $\{x, y\} \in C$ and $\{y, z\} \in C$, then $\{x, z\} \in C$; and trichotomy is defined as either $\{x, y\} \in C$ or $\{y, x\} \in C$ for any $x \neq y \in \mathbb{Z}/12\mathbb{Z}$. The relation \sim is, of course, an order relation on the set of twelve tones by definition. A partial order is one that is reflexive, transitive, and antisymmetric, while a total order (a row), is a partial order that satisfies trichotomy.

Often, pitch-class relations will contain many redundancies due to transitivity. In order to express these relations as oriented graphs, one must first remove, or prune, such redundancies. This process can be reversed and a pitch-class relation can be extended to the point of its transitive closure. It is also common for a pitch-class relation to be absent of any order constraint involving both $\{x, y\}$, in which case we say x and y are incomparable. Such x and y are bound to be struck together, or else be *linearized* by the injection of some constraint that will make them comparable, as long as there remains still a partial order, that is, as long as this process does not introduce a symmetry, for instance. The set of all total orderings that can be linearized out of some partial order is called its total order class. In a completely analogous manner, one can *verticalize* a pitch-class relation by removing constraints, and again minding that the result is still transitive and symmetric. We say a partial order covers another whenever the former is a verticalization of the latter. A simple procedure to guarantee that a verticalization will remain a partial order is to take its union with the free aggregate, then subject this union to an extension operation, thus providing reflexivity in the first step, as well as transitivity in the second. We can say the following about covering, and about unions and intersections of pitch-class relations:

Theorem 1.1.2. [1, 193]

- i. *Covering is transitive;*
- ii. *A pitch-class relation is covered by its extension;*
- iii. *If a pitch-class relation covers another, then the extension of the former covers the extension of the latter.*

Theorem 1.1.3. [1, 194] *Let A and B be partial orders and denote by $\text{Toc}(A)$ and $\text{Toc}(B)$ their respective total order classes. Then*

$$\text{Toc}(A) \cap \text{Toc}(B) = \text{Toc}(\text{Ext}(A \cup B)) , \quad (1-3)$$

where Ext is the extension operator. Moreover, if A_i is a finite sequence of n partial orders, then

$$\bigcap_{i=0}^n \text{Toc}(A_i) = \text{Toc} \left[\text{Ext} \left(\bigcup_{i=0}^n A_i \right) \right] . \quad (1-4)$$

Theorem 1.1.4. [1, 194] *The intersection of two partial orders is again a partial order.*

Th. 1.1.3 will play a crucial role in the development of derivation techniques. Of vital importance is the fact that one can operate on pitch-class relations the same way one operates on pitch-class sets:

Theorem 1.1.5. [1, 195] *Let C be a pitch-class relation and $\{a, b\}$ an element of U such that $\{a, b\} \in C$.*

- i. *If F is a pitch-class operation, then $\{F(a), F(b)\} \in F(C)$ if and only if $\{a, b\} \in C$. In particular, if $R(C)$ is the retrograde of C , then $\{a, b\} \in R(C)$ if and only if $\{b, a\} \in C$.*
- ii. *If C is totally ordered, then $R(C) = (S \setminus D) \cup F$, where S is the simultaneous aggregate and F is the free aggregate.*
- iii. *If C_1 covers C_2 , then $F(C_1)$ covers $F(C_2)$.*
- iv. *Finally, if C is FR -invariant, then all cycles in F have length two.*

1.1.1 Aggregate Realizations

In this section we will define the important concept of *aggregate realizations*, which will, in turn, lead to a classification of partial orders, as well as to many musical applications. An aggregate realization is a particular type of partial order C in which, for any pair of pitch

classes a, b , if a and b are incomparable in C , then the set of pitch classes that precede a in C is equal to the set of pitch classes that precede b in C , and also the set of pitch classes that follow a in C is equal to the set of pitch classes that follow b in C . Aggregate realizations arise naturally from a total order in the sense that they belong to the set of all partial orders that are covered by said total order. An interesting compositional application of aggregate realizations is that of projecting a total order as a middle-ground entity.

Example 1.1.6. [1, 197] *Given a sequence S of partial orders, all of which covered by the same total order, say X , if both X is never stated in the foreground and S contains all order constraints in X , then a musical passage in which S is stated in the foreground will bear X as a middle-ground entity. In the case where S does not comprise all the order constraints in X , some other partial order that covers S will be projected in the middle-ground. In the particular case where a composer is dealing with pitch classes, projecting a partial order is equivalent to inducing the listener to infer its order constraints. If, in this case, two pitch classes are incomparable, then they are bound to be struck together.*

Example 1.1.7. [1, 207] *This examples provides a strategy to unravel the basic total order in Webern's Op. 27. It is somewhat paradoxical in the sense that unveiling the row requires prior knowledge of it. Consider the opening bars in Webern's Op. 27 depicted in Fig. 1-3, as well as their aggregate realization given in Fig. 1-4.*

Sehr mäßig ♩. = ca 40 Anton Webern, Op. 27

Figure 1-3. The initial bars in Webern's Op. 27.

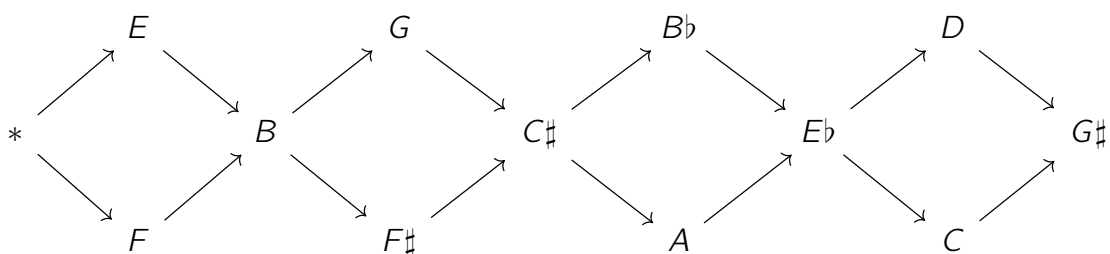


Figure 1-4. An aggregate realization of the initial bars in Webern's Op. 27. At its very first presentation, the total order used to generate the piece cannot be discerned. Moreover, the partial order we are actually able to hear intercalates the total order's two hexachords, a procedure that can be construed as a form of derivation.

Instead of the aggregate realization in Fig. 1-4, however, we use the fact that we know the basic series is $S = \{4, 5, 1, 3, 0, 2, 8, 9, 10, 6, 7, 11\}$, take the initial bars seen in Fig. 1-3, and rewrite an aggregate realization, call it D_1 , of them as in Fig. 1-5.

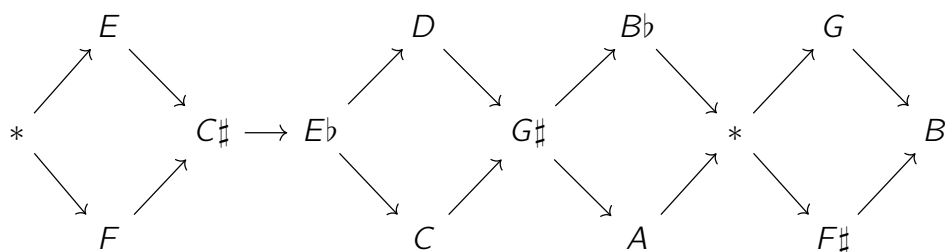


Figure 1-5. We denote the underlying partial order depicted in this aggregate realization by D_1 .

It is not too far-fetched to assume such an analysis. Whereas Fig. 1-4 represented a first-time hearing depiction of bars 1–7, Fig. 1-5 can be achieved by, say, a performer who realizes the voice-crossing of the series along its reflection axis. Having come to this conclusion, parsing bars 8–10 becomes a bit less daunting. Fig. 1-6 shows bars 8–10 in Op. 27, and Fig. 1-7 is a normalized aggregate realization of the passage. By normalized we mean that the series being displayed in the music is $T_{10}l(S) = \{6, 5, 9, 7, 10, 8, 2, 1, 0, 4, 3, 11\}$, but instead we set the aggregate realization to S , since we will want to take intersections of both partial orders later. $T_{10}l(S)$ begins with the right hand in bar 8, moves to the left hand in bar 9, and the very last note (which is not showing) is a high B the right hand again has in bar 11. At this point, our confidence that a series can be heard by the listener is severely damaged. We even start to

doubt that the average performer will have obtained, or even cared to obtain, a good grasp on what the series really is.

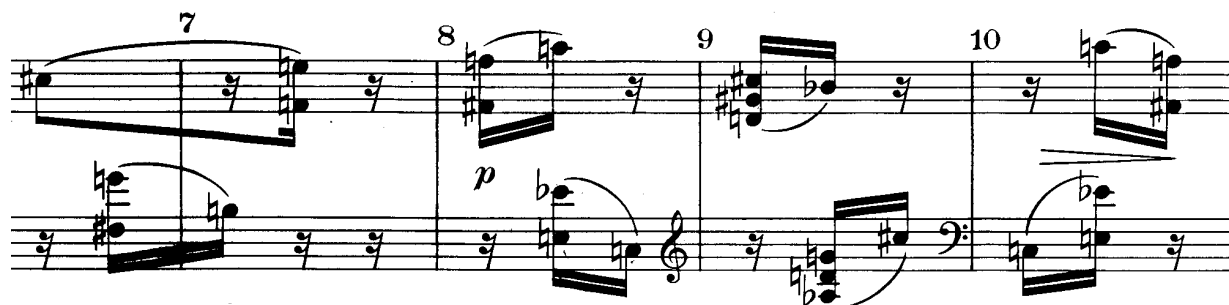


Figure 1-6. Bars 8–10 in Webern's Op. 27.

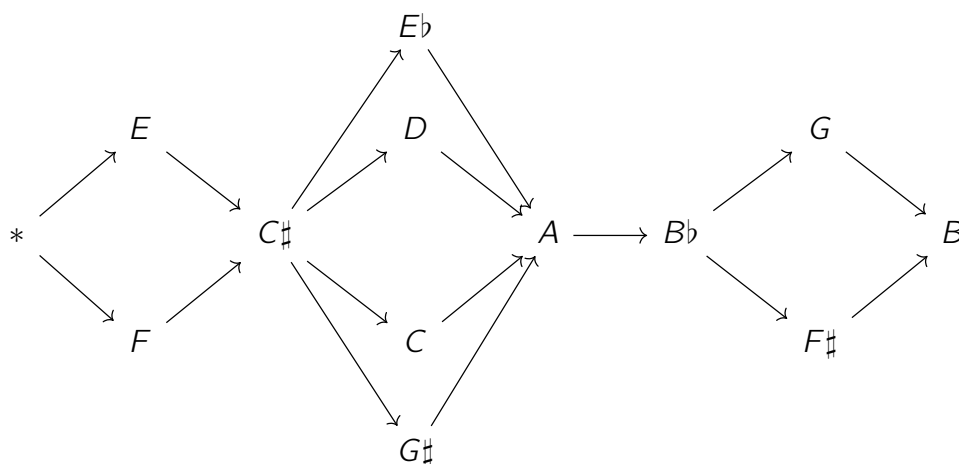


Figure 1-7. We denote the underlying partial order depicted in this aggregate realization by D_2 .

The next excerpt we analyze in the first movement is the last one we need in order to infer what series Webern used for the piece. The musical passage, taken from bars 19–23, is given in Fig. 1-8, and an aggregate realization is displayed in Fig. 1-9. We again normalize it with respect to S . This time, the series we are looking for in the excerpt is $T_3 I(S) = \{11, 10, 2, 0, 3, 1, 7, 6, 5, 9, 8, 4\}$, and again it has a very convoluted presentation, floating around in register, and freely changing hands. We come to the realization that, without the score, it is unlikely that a listener, even a very educated one, will be able to discern the composer's main generative material in one hearing. That well-versed listener might not be

able to discern it in the hundredth hearing, we even suspect. We shall conclude the analysis before coming back to this discussion, however.

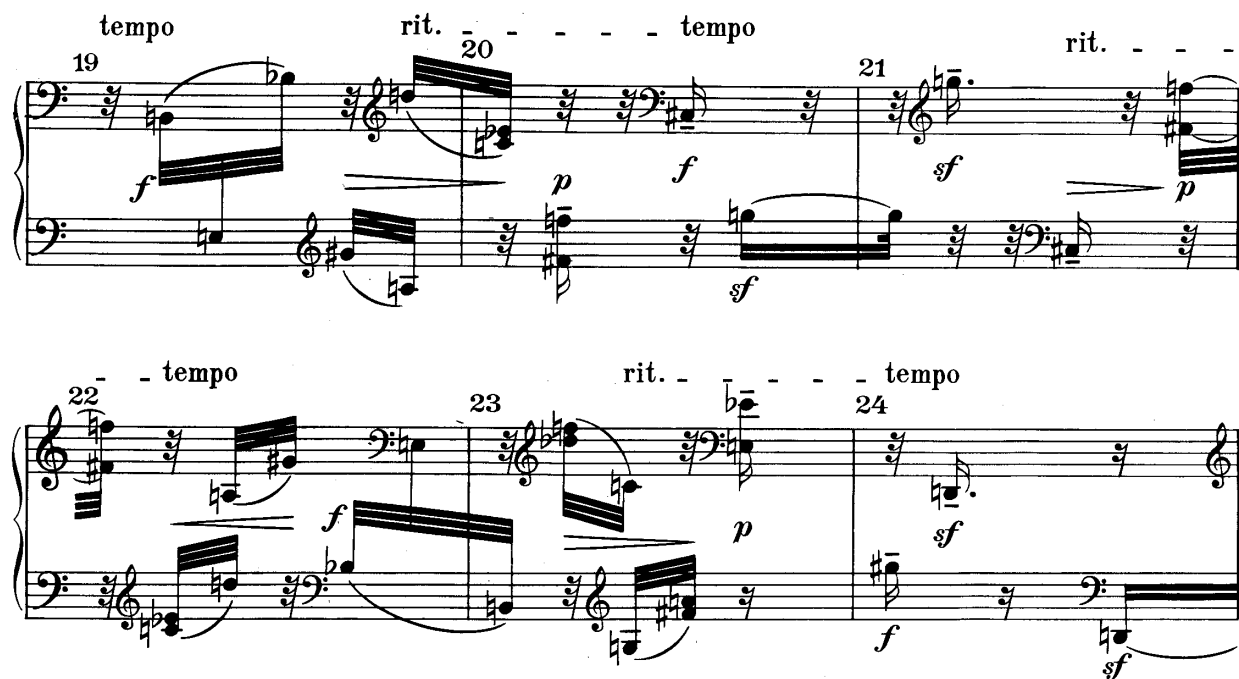


Figure 1-8. Bars 19–23 in Webern's Op. 27.

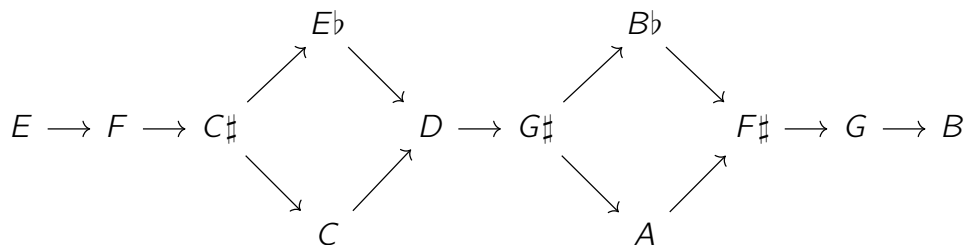


Figure 1-9. We denote the underlying partial order depicted in this aggregate realization by D_3 .

The last step in figuring out Webern's total order, according to our theoretical assumptions so far, is to take intersections of the partial orders depicted above with aggregate realizations. Assuming one could actually hear the presentation of the series without being victimized by any of the numerous pitfalls represented by all the registral displacements in the piece, and furthermore assuming one could freely invert and transpose twelve ordered and different pitch classes in their heads almost instantly, one would possibly arrive with the intersection $D_1 \cap D_2$

at measure 10. An aggregate realization of the intersection is shown in Fig. 1-10. One would still be puzzled, however, since there are still three incomparabilities that prevent one from comprehending the underlying series.

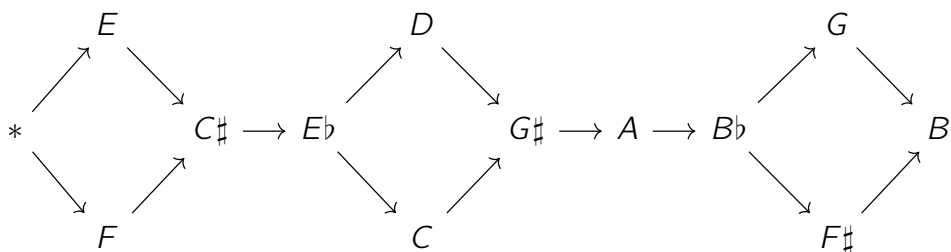


Figure 1-10. The intersection $D_1 \cup D_2$.

The next two pictures depict aggregate realizations for the intersections $D_1 \cap D_3$ and $D_2 \cap D_3$. Having reached measure 23, we are finally in a position to obtain Webern's series. Both intersections, however, still carry incomparabilities, so we will only be able to achieve our goal by taking the intersection of all three aggregate realizations.

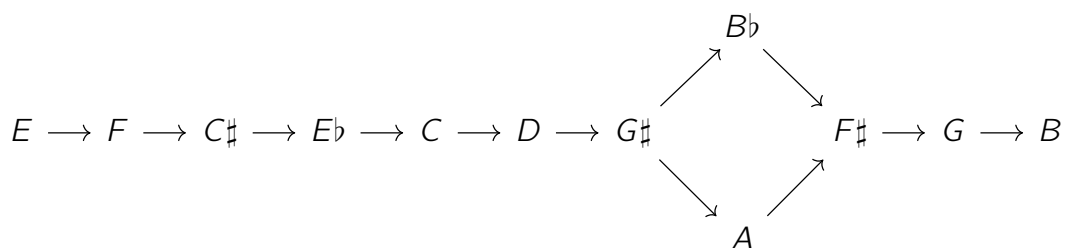


Figure 1-11. The intersection $D_1 \cup D_3$.

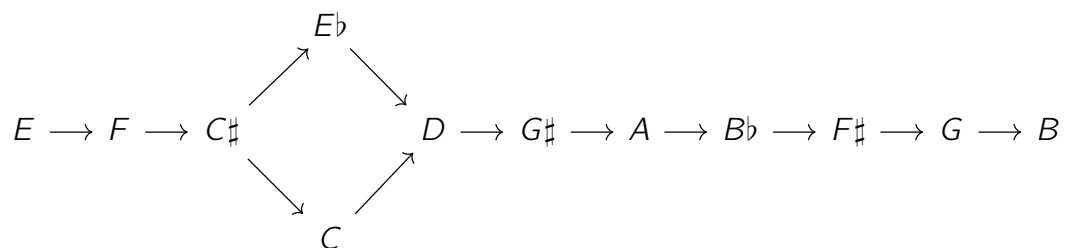


Figure 1-12. The intersection $D_2 \cup D_3$.

It is with bitter-sweet joy that we finally declare victory in Fig. 1-13, as we know we would not stand a chance relying on hearing alone.

$$E \rightarrow F \rightarrow C\sharp \rightarrow E\flat \rightarrow C \rightarrow D \rightarrow G\sharp \rightarrow A \rightarrow B\flat \rightarrow F\sharp \rightarrow G \rightarrow B$$

Figure 1-13. The intersection $D_1 \cup D_2 \cup D_3$.

There is much to be said about Ex. 1.1.7, particularly in what regards the aural perception of the composer's constructs. There is even more to be said if we take into consideration the fact that, as the twentieth-century unraveled, it became in many cases increasingly more difficult to establish how a piece of music was constructed with the presence of the score alone, much less simply by aural inference. It becomes less straightforward to determine the role of the listener in these cases, especially whenever one insists that the listener should be able to aurally infer *every* construct in a musical composition. We argue here that, as composers differentiate themselves from common practice, compositional technique becomes more subjective, and often indiscernible in the musical discourse. That does not mean, however, that musical fruition should be hindered in any sense, or that the composer's channel of communication with the listener has been narrowed in any way. It is simply the case that, even when not every single part of a structure is fathomed, we are still able to experience the structure itself. We do not need a blueprint to live in a house, we do not need a wrench to drive a car, and we certainly do not begin to understand the intricacies of the very universe in which we exist. And we do exist nonetheless.

The role of the analyst, on the other hand, also becomes more difficult to define. Whenever the structure of a piece of music becomes impossible to follow from its score alone, a theorist must reconsider the weight of musicological work in the analysis of such repertoire. In other words, it may very well be impossible to analyze a composition without resorting to the composer, or to a musicological study thereof. That is especially the case with algorithmic composition, which is a major avenue to which we shall apply our main object of study. Analyzing an algorithmically generated piece of music without prior knowledge of the algorithm

itself can only go as far as devising hearing strategies for the piece, as well as conjecturing what the algorithm might have been. It may be of substantial value, it may even carry more value than an analysis of the algorithm itself. And, just like with any piece of software, understanding the code is not a prerequisite to using said software, much less to determining whether it fulfills its purpose, or whether it is a good piece of software or not. However, if one intends to determine precisely how a piece of music was *constructed*, then knowledge of its blueprint becomes essential. And that determination is often of primary interest to composers.

The compositional techniques we are about to define and generalize in this study are notoriously of structural relevance. It does not mean that they cannot be aurally discerned, and in fact many authors devote considerable time devising hearing strategies for them, particularly when they are used to structure pitch. Nevertheless, our approach here will be restricted to the intrinsic qualities of these techniques, and we shall not pursue their aural perception in depth, simply because there may not be any intention from the composer's part for them to be heard at all. A familiar example might be the music of Stravinsky. Upon analyzing his use of rotational arrays, it becomes clear that the composer uses them as a generative techniques, rather than as a foreground musical entities. Analyzing such pieces often resort to techniques that have no connection whatsoever to any sort of hearing strategy, like Forte's employment of K and Kh set complexes, which yield a nexus set that ultimately cannot be heard. We aggravate this discussion with the idea that, more often than not, we shall employ the techniques we are about to present to dimensions other than pitch, and in particular to algorithmically determining spectral components and timbre. In this sense, their outcomes become textural elements of a composition, but still well within the canon of tasks a composer needs to exercise in the craft of a piece.

