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Generative Tools for Interactive Composition: Real-Time Musical Structures Based on Schaeffer's TARTYP and on Klumpenhouwer Networks

Abstract: Interactive computer music is comparable to improvisation because it includes elements of real-time composition performed by the computer. This process of real-time composition often incorporates stochastic techniques that remap a predetermined fundamental structure to a surface of sound processing. The hierarchical structure is used to pose restrictions on the stochastic processes, but, in most cases, the hierarchical structure in itself is not created in real time. This article describes how existing musical analysis methods can be converted into generative compositional tools that allow composers to generate musical structures in real time. It proposes a compositional method based on generative grammars derived from Pierre Schaeffer's TARTYP, and describes the development of a compositional tool for real-time generation of Klumpenhouwer networks. The approach is based on the intersection of musical ideas with fundamental concepts in computer science including generative grammars, predicate logic, concepts of structural representation, and various methods of categorization.

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Music is a time-based sequence of audible events that emerge from an underlying structure. Such a fundamental structure is more often than not multi-layered and hierarchical in nature. Although hierarchical structures are commonly conceptualized as predetermined compositional elements, analysis of jazz performances highlights their existence in improvised music, where performers use their knowledge of the musical language and performance practices to compose in real time. For example, Steven Block has shown sophisticated pitch organizations in free jazz compositions by Ornette Coleman, John Coltrane, Cecil Taylor, and Anthony Braxton. In the conclusion of his study, Block (1990, p. 202) calls for greater analytical attention to "the complexities of the musical fabric in free jazz" and more innovative interpretation of the "hybrid language of many free compositions." Jazz groups, such as the Art Ensemble of Chicago, collectively create complex musical "fabrics" that are unified by hierarchical structures. In many cases, the only pre-composed elements in these compositions are a chord progression or a melody, and in free improvisation the entire musical structure is composed in real time.

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Interactive computer music is comparable to improvisation because it includes elements of real-time composition performed by the computer. Arne Eigenfeldt (2011, p. 13) maintains that "composers of real-time computer music have most often relied upon constrained random procedures to make musical decisions." Hence, the process of real-time composition often incorporates stochastic techniques that remap a predetermined fundamental structure to a surface of sound processing. The hierarchical structure is used to pose restrictions on the stochastic processes and maintain the unity of the piece. Yet, unlike in free jazz improvisation, the hierarchical structure in itself is not created in real time, but only fleshed out by stochastic means.

The eventual goal of my research is to develop software that would allow composers to regenerate musical structures in real time in the same manner as an improviser. In this article, I describe how existing methods used in musical analysis can be converted into generative compositional tools. My approach is based on the intersection of musical ideas with fundamental concepts in computer science, including generative grammars, predicate logic, concepts of structural representation, and

various methods of categorization. The relevancy of such methods to music is rooted in their effectiveness as language definers and structure generators. Since these are fairly simple and commonly used methods, they can also be readily embedded in interactive tools. Because of the central role occupied by the Max language in interactive composition, I restrict my software development to tools that can be embedded and used in Max/MSP and Pure Data (Pd).

The bulk of this article is a revision of a conference paper (Neuman 2013) that proposed a compositional method using an interactive compositional tool based on generative grammars derived from Pierre Schaeffer's *Tableau Récapitulatif de la Typologie* (TARTYP, "Summary Table of Typology [of sound objects]," cf. Schaeffer 1966). These grammars enable the creation of new hierarchical musical structures that are, in turn, derived from the hierarchical structure of Schaeffer's table. These complex structures are brought to life at the surface of the composition in a versatile way, utilizing the spectral signatures of sound objects from Schaeffer's audio examples.

The following background section presents the motivation for creating a TARTYP-based interactive compositional tool, as well as presenting related work. The third section of this article presents the reading of TARTYP that formed the foundation for the generative grammars presented in the fourth section. The following two sections describe the design and implementation of the software. In the seventh section, I describe my current research, which is focused on the development of a compositional tool for real-time generation of Klumpenhouwer networks (Lewin 1990, 1994). In the final section, I voice a call for the development of an extensible tool that gives the composer the freedom to incorporate a broader collection of musical theories, classifications, languages, and generative methods for interactive composition.

Background

In 1957, Noam Chomsky introduced phrase structure (PS) grammars, a form of generation systems denoted $[\sum, F]$, where $\sum$ is a set of initial symbols and F is a set of rewrite rules. Such rewrite rules have proven to be a suitable tool for musical analysis and composition, where a phrase is often expanded or contracted to define the different hierarchical levels of musical structures. Hence, if a set of rewrite rules defines and produces a "legal" musical phrase it can also produce musical structures that are more complex. Steven R. Holtzman (1981) demonstrated the use of the Generative Grammar Definition Language to describe the micro-components of musical objects, as well as complete sections of a composition. Fred Lerdahl and Ray Jackendoff (1993) compare their use of PS grammars for defining hierarchical structures of temporal organization to the processes known in Schenkerian theory as prolongation and reduction.

Both Chomsky's theory and contemporary music in general have strong ties to set theory. Chomsky was interested in classes of derivations and sets of rules that would generate the same terminal language (Chomsky 1966; Lasnik, Depiante, and Stepanov 2000). Yet PS grammars are effective in describing musical language because they can be used to create multiple legal variants of the same sentence. Consider Chomsky's example "the man hit the ball" (Chomsky 1966). In the grammar describing this sentence, the terminals are the words (the, man, hit, the, ball): variants of this sentence can be formed, e.g., by replacing nouns with placeholder variables, yielding "the X hit the Y," where X = [man |woman |boy] and Y = [ball |table |wall]. By replacing each terminal by typed variables denoting classes of words, the same set of rewrite rules would produce legal variants of the original sentence.

The recent focus on classification in musical research corresponds to the introduction of musical set theory, where terms such as "pitch class" and "interval class" are commonly used. Serialism expands the use of classifications to compositional elements other than pitch, such as rhythm, dynamics, articulation, orchestration, and timbre. A well-formed classification method of compositional material, however, is not always sufficient for defining ways for composing out this material. Pierre Boulez's system for multiplication of pitch-class sets produces domains or collections of pitch-class sets that are structurally tied to the twelve-tone

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Figure 1. Pierre Schaeffer's TARTYP (after Chion [1983] 2009). The time-domain terms along the upper row of the table and the frequency-domain terms along the leftmost column are highlighted in gray.

	long duration (macro-objects) of no temporal unity		moderate duration temporal unity → short duration micro-objects			long duration (macro-objects) of no temporal unity	
	unpredictable facture	nonexistent facture	formed sustain	impulse	formed iteration	nonexistent facture	unpredictable facture
fixed mass: definite pitch	(En)	Hn	N	N'	N"	Zn	(An)
fixed mass: complex pitch	(Ex)	Hx	X	X'	X"	Zx	(Ax)
not very variable mass	(Ey)	Tn Tx	Y	Y'	Y"	Zy	(Ay)
unpredictable variation of mass	E	T	W	ϕ	K	P	A
	SAMPLES		← held sound		iterative sound →		ACCUMULATIONS

series from which they originate. Although it is known that Boulez used this classification in *Le marteau sans maître* (1955), the order by which the collections are used in the composition is a matter of some debate among researchers (Koblyakov 1990; Heinemann 1998).