Whereas aggregate realizations correspond to a totally ordered sequence of disjoint subsets of the free aggregate, a *columnar (aggregate) realization* is, on the other hand, a set of disjoint row segments where, even though the internal order of each segment is total, all segments are pairwise incomparable. In addition, we require that a columnar realization contain the

free aggregate as a subset, so that we get all pitch classes belonging to a given base in every column. This is essentially a combination matrix in twelve-tone theory.

Example 1.1.8. [1, 201, 210] *The intersection of the set of all aggregate realizations with the set of all columnar realizations contains the set of all total orders (and thus all row segments), as well as the free aggregate. A total order is trivially an aggregate realization, and it is trivially a columnar realization. Any total order contains the free aggregate per our requirements.*

1.1.2 Row Segments

The concept of a *row segment*, which is fairly straightforward in twelve-tone theory, has an analogue here in the sense that we define it as a pitch-class relation that is reflexive, transitive, and antisymmetric. We impose the additional requirement that some subset of its order constraints also satisfy trichotomy. Arguably more important is the concept of an *embedded segment*. For any partial order that covers some row segment, we say that segment is an embedded segment of the partial order. By transitivity of covering, any other partial order covering the former partial order will have the aforementioned row segment embedded in it, including naturally any total order in its total order class. In this sense, a partial order may be seen as the union (possibly the extension thereof) of its various embedded segments:

Example 1.1.9. [1, 200] *Consider two total orders $X = \{0, 1, 7, 2, 10, 9, 11, 4, 8, 5, 3, 6\}$ and $Y = \{1, 2, 8, 3, 11, 10, 0, 5, 9, 6, 4, 7\}$ where, in particular, $Y = T_1(X)$. Seen as total orders, one can take the intersection $X \cap Y$, then prune it. This process yields a graph whose longest row segments are $\{1, 2, 10, 9, 4\}$, $\{1, 2, 10, 5, 6\}$, $\{1, 2, 11, 5, 6\}$, $\{1, 2, 8, 5, 6\}$, and $\{1, 2, 8, 3, 6\}$. These row segments are, in turn, the longest that are embedded segments of both X and Y .*

It is interesting to point out that the procedure described in Ex. 1.1.9 is in fact an algorithm to find common tones under transposition, and can be extended to any other pitch-class operation. This is a much needed addition to the well-known technique of *counting* common tones.

Theorem 1.1.10. [2, 10] *The number of common tones between a set S and some transposition of itself is given by*

$$|S \cap T_n(S)| = |\{x - y = n : x, y \in S\}| . \quad (1-5)$$

The number of common tones between a set S and some inversion of itself is given by

$$|S \cap T_n I(S)| = 2 \cdot |\{x + y = n : x, y \in S\}| + |\{a \in S : 2a = n\}| . \quad (1-6)$$

Moreover, the cardinality of the set $\{a \in S : 2a = n\}$ is at most 2.

Proof. We must count the occurrences of pairs of pitch classes that are interchanged by the operation at hand and double them, for if x maps onto y under some $T_n I$, then certainly y maps onto x under the same operation, given that every inversion operation has order two. In addition to that, we must account for the occurrences of pitch classes that may map onto themselves under the aforementioned operation. For any pair $a \neq b \in S$, it follows a and b are exchanged by some operation $T_n I$ whenever both $T_n I(a) = b$ and $T_n I(b) = a$ hold. Since $T_n I(a) = -a + n$, and similarly $T_n I(b) = -b + n$, if the pair is exchanged, then we must have $-a + n = b$ and $-b + n = a$ both true. Adding the last two expressions and yields $a + b = n$, which is the first set in the right-hand side of the formula. As discussed above, the cardinality of this set must be doubled. We have for any a that $T_n I(a) = a + n$, hence $a = T_n I(a) \iff a = -a + n$, that is, whenever $2a = n$. That is the second set in the formula. Finally, for any pair (a, n) such that $a = T_n I(a)$, we also have $a + 6 = -(a + 6) + n \iff 2a = n$, so that by the above it follows $a + 6 = T_n I(a + 6)$. Thus the set $\{a \in S : 2a = n\}$ has cardinality at most 2, proving the last assertion. \square

Example 1.1.11. [2, 11] *Write $S = \{0, 1, 4, 5, 8, 9\}$ and consider some inversion operation. An application of Th. 1.1.10 yields the table below.*

In practice, however, many composers choose to compute common tones by writing down an entire matrix. This procedure has the advantage of, not only giving all indices of transposition under which a set shares common tones with itself or other set, but it is also

Table 1-1. Common tones under inversion between $S = \{0, 1, 4, 5, 8, 9\}$ and itself.

n	0	1	2	3	4	5	6	7	8	9	10	11
$2 \cdot \{x + y = n : x, y \in S\} $	2	6	2	0	2	6	2	0	2	6	2	0
$ \{a \in S : 2a = n\} $	1	0	1	0	1	0	1	0	1	0	1	0
Total	3	6	3	0	3	6	3	0	3	6	3	0

possible to determine whether these common tones will preserve their ordering after the transform by examining the matrices' diagonals.

Example 1.1.12. [3, 49] Let X be an n -tone row seen as a column vector, and consider the $n \times n$ matrix $A = [X, \dots, X]$. In particular, the matrix $B = A - A^T$ will have a main diagonal of zeros, which indicates that X shares with itself n common tones under T_0 . If there are k threes in the matrix, then X will share with itself k tones under T_3 . There is no requirement that we compare a row with itself. If, for instance, A is given as above, and \bar{A} is the matrix for the row \bar{X} , then counting the number k of, say, threes in $B = A - \bar{A}^T$, will mean in turn that X and $T_3(\bar{X})$ share k tones under T_3 . Naturally, the main diagonal of B will not comprise only zeros if $A \neq \bar{A}$. To find common tones under inversion, we let $B = A + A^T$ and, similarly, M and $M \circ I$ become $B = A - M(A)^T$ and $B = A + M(A)^T$. Finally, if the indices we are counting are disposed in any of the matrix's diagonals, then they will preserve ordering after the transform, thus becoming embedded segments; if, in addition, they are adjacent, then they will in fact be row segments shared by X and the transform of \bar{X} .

The matrix for finding common tones under transposition that is described in Ex. 1.1.12 has the interesting property that it becomes a symmetric matrix when $A = \bar{A}$ and we take its elements as interval classes. This reflects the fact that, if X shares k tones with $T_i(X)$, then surely $T_i(X)$ will share exactly k tones with $T_{12-i}(X)$. If i is an interval class, then $i = 12 - i$, showing why the matrix will be symmetric. The matrix of common tones under inversion

is always symmetric, regardless we take its elements as interval classes. For multiplicative operations, however, we will often lack multiplicative inverses in twelve tones. For p -TET systems where p is prime, we do get symmetric matrices for multiplicative operations as well, but those will sometimes require a proper definition of multiplicative interval classes.

The importance of the procedure described in Ex. 1.1.9 is due to the fact that the technique in Ex. 1.1.12 can only go as far as counting the number of common tones, whereas the former procedure can actually tell us *what* these common tones are in a more straightforward manner. In addition, it can be very computationally effective if we write the rows we wish to compare as binary square matrices describing their order constraints. Taking then their intersection is easy, since we can rely on binary operations for this type of matrix. Pruning, if we wish to express the result as a graph, is also fast and simple. That being said, neither the above techniques addresses one of our primary concerns regarding derivation: given a set of order numbers and a transformation, what series are capable of producing transforms of *themselves* when pulled from those order numbers. This is in essence the exact opposite of what we have demonstrated above, where we depart from a series and attempt to understand its embedded segments. And it is arguably not a coincidence, as much of the twelve-tone theory devised since Forte has a strong analytical bias. What we are mainly interested, however, is in how these techniques fit onto the compositional scheme of things. And for that, having a two-way street where, on one hand we understand raw compositional materials and, on the other, we formulate them, is crucial. Moreover, as we attempt to construe orderedness as a generative procedure in all generality, it becomes imperative that we break our ties with purely analytical music theory and begin to delve into the mathematics of these general constructs. As the example below suggests, mathematics can greatly simplify the way we approach certain concepts and, depending on the task at hand, may even be decisive in determining whether it is feasible or not to pursue certain compositional avenues. For algorithmic composition, in particular, having a firm theoretical understanding of some generative procedure can greatly simplify the composer's algorithm, as well as make it more efficient.

Example 1.1.13. We can demonstrate 1.1.11, and also the omitted proof of 1.1.10 under transposition in a much simpler way with a little bit of abstract algebra by observing the cycle decomposition of each operation at hand. If $n = 3$, then we have

$$T_3 I = (0\ 3)(1\ 2)(4\ 11)(5\ 10)(6\ 9)(7\ 8) . \quad (1-7)$$

Hence, under $T_3 I$, every pitch-class in $S = \{0, 1, 4, 5, 8, 9\}$ maps to the complement of S . If the operation is, for instance, T_9 , then since

$$T_9 = (0\ 9\ 6\ 3)(1\ 10\ 7\ 4)(2\ 11\ 8\ 5) , \quad (1-8)$$

we get straightforwardly that $S = \{0, 1, 4, 5, 8, 9\}$ shares three common tones with $T_9(S)$, namely $0 \mapsto 9$, $4 \mapsto 1$, and $8 \mapsto 5$.

In a completely analogous manner to the principle of pulling row segments from a series, and in the interest of building two-way roads, we can most certainly concatenate row segments in order to formulate a new series.

Example 1.1.14. [1, 200] Let $X = \{0, 1, 2\}$ and $Y = \{3, 4, 5\}$ be row segments. We actually require that $X \cap Y = \emptyset$ when seeing X and Y as partial orders. The concatenation $X|Y$ will then be the partial order:

$$X \cup Y \cup \{\{a, b\} : a \in X, b \in Y\} . \quad (1-9)$$

It follows immediately that both X and Y are embedded row segments of $X|Y$. Note that our use of concatenation here is sequential, that is, the entire row segment X precedes the entire row segment Y in $X|Y$. In other words, we do not allow intercalation of segments when concatenating.

1.2 A Survey of Derivation Techniques

In this section we devote our attention to expanding the idea first presented in Ex. 1.1.1. In it, we devise a type of derivation in which the series being displayed vertically is unrelated to the series being derived horizontally, except for the fact that both share a row segment when we retrograde one of the rows. The construction is part of a more general procedure, in

which we always match a row with a retrograded transform of itself. In the particular case of Ex. 1.1.1, the transform, say F , was T_0 for simplicity, but arbitrary pitch-class operations may be used. Denote the given series by S , and define similarly the derived row as $V = V_1|V_2$, that is, V is a concatenation of two row segments. The only requirement is that V_1 , the segment we choose to single out, remains invariant under F , which will force V_2 to also be invariant under F . In Ex. 1.1.1 this requirement is satisfied trivially. The aforementioned procedure is given schematically in Table 1-2.

Table 1-2. Schematics of a derivation procedure involving the retrograde and an arbitrary operation F .

	S	$R \circ F(S)$
V	V_1	V_2
$R \circ F(V)$	$R \circ F(V_2)$	$R \circ F(V_1)$

Example 1.2.1. *In this example, we illustrate a derivation procedure similar to that in Ex. 1.1.1 where the operation F is not trivial. We again take the row in Berg's Lulu, $S = \{10, 2, 3, 0, 5, 7, 4, 6, 9, 8, 1, 11\}$, and consider the segment $\vec{s} = [10 \ 0 \ 5 \ 7]^T$ as a column vector. Now let $A^T = [\vec{s} \mid \vec{s} \mid \vec{s} \mid \vec{s}]$ be the square matrix whose every column is equal to \vec{s} . Then*

$$A + A^T = \begin{bmatrix} 2 & 10 & 3 & 5 \\ 10 & 0 & 5 & 7 \\ 3 & 5 & 10 & 0 \\ 5 & 7 & 0 & 2 \end{bmatrix} \pmod{12} . \quad (1-10)$$

In particular, we see that the row segment $\{10, 0, 5, 7\}$ is invariant under RT_5I , since we get a main diagonal of fives when we mirror the matrix above vertically. Thus, by matching S with $RT_5I(S)$, we may get the row segment $\{10, 0, 5, 7\}$ in the derived row V itself, rather than in its retrograde, as was the case in Ex. 1.1.1. Setting it to V_2 , say, yields $V =$

$\{2, 3, 4, 6, 9, 8, 1, 11, 10, 0, 5, 7\}$, so we get the combination matrix below.

$$\left[\begin{array}{cccccccccccc|cccccccc} . & 2 & 3 & . & . & . & 4 & 6 & 9 & 8 & 1 & 11 & . & . & . & . & . & 10 & 0 & 5 & . & . & 7 \\ 10 & . & . & 0 & 5 & 7 & . & . & . & . & . & . & 6 & 4 & 9 & 8 & 11 & 1 & . & . & . & 2 & 3 & . \end{array} \right] \quad (1-11)$$

It is usually the case in this type of derivation that, unlike Ex. 1.2.1, the invariance of V under F , or under $R \circ F$ for that matter, does not preserve any ordering.

Example 1.2.2. [1, 212] Let $S = \{0, 1, 7, 2, 10, 9, 11, 4, 8, 5, 3, 6\}$ and consider the operation

$$T_2 I = (0 \ 2)(3 \ 11)(4 \ 10)(5 \ 9)(6 \ 8) . \quad (1-12)$$

Upon inspection of the cycles of $T_2 I$, we see that the segment $\{0, 1, 7, 2\}$ is invariant under it. If we consider a combination matrix involving $R T_2 I$, however, then we shall not obtain the same ordered result as in Ex. 1.2.1, since both (1) and (7) are fixed points. The same would happen to any $T_k I$ where k is even. In particular, this shows that, in order to obtain the same ordered row segment in both columns of the combination matrix, F cannot be trivial.

$$\left[\begin{array}{cccccccccccc|cccccccc} 0 & . & . & 1 & . & 7 & . & . & . & 2 & . & . & 10 & 9 & . & 11 & 4 & 8 & . & 5 & . & 3 & 6 & . \\ . & 8 & 11 & . & 9 & . & 6 & 10 & 3 & . & 5 & 4 & . & . & 0 & . & . & . & 7 & . & 1 & . & . & 2 \end{array} \right] \quad (1-13)$$

As a consequence of F and the retrograde operation, combination matrices of this type feature two columns that are upside down F -mirrors of each other. In line with our theoretical remarks so far, more can be said about such combination matrices.

Proposition 1.2.3. [1, 211, 214] Consider a 2-row combination matrix C where a row is derived via the retrograde and some operation F . Denote the derived row by $V = V_1 | V_2$. Then the first column is the partial order $C_1 = V_1 \cup R \circ F(V_2)$, and similarly the second column is the partial order $C_2 = V_2 \cup R \circ F(V_1)$, such that $C_2 = R \circ F(C_1)$. If D is a partial order that covers C_1 , then $R \circ F(D)$ will cover C_2 , and if D is in the total order class of C_1 , that is, D is a row that can be linearized from C_1 , then $R \circ F(D)$ is in the total order class of C_2 .

Finally, 2-row derivations of this type exist for arbitrary rows. The number of such combination matrices for any given row depends on the invariances of the chosen partition of V .

It is not clear from the literature, however, how many 2-row combination matrices involving R we can get for an arbitrary row *exactly*. We shall investigate what this number is in the present study.

1.2.1 Folded Derivation

A related technique involving greater than 2-row counterpoint is achieved by *folding* a derivation matrix. The process is equivalent to first constructing a matrix of hexachordal combinatoriality in the traditional sense, that is, where hexachords are seen as tropes rather than as row segments, then deriving rows from this matrix using the techniques above. Let S be a row whose first hexachord is invariant under the operation G . Consider a row $V = V_1|V_2$ and an operation F such that S is in the total order class of $V_1 \cup R \circ F(V_2)$. Then putting S in counterpoint with $G(S)$, as well as deriving V from $S|R \circ F(S)$ yields the schematic representation in Table 1-3:

Table 1-3. Schematics of a folded derivation procedure involving the retrograde.

	S	$R \circ F(S)$
V	V_1	V_2
$R \circ F(V)$	$R \circ F(V_2)$	$R \circ F(V_1)$
$R \circ GF(V)$	$R \circ GF(V_2)$	$R \circ GF(V_1)$
$G(V)$	$G(V_1)$	$G(V_2)$
	$G(S)$	$R \circ GF(S) = R \circ FG(S)$

It is argued without proof in [1, 215] that, for a derivation procedure such as the one in Table 1-3, the folded derivation has to vertically satisfy G , while satisfying F horizontally.

Thus F and G would have to commute in this case. The caveat that the operation chosen for the hexachordal combinatoriality part must commute with the operation chosen for the derivation part still needs to be confirmed, however, as other derivation matrices that have similar constraints do not require commutativity. Ex. 1-3 shows a musical application of folded derivations.

Example 1.2.4. [1, 215] Let $S = \{0, 1, 11, 3, 8, 10, 4, 9, 7, 6, 2, 5\}$ and consider the operation T_6 :

$$T_6 = (0\ 6)(1\ 7)(2\ 8)(3\ 9)(4\ 10)(5\ 11) . \quad (1-14)$$

Let $V_1 = \{1, 3, 8, 9, 7, 2\}$. In particular, since the unordered set V_1 is T_6 -invariant, we get $V_2 = \{11, 0, 10, 4, 5, 6\}$ and the following combination matrix:

$$\left[\begin{array}{cccccc|cccccc} 1 & & 3 & 8 & & 9 & 7 & & 2 & & 11 & 0 & & 10 & 4 & & 5 & 6 \\ 0 & & 11 & & & 10 & 4 & & 6 & 5 & 8 & 1 & 3 & & 2 & 9 & & 7 \end{array} \right] . \quad (1-15)$$

Consider further the operation $T_5|$:

$$T_5| = (0\ 5)(1\ 4)(2\ 3)(6\ 11)(7\ 10)(8\ 9) . \quad (1-16)$$

Then $S_1 = \{0, 1, 11, 3, 8, 10\}$ maps to its complement under $T_5|$, so we can use S in a combination matrix where we match S with its transform under $T_5|$ in the usual way, that is, in a matrix of hexachordal combinatoriality. We can then derive from $T_5|(S)$ the row $T_5|(V)$. Since $T_5|$ commutes with T_6 , as any pitch-class operation does, we get the following folded derivation:

$$\left[\begin{array}{cccccc|cccccc} 1 & & 3 & 8 & & 9 & 7 & & 2 & & 11 & 0 & & 10 & 4 & & 5 & 6 \\ 0 & & 11 & & & 10 & 4 & & 6 & 5 & 8 & 1 & 3 & & 2 & 9 & & 7 \\ \hline 5 & 6 & & 7 & 1 & & 11 & 0 & & 9 & 4 & 2 & & 3 & 8 & & 10 \\ 4 & & 2 & 9 & & 8 & 10 & & 3 & 6 & 5 & & 7 & 1 & & 0 & 11 \end{array} \right] . \quad (1-17)$$

1.2.2 Shifted Derivation

There is a different flavor to folded derivations that arises from shifting horizontally one of the two rows of the derivation matrix. Shifted derivations may be equivalent to folding combinatoriality matrices that involve the retrograde, and there is no requirement here that the combinatoriality be hexachordal. In fact, one can choose segments to formulate a combination matrix, then fold the result. One may even match altogether different foldings of a row, as to bridge different derivations of the same generative material [1, 216].

Table 1-4. Schematics of a shifted derivation procedure involving the retrograde. The asterisk indicates there is no requirement we derive the same row class in both foldings, in which case V would be replaced by some other row V^* and G could be the identity.

	S	$R \circ F(S)$
V	V_1	V_2
$R \circ F(V)$	$R \circ F(V_2)$	$R \circ F(V_1)$
$R \circ G(V)^*$		$R \circ G(V_2)^* \quad R \circ G(V_1)^*$
$GF(V)^*$		$GF(V_1)^* \quad GF(V_2)^*$
		$GF(S) \quad R \circ G(S)$

Ex. 1.2.5 shows an application of shifted derivation where combinatoriality is not hexachordal, but both foldings derive different transforms of the same row:

Example 1.2.5. [1, 216] Consider the row $S = \{0, 1, 7, 2, 10, 9, 11, 4, 8, 5, 3, 6\}$ and the combination matrix given by $R T_{10} I(S)$ against $T_{11}(S)$:

$$\left[\begin{array}{cccc|cccccc} 4 & 7 & 5 & 2 & 6 & 11 & 1 & 0 & 8 & 3 & 9 & 10 \\ 11 & 0 & 6 & 1 & 9 & 8 & 10 & 3 & 7 & 4 & 3 & 5 \end{array} \right] \quad (1-18)$$

Deriving the row $V = V_1|V_2 = \{1, 7, 2, 9, 8, 3\}|\{4, 5, 6, 11, 0, 10\}$ from $S|RT_{10}I(S)$, and following the scheme in Table 1-4, yields the following shifted derivation:

$$\left[\begin{array}{cccccc|cccc|c} & 1 & 7 & 2 & & 9 & & 8 & 3 & 4 & & 5 & & 6 \\ 0 & & & 10 & & 11 & 4 & 5 & 6 & & 7 & & 2 & \\ \hline & & & & & & & & & & 0 & 6 & 1 & 8 & 7 \\ & & & & & & & & & 11 & & 9 & 10 & 3 & \end{array} \right] \dots$$

$$\dots \left[\begin{array}{cccc|cccccc|c} & 6 & 11 & & 0 & & & & 10 & & & & & \\ & & & 1 & & 8 & 3 & 9 & & & & & & \\ \hline & 7 & & & 3 & & & & & 3 & 4 & 5 & 10 & 11 & 9 \\ 3 & & 4 & & & 5 & & & & 6 & 1 & & 0 & 7 & 2 & 8 \end{array} \right] . \quad (1-19)$$

Since the constraints to formulating matrices that feature shifted derivations are more flexible, it seems plausible to conjecture that there are far more combination matrices of this type per row, than there are of the non-shifted type. This question is not at all addressed in the literature, much less how well constructs like these, shifted and not, support combination matrices without the retrograde, or even against rotations of a row. Accounting for the exact number of such constructs in a more general setting than that of twelve tones will constitute one of this paper's goals.

1.2.3 Self-Derivation

The next derivation technique to be discussed is similar to the ones above, with the additional requirement that the derived or folded rows be transforms of the original row. This is called self-derivation and is arguably the most difficult type of derivation to achieve, as not every row will lend itself to self-derivation. It is also the technique that requires the biggest theoretical machinery to understand. Self-derivation has many interesting applications, including the whole class of Mallalieu-type rows, which will be discussed in Sec. 1.3. We shall come back to a summary of our goals after exposing self-derivation and other derivation

techniques that, to this day, still lack a deeper theoretical formulation and generalization. The general scheme for a two-row combination matrix of self-derivation involving the retrograde is given in Table 1-5:

Table 1-5. Schematics of a self-derivation procedure involving the retrograde.

	$G(S)$	$R \circ FG(S)$
S	S_1	S_2
$R \circ F(S)$	$R \circ F(S_2)$	$R \circ F(S_1)$

It is stated without proof in [1, 217] that the operations F and G in Table 1-5 must commute, as well. For this self-derivation on two-row counterpoint case, however, simple inspection of the examples that follow such statement already affords a counter-proof.

Example 1.2.6. [1, 218] Let $S = S_1|S_2 = \{3, 8, 1, 0, 9, 6\}|\{4, 7, 10, 5, 2, 11\}$ and consider the operation $T_9 I$:

$$T_9 I = (0\ 9)(1\ 8)(2\ 7)(3\ 6)(4\ 5)(10\ 11) . \quad (1-20)$$

In particular, both S_1 and S_2 are invariant under $T_9 I$. What is certainly not obvious, is that we can derive S and $T_9 I(S)$ from a combination matrix where the first column is $T_7(S)$ and the second is $T_9 I \circ R T_7(S) = R T_2 I(S)$, as shown in the following self-derivation matrix:

$$\left[\begin{array}{cccccc|cccccc} 3 & 8 & & 1 & & 0 & 9 & 6 & & 4 & 7 & 10 & 5 & 2 & & 11 \\ 10 & & 7 & 4 & & 11 & 2 & 5 & & 3 & 0 & 9 & & 8 & & 1 & 6 \end{array} \right] . \quad (1-21)$$

Here we have $F = T_9 I$ and $G = T_7$. It is certainly not the case that F and G commute, as $T_2 I = F \circ G \neq G \circ F = T_4 I$.

Similarly to general derivation, two-row self-derivations can be folded. What is unique to self-derivation, however, is that the *same* pattern of order numbers that give the self-derived transform of a row can be used to fold each row of a combination matrix, as seen in Ex. 1.2.7.

The folded rows can subsequently be folded, and this procedure can generate many levels of self-derivation.

Example 1.2.7. [1, 221] Let $S = \{0, 11, 5, 10, 4, 2, 7, 9, 8, 3, 6, 1\}$ and consider the following combination matrix given by $T_2(S) | R T_2(S)$, whose derived rows are S and $R(S)$:

$$\left[\begin{array}{cccc|cccc} 0 & 11 & 5 & & 10 & 4 & 2 & \\ 1 & 6 & & 3 & 8 & 9 & 7 & \end{array} \middle| \begin{array}{cccc|cccc} 7 & 9 & & 8 & 3 & & 6 & 1 \\ 2 & 4 & 10 & & 5 & 11 & 0 & \end{array} \right] \quad (1-22)$$

Subjecting the entire matrix to T_1 yields:

$$\left[\begin{array}{cccc|cccc} 1 & 0 & 6 & & 11 & 5 & 3 & \\ 2 & 7 & & 4 & 9 & 10 & 8 & \end{array} \middle| \begin{array}{cccc|cccc} 8 & 10 & & 9 & 4 & & 7 & 2 \\ 3 & 5 & 11 & & 6 & 0 & 1 & \end{array} \right] \quad (1-23)$$

We can then pull the entire matrix in Eq. 1-22 from the first row of Eq. 1-23:

$$\left[\begin{array}{cccc|cccc} & 0 & & 11 & 5 & & & \\ & 1 & & 6 & & & 3 & \\ 2 & 7 & & 4 & 9 & 10 & 8 & \end{array} \middle| \begin{array}{cccc|cccc} & & 10 & & 4 & & & 2 \\ 8 & & & 9 & & & 7 & \\ 3 & 5 & 11 & & 6 & 0 & 1 & \end{array} \right] \quad (1-24)$$

The next example provides a musical application of folded self-derivation matrices that constitute the main compositional procedure in *Ciro Scotto's Tetralogy*.

Example 1.2.8. [4, 180] Let $S = \{0, 4, 7, 3, 11, 2, 10, 1, 6, 8, 9, 5\}$ and consider the self-derivation array in Fig. 1-14.

T_7	7	e 2	t 6	9	5 8	1	3	4 0
$T_7 R$	0 4	3	1	8 5	9	6 t	2 e	7
	T_0				$T_0 R$			

Figure 1-14. Self-derived row in Scotto's *Tetralogy*.

Similarly to Ex. 1.2.7, we can fold the above matrix in order to obtain subsequent levels of derivation. Unlike Ex. 1.2.7, however, Scotto derives a rotated transform of S from $R T_7(S)$.

The rows in Fig. 1-15 are thus $T_2(S)$, $RT_2(S)$, $\rho_6 RT_2(S)$ and $\rho_6 T_2(S)$, where ρ is the cyclical rotation operator.

$\rho_6 T_2(S)$	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100	101	102	103	104	105	106	107	108	109	110	111	112	113	114	115	116	117	118	119	120	121	122	123	124	125	126	127	128	129	130	131	132	133	134	135	136	137	138	139	140	141	142	143	144	145	146	147	148	149	150	151	152	153	154	155	156	157	158	159	160	161	162	163	164	165	166	167	168	169	170	171	172	173	174	175	176	177	178	179	180	181	182	183	184	185	186	187	188	189	190	191	192	193	194	195	196	197	198	199	200	201	202	203	204	205	206	207	208	209	210	211	212	213	214	215	216	217	218	219	220	221	222	223	224	225	226	227	228	229	230	231	232	233	234	235	236	237	238	239	240	241	242	243	244	245	246	247	248	249	250	251	252	253	254	255	256	257	258	259	260	261	262	263	264	265	266	267	268	269	270	271	272	273	274	275	276	277	278	279	280	281	282	283	284	285	286	287	288	289	290	291	292	293	294	295	296	297	298	299	300	301	302	303	304	305	306	307	308	309	310	311	312	313	314	315	316	317	318	319	320	321	322	323	324	325	326	327	328	329	330	331	332	333	334	335	336	337	338	339	340	341	342	343	344	345	346	347	348	349	350	351	352	353	354	355	356	357	358	359	360	361	362	363	364	365	366	367	368	369	370	371	372	373	374	375	376	377	378	379	380	381	382	383	384	385	386	387	388	389	390	391	392	393	394	395	396	397	398	399	400	401	402	403	404	405	406	407	408	409	410	411	412	413	414	415	416	417	418	419	420	421	422	423	424	425	426	427	428	429	430	431	432	433	434	435	436	437	438	439	440	441	442	443	444	445	446	447	448	449	450	451	452	453	454	455	456	457	458	459	460	461	462	463	464	465	466	467	468	469	470	471	472	473	474	475	476	477	478	479	480	481	482	483	484	485	486	487	488	489	490	491	492	493	494	495	496	497	498	499	500	501	502	503	504	505	506	507	508	509	510	511	512	513	514	515	516	517	518	519	520	521	522	523	524	525	526	527	528	529	530	531	532	533	534	535	536	537	538	539	540	541	542	543	544	545	546	547	548	549	550	551	552	553	554	555	556	557	558	559	560	561	562	563	564	565	566	567	568	569	570	571	572	573	574	575	576	577	578	579	580	581	582	583	584	585	586	587	588	589	590	591	592	593	594	595	596	597	598	599	600	601	602	603	604	605	606	607	608	609	610	611	612	613	614	615	616	617	618	619	620	621	622	623	624	625	626	627	628	629	630	631	632	633	634	635	636	637	638	639	640	641	642	643	644	645	646	647	648	649	650	651	652	653	654	655	656	657	658	659	660	661	662	663	664	665	666	667	668	669	670	671	672	673	674	675	676	677	678	679	680	681	682	683	684	685	686	687	688	689	690	691	692	693	694	695	696	697	698	699	700	701	702	703	704	705	706	707	708	709	710	711	712	713	714	715	716	717	718	719	720	721	722	723	724	725	726	727	728	729	730	731	732	733	734	735	736	737	738	739	740	741	742	743	744	745	746	747	748	749	750	751	752	753	754	755	756	757	758	759	760	761	762	763	764	765	766	767	768	769	770	771	772	773	774	775	776	777	778	779	780	781	782	783	784	785	786	787	788	789	790	791	792	793	794	795	796	797	798	799	800	801	802	803	804	805	806	807	808	809	810	811	812	813	814	815	816	817	818	819	820	821	822	823	824	825	826	827	828	829	830	831	832	833	834	835	836	837	838	839	840	841	842	843	844	845	846	847	848	849	850	851	852	853	854	855	856	857	858	859	860	861	862	863	864	865	866	867	868	869	870	871	872	873	874	875	876	877	878	879	880	881	882	883	884	885	886	887	888	889	890	891	892	893	894	895	896	897	898	899	900	901	902	903	904	905	906	907	908	909	910	911	912	913	914	915	916	917	918	919	920	921	922	923	924	925	926	927	928	929	930	931	932	933	934	935	936	937	938	939	940	941	942	943	944	945	946	947	948	949	950	951	952	953	954	955	956	957	958	959	960	961	962	963	964	965	966	967	968	969	970	971	972	973	974	975	976	977	978	979	980	981	982	983	984	985	986	987	988	989	990	991	992	993	994	995	996	997	998	999	1000	1001	1002	1003	1004	1005	1006	1007	1008	1009	1010	1011	1012	1013	1014	1015	1016	1017	1018	1019	1020	1021	1022	1023	1024	1025	1026	1027	1028	1029	1030	1031	1032	1033	1034	1035	1036	1037	1038	1039	1040	1041	1042	1043	1044	1045	1046	1047	1048	1049	1050	1051	1052	1053	1054	1055	1056	1057	1058	1059	1060	1061	1062	1063	1064	1065	1066	1067	1068	1069	1070	1071	1072	1073	1074	1075	1076	1077	1078	1079	1080	1081	1082	1083	1084	1085	1086	1087	1088	1089	1090	1091	1092	1093	1094	1095	1096	1097	1098	1099	1100	1101	1102	1103	1104	1105	1106	1107	1108	1109	1110	1111	1112	1113	1114	1115	1116	1117	1118	1119	1120	1121	1122	1123	1124	1125	1126	1127	1128	1129	1130	1131	1132	1133	1134	1135	1136	1137	1138	1139	1140	1141	1142	1143	1144	1145	1146	1147	1148	1149	1150	1151	1152	1153	1154	1155	1156	1157	1158	1159	1160	1161	1162	1163	1164	1165	1166	1167	1168	1169	1170	1171	1172	1173	1174	1175	1176	1177	1178	1179	1180	1181	1182	1183	1184	1185	1186	1187	1188	1189	1190	1191	1192	1193	1194	1195	1196	1197	1198	1199	1200	1201	1202	1203	1204	1205	1206	1207	1208	1209	1210	1211	1212	1213	1214	1215	1216	1217	1218	1219	1220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Figure 1-17. Musical realization of the middle-ground in Scotto's *Tetralogy*.

background of the piece. The prolongation of the first bar in Fig. 1-16 is depicted in Fig. 1-18, and a musical realization thereof is displayed in Fig. 1-19.

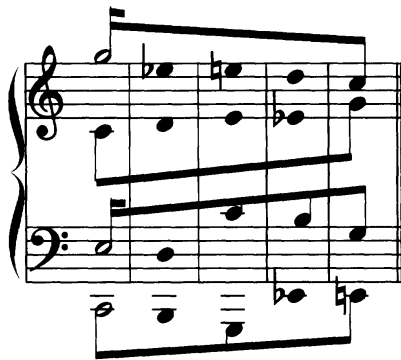


Figure 1-18. Prolongation of the middle-ground structure in Scotto's *Tetralogy*.

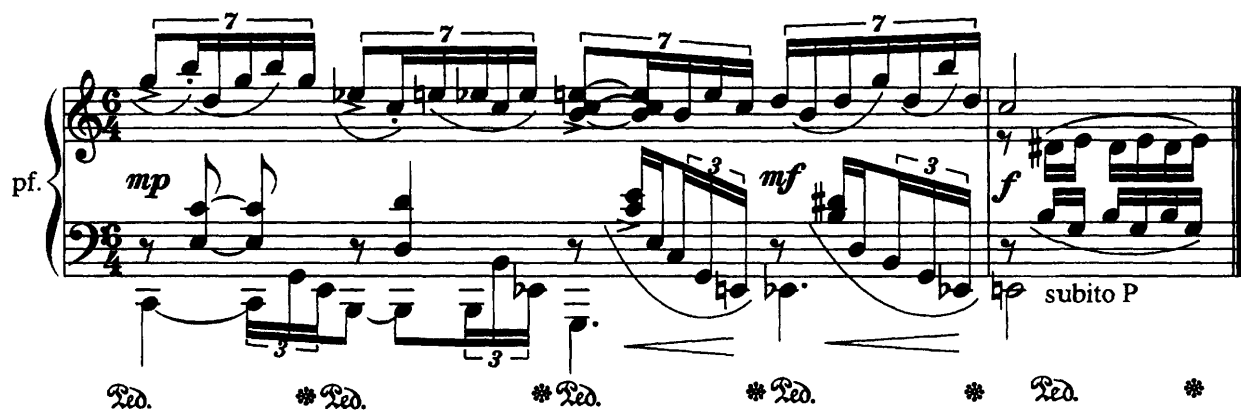


Figure 1-19. Musical realization of the prolonged middle-ground in Scotto's *Tetralogy*.

The only algorithm that currently exists to find self-derivation matrices is brute force, that is, by trial and error. One must often compose the row while trying to derive a transform

of the row itself in a matrix. Self-derivation is the absolute primary concern of this paper, especially because there is so little we know about it. Self-derivation is what makes an order number in a row have multiple functions. Other types of derivation are also important as compositional tools, but they are ultimately special cases of the more constrained type, which is that of self-derivation matrices. In other words, we shall make our priority to investigate the existence of a self-derived matrix for any given row in all generality, that is, for arbitrary n -tone equal temperament systems. We shall then devise a general algorithm to obtain such matrices if they exist, as well as investigate how many such matrices do exist for any particular choice of equal temperament system. We shall finally confront our findings with the results in [5], which uses a brute force algorithm to compute self-derived rows of a few particular types in the 12-TET. For generalized results, there will be nothing with which to compare, as this territory remains, to this day, mostly uncharted.

1.2.4 Derivation from Aggregate Realizations

The remainder of this chapter will be devoted to exposing derivation matrices that do not necessarily involve the retrograde, then exploring the concept of Mallalieu-type rows, which represent a very peculiar class of self-deriving rows. Mallalieu rows are somewhat better understood in the 12-TET than general derivation, and have many beautiful compositional applications.

Example 1.2.9. [1, 224] Let $S = \{0, 1, 7, 2\} | \{10, 9\} | \{11, 4, 8, 5\} | \{3, 6\}$. Given that we always obtain the complement of a row's first hexachord from its second hexachord, we get the trivial case of hexachordal combinatoriality when we match a row with its retrograde. Such combination matrix will have four columns, because of the way we chose to partition S :

$$A = \left[\begin{array}{c|c|c|c} \{0, 1, 7, 2\} & \{10, 9\} & \{11, 4, 8, 5\} & \{3, 6\} \\ \hline \{6, 3\} & \{5, 8, 4, 11\} & \{9, 10\} & \{2, 7, 1, 0\} \end{array} \right]. \quad (1-25)$$

Now consider the cycles of $T_{11} | = (0\ 11)(1\ 10)(2\ 9)(3\ 8)(4\ 7)(5\ 6)$. In particular, the first column of A will comprise the partial order $S_1 \cup R(S_4)$, and this union will, in turn, map

onto its hexachordal complement under $T_{11}I$, as it takes precisely one element from each of the operation's cycles, all of which have length two. Since the second column above is the complement of the first, it will also map onto its complement under $T_{11}I$. Because the third and fourth columns are mirrors of the first two, we do get hexachordal combinatoriality under $T_{11}I$ in every column, that is, for the partial orders $S_1 \cup R(S_4)$ and $S_2 \cup R(S_3)$, as well as their retrogrades. We do not get the same result between S and $T_{11}I(S)$, that is, the first hexachord of $T_{11}I(S)$ is not the complement of the first hexachord of S . This procedure gives us the matrix \hat{A} .

$$\hat{A} = \left[\begin{array}{c|c|c|c} \{0, 1, 7, 2\} & \{10, 9\} & \{11, 4, 8, 5\} & \{3, 6\} \\ \{6, 3\} & \{5, 8, 4, 11\} & \{9, 10\} & \{2, 7, 1, 0\} \\ \{11, 10, 4, 9\} & \{1, 2\} & \{0, 7, 3, 6\} & \{8, 5\} \\ \{5, 8\} & \{6, 3, 7, 0\} & \{2, 1\} & \{9, 4, 10, 11\} \end{array} \right]. \quad (1-26)$$

What we basically have above is a sequence of four columnar realizations. We are interested in deriving members of the same row class from each column. As aforementioned, there is no algorithm to accomplish this but brute force, and there is no a priori way of knowing whether we will succeed at this moment. So far the best we can do is take the intersection of all columns, or transforms thereof and, if the total order class of the intersection is not empty, that is, if it contains the free aggregate and does not contain any symmetry, then Th. 1.1.3 guarantees we will be able to derive representatives of this row class from each column. Let C_1, C_2, C_3, C_4 be the four columns of the matrix \hat{A} . It follows the row $V = \{11, 0, 1, 6, 10, 4, 7, 2, 9, 5, 3, 8\}$ has the property that $T \in \text{Toc}\{\text{Ext}[C_1 \cup R T_{11}I(C_2) \cup T_{11}I(C_3) \cup R(C_4)]\}$. We can therefore derive $[V | R T_{11}I(V) | T_{11}I(V) | R(V)]$ from the columns

of \hat{A} .

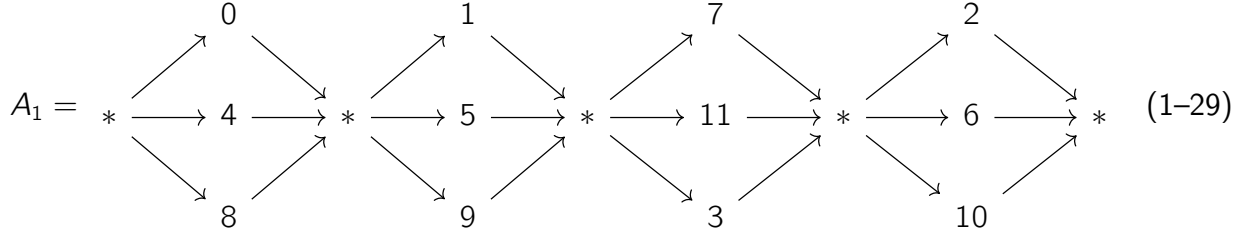
$$\left[\begin{array}{cccc|cccc|c} & 0 & 1 & & 7 & 2 & & & 10 & & 9 & & & \\ & & 6 & & & & 3 & & 5 & 8 & 4 & 11 & & \dots \\ 11 & & 10 & 4 & & 9 & & & & & & & 1 & 2 \\ & & & & & 5 & 8 & & & & 6 & 3 & 7 & 0 \\ & & & & & & & & & & & & & 2 \\ \dots & & & & & 11 & 4 & 8 & 5 & 3 & & & 6 & \\ & & & 9 & & & 10 & & & & 2 & 7 & & 1 & 0 \\ & & 0 & 7 & 3 & 6 & & & 8 & 5 & & & & & \\ 2 & 2 & 1 & & & & & & & 9 & & 4 & 10 & & 11 \end{array} \right] . \quad (1-27)$$

One of the problems that come with the brute force approach is that, not only is it expensive, but it is ultimately counter-intuitive. It is the same as betting on random numbers on a lottery ticket and asking ourselves whether we have won. We can look in the newspaper after the draw, but that does not increase our odds of winning at all. However, that is exactly what happens when we come up with a series out of sheer guesswork, then ask ourselves whether that series would produce some interesting derivation array. What we want is to be able to increase our odds, to somehow figure out what the winning numbers are. Luckily, this is not the lottery, and the process is certainly not random, so there must be a way to tell exactly how to put together arrays like these without any guessing whatsoever. A partial solution to this problem exists when we use some operation's cycles as building blocks for the columnar aggregates in a derivation matrix.

Example 1.2.10. [1, 224] Let $S = \{0, 1, 7, 2\}|\{10, 9, 11, 4\}|\{8, 5, 3, 6\} = S_1|S_2|S_3$ and consider the matrix $A = [S|T_4(S)|T_8(S)]^T$.

$$A = \left[\begin{array}{cccc|cccc|cccc} 0 & 1 & 7 & 2 & 10 & 9 & 11 & 4 & 8 & 5 & 3 & 6 \\ 4 & 5 & 11 & 6 & 2 & 1 & 3 & 8 & 0 & 9 & 7 & 10 \\ 8 & 9 & 3 & 10 & 6 & 5 & 7 & 0 & 4 & 1 & 11 & 2 \end{array} \right] . \quad (1-28)$$

Now let V be in the total order class of the first columnar aggregate of A . Next, rewrite the first columnar aggregate of A as the aggregate realization A_1 .