Schaeffer introduced TARTYP in 1966 as part of his typology of sound objects (Schaeffer 1966). The table is a classification of sound objects based on their properties in the time and frequency domains, and it introduces an alphanumeric notation for sound objects. Its structure alludes to inter-relationships between subcollections of sound objects. Nevertheless, Schaeffer provides limited direction for how to use the classification in a compositional process, focusing mainly on using the table's notation to construct sequences of symbols describing sounds that are more complex (Thoresen 2007).

Most studies of TARTYP offer a translation, adaptation, or revision of this classification of sound objects. Lasse Thoresen (2007), in his adaptation, removes some of the elements defining the time-domain axis of the table. Robert Normandeau (2010), in his revision to the table, interprets its main pairs of sound characteristics: mass-facture, duration-variation, and balance-originality. John Dack (2001) discusses the *Excentric* sound objects, a group of sound objects that were defined by Schaeffer as unsuitable for music, yet according to Dack these objects are commonly used in electroacoustic compositions. These studies, like many others (such as the work described in this article) rely on Michel Chion's *Guide to Sound Objects* ([1983] 2009) for a lexical collection of many terms in Schaefferian theory, including the terms defining TARTYP.

The work of Bernard Bel (1992, 1998; Bel and Kippen 1992) combines the Schaefferian approach to sound objects and generative grammars in a creative environment that he calls the Bol Processor. This environment supports composition and improvisation, using a system of rewrite rules. The grammars of the Bol Processor are derived from the metaphoric language for drumming in Asia and Africa called *Qa'idas*. The focus here is on the mapping of the objects to a structural organization in physical time, hence, the consideration is of the time domain properties of sound objects (i.e., it does not take into account classifications and defining features). The output of the Bol Processor is a list of MIDI messages or a CSound score. Although it has some real-time capabilities, the Bol Processor relies on an external sound processor to produce real-time output.

In contrast, the TARTYP-based compositional tools presented in the following sections utilize existing interactive real-time environments; as extensions of the Java-based MaxObject class, these tools are embedded in Max/MSP or Pd and directly engage the sound-processing capabilities of these environments. The grammars of these tools are based on Schaeffer's classification of sound objects as presented in TARTYP and as interpreted by Chion ([1983] 2009) and Normandeau (2010). These grammars, as well as the compositional process suggested in this article, take into account the characteristics of sound objects in both the time and frequency domain as presented in the TARTYP table and demonstrated by Schaeffer's sound examples (Schaeffer 2012).

TARTYP Sound-Object Classification

Sound-object characteristics are specified in TARTYP at the margins of the table, with time-domain characteristics along the upper row and the frequency-domain characteristics along the leftmost column (see Figure 1). The frequency-domain

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Figure 2. The division of the body of TARTYP into subcollections of sound-object classes.

(En)	Hn	N	N'	N"	Zn	(An)
(Ex)	Hx	X	X'	X"	Zx	(Ax)
(Ey)	Tn Tx	Y	Y'	Y"	Zy	(Ay)
E	T	W	ϕ	K	P	A

SAMPLES
RH_HELD
BALANCED
RH_ITER
ACCUMULATIONS
EXCENTRIC

terms that correspond to rows in the table describe the frequency content of sound objects by their variability on a scale between fixed sound (mass) and unpredictable noise. Hence, *fixed mass* can be of *definite pitch* (harmonic sound) or of *complex pitch* (with some inharmonicity and noise). In addition, the *not very variable mass* is a glissando-like sound and the *unpredictable variation of mass* is a non-periodic noise sound. Variation in this table refers to internal variation in the frequency domain, i.e., sounds such that their endings differ from their beginnings (Chion [1983] 2009).

The seven terms that describe the time domain characteristics correspond to columns in the table. The central column is labeled *impulse,* referring to a very short sound. To the right of this column appear terms describing the characteristics or gain envelopes of *iterative sounds*, including *formed iteration*, (iterative) *nonexistent facture,* and (iterative) *unpredictable facture*. To the left appear terms describing the characteristics of *held sounds* including *formed sustain*, (held) *nonexistent facture,* and (held) *unpredictable facture*. The term *facture* refers to the way a sound evolves over time (Normandeau 2010). *Nonexistent factures* are sounds that are too redundant to exhibit change over time. Similarly, *unpredictable factures* exhibit too much instability to be "formed." A *formed* sound is a sound of medium duration with a "closed" facture, very similar to a traditional musical note (Chion [1983] 2009).

Combinations of time-domain characteristics (i.e., the table's column headings) with frequency-domain characteristics (i.e., the row headings) result in the sound objects notated in the body of the table. Hence, the combination of an impulse-type envelope and a definite pitch points to the sound object notated as N′. Similarly, sound object X″ is defined by a formed-iteration type of envelope and a complex pitch. This notation provides an abstraction of the different types of sound objects. Clearly, there are multiple sound objects that fit the defining characteristics of N′ or X″: thus, in Schaeffer's sound examples, most of the notation symbols are demonstrated by more than one sample (Schaeffer 2012). Each symbol therefore represents a *sound-object class*, a collection of sound objects that share the same TARTYP defining characteristics.

As indicated by Chion ([1983] 2009), TARTYP is subdivided into subcollections of sound-object classes that are not explicitly notated in the table (see Figure 2). The center of the table is a collection of nine sound-object classes (N, N′, N″, X, X′, X″, Y, Y′, Y″). These sound-object classes are called *Balanced* sound objects. The columns to the right and left of the Balanced sound objects (three rows from the top) define the *Redundant and Homogeneous* (*RH*) subcollection, which is further subdivided into *RH_Held* (Hn, Hx, Tn, Tx) and *RH_Iter* (Zn, Zx, Zy). The entire bottom row of the table and the far-right and far-left columns constitute the subcollection of *Excentric* objects, some of which are further subdivided into *Sample* objects (in the far-left column: En, Ex, Ey, E) and *Accumulation* objects (in the far-right column: An, Ax, Ay, A).