When we see the first column of A as an aggregate realization, it becomes clearer that any $V \in \text{Toc}(A_1)$ must be a succession of augmented triads, say, $V = \{4, 8, 0, 9, 1, 5, 11, 7, 3, 2, 10, 6\}$. We know we are able to linearize V from A_1 , but the question we should be asking at this point is whether we can linearize some transform of V from the other columns of A . The answer depends on the chosen operation, T_4 in this case, and on the chosen S . To verify that A_2 is a transform of A_1 , it suffices to check whether there is a base-four RT_nMI operation that maps $S_1 \pmod{4}$ onto $S_2 \pmod{4}$. This is easily verified, as indeed

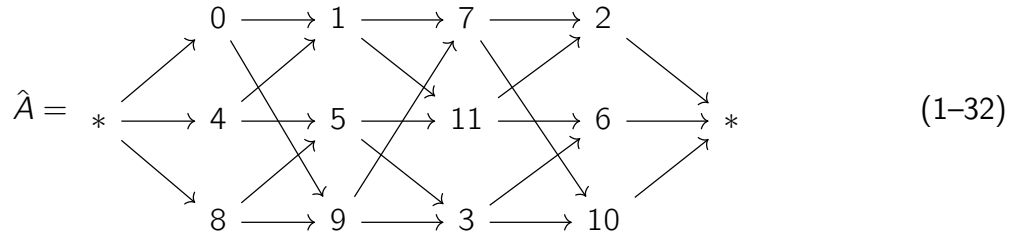
$$S_1 \pmod{4} = \{0, 1, 3, 2\} = T_2 \text{I}(\{2, 1, 3, 0\}) = T_2 \text{I} \circ S_2 \pmod{4} . \quad (1-30)$$

The above method works because the elements in each of A_1 's columns are incomparable, so we pick from within each column in any order we want. In other words, we could flip A_1 horizontally, say, and still have the same aggregate realization. Since we can reduce all of A 's columns $\pmod{4}$ by construction, it becomes enough to only consider each column's residue modulo four, and four-tone operations. Since $S_1 \pmod{4} = S_3 \pmod{4}$, we can derive V itself from A_3 , and thus obtain the following derivation matrix, where the second column is

$T_2 I(V)$:

$$\left[\begin{array}{cccccc|cccc} & 0 & 1 & & 7 & 2 & 10 & & 9 \\ 4 & & & 5 & 11 & & 6 & 2 & 1 & \cdots \\ & 8 & 9 & & & 3 & 10 & 6 & 5 & \end{array} \right. \left. \begin{array}{cccccc|cccc} & & & 11 & 4 & & 8 & & 5 & 3 & 6 \\ \cdots & 3 & & & & 8 & & 0 & 9 & & 7 & 10 \\ & & 7 & 0 & & 4 & & 1 & 11 & & 2 & \end{array} \right] . \quad (1-31)$$

It would be rather undesirable, however, that we should be restricted to rows that are merely the concatenation of cycles from an operation. We can certainly use the machinery hitherto developed to evaluate what other rows can be derived from A . Knowing that the columns of A are related as aggregate realizations by the operation tuple $\mathcal{A} = [T_0 \ T_2 \mid T_0]$, we can regard the A_i as columnar aggregates, then take $\hat{A} = \text{Ext}[\bigcup_i (\mathcal{A}_i \circ A_i)]$. By Th. 1.1.3, any row we are able to linearize from \hat{A} , will be in $\bigcap_i \text{Toc}(A_i)$, and thus we can derive its \mathcal{A}_i -transform from each i -column of A . Below is the columnar aggregate \hat{A} .

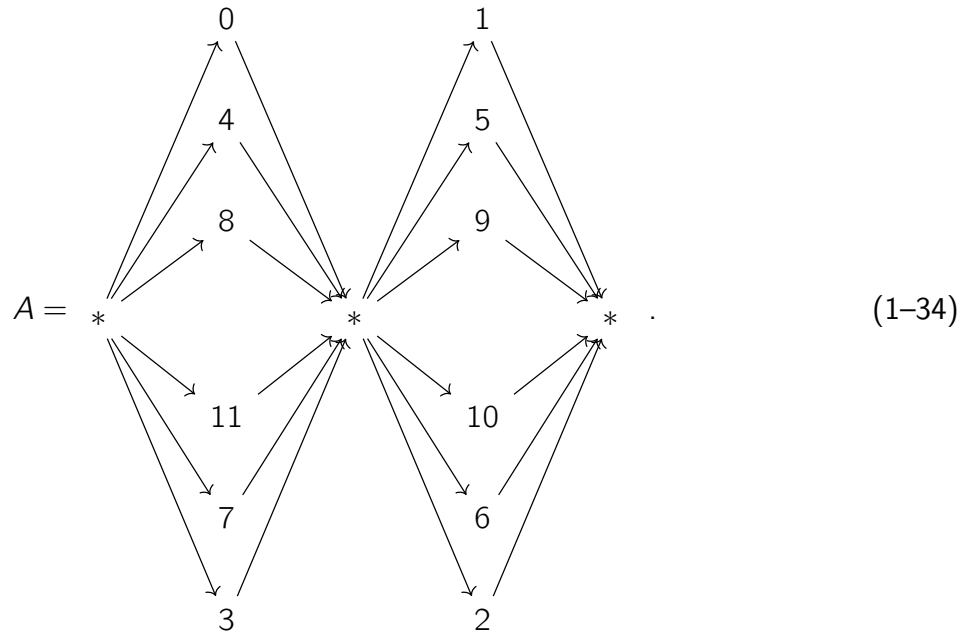


It follows $\hat{V} = \{0, 1, 4, 8, 9, 5, 7, 2, 11, 3, 10, 6\}$ can be linearized from \hat{A} , yielding the derivation matrix below:

$$\left[\begin{array}{cccc|cccc} 0 & & 1 & 7 & & 2 & & 10 \\ & & & & & & & \\ & & 4 & & 5 & 11 & & 6 \\ & & & & & & & \\ 8 & 9 & & & & & 3 & 10 \\ & & & & & & & \end{array} \right] \begin{array}{cccc} 10 \\ 2 & & 1 & \cdots \\ 6 & 5 & & 7 \end{array} \left[\begin{array}{cccc|cccc} & & 9 & & 11 & & 4 & \\ & & & & & & & 8 \\ \cdots & & 3 & & & 8 & & 0 \\ & & & 0 & & & & 9 \\ & & & & & & 4 & 1 \\ & & & & & & 11 & 2 \end{array} \right] \begin{array}{cccc} 8 & & 5 & 3 & 6 \\ 0 & 9 & & 7 & 10 \\ & & & & \\ & & & & \end{array} \right] . \quad (1-33)$$

We conclude this section with a musical example of how self-derivation may be achieved in a 6×144 matrix by exploring the symmetries of an aggregate realization.

Example 1.2.11. Consider the aggregate realization A .



It is easily seen that A is invariant under the set of operations $\Omega = \{T_0, T_4, T_8, T_3 I, T_7 I, T_{11} I\}$.

Thus if $\rho \in \text{Toc}(A)$, then also $\Omega_i(\rho) \in \text{Toc}(A)$. It is also easy to see that $R(\rho) \in$

$\text{Toc}(R \circ \Omega_i(A))$. Now let $S = \{0, 1, 5, 8, 9, 4, 10, 3, 7, 6, 2, 11\}$, and consider the combination matrix $\mathcal{A} = [\mathcal{A}_1 | \cdots | \mathcal{A}_6]$.

$$\mathcal{A} = \left[\begin{array}{cc|cc|cc|cc|cc|cc} 0 & 1 & 5 & 8 & 9 & 4 & 10 & 3 & 7 & 6 & 2 & 11 \\ 4 & 5 & 9 & 0 & 1 & 8 & 2 & 7 & 11 & 10 & 6 & 3 \\ 8 & 9 & 1 & 4 & 5 & 0 & 6 & 11 & 3 & 2 & 10 & 7 \\ 11 & 10 & 6 & 3 & 2 & 7 & 1 & 8 & 4 & 5 & 9 & 0 \\ 7 & 6 & 2 & 11 & 10 & 3 & 9 & 4 & 0 & 1 & 5 & 8 \\ 3 & 2 & 10 & 7 & 6 & 11 & 5 & 0 & 8 & 9 & 1 & 4 \end{array} \right]. \quad (1-35)$$

By construction, every row of \mathcal{A} is an Ω -transform of S . Also by construction, every \mathcal{A}_i is an instance of either A or $R(A)$, seen as a columnar aggregate, and thus Ω -invariant. It follows we can derive a transform of S from every \mathcal{A}_i . Since $T_7(S) \in \text{Toc}(\mathcal{A}_1)$ and $R_{T_0 I}(S) \in \text{Toc}(\mathcal{A}_2)$, we get the self-derivation matrix X .

$$X = \left[\begin{array}{cccccc|cccccc} & & & 11 & 10 & & & & & & \\ & & & & & & 6 & & 3 & & \\ & & 4 & 5 & & & & 9 & & & 0 \\ & 3 & & & 2 & & 10 & & & 7 & \\ & & 0 & & & 1 & & 5 & 8 & & \\ 8 & & & & & & 9 & & & & \\ 7 & & & & & & & 6 & & & \\ & & & & & & & & 2 & & 11 \end{array} \right]_{(1-36)}.$$

It is important to point out that, although we could extend the matrix X to a 6×144 derivation matrix wherein all columns of \mathcal{A} are presented, we could not do so with arbitrary transforms of S . Upon inspection, we see that the transforms of S we can derive from \mathcal{A}_1 and \mathcal{A}_5 are in

$$\{T_3, T_7, T_{11}, RT_1, RT_5, RT_9, T_0I, T_4I, T_8I, RT_2I, RT_6I, RT_{10}I\} . \quad (1-37)$$

For the columns $\mathcal{A}_2, \mathcal{A}_3, \mathcal{A}_4$ and \mathcal{A}_6 , we can derive transforms of S that are in

$$\{T_1, T_5, T_9, RT_3, RT_7, RT_{11}, T_2I, T_6I, T_{10}I, RT_0I, RT_4I, RT_8I\} . \quad (1-38)$$

Rather than a hinderance, one could take advantage of this fact by exploring contrasting harmonic regions. Fig. 1-20 shows a musical realization of X :

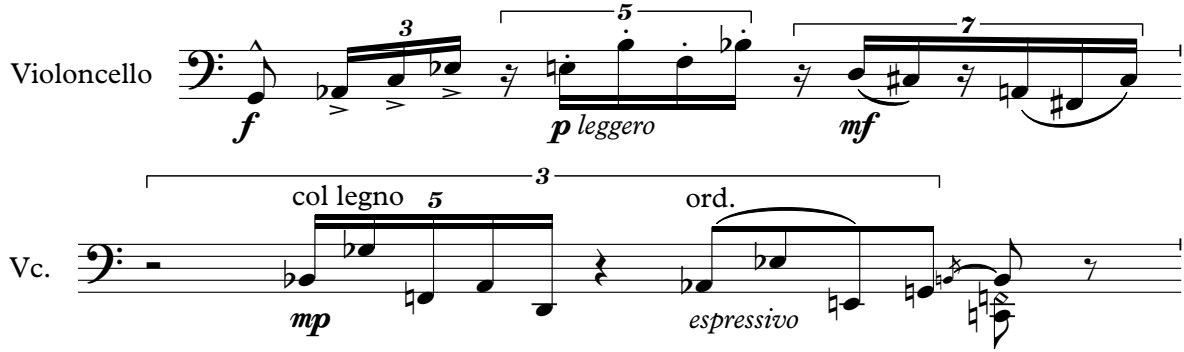


Figure 1-20. Self-derivation in Damiani's *Stingray*.

1.3 The Mallalieu Property

We now consider the $T_n MI$ class of 12-tone rows with representative

$$S = \{0, 1, 4, 2, 9, 5, 11, 3, 8, 10, 7, 6\} . \quad (1-39)$$

This series has the remarkable property that, if we include a dummy 13th element, usually represented by an asterisk, then taking every n^{th} element of S produces a transposition of it, so that deriving transforms of a S becomes a mechanical process.

Example 1.3.1. Put $S^* = \{0, 1, 4, 2, 9, 5, 11, 3, 8, 10, 7, 6, *\}$. Then taking every zeroth order number of $S^* \bmod 13$ yields trivially S^* itself. Taking every first order number yields the row $\{1, 2, 5, 3, 10, 6, 0, 4, 9, 11, 8, 7, *\}$ which, upon removing the dummy symbol, becomes $T_1(S)$. Repeating this procedure for every n^{th} order number gives the sequence of T_i -transforms of S where the indices of transposition are totally-ordered, and correspond to the elements of S .

This most peculiar property, commonly known as the *mallalieu* property, was first discovered by Pohlman Mallalieu [6, 285]. It is natural to ask at this point how many different

12-tone rows are there sharing this property. Unfortunately, there is only one such 12-tone row class under $T_n M I$. We phrase below a little differently an argument given in [7, 17].

Proposition 1.3.2. [7, 17] *A 12-tone row has the mallalieu property if and only if it is related by $T_n M I$ to the row $S = \{0, 1, 4, 2, 9, 5, 11, 3, 8, 10, 7, 6\}$.*

Proof. One direction is just the straightforward check that every $T_n M I$ transform of S possesses the mallalieu property and is left to the reader. Conversely, if a row R in its untransposed prime form has the mallalieu property, then there is a transposition that takes its order numbers in zeroth rotation, that is, the set $\{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}$ to its order numbers in, say, first rotation, id est, the set $\{1, 3, 5, 7, 9, 11, 0, 2, 4, 6, 8, 10\}$. We can write this transposition as a permutation $0 \mapsto 1, 1 \mapsto 3, 2 \mapsto 5, \dots, 11 \mapsto 10$, or in cycle notation as $\hat{T}_k = (0\ 1\ 3\ 7\ 2\ 5\ 11\ 10\ 8\ 4\ 9\ 6)$. Note that \hat{T}_k is an operation on order numbers. Since \hat{T}_k corresponds to a transposition, there are only four candidates for T_k , its pitch-class domain counterpart, namely $k \in \{1, 5, 7, 11\}$, because these are the only indices for which a transposition of pitch classes in cycle notation is a 12-cycle. Moreover, we do not need to consider the cases where $k \in \{5, 7, 11\}$, as $T_5 = M \circ T_1$, $T_7 = M I \circ T_1$, and $T_{11} = I \circ T_1$. Hence, without loss, we can set $k = 1$. But then S is the only row in untransposed prime form where T_1 induces the permutation \hat{T}_k from its order numbers in zeroth rotation to its order numbers in first rotation. To see that, one needs to equate the cycles of \hat{T}_k with those of T_1 . □

A way of looking at the mallalieu property from the standpoint of replacing, for any 12-tone row, its order-number row by the array of integers $\{1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12\}$ modulo 13 is provided in [6, 278]. It is easy to see that such an array has the same structure as the array S^* constructed above, if we consider multiplication as the group operation. This is easily seen to be an isomorphism between the integers modulo 12 and the group of units modulo 13. One of the advantages of this approach is that we can dispense with the extra symbol altogether, and just use the indices from 1 to $p - 1$. We shall, however, still refer to the row of order numbers as S^* , the context making it clear whether we are constructing it with an

asterisk or not. The process of taking every n^{th} element of a 12-tone row becomes then just the aforementioned multiplicative group operation on order numbers, that is, multiplying order numbers by $k \pmod{13}$ is the same as taking every k^{th} element of a row.

Example 1.3.3. *Let $S = \{0, 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11\}$ and S^* be as above. Then $M_3(S^*) = \{3, 6, 9, 12, 2, 5, 8, 11, 1, 4, 7, 10\}$, which corresponds to the row $V = \{2, 5, 8, 11, 1, 4, 7, 10, 0, 3, 6, 9\}$. The row V can be equivalently constructed by placing an asterisk at the 13th order number of S , then taking every third element. However being able to express the process through multiplication, rather than mechanically, greatly facilitates its theoretical description, as well as any algorithmic implementation thereof. The fact that V and S are not related by $T_n M I$ reflects the fact that neither S nor V have the mallalieu property.*

It should be of interest to many composers whether other n -TET systems are capable of producing mallalieu rows, and if so, how many. Unfortunately, answering this question is not as straightforward as the above discussion, since we cannot in general rely on the isomorphism that constitutes the proof of 1.3.4. Whenever we can, however, the existence of mallalieu rows is easily verified.

Proposition 1.3.4. [6, 285] *For p a prime, every $(p - 1)$ -TET system is capable of producing a mallalieu row.*

Proof. For every prime p , the group of units modulo p is isomorphic to $\mathbb{Z}/(p - 1)\mathbb{Z}$. The mallalieu property in these cases can be seen as the aforementioned isomorphism, where $\mathbb{Z}/(p - 1)\mathbb{Z}$ is the group of transpositions of a row, and $(\mathbb{Z}/p\mathbb{Z})^\times$ is its multiplicative group on order numbers. The number of mallalieu rows in each $(p - 1)$ -TET system is then the number of isomorphisms $\mathbb{Z}/(p - 1)\mathbb{Z} \rightarrow (\mathbb{Z}/p\mathbb{Z})^\times$, that is, the order of the group of automorphisms of $\mathbb{Z}/(p - 1)\mathbb{Z}$. Since for every prime p we have $|\text{Aut}(\mathbb{Z}/(p - 1)\mathbb{Z})| \geq 1$, every $(p - 1)$ -TET system is capable of producing a mallalieu row, as desired. \square

In face of 1.3.4, 1.3.2 becomes just the special case where $p = 13$, as demonstrated in the next example.

Example 1.3.5. [8, 8] [9, 9] The number of isomorphisms $\mathbb{Z}/12\mathbb{Z} \rightarrow (\mathbb{Z}/13\mathbb{Z})^\times$ is equal to

$$|\text{Aut}((\mathbb{Z}/12\mathbb{Z})^\times)| = 4 . \quad (1-40)$$

We can construct these isomorphisms by mapping a generator of $\mathbb{Z}/12\mathbb{Z}$, say $\bar{1}$, to the generators of $(\mathbb{Z}/13\mathbb{Z})^\times$, namely $\bar{2}, \bar{6}, \bar{7}$ and $\bar{11}$. Explicitly, we get the four maps $i \pmod{12} \mapsto 2^i \pmod{13}$, $i \pmod{12} \mapsto 6^i \pmod{13}$, $i \pmod{12} \mapsto 7^i \pmod{13}$, and $i \pmod{12} \mapsto 11^i \pmod{13}$. We leave the verification that these maps are well defined and bijective to the reader. Denote the first map by φ . Then

$$\varphi(a + b) = 2^{a+b} = 2^a \cdot 2^b = \varphi(a) \cdot \varphi(b) , \quad (1-41)$$

so φ is an isomorphism. The verification that the other three maps are isomorphisms is identical. Define $\varphi^{-1} : (\mathbb{Z}/13\mathbb{Z})^\times \rightarrow \mathbb{Z}/12\mathbb{Z}$ by $\varphi^{-1}(\log i \pmod{13}) = i \pmod{12}$. Then φ^{-1} is easily seen to be the inverse of φ . Let $S^* = \{1, 2, \dots, 11, 12\}$ be a series of order numbers written multiplicatively. Then

$$\varphi^{-1}(S^*) = \{\log 1, \log 2, \dots, \log 12\} \pmod{13} = \{0, 1, 4, \dots, 7, 6\} , \quad (1-42)$$

which by 1.3.2 is one of the untransposed 12-tone rows that have the mallalieu property.

We conclude this section by exposing some well-known isomorphisms between groups of pitch-class operations and abstract groups.

Proposition 1.3.6. [10, 127] We have the following isomorphisms:

$$\langle T \rangle \cong C_{12} \quad (1-43)$$

$$\langle T, I \rangle \cong D_{24} \quad (1-44)$$

$$\langle I, R \rangle \cong V_4 \quad (1-45)$$

$$\langle T, I, R \rangle \cong D_{24} \oplus \mathbb{F}_2 \quad (1-46)$$

$$\langle T, I, M \rangle \cong \text{Aff}_1(C_{12}) \quad (1-47)$$

$$\langle T, I, M, R \rangle \cong \text{Aff}_1(C_{12}) \oplus \mathbb{F}_2 \quad (1-48)$$

1.4 Final Remarks

We now devote our attention to summarizing the theoretical objectives of this research. The main motivation is to understand the construction of self-derivation precisely, that is, for any given row, whether it is capable of producing any known form of self-derivation. Conversely, given some self-derivation procedure, we would like to be able to provide a complete description of the class of rows that participate therein. All the above shall be done in all generality, that is, for arbitrary n -tone temperament systems. After having dealt with the more constrained case of self-derivation, we shall attempt to extend the above ideas to the general derivation setting, *id est*, without the requirement that the derived row be in the same row class as the originating row. General derivation is less strict and better understood than self-derivation, but lacks the latter's potential for cohesiveness. Whatever is already present in the literature, shall be extended to other equal temperament systems than the 12-TET. We shall also attempt to describe how specific patterns of derivation arise. In other words, given a pattern of order numbers, for what rows, and under which operations, do we get known forms of derivation and self-derivation. Analogously, we would like to investigate how chains of pitch-class operations are induced by derivation procedures, as to determine how a piece may be composed from the standpoint of its syntax, perhaps even prior to establishing any compositional surface. Many well-known derivation procedures described in this chapter also lack a more rigorous treatment. We shall make precise, providing proofs when necessary, what the constraints regarding the choice of operation are for folded and shifted derivations. In particular, we will investigate the need for commutativity, as well as determine which of the aforementioned forms support derivation matrices that do not involve the retrograde. We shall also take into account the role of the cyclic rotation operator, particularly in what regards folded self-derivations. Cyclic rotation and its invariances will be intimately connected with our combinatorial findings (in the mathematical sense). We shall make use of known brute-force algorithms, such as [5], to confront our findings, and also verify their correctness if appropriate. Finally, we will generalize mallalieu-type rows to arbitrary equal temperament systems, giving

a precise count and description of their untransposed representatives. In addition, we will investigate generalizations of the mallalieu property by relaxing the requirement that we get a copy of the row at every single index, as proposed in [11]. We shall also investigate whether transposition is the only operation that affords the mallalieu property.