Note that the sound-object classes in the bottom row of table (E, T, W, Φ, K, P, A) are simply referred to as Excentric objects. Hence, the term "Excentric" is applied to two layers of subcollections: a larger subcollection of Excentric objects that includes the smaller subcollections of Sample and Accumulation objects; and the smaller, second layer, subcollection of Excentric objects. The sound-object class E is a member of both the Sample objects and the smaller subcollection of Excentric objects, and the sound-object class A is a member of both the Accumulation objects and the smaller subcollection of Excentric objects.

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TARTYP-Derived Grammars

In this section, I present generative grammars derived from TARTYP classifications of sound objects and its defining elements as well as from the structure of the table and its subcollections. The rewrite rules of these grammars use the time and frequency properties specified at the margins of the table as terminals. For each of the subcollections of the table, I define a grammar in which each terminal equals a subset of the notated sound-object classes. A set of rewrite rules in such a grammar yields a large number of paths, each of which can be composed out as a sequence of sound objects. In addition, I present a table grammar that unifies all the subcollection-based grammars and initiates a hierarchical structure of sound object sequences.

To explain and exemplify a subcollection-based grammar, the following discussion will focus on the grammar of the Balanced object subcollection. As stated previously, this collection includes the nine sound-object classes at the center of the table (N, N′, N″, X, X′, X″, Y, Y′, Y″). The grammar for this subcollection uses the set of terminals specified in Equations 1.1 through 1.6. The right-hand side of these definitions also specifies the subsets of the Balanced object subcollection that are equivalent to each one of these terminals.

$$\text{DEFINITE} = \{[N \mid N' \mid N'' \mid]+\} \quad (1.1)$$

$$\text{COMPLEX} = \{[X \mid X' \mid X'' \mid]+\} \quad (1.2)$$

$$\text{VARIABLE} = \{[Y \mid Y' \mid Y'' \mid]+\} \quad (1.3)$$

$$\text{IMPULSE} = \{[N' \mid X' \mid Y' \mid]+\} \quad (1.4)$$

$$\text{FORMED_ITER} = \{[N'' \mid X'' \mid Y'' \mid]+\} \quad (1.5)$$

$$\text{FORMED_SUS} = \{[N \mid X \mid Y \mid]+\} \quad (1.6)$$

The general structure of a rewrite rule in a generative grammar is:

head -> body (2)

denoting that the head of the rule can be rewritten as the body. More specifically, the structure of rules in the subcollection-based grammars discussed in this section is:

head -> [terminal] terminal [non-terminal] (3)

where the items in [] are optional, yielding four different legal instantiations:

head -> terminal (4.1)
head -> terminal terminal (4.2)
head -> terminal non-terminal (4.3)
head -> terminal terminal non-terminal (4.4)

A terminal corresponds to subsets of sound-object classes, and a non-terminal may be any other symbol. The head is always selected from the set of non-terminal symbols plus a special start symbol.

An example of a legal set of rewrite rules for the Balanced grammar having special start symbol "balanced" is:

bal_expre_v -> VARIABLE (5.1)
bal_expre_fs -> FORMED_SUS (5.2)
bal_expre_fi -> FORMED_ITER COMPLEX (5.3)
bal_expre_fs -> FORMED_SUS IMPULSE (5.4)
bal_expre_i -> IMPULSE FORMED_SUS bal_expre_fs (5.5)
bal_expre_v -> VARIABLE FORMED_ITER bal_expre_fi (5.6)
bal_expre_fi -> FORMED_ITER IMPULSE bal_expre_i (5.7)
bal_expre_fi -> FORMED_ITER VARIABLE bal_expre_v (5.8)
bal_expre_v -> VARIABLE FORMED_SUS bal_expre_fs (5.9)
bal_expre_fs -> FORM_SUS FORM_SUS bal_expre_fs (5.10)
bal_expre_fs -> FORMED_SUS IMPULSE bal_expre_i (5.11)
bal_expre_i -> IMPULSE IMPULSE bal_expre_i (5.12)
bal_expre_v -> VARIABLE IMPULSE bal_expre_i (5.13)
bal_expre_c -> COMPLEX FORMED_SUS bal_expre_fs (5.14)
bal_expre_fs -> FORMED_SUS COMPLEX bal_expre_c (5.15)
bal_expre_d -> DEFINITE FORMED_SUS bal_expre_fs (5.16)
bal_expre_c -> COMPLEX FORMED_ITER bal_expre_fi (5.17)
bal_expre_v -> VARIABLE VARIABLE bal_expre_v (5.18)
balanced -> FORMED_SUS bal_expre_fs (5.19)
balanced -> IMPULSE bal_expre_i (5.20)

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Figure 3. A path generated from the sample rule set of Equations 5.1–5.20. This is one of many alternative legal paths through the space defined by these rules.

Here, all caps indicate terminals, and lower case indicates non-terminals. A rule set is legal when: (1) it contains at least one rule with a start head, (2) it contains no duplicate rules, and (3) all non-terminal symbols that appear in the body of a rule have at least one other corresponding rule where they appear only in the head.

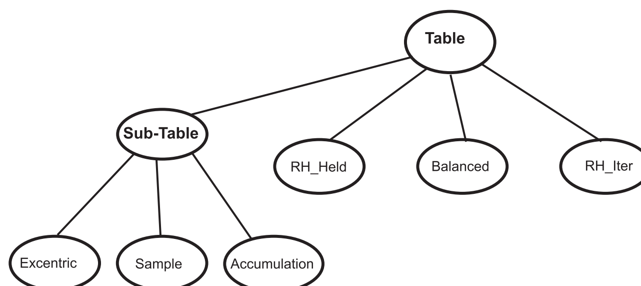
The rewrite rules are used to construct a path, that is, a sequence of terminal symbols selected according to the grammar expressed in the rewrite rules. To construct a path, set it initially to the special start symbol (e.g., "balanced" in rules 5.19 and 5.20). While the path contains non-terminals symbols, select at random a rule having that non-terminal as the head, and replace the non-terminal with the body of the rule. Figure 3 shows an example of a path constructed by the set of rules from Equations 5.1–5.20, consisting of a sequence of terminals derived from rules 5.20, 5.12, 5.5, and 5.2.

The structure of a rewrite rule and a rule-set in the other grammars—RH_Held, RH_Iter, Excentric, Sample, and Accumulation—is similar to that of Balanced grammar. The differences between these grammars lie in the set of terminal symbols of each grammar and in the equivalent subsets of sound-object classes. The following example specifies the set of terminals and the equivalent subsets of sound-object classes for the Sample grammar:

$$\text{DEFINITE} = \{[\text{ En }]+\} \quad (6.1)$$
$$\text{COMPLEX} = \{[\text{ Ex }]+\} \quad (6.2)$$
$$\text{VARIABLE} = \{[\text{ Ey}]+\} \quad (6.3)$$
$$\text{UNPREDICTABLE} = \{[\text{ E }]+\} \quad (6.4)$$
$$\text{HELD_UF} = \{[\text{En} \mid \text{Ex} \mid \text{Ey} \mid \text{E }]+\} \quad (6.5)$$

To combine these six grammars into a single process, I add collections of rules whose terminals correspond to the six different special start symbols of the six different grammars. Thus, generating a path in this Table grammar consists of sequencing invocations of the other six grammars accordingly, starting from the new global special start symbol

Figure 4. Grammar-based hierarchical structure enabled by the Table and Sub-Table grammars. This tree-like hierarchy unifies all the types of grammar.



"start." Note that the new grammar reflects the structure of TARTYP subcollections; thus, I can implement the Sub-Table grammar as shown in Figure 4. The latter represents the larger subcollection of Excentric objects. The title "Sub-Table" is used to prevent duplication. Hence, in the grammars, the name "Excentric" represents only the smaller subcollection of Excentric objects in the bottom row of the TARTYP table.

Rule Generation

I implemented a generate-and-test algorithm designed to produce a set of rewrite rules that conforms to the three legality criteria discussed in the previous section. The input to this generation algorithm consists of a set of parameters indicating how many rules are in the rule set, how many of these rules are required for each special start symbol, and how many rules have bodies consisting solely of terminal nodes. The algorithm selects the next rule to generate in accordance with the rule set parameters (e.g., having a special start symbol as head, or having only terminals in the body). The terminals in the rule body are randomly selected from the terminal symbols and then, optionally, a non-terminal symbol is included in accordance with the terminal symbols used. The head of the rule is either a special start symbol or one of the other non-terminal symbols. Duplicate rules are rejected, and a new rule is generated to replace it. Once the rule set is complete, it is checked for consistency, ensuring that every non-terminal in a rule body has at least one matching head in some other rule in the rule set. If a rule with no such match exists, it is

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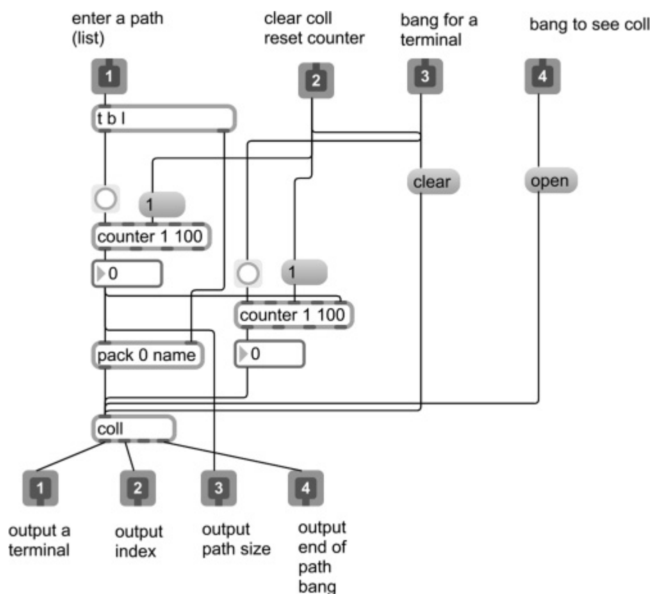
Figure 5. Formal specification of an algorithm for generating legal rule sets as described in text.

```
define (n_start: int, n_continue: int, n_end int)
  while (n_start>0 or n_continue>0 or n_end>0)
    # Generate complete set of rules
    while (n_start>0 or n_continue>0 or n_end>0)
       generate rule i
     # Check for duplicates
       if (rule i is not a duplicate)
          add rule to rule-set
          decrement n_start, n_continue or n_end
          as appropriate
    endwhile

    # Ensure rule set is legal
    while (n_start=0 and n_continue=0 and end=0)
       for rule in ruleset
          for each non-terminal in body of rule
            if (no other rule has head that matches
              non-terminal)
               delete rule
               increment n_start, n_continue or
               n_end as appropriate
    endwhile
  endwhile!
```

Figure 6. A Max/MSP patch using a coll object for storing and accessing a path as a list.



eliminated, and a new rule is generated to replace it (see Figure 5).

Once a legal rule set is produced, a second algorithm can be used to repeatedly extract a path or a sequence of terminals. First, a rule is randomly selected from among all the rules whose head matches the start symbol. Next, a rule is randomly selected from among all the rules whose head matches the non-terminal ending of the rule previously selected. Finally, if the rule selected in the second step has a non-terminal, the second step is repeated.

Interactive Interface and Composition

These algorithms were implemented as four Java classes. The four classes are embedded in the Max/MSP or the Pd environments as extensions of the MaxObject class. They are combined to create an `mxj` type object (or `pdj` object in Pd) that creates, in real time, a legal set of rules in one of the grammars and then constructs (again, in real time) multiple legal paths from the same set of rules. The process repeats, generating new sets of rules and extracting additional paths. There are `mxj` objects available for all grammars—Balanced, RH_Held, RH_Iter, Excentric, Sample, and Accumulation, as well as for the structural grammars Table and Sub-Table. These grammar objects function in a simple way. They receive a list of integers in the left inlet. This list is interpreted by the object as the number of rules of each type to be generated. The set of rules is posted in the Max window. Following the generation of the rule set, with each bang received in the left inlet the object outputs a path or a sequence of terminals as a symbol list from its outlet.

I now present a way to create an interactive interface with the `mxj` grammar objects, as well as a method to compose with this interactive interface. Because an `mxj` grammar object produces a path as a symbol list, this list can be stored in a `coll` object to allow access to items on this list. The list is entered into the `coll` object and read from it using the patch shown in Figure 6. The list is read, in this case, using an arbitrary timing based on the bangs generated by a `metro` object; however, a similar patch can be used to reflect a structural time organization instead.