Our theoretical framework will be purely mathematical, with the sole exception of a few brute-force algorithms that will be used to guide our findings. As previously discussed, mathematics can greatly simplify our search for answers, and a solid mathematical theory of the musical objects that pertain to this study are a requirement for mature compositional decisions that involve the techniques here discussed. Anticipating, as much as possible, the symmetries of a musical construct of the sort with which we will be concerned can help a composer determine the outlook and feasibility of an entire piece. Mathematics is also crucial for constructing efficient computer algorithms that employ such techniques, and is the only resource we actually have against brute force. Much of the mathematics required by our findings will be mentioned in the theoretical framework, although some basic knowledge is omitted. We assume the reader will have some basic knowledge of abstract algebra, to the extent that many graduate texts in atonal music theory will require. Our treatment shall depart from the concept of group actions. A working knowledge of twelve-tone theory is also required. We assume the reader is familiar with such basic concepts as contour, pitch, and pitch-class spaces, intervals and interval classes, set classes, operations, and associated group-theoretic notions.

The last chapter of the present work will deal with some musical applications of derivation techniques. Given the historical application of these techniques to almost exclusively the pitch domain, and in the interest of shedding new light onto such procedures, the compositional applications we shall describe will have a certain bias toward employing derivation in dimensions other than pitch. Also, given that most examples of derivation in the twentieth-century repertoire are of instrumental music, we shall here pursue the electroacoustic music avenue, with a particular interest in algorithmic processes. Beyond uniqueness and innovation, we justify and

motivate our choices by the fact that many of our generalizations, such as, say, constructing a mallalieu row in 50 elements, become problematic, if not incompatible, with instrumental music.

CHAPTER 2 LITERATURE REVIEW

2.1 Discovering Derivation

The beginnings of derivation techniques can be traced back to Donald Martino's *The Source Set and Its Aggregate Formations* [12], a paper whose main purpose is another, namely to generalize the construction of columnar realizations, although this latter term appears to have been coined by [1]. The techniques employed by Martino are heavily influenced by Babbitt's ideas on combinatoriality [12, 224], and make extensive use of tables. Below is a fragment of the source hexachords table given in [12, 229]. The author, in the interest of generalizing the procedure, provides also trichordal, tetrachordal, and even pentachordal combinatoriality tables, as well as a somewhat brief discussion on uneven partitions of a row and their combinatoriality implications [12, 267].

Table 2-1. Fragment of a table for consulting source hexachords in [12, 229].

No.	Set	Interval Vector	TTO's
A1	{0, 1, 2, 3, 4, 5}	$\langle 5, 4, 3, 2, 1, 0 \rangle$	$\{T_6, T_{11} I, R T_{11}, R T_6 I\}$
B2	{0, 2, 3, 4, 5, 7}	$\langle 3, 4, 3, 2, 3, 0 \rangle$	$\{T_6, T_1 I, R T_1, R T_6 I\}$
3	{0, 1, 3, 4, 5, 8}	$\langle 3, 2, 3, 4, 3, 0 \rangle$	$\{T_6, R T_2\}$
E4	{0, 1, 4, 5, 8, 9}	$\langle 3, 0, 3, 6, 3, 0 \rangle$	$\{T_{2,6,10}, T_{3,7,11} I, R T_{3,7,11}, R T_{2,6,10} I\}$
C5	{0, 2, 4, 5, 7, 9}	$\langle 1, 4, 3, 2, 5, 0 \rangle$	$\{T_6, T_3 I, R T_3, R T_6 I\}$

Martino acknowledges the aggregates formed by combinatoriality are not necessarily ordered [12, 228], rather seeing it from the bright side of diversity, in which the set union of a columnar aggregate being capable of *deriving* a different row class is actually more appealing than self-similarity, which is not at all considered. The same passage brings, to our knowledge, the first *explicit* mention in the literature of a technique for deriving new rows from columnar

aggregates in more generality than what we see in Schoenberg's fourth string quartet, as seen in 2.1.1. In mentioning derivation, Martino juxtaposes it to another, in his view, way of progressing through hexachords, namely the *fragmentation* or partitioning of the original series, ultimately deeming both procedures essentially the same, as derivation via aggregate realizations can surely be seen as the fragmentation of the (new) series obtained vertically.

Example 2.1.1. [12, 230] Let $S = \{0, 4, 11, 3, 1, 2, 5, 6, 9, 8, 10, 7\}$ and consider the trivial combination matrix given below.

$$\hat{A} = [\hat{A}_1 | \hat{A}_2 | \hat{A}_3 | \hat{A}_4] = \left[\begin{array}{ccc|ccc|ccc} 0 & 4 & 11 & 3 & 1 & 2 & 5 & 6 & 9 & 8 & 10 & 7 \\ 7 & 10 & 8 & 9 & 6 & 5 & 2 & 1 & 3 & 11 & 4 & 0 \end{array} \right]. \quad (2-1)$$

In particular, the hexachords given by \hat{A}_i can be combined with their transforms under T_1 l, yielding the following matrix:

$$A = [A_1 | A_2 | A_3 | A_4] = \left[\begin{array}{ccc|ccc|ccc} 0 & 4 & 11 & 3 & 1 & 2 & 5 & 6 & 9 & 8 & 10 & 7 \\ 7 & 10 & 8 & 9 & 6 & 5 & 2 & 1 & 3 & 11 & 4 & 0 \\ \hline 1 & 9 & 2 & 10 & 0 & 11 & 8 & 7 & 4 & 5 & 3 & 6 \\ 6 & 3 & 5 & 4 & 7 & 8 & 11 & 0 & 10 & 2 & 9 & 1 \end{array} \right]. \quad (2-2)$$

We can then **almost** derive transforms of the row $Q = \{7, 0, 10, 6, 4, 1, 3, 5, 8, 9, 2, 11\}$ from the columns of A , except for a single symmetry between 6 and 5, as seen below.

$$\left[\begin{array}{cccc|cccc} 0 & & 4 & & 11 & & 3 & 1 & & 2 & & \\ 7 & & 10 & & 8 & & 9 & & & & \boxed{6} & \boxed{5} \\ \hline & & & 1 & & 9 & 2 & & 10 & 0 & & 11 \\ & & 6 & & 3 & 5 & & 4 & 7 & & & 8 \end{array} \right] \dots \quad (2-3)$$

This apparent failure did not seem to bother Martino at all, as his focus remained in establishing a concrete foundation for combinatoriality. In order to extend the above procedure to eight rows of counterpoint, some adjustments must be made, namely we need columnar aggregates whose rows are allowed to have different numbers of elements, as seen below. This second

folding is otherwise accomplished much the same way, by choosing a hexachord from A_1 , and determining its combinatoriality properties via table lookup.

$$\begin{array}{c|c|c|c|c}
 \begin{array}{c} 0 \quad 4 \\ 7 \quad 10 \\ 1 \\ 6 \\ 2 \\ 9 \\ 3 \quad 11 \\ 8 \quad 5 \end{array} & \begin{array}{c} 11 \\ 8 \\ 9 \quad 2 \\ 3 \quad 5 \\ 6 \quad 1 \\ 0 \quad 10 \\ 4 \\ 7 \end{array} & \begin{array}{c} 3 \quad 1 \\ 9 \\ 10 \\ 4 \quad 7 \\ 5 \\ 11 \quad 8 \\ 0 \quad 2 \\ 6 \end{array} & \begin{array}{c} 2 \\ 6 \quad 5 \\ 0 \quad 11 \\ 8 \\ 3 \quad 4 \\ 7 \\ 1 \\ 9 \quad 10 \end{array} & \dots
 \end{array} \quad (2-4)$$

It is easy to understand why Martino was so motivated by creating as much diversity as possible from a single row in a structured manner. If not because creating variation upon some fixed foundation has been a constant in music composition since Bach, serialism up to that point had seen countless pieces in which the very same series was presented over and over again, frequently in the same RT_nI form for entire passages. As innovative as it is, not even the first movement of Schoenberg's fourth string quartet escapes this paradigm. The idea of having a systematic approach to syntactically moving from one row class to another, although latent in late Schoenberg, ultimately defines one of the most remarkable trends in the next chapter of serialism. Martino actually manages to solve both problems at once with derivation, as it gives the composer the opportunity to focus on the derived rows, while using a somewhat more abstract row to generate syntax, even though we only see this potential explored in his later pieces, and not quite yet in [12]. For now, what is most important is to derive as much harmonic diversity from the rigidity of an omnipresent series as possible.

What [1] terms *skewed polyphonization*, and what we called shifted derivation in Sec. 1.2.2, has too an origin in what Martino calls, in turn, *oblique combination*. Ex. 2.1.2 deals with the tetrachordal case, although other cases, including those where the overlap occurs at unequal partitionings of the row are considered. Similarly to our intuition in Sec. 1.2.2,

oblique combinations are seen as special, yet straightforward cases of other types of combinatoriality [12, 267].

Example 2.1.2. [12, 241] Let $S = S_1|S_2|S_3$ be a twelve-tone row, partitioned into tetrachords.

Let f and g be TTO's, and considered the following oblique combination matrix:

$$\left[\begin{array}{c|c|c|c|c} S_1 & S_2 & S_3 & . & . \\ . & f(S_3) & f(S_2) & f(S_1) & . \\ . & . & g(S_1) & g(S_2) & g(S_3) \end{array} \right] . \quad (2-5)$$

It follows:

- i. If $S_1 = T_i| (S_1)$ **only** for some i , then $f = R T_j$ for some j , and $g = T_k|$ for some k ;
- ii. If $S_3 = T_i| (S_3)$ **only** for some i , then $f = R T_j|$ for some j , and $g = T_k$ for some k ;
- iii. If $S_1 = T_i| (S_1)$ **only** for some i and $S_3 = T_j| (S_3)$ for some j , then $f = R T_k|$ for some k , and $g = T_\ell|$ for some ℓ ;
- iv. If $S_1 = T_i| (S_1)$ **only** for some i , $S_3 = T_j| (S_3)$ for some j , and $S_1 = T_k(S_3)$ for some k , then $f = T_\ell|$ or $f = R T_\ell|$ for some ℓ , and $g = T_m|$ or $g = R T_m|$ for some m ;
- v. If $S_1 = T_i(S_3)$ **only** for some i , then $f = T_j$ or $f = R T_j$ for some j , and $g = T_k$ or $g = R T_k$ for some k ;
- vi. If $S_3 = T_i| (S_1)$ **only** for some i , then $f = T_j|$ or $f = R T_j$ for some j , and $g = T_k$ or $g = R T_k|$ for some k .

CHAPTER 3 THEORETICAL FRAMEWORK

3.1 Group Actions

Definition 3.1.1. [13, 99] [14, 41] Let X be a set and G a group. An **action** of G on X is a function $G \times X \rightarrow X$ given by $(g, x) \mapsto gx$, such that:

- i. $(gh)x = g(hx)$ for all $g, h \in G$ and $x \in X$;
- ii. $1x = x$ for all $x \in X$, where $1 \in G$ is the identity.

Proposition 3.1.2. [13, 99] [14, 42] If a group G acts on a set X then, for every $g \in G$, the function $f_g : X \rightarrow X$ given by $f_g(x) = gx$ is a permutation of X . Further, the function $f : G \rightarrow S_X$ given by $f(g) = f_g$ is a homomorphism and, conversely, for any homomorphism $\phi : G \rightarrow S_X$, there is a corresponding group action given by $\phi(g)(x)$.

Theorem 3.1.3 (Cayley). [13, 96] [14, 120] Every group is isomorphic to a subgroup of the symmetric group S_G . In particular, if $|G| = n$, then G is isomorphic to a subgroup of S_n .

Theorem 3.1.4. [13, 97] Let $H \leq G$ be a subgroup of finite index n . Then there exists a homomorphism $\phi : G \rightarrow S_n$ such that $\ker \phi \leq H$. In particular, when $H = \{1\}$, we get Cayley's theorem.

Example 3.1.5. [14, 122] A group acts on itself by conjugation. Let $g, h \in G$ and $x \in G$. Then $1x1^{-1} = x$ and

$$g(hx) = g(hxh^{-1}) = ghxh^{-1}g^{-1} = (gh)x(gh)^{-1} = (gh)x . \quad (3-1)$$

It is also immediate from the above that a group acts on its power set by conjugation. In particular, a group acts on the set of all its subgroups.

Definition 3.1.6. [13, 100] [14, 112] If G acts on X , then the **orbit** of $x \in X$ is the set

$$\mathcal{O}(x) = \{gx : g \in G\} \subseteq X . \quad (3-2)$$

We say an action is **transitive** if there is only one orbit. The **kernel** of the action is the set

$$\{g \in G : gx = x, \forall x \in X\} . \quad (3-3)$$

We say an action is **faithful** if the kernel is the identity. The **stabilizer** of x in G is the group

$$G_x = \{g \in G : gx = x\} \leq G . \quad (3-4)$$

When a group acts on itself by conjugation, we call the orbits **conjugacy classes**. The stabilizer of some $g \in G$ is the **centralizer** of g in G , denoted $C_G(g)$. When a group acts on the set of its subgroups by conjugation, the stabilizer of a subgroup $H \leq G$ is the **normalizer** of H in G , denoted by $N_G(H)$.

Proposition 3.1.7. [13, 102] [14, 114] [15, 250] If G acts on X , for $x_1, x_2 \in X$, the relation $x_1 \sim x_2$ given by $x_1 = gx_2$ is an equivalence relation. It follows immediately that the equivalence classes are the orbits of the action of G on X and that

$$|X| = \sum_i |\mathcal{O}(x_i)| , \quad (3-5)$$

where x_i is a single representative from each orbit.

Theorem 3.1.8 (Orbit-Stabilizer). [13, 102] If G acts on X , then for each $x \in X$

$$|\mathcal{O}(x)| = [G : G_x] . \quad (3-6)$$

Corollary 3.1.9. [13, 103] If G is finite and acts on X , then the size of any orbit is a divisor of $|G|$.

Proposition 3.1.10. [14, 123] The number of conjugates of a subset S in a group G is $|G : N_G(S)|$, the index of the normalizer of S . In particular, the number of conjugates of an element s is $|G : C_G(s)|$, the index of the centralizer of s .

Proposition 3.1.11. [14, 125] Let $\sigma, \tau \in S_n$. If

$$\sigma = (a_1 a_2 \cdots a_j)(b_1 b_2 \cdots b_k) \cdots , \quad (3-7)$$

then

$$\tau \sigma \tau^{-1} = (\tau(a_1) \tau(a_2) \cdots \tau(a_j))(\tau(b_1) \tau(b_2) \cdots \tau(b_k)) \cdots . \quad (3-8)$$

Example 3.1.12. [14, 127] Let $\sigma \in S_n$ be an m -cycle. The number of conjugates of σ is

$$\frac{|S_n|}{|C_{S_n}(\sigma)|} = \frac{n(n-1)(n-m+1)}{m}, \quad (3-9)$$

so that $|C_{S_n}(\sigma)| = m(n-m)!$. Since σ commutes with its powers, and also with any permutation in S_n whose cycles are disjoint from it, and there are $(n-m)!$ of those, the number computed above is the full centralizer of σ .

Example 3.1.13. [14, 132] The size of each conjugacy class in S_n is

$$\frac{n!}{\prod_r r^{n_r} n_r!}, \quad (3-10)$$

where, for each r -cycle, we divide by r to account for the cyclical permutations of elements within a cycle. Further, if there are n_r cycles of length r , we divide by $n_r!$ to account for the different orders in which those cycles may appear.

Proposition 3.1.14. [14, 126] Two elements in S_n are conjugate if and only if they have the same cycle type. The number of conjugacy classes of S_n is the number of partitions of n .

Definition 3.1.15. [14, 133] An isomorphism from a group G to itself is called an **auto-morphism** of G . The group under composition of all automorphisms of G is denoted by $\text{Aut}(G)$.

Proposition 3.1.16. [14, 133] If H is a normal subgroup of G , then the action of G by conjugation on H is, for each $g \in G$, an automorphism of H . The kernel of the action is $C_G(H)$. In particular, $G/C_G(H)$ is a subgroup of $\text{Aut}(H)$.

Corollary 3.1.17. [14, 134] For any subgroup $H < G$ and $g \in G$, $H \cong gHg^{-1}$. Moreover, $N_G(H)/C_G(H)$ (and also $G/Z(G)$ when $G = H$) is isomorphic to a subgroup of $\text{Aut}(H)$.

Definition 3.1.18. [14, 135] A subgroup $H < G$ is called **characteristic** if every automorphism of G maps H to itself.

Proposition 3.1.19. [14, 135] Characteristic subgroups are normal. Unique subgroups of a given order are characteristic. A characteristic subgroup of a normal subgroup is normal. In particular, every subgroup of a cyclic group is characteristic.

Proposition 3.1.20. [14, 135] If G is cyclic of order n , then $\text{Aut}(G) \cong (\mathbb{Z}/n\mathbb{Z})^\times$, and $|\text{Aut}(G)| = \varphi(n)$, where φ is Euler's totient function.

Corollary 3.1.21. [14, 136] Let $|G| = pq$, with $p \leq q$ primes. If $p \nmid q - 1$, then G is abelian. If, further, $p < q$, then G is cyclic.

Proposition 3.1.22. [14, 136] If $|G| = p^n$, with p an odd prime, then

$$|\text{Aut}(G)| = p^{n-1}(p - 1) \quad (3-11)$$

and the latter group is also cyclic. If $|G| = 2^n$ is cyclic, with $n \geq 3$, then

$$\text{Aut}(G) \cong \mathbb{Z}/2\mathbb{Z} \times \mathbb{Z}/2^{n-2}\mathbb{Z} \quad (3-12)$$

and the latter is not cyclic, but has a cyclic subgroup of index 2. If V is the elementary abelian group of order p^n , then $pv = 0$ for all $v \in V$ and V is an n -dimensional vector space over the field $\mathbb{F}_p = \mathbb{Z}/p\mathbb{Z}$. The automorphisms of V are the nonsingular linear transformations from V to itself:

$$\text{Aut}(V) \cong GL(V) \cong GL_n(\mathbb{F}_p) , \quad (3-13)$$

and if F is the finite field of order q , then

$$|GL_n(F)| = (q^n - 1)(q^n - q)(q^n - q^2) \cdots (q^n - q^{n-1}) . \quad (3-14)$$

For all $n \neq 6$, we have $\text{Aut}(S_n) \cong S_n$. Finally, $\text{Aut}(D_8) \cong D_8$ and $\text{Aut}(Q_8) \cong S_4$.

Example 3.1.23. [14, 137] The Klein 4-group is the elementary abelian group of order 4. It follows $\text{Aut}(V_4) \cong GL_2(\mathbb{F}_2)$, and $|\text{Aut}(V_4)| = 6$. Since the action of $\text{Aut}(V_4)$ on V_4 permutes the latter's 3 nonidentity elements, by order considerations we have

$$\text{Aut}(V_4) \cong GL_2(\mathbb{F}_2) \cong S_3 . \quad (3-15)$$

Proposition 3.1.24. [14, 314] A finite subgroup of the multiplicative group of a field is cyclic. In particular, if F is a finite field, then F^\times is cyclic.

Corollary 3.1.25. [14, 314] For p a prime, $(\mathbb{Z}/p\mathbb{Z})^\times$ is cyclic.

3.2 Polya's Enumeration Formula

Definition 3.2.1. [16, 85] Let N be a set of n beads and R be a set of r colors. A colored necklace is a function $f : N \rightarrow R$. Denote the set of all such functions by R^N , so that $|R^N| = r^n$. Define the **weight** associated to a coloring f by

$$w(f) = \prod_{i \in N} x_{f(i)} , \quad (3-16)$$

where x_j is a variable associated with the color $j \in R$.

Proposition 3.2.2. [13, 110] Let G be a group and $X = \{1, \dots, n\}$ be a set. Let \mathcal{C} be a set of q colors. Then G acts on the set \mathcal{C}^n of n -tuples of colors by

$$\tau(c_1, \dots, c_n) = (c_{\tau 1}, \dots, c_{\tau n}), \forall \tau \in G . \quad (3-17)$$

Proposition 3.2.3. [16, 85] [13, 110] If G is a group acting on the set N , then two colorings f and f' are equivalent whenever $f = f' \circ g$ for some $g \in G$. This is an equivalence relation that partitions R^N into equivalence classes denoted **patterns**. Under the conditions of 3.2.2, an orbit $(c_1, \dots, c_n) \in \mathcal{C}^n$ is called a (q, G) -**coloring** of X . Moreover, two equivalent colorings have the same weight, so that we may refer to the weight of a class of colorings rather than the weights of its representatives.

Definition 3.2.4. [16, 85] Let N be a set of n beads and R be a set of r colors. Let G be a group acting on the set N and x_j the variable associated with the color $j \in R$. Let \mathcal{M} be the set of patterns. Define the **pattern enumerator** by

$$w(R^N, G) = \sum_{M \in \mathcal{M}} w(M) . \quad (3-18)$$

In particular, when $x_j = 1$ for all $j \in R$, we get $w(R^N, G) = |\mathcal{M}|$.

Definition 3.2.5. [16, 86] Let G be a group acting on a set X . Define for every $g \in G$ its **fixed-point set** by

$$\text{Fix}(g) = \{x \in X : gx = x\} . \quad (3-19)$$

Lemma 3.2.6. [13, 112] Let $G < S_n$ be a group and let \mathcal{C} be a set of q colors. For $\tau \in G$,

$$|\text{Fix}(\tau)| = q^{t(\tau)} , \quad (3-20)$$

where $t(\tau)$ is the number of cycles in the complete factorization of τ .