The patch in Figure 6 is embedded in the patch in Figure 7. The latter includes the grammar object `mxj_BalRuleM`. As shown in the figure, a message box sends a list to the inlet of this object that specifies the number of rules to be generated. The `live.text` object bangs the `mxj_BalRuleM` object to output a path. The patch in Figure 7 is part of a larger patch that simulates the tree-like hierarchy

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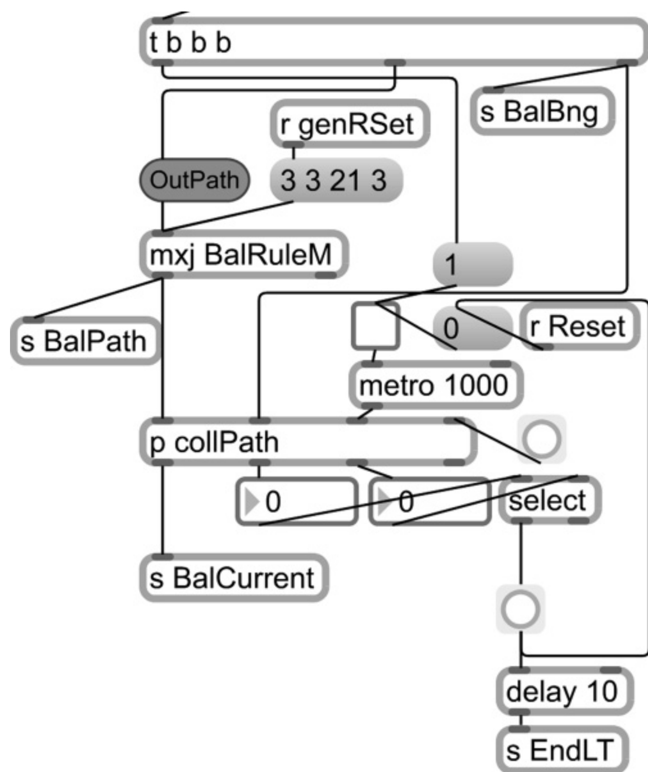
Figure 7. A Max/MSP patch using a grammar object to generate rule sets and paths.



represented in Figure 4. The upper part of this larger patch includes the grammar object mxj_TabRuleM that generates a rule set in the Table grammar. When a path is output by this object, the list of terminals is compared in a select object that activates the grammars Balanced, RH_Held, or RH_Iter, or the Sub-Table grammar that, in turn, would activate the grammars Excentric, Sample, and Accumulation. The activity in this tree-like patch is monitored in an interface such as the one shown in Figure 8.

In the tree-like hierarchy shown in Figure 4, the Table and Sub-Table grammars provide the background level of the structural organization while the other grammars are the middle ground of this organization. A path extracted in the Table or Sub-Table grammars would be advanced in relation to the paths extracted in the middle-ground grammars. If, for example, the path [BALANCED, RH_HELD, BALANCED, RH_ITER] is extracted in the Table grammar, when the first terminal is read it activates a path in the Balanced grammar. The second terminal will be read only when the path in the Balanced grammar has ended. Therefore, the middle-ground grammars are a defining element in the time organization of the hierarchical structure generated by this patch.

There are many ways to connect such a structure to a foreground of sound generation and processing. One possible way is to map the terminals through select objects to bang messages that activate the playback of sound files. An alternative method uses spectral signatures derived from Pierre Schaeffer's sound recordings that exemplified TARTYP and its defining characteristics (Schaeffer 2012). From each one of the sound objects in these examples of Schaeffer's, I extracted 64-bin frames from a fast Fourier transform (FFT) to create a spectral signature. These frames were saved as lists of values in simple text files. In a Pd patch like the one shown in Figure 9, the FFT frames are used to filter a live sound and apply the spectral signature of a Schaefferian sound object on the live sound. Similarly, the waveform of a Schaefferian sound object, stored in an array object, is used to generate the amplitude envelope of the processed signal.

The sub-patch [pd_Paths] in the upper-right corner of Figure 9 uses the grammar objects to generate rule-sets and sequences of terminals in the way exemplified in Figures 6 and 7. The patch then selects FFT frames and waveforms originating from sound objects that are members of the subsets equivalent to terminals in the sequence. The data of these FFT frames and waveforms are entered into the arrays FFTframe and AmpEnv. For example, if the terminal DEFINITE is part of a path extracted from the Balanced grammar it will cause the selection of FFT frames and waveforms extracted from the sound objects exemplifying the sound-object classes N, N′, or N″.

This sound-processing system is combined with the hierarchical structure generated by the grammars discussed in previous sections. As discussed before, the subcollection grammars define the time organization at the middle ground of this compositional process. At the foreground, the temporal organization is derived from the amplitude envelopes generated by the waveforms selected from Schaefferian sound objects. For example, if the

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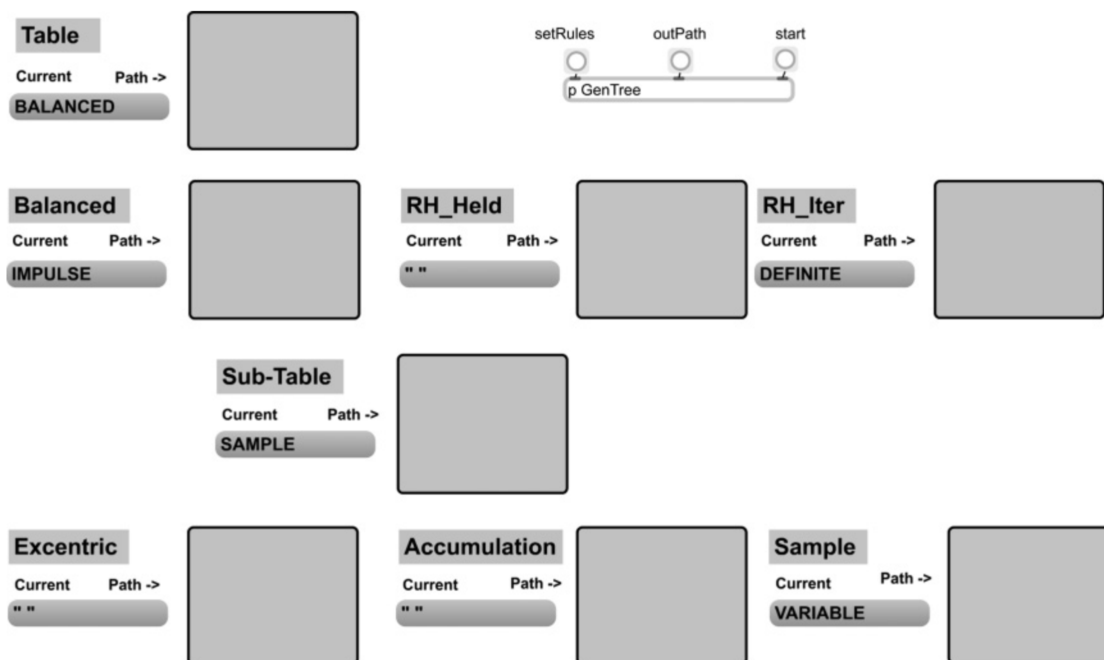
Figure 8. A sample interface used to monitor the activity in the tree-like Max/MSP patch described in the text. In this interface, for each grammar the extracted path is shown in a large box, and the terminal currently playing is shown in the message box under the title of the grammar.



DEFINITE terminal of the previous paragraph is followed by an IMPULSE terminal, the latter will be read once the envelope generated for the DEFINITE terminal ends.

Interactive Klumpenhouwer Networks

The discussion so far has focused on using Schaeffer's taxonomy of sound objects, as expressed in TARTYP, to create a generative compositional tool. In this section, I will describe the development of an interactive tool for real-time generation of Klumpenhouwer networks (K-networks) that provides the composer more flexibility in defining underlying structures and the context of application. Henry Klumpenhouwer and David Lewin introduced the K-networks in 1990 (Lewin 1994) to describe the pitch organization of post-tonal compositions based on transformational relationships. Although K-networks are traditionally an analytical tool used to identify structural pitch-class relationships in a composition, I have applied a generative approach to this method for incorporating such networks as structural elements in real-time composition. In the following paragraphs, I present a very basic introduction to the K-network analytical method and the generative compositional tool that is based on this method.

The basic element of the network is the graph describing transformational relationships within a pitch-class set. The nodes of this graph represent pitch classes and the edges represent the transformations between these pitch classes. There are two types of edges: unidirectional edges for transposition (marked T_n where n is an integer mod 12) and bidirectional edges for inversion (marked I_n where n is an integer mod 12). A K-network is expanded to include multiple pitch-class sets by isomorphism. Two networks are considered *isographic* if they have the same configuration of nodes and arrows and there exists a function that maps the transformation system used to label the arrows of one network into the transformation system used to label the arrows of the other. Hence, if the transformation X labels an arrow of the one network, then the transformation $F(X)$ labels the corresponding arrow of the other (Lewin 1990).

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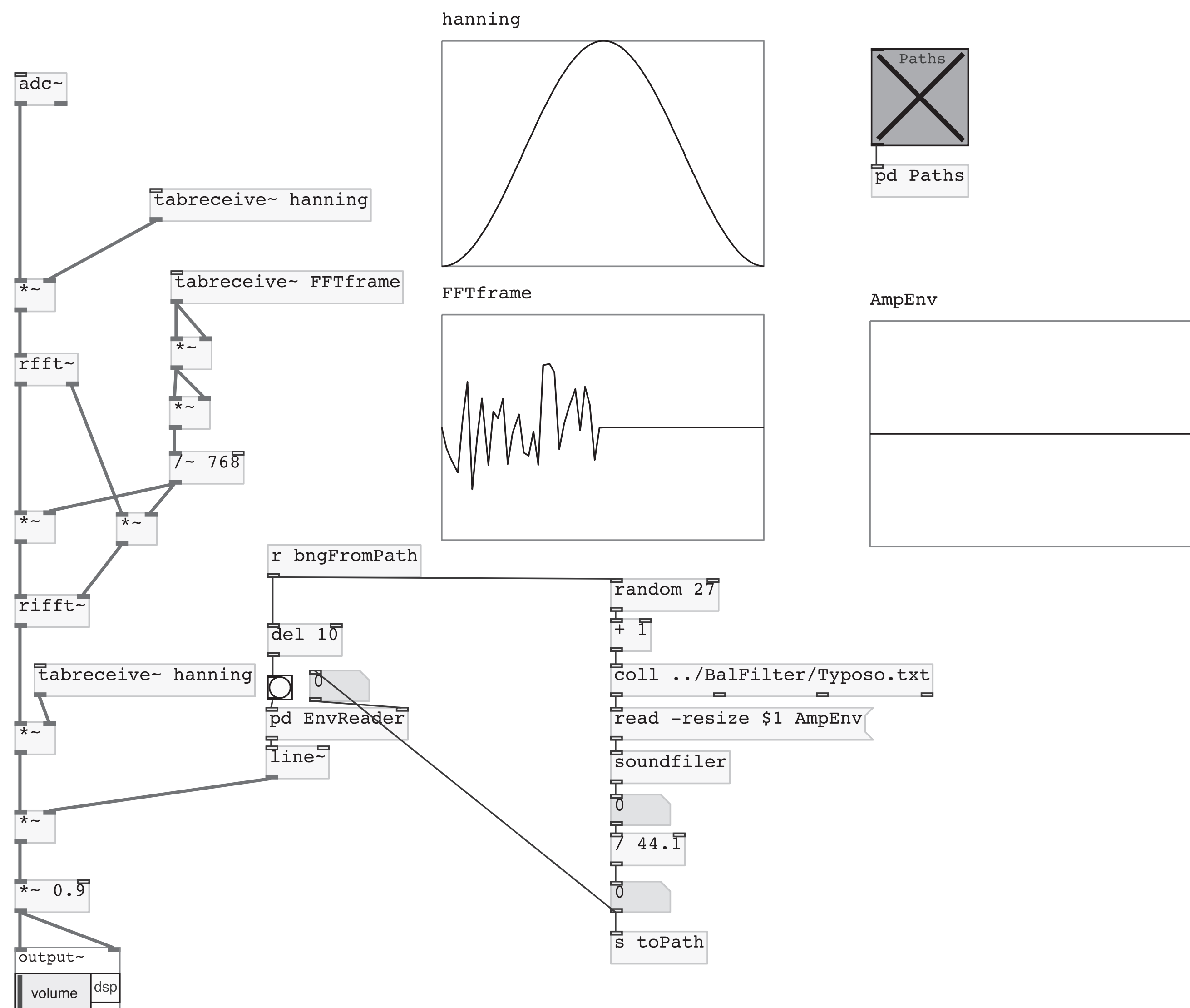
Figure 9. A sample sound-processing Pd patch applying the spectral signature of a Schaefferian sound object on live sound.



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Five rules for isomorphism apply to Klumpenhouwer networks (Lewin 1990). The first four rules are summarized in the following equations:

$$F\langle 1, j\rangle(T_n) = T_n; \quad F\langle 1, j\rangle(I_n) = I_{n+j} \qquad (7.1)$$

$$F\langle 11, j\rangle(T_n) = T_{11n}; \quad F\langle 11, j\rangle(I_n) = I_{11n+j} \qquad (7.2)$$

$$F\langle 5, j\rangle(T_n) = T_{5n}; \quad F\langle 5, j\rangle(I_n) = I_{5n+j} \qquad (7.3)$$

$$F\langle 7, j\rangle(T_n) = T_{7n}; \quad F\langle 7, j\rangle(I_n) = I_{7n+j} \qquad (7.4)$$

The fifth and last rule simply states that two K-networks will be isographic only if one of the rules expressed in Equations 7.1–7.4 holds.