Lemma 3.2.7 (Burnside). [13, 109] [15, 251] If G acts on a finite set X , then the number of orbits N is

$$N = \frac{1}{|G|} \sum_{\tau \in G} |\text{Fix}(\tau)| . \quad (3-21)$$

Corollary 3.2.8. [13, 112] Let G be a group acting on a finite set X . The number N of (q, G) -colorings of X is

$$N = \frac{1}{|G|} \sum_{\tau \in G} q^{t(\tau)} . \quad (3-22)$$

Corollary 3.2.9. [17, 54] [10, 127] The number of n -tone rows under RT_n is

$$\begin{cases} \frac{1}{4} [(n-1)! + (n-1)(n-3) \cdots (2)] & n \text{ odd} \\ \frac{1}{4} [(n-1)! + (n-2)(n-4) \cdots (2)(1 + \frac{n}{2})] & n \text{ even} \end{cases} \quad (3-23)$$

In particular, there are 9985920 twelve-tone rows.

Definition 3.2.10. [16, 87] Let g be a group acting on R^N . Define the **cycle indicator** of G by

$$P_G(z_1, z_2, \dots, z_n) = \frac{1}{|G|} \sum_{g \in G} z_1^{b_1(g)} z_2^{b_2(g)} \cdots z_n^{b_n(g)} , \quad (3-24)$$

where $z_i^{b_i(g)}$ corresponds to the number of cycles in the complete factorization of g that have length i .

Example 3.2.11. The cycle indicator of S_3 is

$$P_{S_3}(x_1, x_2, x_3) = \frac{1}{6}(x_1^3 + 3x_1^1 x_2^1 + 2x_3^1) , \quad (3-25)$$

since there are two elements in S_3 that comprise one cycle of length three, three elements that comprise one cycle of length one, and one cycle of length two, and one element that comprises three cycles of length one.

Example 3.2.12. Let C_n be the cyclic group of order n . Then

$$P_{C_n} = \frac{1}{n} \sum_{d|n} \varphi(d) z_d^{n/d} . \quad (3-26)$$

Example 3.2.13. For S_n we have

$$P_{S_n} = \sum_{j_1+2j_2+\dots+nj_n=n} \frac{1}{\prod_{k=1}^n k^{j_k} j_k!} \prod_{k=1}^n a_k^{j_k} . \quad (3-27)$$

In words, there is a summand for each conjugacy class in S_n , and we divide each summand by the size of its corresponding conjugacy class.

Example 3.2.14. For D_n we have

$$P_{D_n} = \frac{1}{2} P_{C_n} + \begin{cases} \frac{1}{2} a_1 a_2^{(n-1)/2} & n \text{ odd} \\ \frac{1}{4} (a_1^2 a_2^{(n-2)/2} + a_2^{n/2}) & n \text{ even} \end{cases} \quad (3-28)$$

In particular, we obtain

$$P_{D_{24}}(1+x, \dots, 1+x^{12}) = \frac{1}{24} (x_1^{12} + 6x_1^2 x_2^5 + 7x_2^6 + 2x_3^4 + 2x_4^3 + 2x_6^2 + 4x_{12}) . \quad (3-29)$$

Example 3.2.15. [10, 120] For $\text{Aff}_1(C_{12})$ we have

$$P_{\text{Aff}_1(C_{12})}(1+x, \dots, 1+x^{12}) = \frac{1}{48} (x_1^{12} + 2x_1^6 x_2^3 + 3x_1^4 x_2^4 + 6x_1^2 x_2^5 + 12x_2^6 + 4x_2^3 x_6 + 2x_3^4 + 8x_4^3 + 6x_6^2 + 4x_{12}) . \quad (3-30)$$

Theorem 3.2.16 (Polya). [16, 88] [15, 256] Let N be a set of cardinality n and R be a set of cardinality r . Let G be a group acting on the set N and x_j be arbitrary variables with $j \in R$.

Let $w(R^N, G)$ be the pattern enumerator for the action of G on R^N . Then

$$w(R^N, G) = \sum_{M \in \mathcal{M}} w(M) = P_G \left(\sum_{j \in R} x_j, \sum_{j \in R} x_j^2, \dots, \sum_{j \in R} x_j^n \right) . \quad (3-31)$$

Corollary 3.2.17. [16, 89] [15, 254] Let $x_j = 1$ for all $j \in R$. Then $\sum_{j \in R} x_j^k = |R| = r$ for all k , hence

$$P_G(r, \dots, r) = |\mathcal{M}| . \quad (3-32)$$

Corollary 3.2.18. [16, 89] Let $|R| = r = 2$. Let $x_1 = x_{\text{white}} = x$ and $x_2 = x_{\text{black}} = 1$. Then

$$P_G(x + 1, x^2 + 1, \dots, x^n + 1) = \sum_{k=0}^n a_k x^k , \quad (3-33)$$

where a_k is the number of patterns in which the color white occurs exactly k times.

Example 3.2.19. [16, 89] The number of necklaces with n beads and r colors is

$$\frac{1}{n} \sum_{d|n} \varphi(d) r_d^{n/d} . \quad (3-34)$$

Example 3.2.20. [16, 86] The definition of a weight function is useful in order to count how many necklaces contain precisely x_j beads of color j . Set W to be the color white and B to be the color black. Then a 4-bead necklace with exactly 2 white and 2 black beads is expressed by $W^2 B^2$. If we do not wish to account for a particular color, per 3.2.18 we may assign its weight to 1. If we chose not to account for the color black, say, then the representation above would become simply $W^2 1^2 = W^2$.

Example 3.2.21. We use Polya's theorem to describe the pattern inventory of 3-bead necklaces under the action of S_3 . Let the colors be A and B . Then

$$P_{S_3}(A + B, A^2 + B^2, A^3 + B^3) = \frac{1}{6} [(A + B)^3 + 3(A + B)(A^2 + B^2) + 2(A^3 + B^3)] \quad (3-35)$$

$$= A^3 + A^2 B + A B^2 + B^3 . \quad (3-36)$$

In words, we have one necklace with three A beads, one with two A and one B bead, one with one A and two B beads, and one with three B beads.

Example 3.2.22. We can use Polya's theorem to count chords in 12 tones that are equivalent under transposition by setting our set of colors to be $R = \{r_0, r_1\}$. We then disregard one of the colors, say r_0 , by setting $w(r_0) = 1$ and $w(r_1) = C$. The group of transpositions is just

$C_{12} = \mathbb{Z}/12\mathbb{Z}$, so we get

$$P_{C_{12}}(1+x, \dots, 1+x^{12}) = \frac{1}{12} \sum_{d \in \{1,2,3,4,6,12\}} \varphi(d) x_d^{12/d} \quad (3-37)$$

$$= \frac{1}{12} (x_1^{12} + x_2^6 + 2x_3^4 + 2x_4^3 + 2x_6^2 + 4x_{12}) \quad (3-38)$$

$$= \frac{1}{12} [(1+C)^{12} + (1+C^2)^6 + 2(1+C^3)^4 \quad (3-39)$$

$$+ 2(1+C^4)^3 + 2(1+C^6)^2 + 4(1+C^{12})] \quad (3-40)$$

$$= C^{12} + C^{11} + \dots \quad (3-41)$$

$$\dots + 80C^6 + 66C^5 + 43C^4 + 19C^3 + 6C^2 + C^1 + C^0 . \quad (3-42)$$

In particular, there are 43 tetrachords and 19 trichords that are transpositionally equivalent.

Example 3.2.23. [17, 53] More generally, the number of k -chords under the action of C_n is

$$\frac{1}{n} \sum_{j|(n,k)} \varphi(j) \binom{n/j}{k/j} . \quad (3-43)$$

Under the action of the dihedral group D_{2n} , we obtain

$$\begin{cases} \frac{1}{2n} \left[\sum_{j|(n,k)} \varphi(j) \binom{n/j}{k/j} + n \binom{(n-1)/2}{k/2} \right] & n \text{ odd} \\ \frac{1}{2n} \left[\sum_{j|(n,k)} \varphi(j) \binom{n/j}{k/j} + n \binom{n/2}{k/2} \right] & n \text{ even and } k \text{ even} \\ \frac{1}{2n} \left[\sum_{j|(n,k)} \varphi(j) \binom{n/j}{k/j} + n \binom{(n/2)-1}{k/2} \right] & n \text{ even and } k \text{ odd} \end{cases} \quad (3-44)$$

In particular, the pattern inventory of k -chords in 12 tones that are equivalent under T_n is

$$P_{D_{24}}(1+x, \dots, 1+x^{12}) = C^{12} + \dots + 50C^6 + 38C^5 + 29C^4 + 12C^3 + 6C^2 + C^1 + C^0 . \quad (3-45)$$

Example 3.2.24. [15, 249] Consider the action of the dihedral group D_8 on the 16-element set of colorings in black and white of the corners of a square. The cycle indicator of D_8 is

$$P_{D_8}(x_1, x_2, x_3, x_4) = \frac{1}{8} (x_1^4 + 2x_1^2x_2 + 3x_2^2 + x_4^1) . \quad (3-46)$$

Note that, in particular, we get no x_3 factors by Lagrange. The identity element in D_8 fixes all colorings, and is represented as a permutation by four cycles of length one. By Polya's formula, we make the substitution

$$x_1^4 = (B^1 + W^1)^4 = B^4 + 4B^3W + 6B^2W^2 + 4BW^3 + W^4 , \quad (3-47)$$

where the exponent outside the parenthesis is the number of cycles, and the exponents inside the parenthesis correspond to the lengths of the cycles, for each color. The element of order four in D_8 has one cycle of length four, so we get

$$x_4^1 = (B^4 + W^4)^1 = B^4 + W^4 , \quad (3-48)$$

that is, the permutation $r = (1\ 2\ 3\ 4)$ fixes the squares whose corners are all black or all white. Next, there are three elements in D_8 which comprise two cycles of length two, so each of those yield

$$x_2^2 = (B^2 + W^2)^2 = B^4 + 2B^2W^2 + W^4 . \quad (3-49)$$

The last two elements in D_8 both have two cycles of length one, plus one cycle of length two, which gives

$$x_1^2 x_2 = (B + W)^2 (B^2 + W^2) = B^4 + 2B^3W + 2B^2W^2 + 2BW^2 + W^4 . \quad (3-50)$$

Putting it all together, we get the following pattern inventory of orbits:

$$P_{D_8}(B + W, B^2 + W^2, B^3 + W^3, B^4 + W^4) = B^4 + 4B^3W + 6B^2W^2 + 4BW^3 + W^4 . \quad (3-51)$$

CHAPTER 4

THEORETICAL FRAMEWORK

This section proposes a model to describe derivation in a general setting. After writing the chapter, Luis will come back here and summarize what he wrote.

4.1 Defining an algorithm to compute a row class

In a traditional setting, a composer will usually define a class of transforms of a basic row by computing by hand what is commonly termed as a 12-tone matrix. The general procedure is usually to fill the top row of the matrix with a transform of the row beginning with zero. The second step is to fill the leftmost column of the matrix with the inverse transform of the top row. The subsequent steps comprise going row-by-row and filling them with a transposition of the top row. The particular transposition for each row is the first pitch-class of the row. So if a row begins with, say, pitch-class 5, then the entire row will be the T_5 transform of the top row. Then 12-tone matrix will hold all 48 transforms of a row: reading every row from left to right gives all transpositions, reading them from right to left gives all retrogrades, reading all columns from top to bottom gives all inversions, and reading them from bottom to top gives all retrograde inversions.

Although somewhat tedious, computing 12-tone matrices by hand is a well-established procedure. The 48 transforms that can be inferred from the matrix are not necessarily unique, given that a 12-tone may be retrograde, or retrograde-inverse invariant. It is straightforward to generalize the procedure to n -tone matrices. However, the graphical idea of reading the matrix from right to left, or bottom to top, is not ideal for computing self-deriving combination matrices, as it is faster to read a transform of a row that is written contiguously in memory. Another caveat is that the procedure does not necessarily define a canonical form for the top row. Every row in a matrix is a representative of an equivalence class of rows under the action of $RT_N I$. The size of each orbit is $4n$ if the row is not retrograde or retrograde-inverse invariant, and $2n$ otherwise. Defining a canonical form for the first row in a data structure that

holds a row class is desirable in any algorithm that iterates through row classes in lexicographic order.

4.1.1 The canonical form of a row

This section describes an algorithm to obtain a canonical form for a row. The canonical form defined here is simply the least element in a lexicographic ordering of a row class. Given an arbitrary representative of a row class, that representative will be considered retrograded if any interval class between two consecutive elements of the row, counted from right to left, is strictly less than the corresponding interval class counted from left to right. Finding the interval class between two pitch-classes is illustrated in Listing 4.1, which takes as input two pitch-classes a and b , and the base n , returning the interval class between the two. The interval class between $a \pmod n$ and $b \pmod n$ is expressed mathematically as $\min\{(a - b) \pmod n, (b - a) \pmod n\}$.

Listing 4.1. Computing the interval class between two pitch-classes.

```

number intervalClass(number a, number b, number rowSize) {           1
    number interval = abs(a - b);                                     2
    return min(interval, rowSize - interval);                         3
}                                                                       4

```

1. *intervalClass* takes as input two pitch-classes a and b , as well as the base n so that $a, b \in \mathbb{Z}/n\mathbb{Z}$.
2. Line 2 simply computes the distance between a and b .
3. Line 3 returns the least between the above interval and its complement, that is, the interval class between the two given pitch-classes.

The procedure for determining whether a row is retrograded utilizes Listing 4.1 as a subroutine, and is outlined in Listing 4.2. The sole parameter to Listing 4.2 is the row at hand, which can be any of the representatives of its row class, and the returned value is a boolean indicating whether the row is retrograded or not.

Listing 4.2. Determining whether a representative of a row class is retrograded.

```

bool isRetrograded(const number *row, number rowSize, bool isInvariant) {      1
    if (isInvariant || rowSize < 5)                                           2
        return false;                                                         3
                                                                              4

    number front, back;                                                       5
                                                                              6

    for (number i = 0; i < rowSize; ++i) {                                    7
        front = intervalClass(row[i + 1], row[i], rowSize);                 8
        back = intervalClass(row[rowSize - i - 1], row[rowSize - i - 2],    9
                               rowSize);
                                                                              10

        if (back < front)                                                     11
            return true;                                                       12
    }                                                                           13
                                                                              14

    return false;                                                             15
}                                                                              16

```

1. *isRetrograded* has three parameters, namely a pointer to a row, its size, and a boolean representing whether the row is retrograde or retrograde inverse-invariant.
2. Lines 2 and 3 perform a straightforward sanity check. It will be shown below that all rows of size 4 or less are necessarily retrograde or retrograde-invariant. If a row with 5 or more elements is known to be invariant, we skip the test.
5. Line 5 declares the variables that will represent interval classes seen from left to right, and from right to left, respectively.
8. Lines 8 and 9 simply update the variables front and back using Listing 4.1 defined above. As *i* increases, front traverses all interval classes in the row from left to right, whereas back does the same from right to left, that is, back looks at the row as if it were retrograded.
11. Line 11 compares the front and back interval classes and line 12 returns true if any interval class seen from right to left is strictly less than the corresponding interval class

seen from left to right, which would indicate that retrograding the row would produce a lexicographically lower-positioned row than the one given as input.

15. If all interval classes seen from both directions are equal, then the row is retrograde or retrograde inverse-invariant. Line 15 then returns false to avoid unnecessarily reversing a row that is invariant.

The next step in determining the canonical form of a row consists of finding whether its inverse has a lower lexicographic position within the row class. The procedure is described in Listing 4.5, which in turn depends on two small subroutines, namely Listing 4.3 and Listing 4.4. The former simply computes $\text{modulo}(x, n) = x \pmod n$. However, it needs to be defined in a subroutine this way because the result of C-language built-in modulo operator is signed, and for practical reasons that will be elaborated below, it is best that all pitch-classes be represented as unsigned integers ranging from 0 to $n - 1$.

Listing 4.3. A subroutine to compute $x \pmod n$ such that the result is non-negative.

```
number modulo(number x, number base) {                                1
    x %= base;                                                         2
    return x < 0 ? x + base : x;                                       3
}                                                                        4
```

2. Line 2 simply computes $x \pmod n$ using the C-language built operator.

3. Line 3 then returns then same congruence class but in the range $[0, n - 1]$.

Listing 4.4 is a simple convenience method that is used to check whether $x \equiv X \pmod n$, which is also needed in Listing 4.5.

Listing 4.4. A subroutine that returns true if a pitch-class is its own inverse.

```
bool isOwnInverse(number x, number base) {                             1
    return x == 0 || x == base - x;                                    2
}                                                                        3
```

1. The input x is assumed to be in the range $[0, n - 1]$.

2. Since x is non-negative, it can only be its own inverse if it is the identity, or if $x \equiv -x \pmod{n}$. It is also possible to check that if n is even and x is equal to $n/2$, then x is its own inverse. But this alternative method is far more computationally expensive than the one in Listing 4.4.

In order to determine whether the inverse transform of a row has a lower lexicographical position than itself, it is necessary in this implementation to consider if its retrograde transform also sits in a lower lexicographical position. The reason for that is because the input row has not been transformed at all up to this point. A prerequisite to calling Listing 4.5 is to have previously called Listing 4.2, the result thereof being used as one of the inputs to Listing 4.5.

Listing 4.5. Determining whether a representative of a row class is inverted.

```
bool isInverted(const number *r, number rowSize, bool R) { 1
    if (R) { 2
        for (number i = rowSize - 1; i >= rowSize / 2; --i) { 3
            number mod = modulo(r[i] - r[rowSize - 1], rowSize); 4
            5
            if (!isOwnInverse(mod, rowSize)) 6
                return mod > rowSize - mod; 7
        } 8
    } else { 9
        for (number i = 0; i < rowSize / 2; ++i) { 10
            number mod = modulo(r[i] - r[0], rowSize); 11
            12
            if (!isOwnInverse(mod, rowSize)) 13
                return mod > rowSize - mod; 14
        } 15
    } 16
    17
    return false; 18
} 19
```

1. The inputs are a row, its size, and a boolean representing whether the row is retrograded.

3. If r is retrograded, line 3 begins iteration in reverse order, that is, starting with the last element of the row.
4. Line 4 computes the ordered interval between the pitch-class at hand, and the first pitch-class of the row, which in this case is the last because the row is retrograded.
6. Line 6 checks if the interval is not its own inverse and, if not, line 7 checks if the interval is greater than its inverse. If so, an inverted form of the row would sit in a lower lexicographical position within the entire row class, and the row is inverted.
10. If the input row is not retrograded, then lines 10 to 14 perform essentially the same check as the previous branch, only traversing the row from left to right, instead of the right to left traversal done for a retrograded row. In both branches, it is important to note that the loops iterate at most twice. If the row size is odd, then the very first iteration will decide if the row is inverted. If, on the other hand, the row size is even, then there is the possibility that the very first interval will be its own inverse, in which case the next iteration will invariably be able to tell if the row is inverted.
18. Line 18 should never be reached for well-defined inputs, and is included for correctness.

Determining that an arbitrary representative of a row class is retrograded or inverted are essential subroutines used in Listing 4.8, which in turn does transform the input row into its canonical form. This transformation happens in Listing 4.7, and the latter relies on a straightforward method to in-place swap row entries, described below in Listing 4.6.

Listing 4.6. Swapping two entries in a row.

```

void swapInPlace(number *row, number i, number j) {           1
    number tmp = row[i];                                       2
    row[i] = row[j];                                           3
    row[j] = tmp;                                              4
}                                                                5

```

The procedure in Listing 4.6 is very common-place, so the details are omitted. Listing 4.7 is also straightforward and represents the main subroutine in Listing 4.8.

Listing 4.7. Transforming a row in place.

```

void getTransformInPlace(number *row, number rowSize, number T, bool I, bool R 1
) {
    if (R) {
        for (number i = 0; i < rowSize / 2; ++i)
            swapInPlace(row, i, rowSize - 1 - i);
    }

    if (I) {
        for (number i = 0; i < rowSize; ++i)
            row[i] = (rowSize - row[i] + T) % rowSize;
    } else if (T != 0 % rowSize) {
        for (number i = 0; i < rowSize; ++i)
            row[i] = (row[i] + T) % rowSize;
    }
}

```

1. The inputs are a row, its size, a non-negative integer representing an offset to be added to the entire row, a boolean representing whether the row is inverted, and another boolean representing whether the row is retrograded.
3. If the row is retrograded, lines 3 and 4 simply reverse the row using Listing 4.6.
8. If the row is inverted, lines 8 and 9 invert the row and add the offset to each row entry.
11. Otherwise, if the row is not inverted, lines 11 and 12 only add the offset to the entire row.

The procedure illustrated in Listing 4.7 is used below in Listing 4.8, but it will also be used many times over to construct a row class in memory. In the particular case where the canonical form of the row is desired, that is, the lowest element in a lexicographical ordering of the row class, the offset used will be the additive inverse of the row's first element. It is important to observe that Listing 4.8 requires prior knowledge as to whether the row is retrograde or

retrograde inverse-invariant. In the grand scheme of things, that knowledge will already be available when calling Listing 4.8.

Listing 4.8. Transforming a row into its canonical form.

```

void getCanonicalForm(number *row, number rowSize, bool isInvariant) {      1
    bool R = isRetrograded(row, rowSize, isInvariant);                      2
    bool I = isInverted(row, rowSize, R);                                    3
    number T = row[R ? rowSize - 1 : 0];                                    4
    getTransformInPlace(row, rowSize, I ? T : rowSize - T, I, R);          5
}                                                                              6

```

1. The inputs are a row, its size, and whether the row is retrograde or retrograde inverse-invariant.
2. Lines 2 and 3 simply call Listing 4.2 and Listing 4.5 respectively, storing the results.
4. Line 4 just stores the first element of the row, which may be the last if the row is retrograded.
5. Line 5 is a call to Listing 4.7. The third argument is the additive inverse of the row's start element. It varies, naturally, if the row is inverted.