Positively isographic networks are networks that share the same configuration of nodes and arrows, where the transposition levels of corresponding arrows are equal and the inversion indices of corresponding arrows differ by some constant j mod 12. Negatively isographic networks are networks that share the same configuration of nodes and arrows, where the transposition levels of corresponding arrows are complements and the inversion indices of corresponding arrows differ by some constant j mod 12 (Lewin 1990). The transformation between two pitch-class set networks is often referred to

as hyper-transformation (Lambert 2002). Based on Equations 7.1–7.4, the hyper-transformation between two isographic K-networks is marked $F\langle u, j\rangle$ where $u \in \{1, 5, 7, 11\}$ and j is some constant mod 12. The hyper-transformation between two K-networks, which are both isographic to a given third K-network, can be calculated by Lewin's formula 1 (Lewin 1990):

$$F\langle u, j\rangle F\langle v, k\rangle = F\langle uv, uk + j\rangle \quad (8.1)$$

$$F\langle u, j\rangle F\langle v, k\rangle(T_n) = F\langle u, j\rangle(T_{vn}) = T_{uvn} \quad (8.2)$$

$$F\langle u, j\rangle F\langle v, k\rangle(I_n) = F\langle u, j\rangle(I_{vn+k}) = I_{uvn+uk+j} \quad (8.3)$$

In positive and negative isographs, two types of hyper-transformations are considered: hyperT for positive isographs and hyperI for negative isographs, with $u \in \{1, 11\}$, respectively. Hence, the relationships expressed in Equations 8.1–8.3 yield four possible cases specified by Lewin's formula 2 (Lewin 1990):

$$\langle 1, j\rangle\langle 1, k\rangle = \langle 1, j + k\rangle \quad hyper\,T_{j+k} \quad (9.1)$$

$$\langle 1, j\rangle\langle 11, k\rangle = \langle 11, j + k\rangle \quad hyper\,I_{j+k} \quad (9.2)$$

$$\langle 11, j\rangle\langle 1, k\rangle = \langle 11, j - k\rangle \quad hyper\,I_{j-k} \quad (9.3)$$

$$\langle 11, j\rangle\langle 11, k\rangle = \langle 1, j - k\rangle \quad hyper\,T_{j-k} \quad (9.4)$$

Using predicate logic and the Prolog programming language, I have designed a tool that generates a K-network and subsequently extracts random paths from within the network. A path is a sequence of pitch-class sets that can be incorporated in the pitch organization of a composition or that can be mapped to other compositional elements. The Prolog program that implements the tool thus necessarily has two modes, one to generate the K-network and one to extract paths from an existing network. In the first mode, the program receives a set of user-defined parameters and generates the K-network accordingly. These parameters include an initial pitch-class set, a set of u values (such that $u \in \{1,11\}^{+}$) specifying positive and negative isographs, a set of constant j values and a set of transposition levels specifying the "bass note" of each newly generated pitch-class set. The program analyzes the initial set, generates isographs according to the specified parameters, and returns the generated network as well as all its hyperT and hyperI relations.

Figure 10. Prolog code generating a K-network.

```
genAndAssert(Set,U,J,P,S) :-
%%top-level call to generate a network
      genKNet(Set,U,J,P,S),
      neg(aKNet([Set|S],_)),
      gensym(aknet,L),
      assertz(aKNet([Set|S],L)),
      genHyperStmts(Set,1,0,S,U,J,L).

genKNet(_,[],[],[],[]).
genKNet(Set,[UH|UT],[JH|JT],[PH|PT],[SH|ST]) :-
%%generates a network
      genIsoG(Set,UH,JH,PH,SH),
      genKNet(Set,UT,JT,PT,ST).

genHyperStmts(S,US,JS,[SH|ST],[UH|UT],[JH|JT],L) :-
%%specifies the hyper-transformation in a network
      addHyperStmt(S,SH,US,UH,JS,JH,L),
      genHyperStmts(S,US,JS,ST,UT,JT,L),
      genHyperStmts(SH,UH,JH,ST,UT,JT,L).
genHyperStmts(_,_,_,[],[],[],_).

addHyperStmt(S1,S2,U1,U2,J1,J2,L) :-
%%specifies the hyperI between two sets
      U1 \= U2,
      F1 is mod(((U1*J2)+J1),12),
      neg(hyperI(S1,S2,F1,L)),
      assertz(hyperI(S1,S2,F1,L)).
addHyperStmt(S1,S2,U,U,J1,J2,L) :-
%%specifies the hyperT between two sets
      F2 is mod(((U*J2)+J1),12),
      neg(hyperT(S1,S2,F2,L)),
      assertz(hyperT(S1,S2,F2,L)).
```

The Prolog code in Figure 10 generates a K-network that includes multiple pitch-class sets. The genAndAssert() statement is the top-level call invoked to generate a network. It returns an aKNet() statement that specifies the pitch-class sets of a K-network and a new unique label L assigned to this K-network. Furthermore, genAndAssert() inserts aKNet() statements into a database, which then can be used to derive the hyperI() and hyperT() statements that define the internal structure of the network.

For example, consider the following query:

```
genAndAssert([3,10,4],[11,11,11,11,1],
      [2,1,8,2,6],[4,10,5,10,6],_).
```

which inserts the following K-network description in the database:

```
aKNet([[3,10,4],[4,9,3],[10,2,9],
   [5,2,4],[10,3,9],[6,1,7]],aknet0).
```

The unique newly generated label for this network is "aknet0." The query also inserts the following

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associated set of hyper-transformations into the database:

```
hyperT([3,10,4],[6,1,7],6,aknet0).
hyperT([5,2,4],[10,3,9],6,aknet0).
hyperT([10,2,9],[5,2,4],5,aknet0).
hyperT([10,2,9],[10,3,9],11,aknet0).
hyperT([4,9,3],[10,2,9],1,aknet0).
hyperT([4,9,3],[5,2,4],6,aknet0).
hyperT([4,9,3],[10,3,9],0,aknet0).
hyperI([3,10,4],[4,9,3],2,aknet0).
hyperI([3,10,4],[10,2,9],1,aknet0).
hyperI([3,10,4],[5,2,4],8,aknet0).
hyperI([3,10,4],[10,3,9],2,aknet0).
hyperI([10,3,9],[6,1,7],8,aknet0).
hyperI([5,2,4],[6,1,7],2,aknet0).
hyperI([10,2,9],[6,1,7],7,aknet0).
hyperI([4,9,3],[6,1,7],8,aknet0).
```