4.1.2 Storing a row class in memory

The purpose of the procedures described in this section is to store an entire row class contiguously in memory. That consists of creating an array large enough to hold all transforms of a row, and copying sequentially into this array said transforms. Even for rows whose base are considered large, a row class under RTN_l is still very small. Thus holding these transforms in memory makes sense for execution speed purposes. The size of the row class array depends on whether the row is reverse or reverse inverse-invariant. The row class array begins with the canonical for of the row, followed by all its transpositions, in ascending order, followed by all transpositions of the inversion of the canonical for, also in ascending order. If the row is not reverse or reverse inverse-invariant, the row class array is appended by all transpositions of the reverse of the canonical order, followed by all transpositions of the retrograde inverse of the

canonical order. Therefore, the overall size of the row class array is $2n^2$ if the row is retrograde or retrograde inverse-invariant, or $4n^2$ otherwise, where n is the row size. The main routine for creating the row class array is described below in Listing 4.11. It depends on two subroutines, namely Listing 4.9 and Listing 4.10 that are described below.

Lemma 4.1.1. *In a retrograde-invariant row, the interval between every entry seen from left to right, and the corresponding entry seen from right to left, must equal half the size of the row.*

Proof. □

Corollary 4.1.2. *A row with odd size greater than 3 cannot be retrograde-invariant.*

Proof. □

Listing 4.9. Determining whether a row is retrograde-invariant.

```

bool isRetrogradeInvariant(const number *row, number rowSize) {           1
    if (rowSize > 3 rowSize % 2 == 1)                                       2
        return false;                                                       3
                                                                              4
    number half = rowSize / 2;                                              5
                                                                              6

    for (number i = 0; i < half; ++i) {                                     7
        if (modulo(row[rowSize - i - 1] - row[i], rowSize) != half)       8
            return false;                                                  9
    }                                                                        10
                                                                              11

    return true;                                                            12
}                                                                            13

```

1. The only inputs are a row and its size.
2. Line 2 utilizes Th. 4.1.2 as a sanity check. If the test in line 2 succeeds, line 3 returns false.
5. Line 5 just computes half the row size for convenience. Retrograde-invariance can be determined by iterating through at most half the size of the row.

7. Line 7 iterates through the row from left to right, and line 8 applies Th. 4.1.1. Line 9 then returns false if any of the intervals is not equal to half the row size.
12. If all pairs coming from both directions are equal to half the row size, then the row is retrograde-invariant and line 12 returns true.

Unlike retrograde-invariance, every row size can produce retrograde inverse-invariance. A simple example is the lowest lexicographically-order row of any size, that is, a chromatic scale. Retrograding, inverting, and transposing by -1 always yields back the initial row. Listing 4.10 outlines the procedure in all generality.

Lemma 4.1.3. *In a retrograde inverse-invariant row r , the interval between every entry seen from left to right, and the corresponding entry seen from right to left, must be equal to $r_0 + r_{n-1} \pmod{n}$, where n is the base of the row.*

Proof.

□

Listing 4.10. Determining whether a row is retrograde inverse-invariant.

```

bool isRetrogradeInverseInvariant(const number *row, number rowSize) {           1
    number half = rowSize / 2;                                                    2
    number first = modulo(row[rowSize - 1] + row[0], rowSize);                    3
                                                                                     4
    for (number i = 1; i < half; ++i) {                                           5
        if (modulo(row[rowSize - i - 1] + row[i], rowSize) != first)              6
            return false;                                                         7
    }                                                                               8
                                                                                     9
    return true;                                                                    10
}                                                                                  11

```

1. The inputs are a row and its size.
2. Line 2 computes half the row size for convenience. Like Listing 4.9, retrograde inverse-invariance can be determined by traversing only half the row size.
3. Line 3 computes $r_0 + r_{n-1} \pmod{n}$ for later use.

5. Line 5 begins iteration from the second entry onward, since the first pair was already computed in line 3. Line 6 then compares the subsequent corresponding pairs, and line 7 returns false if any of them is not equal to the first pair.
10. If line 10 is reached, it means the row is retrograde inverse-invariant, so the algorithm returns true.

The procedure to compute and store an entire row class in memory is outlined below in Listing 4.11. It returns a memory address that must be freed by the caller. While computing combination matrices of self-derivation, this memory location will be held for the duration of the program, and possibly also be shared by many different threads of execution. The procedure makes heavy use of Listing 4.7 to sequentially store in memory all transforms of the canonical form of the row. It also takes the input row and transforms it in-place into its canonical form. Any representative of a row class can therefore be used to construct a row class with Listing 4.11.

Listing 4.11. Computing and storing a row class in memory.

```

number *getRowClass(range *classSize , number *row , number rowSize , bool      1
    isInvariant) {
    getCanonicalForm(row , rowSize , isInvariant);                               2
    *classSize = isInvariant ? rowSize * 2 : rowSize * 4;                       3
                                                                                   4
    number *rowClass = malloc(rowSize * *classSize * sizeof(number));           5
    memcpy(rowClass , row , rowSize * sizeof(number));                          6
                                                                                   7
    for (number i = 1; i < rowSize; ++i) {                                       8
        number *rep = &rowClass[i * rowSize];                                  9
        memcpy(rep , rowClass , rowSize * sizeof(number));                    10
        getTransformInPlace(rep , rowSize , i , false , false);                11
    }                                                                            12
                                                                                   13
    for (number i = rowSize; i < rowSize * 2; ++i) {                            14

```

```

    number *rep = &rowClass[i * rowSize];           15
    memcpy(rep, rowClass, rowSize * sizeof(number)); 16
    getTransformInPlace(rep, rowSize, i, true, false); 17
}                                                     18
                                                     19
if (*classSize == rowSize * 2)                       20
    return rowClass;                                 21
                                                     22

for (number i = rowSize * 2; i < rowSize * 3; ++i) { 23
    number *rep = &rowClass[i * rowSize];           24
    memcpy(rep, rowClass, rowSize * sizeof(number)); 25
    getTransformInPlace(rep, rowSize, i, false, true); 26
}                                                     27
                                                     28

for (number i = rowSize * 3; i < rowSize * 4; ++i) { 29
    number *rep = &rowClass[i * rowSize];           30
    memcpy(rep, rowClass, rowSize * sizeof(number)); 31
    getTransformInPlace(rep, rowSize, i, true, true); 32
}                                                     33
                                                     34

return rowClass;                                     35
}                                                     36

```

1. The inputs are a pointer to the size of the row class, which will be computed by Listing 4.11 and stored in the address provided, a row, its size, and a boolean representing whether the row is retrograde or retrograde inverse-invariant. This boolean will be computed by the caller before calling Listing 4.11, utilizing the aforementioned procedures Listing 4.9 and Listing 4.10. The output is a memory location containing the entire row class.
2. As mentioned above, line 2 simply computes the canonical form of the given row in place.

3. Line 3 computes the class size based on whether the row is retrograde or retrograde inverse-invariant. It is important to notice here that the row class size is not the length of the row class array, but the number of transforms of the canonical form that the row class array contains. This number is stored in the address provided by the caller.
5. Line 5 allocates in the heap the memory space that will be used to store the entire row class, and line 6 copies the canonical form of the row to the beginning of this allocated space.
8. Line 8 starts from the second row in the row class, which is the first transposition of the canonical form, and the block adds all subsequent transpositions to the row class. Line 9 computes the address where the current transposition should start, line 10 copies the canonical form of the row into this address, and line 11 transforms the canonical form into the desired transposition in place.
14. Line 14 starts from the thirteenth row in the row class, that is, the $T_0/$ transform of the row. Lines 15 to 17 add the subsequent $T_n/$ transforms of the canonical form of the row in the same way the T_n transforms were added above, only specifying in the call to Listing 4.7 that the transforms now need to be inverted.
20. Line 20 checks if the row is retrograde or retrograde inverse-invariant and, if so, halts the process and returns the memory location allocated in line 5.
23. If the row is retrograde or retrograde inverse-invariant, lines 23 to 26 add all RT_n transforms of the row to the row class as above.
29. Similarly, lines 29 to 32 add all the $RT_n/$ transforms of the row.
35. Line 36 then simply returns the memory location allocated in line 5.

4.2 Defining an algorithm to compute semi-magical squares

A key component in the definition of a combination matrix of self-derivation is a semi-magic square. By definition, a semi-magic square is a square matrix where the sum of all elements, for each row and column, is a constant. For our purposes, that constant will be the base n of the row. Seeing each entry in a semi-magic square as a real number and dividing

each entry in the matrix by n produces a doubly stochastic matrix, in which every row and every column sum to one. A magic square is a semi-magic square where, in addition, both main diagonals add up to the same constant as the rows and columns.

4.2.1 Computing the partitions of an integer

By the definition above of a semi-magic square, every row therein is a permutation of an integer partition of n . In fact, every column is also a permutation of an integer partition of n , but the algorithm described below in Listing 4.14 shall concentrate on computing all integer partitions of n and their permutations as rows that will ultimately become the rows of a semi-magic square. Since these integer partitions of n are completely independent of the row at hand, they can be computed only once for each n and stored as a file, speeding up the process of computing combination matrices for other rows. Before describing Listing 4.14, a couple subroutines for reading and writing files are outlined.

Listing 4.12. Retrieving the size of a file.

```
long getFileSize(FILE *file) {                                1
    fseek(file, 0, SEEK_END);                                  2
    long fileSize = ftell(file);                                3
    fseek(file, 0, SEEK_SET);                                  4
    return fileSize;                                           5
}                                                                6
```

Listing 4.12 is a completely common-place procedure in the C-language, and its details are omitted. It is used as a subroutine in Listing 4.13, which is described next.

Listing 4.13. Reading the contents of a file.

```
number *readFile(const char *fileName, length *numLines, number problemSize) { 1
    FILE *file = fopen(fileName, "rb");                                         2
                                                                                   3
    if (file == NULL)                                                            4
        return NULL;                                                            5
                                                                                   6
```

```

    long fileSize = getFileSize(file);           7
    number *buffer = malloc(fileSize);           8
    *numLines = (length) (fileSize / sizeof(number)) / problemSize; 9
    fread(buffer, fileSize, 1, file);            10
    fclose(file);                                11
                                                12
    return buffer;                               13
}                                                 14

```

1. The inputs are the file name, assuming both the main executable and the file are in the same folder, a memory address where the number of lines read will be stored, and the problem size, which is the size of the magic square. The output is a memory location with the contents of the file, or a NULL pointer if the operation fails.
 2. Line 2 simply opens the file at the given path for reading. Line 4 performs a sanity check and line 5 returns a NULL pointer if the file cannot be read.
 7. Line 7 is a call to Listing 4.12 so that the correct amount of memory can be allocated. The value computed in line 7 is already in bytes. Line 8 then allocates the memory whose address will be returned.
 9. Line 9 computes the number of lines in the file, that is, the number of integer partitions of n with length *problemSize* that have been previously computed and stored in the file. The value is then stored in the memory address provided in the input list to store the number of lines in the file.
 10. Line 10 simply reads the entire contents of the file into the buffer allocated in line 8, line 11 frees the FILE data structure created in line 2, and line 13 returns the allocated memory. It is the responsibility of the caller to free this memory when no longer needed.
- The procedure described in Listing 4.15 effectively writes all integer partitions of n with a certain size to a file. It depends on Listing 4.14 to compute all said partitions recursively, which is described next. One important feature of Listing 4.14 is that it skips partitions whose all but one entries are zero. The reason for this is because the remaining entry would be forced

to be equal to n . In any semi-magic square where there is an entry equal to n , both the row and column to which this entry belongs will necessarily contain only zeros except, of course, for the entry with value n . This means that the linearized top of the combination matrix at that semi-magic square's column will inevitably be trivially polyphonized, that is, the corresponding square cell would simply have the entire row at the top. Therefore any combination matrix can be extended by adding a column and a row at an arbitrary indices, and making that square entry contain n elements, that is, a linearized statement of a row form. Since this procedure is completely general, the semi-magic squares computed below include entries only up to $n - 1$.

Listing 4.14. Recursively computing all partitions of a number n and permutations thereof with a certain size.

```

void allPartitionsRecursive(number *tmp, number currentSize, number      1
    problemSize, number currentSum, number rowSize, FILE *file) {
    if (currentSize == problemSize - 1) {                                2
        if (currentSum > 0) { // skip the [0, ..., 0, rowSize] partition  3
            tmp[currentSize] = rowSize - currentSum;                    4
            fwrite(tmp, sizeof(number), problemSize, file);            5
        }                                                                6
    }                                                                    7

    return;                                                            8
}                                                                      9

for (number i = 0; i < rowSize; ++i) {                               10
    if (i + currentSum <= rowSize) {                                    11
        tmp[currentSize++] = i;                                         12
        allPartitionsRecursive(tmp, currentSize, problemSize, i +      13
            currentSum, rowSize, file);                                  14
        currentSize--;                                                  15
    }                                                                    16
}                                                                        17
}                                                                        18

```

1. The inputs are the address of some scratch memory previously allocated with the same length of the problem size, the current number of entries already placed in the scratch memory, the problem size, the current sum of the entries in the scratch memory, the base n , and a pointer to a FILE data structure where the partitions will be stored, line by line.
2. Line 2 deals with the base case of the recursion, that is, when the current number of elements in the scratch memory is one less than the problem size. If that is the case, then the last element in the scratch memory array must be equal to n minus the sum of all previous elements.
3. Line 3 deals with the edge case where all entries up to problem size minus one are zero. That would force the very last element of the scratch memory array to be equal to n which, by the discussion above is avoided in this implementation.
4. Line 4 sets the last element of the scratch memory array to n minus the sum of its previous elements and line 5 writes the current partition to the given file. Having completed an entire partition, line 8 returns, so the function recurses no further.
11. For the recursion cases where the scratch memory array has been filled with less than problem size minus one elements, the loop in line 11 iterates from zero to $n - 1$. Line 12 is a sanity check that the sum of the current element being appended to the scratch memory array with the current sum of all elements so far introduced is no greater than n . Line 13 then appends the current element to the end of the scratch memory array, increases the current size counter, and line 14 pushes to the call stack another recursive call to Listing 4.14.
13. Line 15 backtracks the current size so that all combinations of integers in the range $[0, n - 1]$ are tried.

Listing 4.15 described below is essentially a wrapper around Listing 4.14. Partitions files are saved in the same location where the main executable is built, in order to facilitate dealing with file paths. In general, these files are very small even for large n , but the speed gains in precomputing them are worthwhile, given the recursive nature of Listing 4.14.

Listing 4.15. Writing all partitions to a file.

```
void writeAllPartitions(number problemSize, number rowSize) { 1
    char fileName[32]; 2
    sprintf(fileName, "all_partitions_%i_%i.dat", problemSize, rowSize); 3
    FILE *file = fopen(fileName, "wb"); 4
    5
    number *tmp = malloc(problemSize * sizeof(number)); 6
    allPartitionsRecursive(tmp, 0, problemSize, 0, rowSize, file); 7
    8
    free(tmp); 9
    fclose(file); 10
} 11
```

1. The inputs are a problem size, which is the size of the semi-magic square, and a row size, which is the row base n .
2. Line 2 creates an array of 32 characters to hold the file name. This file name array length is large enough to accommodate all file names in this implementation. Line 3 writes the name of the file into the buffer defined in the previous line, and line 4 opens a C-type FILE for writing at the specified path.
6. Line 6 allocates the scratch memory needed for the call to Listing 4.14 in the following line. Being that Line 7 is the bottommost call on the call stack for Listing 4.14, the arguments given for the current size and current sum parameters are both zero.
9. Line 9 frees the scratch memory used in the calls to Listing 4.14, and line 10 closes and releases the file created in line 4.

The counterpart to Listing 4.15 is Listing 4.16, which is designed to not only read a partitions file, but to also generate one in case the particularly sought partitions file had not been previously created.

Listing 4.16. Reading all partitions from a file.

```

number *readAllPartitions(length *numPartitions, number problemSize, number      1
    rowSize) {
    char fileName[32];                                                            2
    sprintf(fileName, "all_partitions_%i_%i.dat", problemSize, rowSize);          3
                                                                                   4
    number *allPartitions = readFile(fileName, numPartitions, problemSize);        5
                                                                                   6

    if (allPartitions == NULL) {                                                  7
        printf("Writing partitions file ... \n");                                8
        writeAllPartitions(problemSize, rowSize);                                9
        allPartitions = readFile(fileName, numPartitions, problemSize);          10
    }                                                                              11
                                                                                   12

    return allPartitions;                                                         13
}                                                                                  14

```

1. The inputs are a memory address to store the number of lines in the partitions file to be read, the problem size and the row size. The output is a memory address with the contents of the partitions file. It is the responsibility of the caller to free the returned memory when no longer needed.
2. Lines 2 and 3 store the file name in a buffer, similarly to Listing [4.15](#).
5. Line 5 attempts to read an existing file.
7. Line 7 checks that the operation in line 5 succeeded. If it failed, lines 8 to 10 print to the console that a partitions file will be created, create the file by calling Listing [4.15](#), and attempt to read the file again.
13. Line 13 simply returns the memory address with the contents of the file, or NULL if creating the file failed.

4.2.2 Combining partition rows into squares

This section describes an algorithm to combine integer partition rows into semi-magic squares. The overall procedure consists of appending integer partition rows to the square and

adding the the rows as vectors. It is a backtracking recursive algorithm similar to Listing 4.14, the main difference being that the backtracking step consists of subtracting from the vector sum the previously added row after pushing onto the stack another recursive call. Adding two integer partition rows, seen as vectors, is described next in Listing 4.17.

Listing 4.17. Adding two vectors.

```
void plus(number *a, const number *b, number problemSize) {           1
    for (number i = 0; i < problemSize; ++i)                             2
        a[i] += b[i];                                                  3
}                                                                           4
```

1. The inputs are the memory locations of two vectors and their size, which assumed to be the same.
2. Line 2 simply iterates through the length of the vectors and line 3 adds point-wise the second vector to the first.

The counterpart to Listing 4.17 is Listing 4.18. It is important to notice that vector addition and subtraction can be vectorized for speed, that is, SIMD instructions from the processor architecture at hand can replace much of the work the for-loops in Listing 4.17 is Listing 4.18 do to great effect. This option is not explored in this implementation, however. Details are omitted for Listing 4.18, as is essentially the same as Listing 4.17, only with the inverse operation.

Listing 4.18. Subtracting one vector from another.

```
void minus(number *a, const number *b, number problemSize) {          1
    for (number i = 0; i < problemSize; ++i)                             2
        a[i] -= b[i];                                                  3
}                                                                           4
```

Listing 4.19 is also used as subroutine in Listing 4.20 to validate whether the integer partition row that had just been added to the sum of rows vector does not violate the semi-magic square constraints.

Listing 4.19. Validating a sum of integer partition rows.

```

bool validate(const number *currentSum , number problemSize , number rowSize) { 1
    for (number i = 0; i < problemSize; ++i) { 2
        if (currentSum[i] > rowSize) 3
            return false; 4
    } 5
    return true; 6
} 7

```

1. The inputs are the memory location of the current sum of rows, the problem size, and the row size n .
2. Line 2 iterates through the size of the magic square, checking in line 3 whether any entry in the current sum vector is already greater than n , fact that would violate the semi-magic square definition. If so, line 4 returns false.
7. If all entries in the current sum vector are less than or equal to n , this is still a viable semi-magic square, so line 7 returns true.

Listing 4.20 utilizes the previously computed integer partition rows to form all possible semi-magic squares of size n , with entries in the range $[0, n - 1]$. It is described here because it facilitates understanding of Listing 4.3.3, but it is not used in computing combination matrices of self-derivation. For the latter purpose, computing *all* possible semi-magical squares would be impractical, but this discussion is deferred to the next sections. Although Listing 4.20 takes as input a pointer to a FILE data structure, a procedure to save all semi-magic squares is omitted, as the number of such squares is overwhelmingly large and grows with both the problem size and n .

Listing 4.20. Recursively computing all semi-magic squares of a certain size.

```

void allSquaresRecursive(number *tmp, number *currentSum , number currentSize , 1
    number problemSize , number rowSize , const number *partitions , length
    numPartitions , FILE *file) {

```

```

    if (currentSize == problemSize) {                2
        fwrite(tmp, sizeof(number), problemSize, file); 3
        return;                                        4
    }                                                  5
                                                    6

    number start = 0;                                7
                                                    8

    if (currentSize == 0)                             9
        memset(currentSum, 0, problemSize * sizeof(number)); 10
    else                                              11
        start = tmp[currentSize - 1];                12
                                                    13

    for (length i = start; i < numPartitions; ++i) { 14
        const number *p = &partitions[i * problemSize]; 15
        plus(currentSum, p, problemSize);            16
                                                    17

        if (validate(currentSum, problemSize, rowSize)) { 18
            tmp[currentSize++] = i;                  19
            allSquaresRecursive(tmp, currentSum, currentSize, problemSize, 20
                rowSize, partitions, numPartitions, file);
            currentSize--;                             21
        }                                              22
                                                    23

        minus(currentSum, p, problemSize);            24
    }                                                  25
}                                                    26

```

1. The inputs are the memory address for some scratch memory where the semi-magical square will be stored as a sequence of indices into the integer partitions array. The size of this allocated memory must this be equal to the problem size. The memory address of another scratch memory space to hold the current sum of integer partition rows, with size equal to the problem size, the current number of rows already appended to the

square, the problem size, the row size n , a pointer to the contents of a partitions file, previously computed using Listing 4.14, the total number of integer partition rows, and a pointer to a FILE data structure.

2. Line 2 deals with the base case of the recursion, that is, when all rows have been appended to the square. When that is the case, the algorithm writes the square to the file and returns.
7. Line 7 defines a variable for where iteration of integer partition rows should start. This is a mechanism to avoid permutations of integer partition rows within a semi-magic square by enforcing that the rows of the constructed semi-magic square, seen as indices in the range between zero and the total number of integer partitions, be a nondecreasing sequence. The next section shall expand on the discussion of avoiding permutations of rows in semi-magical squares.
9. Even though the current size is normally set to zero on a very first call to Listing 4.20, the backtracking nature of the algorithm will push onto the call stack many other calls to Listing 4.20 where the current sum scratch memory might have been previously used, thus containing left over data. Line 9 then checks if the current size is zero, and line 10 sets all entries in the current sum scratch space to zero, to clear any left over data. If, on the other hand, the current size is greater than zero, then line 12 sets the start of the iteration to the very last index into the integer partition rows seen so far, guaranteeing that the sequence of indices in each square is nondecreasing.
14. Line 14 begins iteration from the last index already in the square. In line 15, the variable p stores the memory location of the integer partition row at the current index of iteration, and line 16 utilizes Listing 4.17 to add this integer partition row to the current sum scratch memory.
18. Line 18 calls Listing 4.19 to validate the current sum and, if the sum is valid, line 19 sets the next index in the current square scratch memory, here represented by the variable

tmp to the current iteration index and increases the current size. Line 20 then pushes another call to Listing 4.20 onto the stack, and line 21 backtracks the current size.

24. Regardless whether the validation test in line 18 succeeded, the current sum must be backtracked inside the same block where Listing 4.17 was called. Line 24 accomplishes that with a balancing call to Listing 4.18.

4.3 Computing all possible combination matrices for a row

This section outlines a procedure that produces all combination matrices of self-derivation of a certain size for a particular row. The main idea relies on departing from a top row, which is a concatenation of transforms of the canonical form of a row r . If the row size is n , and the problem size is m , then the size of the top row is $m \times n$. In terms of derivation theory, the top row is completely linearized, and each of its m transforms of the row r will constitute a column of the combination matrix, if a solution for the top exists. The top itself is not part of the combination matrix, but rather the linearization thereof. It is, nonetheless, the point of departure of the main algorithm in this implementation. The combination matrix per se consists of a semi-magic square of size m by m , where each column in the square defines a partition of the transform of r for the corresponding section of the top. The last component in this view of a combination matrix of self-derivation are the transforms of the row r that can be derived from the top row as a whole from the integer partitions given by the rows of the semi-magic square. These derived rows are a column vector of size m which are called the sides of the combination matrix.

Example 4.3.1. Let $S = \{3, 8, 1, 0, 9, 6, 4, 7, 10, 5, 2, 11\}$ as in Ex. 1.2.6 and consider the combination matrix of self-derivation in Eq. 1–21. In it, the top vector is $[T_7(S) | R T_2 I(S)]$, the side vector is $[S | T_9 I(S)]^T$, and the semi-magic square is

$$\left[\begin{array}{c|c} 6 & 6 \\ \hline 6 & 6 \end{array} \right]. \quad (4-1)$$

The row S is not in its canonical form. An application of Listing 4.8 reveals that the canonical form of S is in fact the row $r = \{0, 3, 6, 11, 8, 5, 7, 10, 1, 2, 9, 4\}$, so that $S = RT_{11}(r)$.

Theorem 4.3.2. *Let r be a row. If a solution exists for a combination of top, side and square, then it is unique.*

Proof. Suppose there exist two different solutions for the same combination of top, side and square. Then each solution comprises a combination matrix of self-derivation, say M_1 and M_2 . By assumption $M_1 \neq M_2$. Now consider the linearized top and the first row of M_1 , which is a transform of r , say $S_1(r)$. Since M_1 is a solution, when $S_1(r)$ is partitioned using the partition scheme given by the first row of the square, each partition of $S_1(r)$ fits exactly under each column of the top. Each column of the top is totally ordered, and so is each partition of $S_1(r)$. So there is only one way in which one can fit under another. The same reasoning applies to the first row of M_2 , and to all subsequent rows of M_1 and M_2 . Hence it must be that $M_1 = M_2$ and the solution is unique, as desired. \square

4.3.1 Computing the side and top rows of a combination matrix

```

void allSidesRecursive(number *tmp, number currentSize, number problemSize,      1
    range classSize, FILE *file) {
    if (currentSize == problemSize) {                                          2
        fwrite(tmp, sizeof(number), problemSize, file);                      3
        return;                                                                4
    }                                                                            5
                                                                                6
    number start = currentSize == 0 ? 0 : tmp[currentSize - 1];              7
                                                                                8

    for (range i = start; i < classSize; ++i) {                              9
        tmp[currentSize++] = i;                                               10
        allSidesRecursive(tmp, currentSize, problemSize, classSize, file);  11
        currentSize--;                                                        12
    }                                                                           13

```

```
} 14
```

2.

```
void allTopsRecursive(number *tmp, number currentSize, number problemSize, 1
    range classSize, FILE *file) {
    if (currentSize == problemSize) { 2
        fwrite(tmp, sizeof(number), problemSize, file); 3
        return; 4
    } 5
    // FIXME: this implementation cannot produce the R|P top, for example. 6
    if (currentSize == 0) 7
        tmp[currentSize++] = 0; 8
    for (range i = 0; i < classSize; ++i) { 9
        tmp[currentSize++] = i; 10
        allTopsRecursive(tmp, currentSize, problemSize, classSize, file); 11
        currentSize--; 12
    } 13
} 14
} 15
} 16
} 17
```

2.

```
void writeAllTops(number problemSize, range classSize) { 1
    char fileName[NAME_SIZE]; 2
    sprintf(fileName, TOPS_FILE, problemSize, classSize); 3
    FILE *file = fopen(fileName, "wb"); 4
    number *tmp = malloc(problemSize * sizeof(number)); 5
    allTopsRecursive(tmp, 0, problemSize, classSize, file); 6
    free(tmp); 7
    fclose(file); 8
}
```

```
} 11
```

2.

```
number *readAllTops(length *numTops, number problemSize, range classSize) { 1
    char fileName[NAME_SIZE]; 2
    sprintf(fileName, TOPS_FILE, problemSize, classSize); 3
    4
    number *allTops = readFile(fileName, numTops, problemSize); 5
    6
    if (allTops == NULL) { 7
        printf("Writing top combos file ... \n"); 8
        writeAllTops(problemSize, classSize); 9
        allTops = readFile(fileName, numTops, problemSize); 10
    } 11
    12
    return allTops; 13
} 14
```

2.

4.3.2 Writing a solution as text

```
void writeRow(const number *row, number rowSize, range topSize, bool newLine, 1
    FILE *file) {
    for (range i = 0; i < topSize; ++i) { 2
        if (i > 0 && i % rowSize == 0) 3
            write(file, "| "); 4
            5
        if (row[i] < 0) 6
            write(file, " "); 7
        else if (row[i] < 10) 8
            write(file, "%i ", row[i]); 9
        else 10
            write(file, "%i ", row[i]); 11
    } 12
```

	13
if (newLine)	14
write(file , "\n");	15
}	16
2.	
void writeSolution(thread_data *d, common_data *cd, FILE *solutionsFile) {	1
if (cd->problemSize > 0) {	2
for (number k = 0; k < cd->problemSize; ++k) {	3
write(solutionsFile , "%i_", d->tmpSide[k]);	4
const number *p = &cd->allPartitions[d->tmpSquare[k] * cd->	5
problemSize];	6
for (int i = 0; i < cd->problemSize; ++i)	7
write(solutionsFile , "%i_", p[i]);	8
}	9
	10
write(solutionsFile , "\n");	11
return ;	12
}	13
	14
write(solutionsFile , " Solution_%lu:\n\n", d->counter);	15
writeRow(d->tmpTops, cd->rowSize, cd->topSize, true , solutionsFile);	16
	17
for (number i = 0; i < cd->problemSize; ++i) {	18
range topIndex = 0;	19
number rowIndex = 0;	20
const number *p = &cd->allPartitions[d->tmpSquare[i] * cd->problemSize	21
];	
const number *r = &cd->rowClass[d->tmpSide[i] * cd->rowSize];	22
memset(d->currentTop, -1, cd->topSize * sizeof (number));	23
	24
for (number j = 0; j < cd->problemSize; ++j) {	25

```

    number pj = p[j];
    26
    27
    for (range k = topIndex; k < topIndex + cd->rowSize; ++k) {
    28
        if (pj == 0)
    29
            break;
    30
    31
        if (d->tmpTops[k] == r[rowIndex]) {
    32
            d->currentTop[k] = r[rowIndex];
    33
            rowIndex++;
    34
            pj--;
    35
        }
    36
    }
    37
    38
    topIndex += cd->rowSize;
    39
}
    40
    41
    if (d->tmpSide[i] < 10)
    42
        write(solutionsFile, "%i | ", d->tmpSide[i]);
    43
    else
    44
        write(solutionsFile, "%i | ", d->tmpSide[i]);
    45
    46
    writeRow(d->currentTop, cd->rowSize, cd->topSize, false, solutionsFile
    47
        );
    write(solutionsFile, " | %lu\n", d->tmpSquare[i]);
    48
}
    49
    50
    write(solutionsFile, "\n");
    51
}
    52

```

2.

4.3.3 Computing all possible solutions for a given combination matrix

```

bool matchRowWithTop(number *top, const number *row, const number *partitions, 1
    number problemSize, number rowSize) {

```

```

range topIndex = 0;
number rowIndex = 0;

for (number i = 0; i < problemSize; ++i) {
    number p = partitions[i];

    for (range j = topIndex; j < topIndex + rowSize; ++j) {
        if (p == 0)
            break;

        if (top[j] == row[rowIndex]) {
            top[j] = -1;
            rowIndex++;
            p--;
        }
    }

    if (p > 0)
        return false;

    topIndex += rowSize;
}

return rowIndex == rowSize;
}

```

2.

```

void allSolutionsRecursive(thread_data *d, common_data *cd, FILE *
solutionsFile, number currentSize) {
    if (currentSize == cd->problemSize) {
        d->counter++;
        writeSolution(d, cd, solutionsFile);
        return;
    }
}

```

```

}                                                                 6
                                                                 7
length start = 0;                                              8
                                                                 9
if (currentSize > 0) {                                         10
    start = d->tmpSquare[currentSize - 1];                     11
    memcpy(&d->tmpTops[currentSize * cd->topSize], d->currentTop, cd-> 12
        topSize * sizeof(number));
}                                                                 13
                                                                 14
for (length i = start; i < cd->numPartitions; ++i) {           15
    const number *p = &cd->allPartitions[i * cd->problemSize]; 16
    plus(d->currentSum, p, cd->problemSize);                     17
                                                                 18
    if (validate(d->currentSum, cd->problemSize, cd->rowSize)) { 19
        d->tmpSquare[currentSize] = i;                          20
                                                                 21
        // If the previous square index is the same as the current square 22
        index,
        // then we don't start from zero. Instead, we start from the      23
        previous row index plus one.
        // The sequence of row indices can be strictly increasing, since 24
        equal indices produce
        // equal rows, which cannot both equally fit into the same      25
        partition scheme given by the
        // current square index, which is the same as the previous square 26
        index by assumption.
                                                                 27
        number rowStart = 0;                                     28
                                                                 29
        if (currentSize > 0 && start == i)                      30
            rowStart = d->tmpSide[currentSize - 1] + 1;        31
                                                                 32

```



```

    for (range j = rowStart; j < cd->classSize; ++j) {
        const number *r = &cd->rowClass[j * cd->rowSize];

        if (matchRowWithTop(d->currentTop, r, p, cd->problemSize, cd->
            rowSize)) {
            d->tmpSide[currentSize++] = j;
            allSolutionsRecursive(d, cd, solutionsFile, currentSize);
            currentSize--;
        }

        memcpy(d->currentTop, &d->tmpTops[currentSize * cd->topSize],
            cd->topSize * sizeof(number));
    }
}

minus(d->currentSum, p, cd->problemSize);
}
}

```

2.

4.4 Creating work data for use in concurrent threads

```

void createCommonData(common_data *cd, int argc, char *argv[]) {
    number problemSize = (number) strtol(argv[1], NULL, 10);
    number rowSize = argc - 2;
    number *row = malloc(rowSize * sizeof(number));

    for (number i = 0; i < rowSize; ++i)
        row[i] = (number) strtol(argv[i + 2], NULL, 10);

    cd->problemSize = problemSize;
    cd->rowSize = rowSize;
    cd->topSize = problemSize * rowSize;
}

```

```

    bool rInvariant = isRetrogradeInvariant(row, rowSize);           13
    bool riInvariant = isRetrogradeInverseInvariant(row, rowSize);   14
                                                                    15
    cd->isInvariant = rInvariant || riInvariant;                       16
    cd->rowClass = getRowClass(&cd->classSize, row, rowSize, cd->isInvariant); 17
    cd->rMap = malloc(cd->classSize * sizeof(number));                 18
    cd->riMap = malloc(cd->classSize * sizeof(number));                19
    cd->allPartitions = readAllPartitions(&cd->numPartitions, problemSize, 20
        rowSize);
    cd->allTops = readAllTops(&cd->numTops, problemSize, cd->classSize); 21
                                                                    22
    if (rInvariant) {                                                23
        for (int i = 0; i < rowSize; ++i)                            24
            cd->rMap[i] = cd->rowClass[(i + 1) * rowSize - 1];       25
                                                                    26

        for (int i = rowSize; i < cd->classSize; ++i)                27
            cd->rMap[i] = cd->rowClass[(i + 1) * rowSize - 1] + rowSize; 28
    } else {                                                         29
        for (int i = 0; i < rowSize; ++i)                            30
            cd->rMap[i] = cd->rowClass[(i + 1) * rowSize - 1] + rowSize; 31
                                                                    32

        for (int i = rowSize; i < cd->classSize; ++i)                33
            cd->rMap[i] = cd->rowClass[(i + 1) * rowSize - 1];       34
    }                                                                35
                                                                    36

    for (int i = 0; i < cd->classSize; ++i)                          37
        cd->riMap[i] = (cd->rMap[i] == 0 || cd->rMap[i] == rowSize)    38
            ? modulo(cd->rMap[i] + rowSize, cd->classSize)            39
            : modulo(-cd->rMap[i], cd->classSize);                    40
                                                                    41

    free(row);                                                       42
}                                                                     43

```

2.

```
void destroyCommonData(common_data *cd) { 1
    free(cd->rowClass); 2
    free(cd->rMap); 3
    free(cd->riMap); 4
    free(cd->allPartitions); 5
    free(cd->allTops); 6
} 7
```

2.

```
FILE *createSolutionsFile(number *row, number problemSize, number rowSize, 1
    length startTop, length endTop) {
    char fileName[64]; 2
    sprintf(fileName, "all_solutions_%i", problemSize); 3
    char offset = problemSize < 10 ? 15 : 16; 4
    5
    for (number i = 0; i < rowSize; ++i) { 6
        sprintf(&fileName[offset], "_%i", row[i]); 7
        offset += row[i] < 10 ? 2 : 3; 8
    } 9
    10
    sprintf(&fileName[offset], "_%lu_%lu.txt", startTop, endTop); 11
    12
    return fopen(fileName, "wt"); 13
} 14
```

2.

```
void fillTop(thread_data *d, common_data *cd, const number *combo) { 1
    for (number i = 0; i < cd->problemSize; ++i) 2
        memcpy(&d->currentTop[i * cd->rowSize], 3
            &cd->rowClass[combo[i] * cd->rowSize], 4
            cd->rowSize * sizeof(number)); 5
} 6
```

2.

```
// 1. Compute the R or RI-transform of the top. 1
// 2. Transpose the above so it starts with zero. 2
// 3. Go from left to right and return true if: 3
// 3.1. There is an entry greater than the top or; 4
// 3.2. There are no entries less than the top, implying the top is R or RI 5
// -invariant.
bool unseen(const number *top, common_data *cd) { 6
    number last = cd->problemSize - 1; 7
    number offset = cd->rMap[top[last]]; 8
    bool invert = offset >= cd->rowSize; 9
    10
    if (invert) 11
        offset = cd->riMap[top[last]]; 12
    13
    for (number i = 1; i < cd->problemSize; ++i) { 14
        number front = top[i]; 15
        number back = invert ? cd->riMap[top[last - i]] : cd->rMap[top[last - 16
            i]];
        17
        if (back < cd->rowSize) 18
            back = modulo(back - offset, cd->rowSize); 19
        else { 20
            back = modulo(back - offset - cd->rowSize, cd->rowSize); 21
            back += cd->rowSize; 22
        } 23
        24
        if (back > front) 25
            return true; 26
        else if (back < front) 27
            return false; 28
    } 29
```

```

return true;
}

```

2.

```

void createThreadData(thread_data *d, common_data *cd) {
    d->counter = 0;
    d->tmpSide = malloc(cd->problemSize * sizeof(number));
    d->currentTop = malloc(cd->topSize * sizeof(number));
    d->tmpTops = malloc(cd->problemSize * cd->topSize * sizeof(number));
    d->currentSum = malloc(cd->problemSize * sizeof(number));
    d->tmpSquare = malloc(cd->problemSize * sizeof(length));
}

```

2.

```

void destroyThreadData(thread_data *d) {
    free(d->tmpSide);
    free(d->currentTop);
    free(d->tmpTops);
    free(d->currentSum);
    free(d->tmpSquare);
}

```

2.

4.5 Defining a top-level procedure for computing all solutions for a given row class

```

length writeSolutions(thread_data *d, common_data *cd, length startTop, length
    endTop) {
    //printMatrix(cd->rowClass, cd->classSize, cd->rowSize);
    length topCounter = 0;

    FILE *solutionsFile = createSolutionsFile(&cd->rowClass[0], cd->
        problemSize, cd->rowSize, startTop, endTop);
}

```

```

#if 0 7
    for (int first = 0; first < cd->classSize; ++first) 8
    for (length i = startTop; i < endTop; ++i) { 9
        number *combo = &cd->allTops[i * cd->problemSize]; 10
        combo[0] = first; 11
#else 12
    for (length i = 0; i < 124; i += cd->problemSize) { 13
        const number *combo = &combos[i]; 14
#endif 15
        if (cd->isInvariant && !unseen(combo, cd)) 16
            continue; 17
        18
        fillTop(d, cd, combo); 19
        memcpy(d->tmpTops, d->currentTop, cd->topSize * sizeof(number)); 20
        memset(d->currentSum, 0, cd->problemSize * sizeof(number)); 21
        allSolutionsRecursive(d, cd, solutionsFile, 0); 22
        topCounter++; 23
    } 24
    25
    fclose(solutionsFile); 26
    27
    return topCounter; 28
} 29

```

2.

4.5.1 Directions for the future

Vectorize vector addition and subtraction.

APPENDIX A

A.1 ELEMENTARY TWELVE-TONE THEORY

Definition A.1.1. *Let x and y be arbitrary pitches. The **ordered pitch interval** between x and y is given by*

$$i(x, y) = y - x . \quad (\text{A-1})$$

*The **ordered pitch-class interval** between x and y is given by*

$$i(\bar{x}, \bar{y}) = \bar{y} - \bar{x} . \quad (\text{A-2})$$

*The **unordered pitch interval** between x and y is given by*

$$\bar{i}(x, y) = |x - y| . \quad (\text{A-3})$$

*The **unordered pitch-class interval**, or simply **interval class**, between x and y is given by*

$$\bar{i}(\bar{x}, \bar{y}) = \min\{i(\bar{x}, \bar{y}), i(\bar{y}, \bar{x})\} . \quad (\text{A-4})$$

Example A.1.2. *Put $x = 43$ and $y = -13$. Then*

$$i(x, y) = -56 \quad (\text{A-5})$$

$$i(\bar{x}, \bar{y}) = \overline{11} - \bar{7} = \bar{4} \quad (\text{A-6})$$

$$\bar{i}(x, y) = 56 \quad (\text{A-7})$$

$$\bar{i}(\bar{x}, \bar{y}) = \bar{4} \quad (\text{A-8})$$

Whenever the context is clear, we shall drop quotient notation and subscripts. In most situations, we are interested in the interval class between x and y , in which case we will simply write $i(7, -1) = 4$. Interval classes can also be seen graph-theoretically as the edge connecting two members of a pitch-class set, displayed clockwise.

APPENDIX B
ELEMENTARY GROUP THEORY

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BIOGRAPHICAL SKETCH

Luis F. Vieira Damiani earned in 2002 a Bachelor of Music degree in violin performance from Rio Grande do Sul's Federal University, under the orientation of Prof. Marcello Guerchfeld, a former student of Galamian. In 2003, Luis entered Porto Alegre Symphony, with which he performed as soloist in the 2005 season. In 2004, he was appointed Assistant Concertmaster of the Catholic University of Rio Grande do Sul's Philharmonic Orchestra, and from 2009 until 2011, Luis was a member of Minas Gerais Philharmonic, one of the top Brazilian groups of its kind. In Italy, he studied with Boris Belkin and Giuliano Carmignola at the Accademia Chigiana. Other teachers include Jennifer John at the Aspen Music Festival in 1996, and Kurt Sassmannshaus at University of Cincinnati's College-Conservatory of Music in 1999. As a performer, Luis researched, engraved and premiered works by 20th Century Southern Brazilian composers Bruno Kiefer and Armando Albuquerque, as well as recorded in 2006 of the *Duo for Violin and Cello* (2000) by composer Pablo Castellar, a recording that won the Açorianos Prize from the Municipal Office of Culture of Porto Alegre in 2008.

As a composer, Luis wrote in 2008 the original music for the motion picture *O Guri*. For television, his commissioned works include the soundtrack for the short film *O Sabiá*, aired in 2010. In the same year, he received the prestigious Classical Composition Award from the National Foundation of Arts in Brazil for his *Solo Violin Suite*, making him take a turn from a well-established orchestral career into pursuing graduate studies in the USA. Luis' awards since include Best Feature Soundtrack at the 6th Cinefantasy International Fantastic Film Festival in 2011 and the University of South Florida's 2012 Percussion Composition Prize, among numerous academic awards. In 2013, he received a Master of Music degree in music composition from the University of South Florida, under the orientation of Dr. Baljinder Sekhon. In the same year, Luis was awarded a fellowship to pursue Ph.D. studies in music composition at the University of Florida, where he currently works as a graduate teaching assistant, under the orientation of Dr. James Paul Sain.