Once the network has been generated, the program, operating in the second mode, can perform a random-walk search to extract paths from this network on demand. Although the search tree of any K-network can potentially grow exponentially as the size of the network increases, the user can specify the start and end nodes (pitch-class sets), the maximum depth of the search, and a limit to the number of repetitions (cycles) in the generated path when issuing the appropriate chain() statements, as shown in Figure 11. A chain() statement is the Prolog query that generates a path from a known network with optional start and destination sets. The search tree is rooted in the hyperI() and hyperT() statements. The program looks for a random path in this tree, meaning it picks a random branch at each choice point as well as a random instantiation from among the legal instantiations at the root hyperI() and hyperT() statements. Recall that hyperT() is a unidirectional edge in the network graph, and hyperI() is a bidirectional edge; hence, there are three possible mapping functions between two sets in the network. These mapping are represented explicitly by the following three statements.

```
related(X,Y,T,L,0) :- hyperT(X,Y,T,L).
related(X,Y,I,L,1) :- hyperI(X,Y,I,L).
related(X,Y,I,L,2) :- hyperI(Y,X,I,L).
```

Figure 11. Prolog code generating a path from a known K-network.

```
chain(_,_,_,_,D,_,H,_) :- D>H,!,fail.
chain(X,Y,[X,Y],L,_,0,_,_) :-
      random(0,3,S),
      modrelated(X,Y,_,L,S).
chain(X,Y,[X|Z],L,D,1,H,R) :-
      random(0,3,S),
      modrelated(X,W,_,L,S),
      D2 is D+1,
      random(0,2,S2),
      modchain(W,Y,Z,L,D2,S2,H,R),
      count(X,Z,C),
      limit(C,R).

modchain(X,Y,W,L,D,S,H,R) :-
      N is mod(S,2),
      chain(X,Y,W,L,D,N,H,R).
modchain(X,Y,W,L,D,S,H,R) :-
      N is mod(S+1,2),
      chain(X,Y,W,L,D,N,H,R).
```

Using a random number generator (that has been seeded randomly) to elect which of the three legal paths to take at each call to a related() statement, the modrelated() statements shown here step through all three related clauses in some randomly chosen but deterministic order determined by the input random "seed," S:

```
modrelated(X,Y,T,L,S) :-
  N is mod(S,3),related(X,Y,T,L,N).
modrelated(X,Y,T,L,S) :-
  N is mod(S+1,3),related(X,Y,T,L,N).
modrelated(X,Y,T,L,S) :-
  N is mod(S+2,3),related(X,Y,T,L,N).
```

The chain() statement in Figure 11 uses the modrelated() statements to build a path. The user can impose a fixed horizon by specifying a value for the parameter H. For example, if $H = 4$ the program will execute four recursive steps and return a path of length five or less. The user can also limit the maximum number of repetitions (or cycles) in the path by specifying a value for D. For example, to find a path from source set [3,10,4] to destination set [6,1,7] with a length of no more than four steps, and with no more than two copies of any set in the network labeled aknet0, the query is:

```
findPath([3,10,4],[6,1,7],
  Path, aknet0,4,2).
```

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The program may return, depending on the initial random seed, for example:

```
Path = [[3,10,4],[6,1,7],[5,2,4],
        [10,3,9],[6,1,7]]
```

Future Work

The latest research in musical artificial intelligence has followed trends and computational models derived from biological evolution, cultural evolution, and social interaction (Miranda 2011). A great deal of attention has been given to the development of compositional tools for interactive music and computer improvisation. For example, Eigenfeldt (2011) uses multi-agent social interaction software and evolutionary systems to model the spontaneity of improvisation and the musical interaction between improvisers. David Plans and Davide Morelli (2011) attribute the success of free improvisers to experience-based acquisition of listening skill and "thin-slicing" intuition. They have used machine learning, genetic coevolution algorithms, and fast-and-frugal heuristics to develop software to mimic these skills. Free improvisers, however, as noted in the beginning of this article, define their own "hybrid language." Their listening skill and thin-slicing intuition emerge, by and large, from mastering this musical language. Although machine-learning techniques generally require a great deal of sample data and can be cumbersome to apply in a real-time context, tools for defining musical languages and generating musical structures are inexpensive and can be embedded in interactive environments such as Max/MSP.

It is straightforward to implement the tools that were presented in this preliminary research as real-time musical structure generators for the Max/MSP and Pd environments. The implementation's limitations emerge from what Miller Puckette defines as the Max paradigm. The latter, according to Puckette (2002, p. 31), is "a way of combining predesigned building blocks into configurations useful for real-time computer music performance." These predesigned building blocks insulate the user from basic programming elements such as data structures, Boolean functions, logic operation, and type definitions, all of which are common constructs in conventional programming languages, including C, the underlying language of Max/MSP. This limits the user's ability to implement complex algorithms and manipulate more elaborate data structures such as multi-dimensional arrays. In order to create the tools described in this article, I have written new Max externals. My implementation entails making contextual choices that limit the flexibility available to the composer. Hence, the composer can use my TARTYP-based grammar object to regenerate different sets of rewrite rules, but cannot, for example, change the set of terminal symbols in order to refer to a different sound taxonomy or compositional classification. Similarly, the composer cannot change the functions in the K-network code to generate a new type of network, because such changes would require rewriting the externals' code.

In future work I propose to develop software to allow composers of interactive music to generate musical structures in real time in the manner of a free improviser. My goal is to design a tool that enables the composer to define a musical language and specify a generative method without resorting to writing his or her own Max externals. The main challenge in developing such a tool will be to accommodate the largest possible array of creative ideas. My plan is to follow the model of the FTM shared library developed by the Real-Time Musical Interactions research team at the Institut de Recherche et de Coordination Acoustique/Musique (IRCAM). This model emerged from the idea that the integration and manipulation of data structures in Max/MSP that are more complex will "open new possibilities to the user for powerful and efficient data representations and modularization of applications" (Schnell et al. 2005). FTM has been used as the foundation for the design of applications for score following, sound analysis and re-synthesis, statistical modeling, database access, advanced signal processing, and gestural analysis. It includes data structures, editors and visualization tools, expression evaluation, and file import and export. It allows the static and dynamic instantiation of FTM classes and the dynamic creation of objects.

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Conclusion

This article has presented two generative compositional tools that generate and re-compose unified musical structures in real time. The first tool is based on generative grammars that reflect the structure of Schaeffer's classification of sound objects as presented in his TARTYP, while the grammars preserve the terminology and meaningful interclass relationships which are an essential part of this table. The article presents a compositional method that utilizes this tool and maintains contextual ties to the same resource. The second tool continues this same generative approach with Klumpenhouwer networks. The level of structural relationships generated by these tools is achieved partly by predetermined programming elements, as well as by a predetermined choice of context and resources. In future work, I hope to develop tools that will allow the user to define musical languages and specify generative methods according to the composer's choices of context and resources, while maintaining the same level of structural relationships.

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