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An Introduction to Aspect Oriented Music Representation

Abstract

The composition of music in many idioms involves the exploitation of recurrent, recombinant musical fragments. Any given fragment may, as a consequence, appear in arbitrarily many structures, in its original or transformed state. Such a fragment is said to crosscut the musical structure, in the sense that the modification of such a fragment implies that revisions should be made to related structures.

Aspect-Oriented Music Representation (AOMR), is an approach to music representation that draws inspiration from Aspect-Oriented Programming techniques in computer software. In overview, AOMR enables fragments of music to be encapsulated and associated with user-defined areas of compositional interest. New fragments may be generated by specifying transformational and combinatorial relationships with other fragments, by reference to their area of interest. In this way, AOMR separates structure from content, and enables crosscutting fragments to be stated once, with any subsequent revisions to a fragment being automatically propagated to all related fragments.

In order to remain recombinant, each fragment must be independent of its ultimate temporal location. AOMR provides an approach to the arrangement of fragments within a temporal framework, and enables the content of fragments to be conditionally modified, based on factors such as location, context and provenance.

Introduction

Computer music systems serve diverse purposes. To this end, some draw on contrasting computing paradigms including procedural, object-oriented, data-flow, functional and logic programming. All such systems, provided they are sufficiently developed, are Turing complete, but different paradigms can help facilitate different kinds of approach to music computing and new kinds of music manipulation.

In general purpose programming, aspect-oriented programming and related techniques are recent developments that have been claimed, broadly speaking, to offer new kinds of flexibility and ease of variation. The system presented here, AspectMusic, is the first substantial work we are aware of to adapt ideas from aspect oriented programming and related techniques and explore how they might be applied to facilitate new approaches to musical exploration and manipulation. AspectMusic is an implemented framework that applies ideas at the root of AOP to the manipulation of musical materials and structures. To introduce AspectMusic, and more generally, Aspect Oriented Music Representation (AOMR), we will start by reflecting on some various well-known features of current Computer Music systems.

Interactive scoring systems effectively provide "musical word-processor"-style environments, enabling musical detail to be entered and edited on a note-by-note basis. Other approaches, such as JMusic and Common Music aim to provide generalized music programming environments, albeit with a prescribed musical ontology, embedded within general-purpose programming languages. Computer music environments such as Pope's MODE system (Pope 1991) have evolved out of the requirement to support particular compositional needs, and therefore while multiple approaches are supported, ontological generality is not a prime concern.

In these, and other ways, most music representations allow music to be represented and manipulated only within a prescribed range of preconceived musical ontologies. In contrast, AOMR has the distinctive aim of supporting whatever ontologies may be preferred by particular users. This is largely achieved by abstracting music constructs in terms of discrete areas of interest, or concerns, that may be composed together. In this way, AOMR aims to support any perspective as a first-class entity however its operations may crosscut, or be scattered across, existing organisational hierarchies.

In this paper, in order to explain AOMR as clearly as possible, we have focused on familiar and relatively simple examples using western tonal music. For clarity, we proceed from the traditional dimensions of tonal music, and show how AOMR supports various operations and conceptions that cross-cut these boundaries.

AOMR appears to be particularly relevant for those musical genres in which musical composition may be characterized in terms of a, typically limited, set of musical "raw materials" which are combined and reused in various ways, addressing different musical areas of interest within a particular piece of music. Well known examples of such materials in Western tonal music include pitch sequences, rhythmic figures, and harmonic progressions which may appear in exact and transformed forms throughout a musical work. Similar transformational processes can occur at abstract levels in other genres, with materials such as sequences of parameters that form the inputs to generative processes. Equally, AOMR is applicable to musical works and fragments based on structural prototypes that are formed through a finite set of combinatorial

operations. AOMR appears applicable wherever explicit support for maintaining coherence across representational or functional shifts is useful to a composer.

In traditional areas, such as those genres we focus on in this paper, it is generally argued (Schoenberg 1967) (Cook 1987) (Sloboda 1985) (Belkin 1995-1999) that the reuse of materials, such as those mentioned above, is the principal method by which a composer achieves musical coherence and stability, across different musical dimensions. Additionally, of course, composers may reuse materials inter-opus. In relevant genres, the general process of musical composition therefore typically requires that the composer merge together selected musical fragments to form new constructs. As a consequence, musical materials cannot generally be localized to any particular musical construct. To take an extremely simple example, not problematic using conventional systems, a single melodic figure might be merged with a number of rhythmic variants, forming different phrases. Musical materials therefore tend to be explicitly restated and transformational processes re-applied at each occurrence. Hierarchical structures are prominent in music, as indicated by the analytical work of theorists such as Schenker and Lerdahl and Jackendoff (Lerdahl and Jackendoff 1983). But since the hierarchies formed in different dimensions do not necessarily align, musical compositions tend to contain tangled hierarchies and polyarchies. For example, consider a simple pitch sequence P1 consisting of two parts PA and PB, and a simple rhythmic sequence R1 consisting of three parts RA, RB and RC. A single melodic figure constructed from these sequences results in a tangled hierarchic relationship in which there is not necessarily any correspondence between any of the parts of P1 and those of R1. Polyarchic relationships occur when a node is shared between hierarchies. Consider, for example, another pitch sequence P2, that also uses PB. Tangled polyarchies occur when elements from polyarchies in different dimensions are combined. These two scenarios are shown graphically in figure 1.
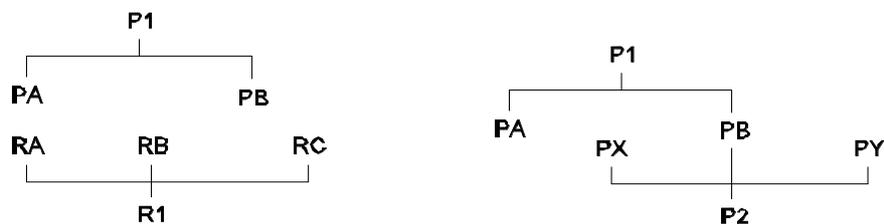

Figure 1

In addition to deriving core musical materials, in composing and arranging a musical work, composers often make associations between musical context, and events occurring in orthogonal dimensions. Another simple and non-problematic example is the modification of dynamic at a particular point within a piece of music, either based upon metrical location, or musical content. More sophisticated examples include the derivation of parts from musical events occurring in one or more other parts, such as accentuating particular notes through doubling. A key point is that the potential complexity of hierarchical tangling that may arise from such derivations is, in principle, unlimited. Also, even simple hierarchical tanglings can lead to unlimited complexity when multiplied or iterated. An equally important related point is that, in a finished score, compositional intent is often lost, and again these derivation processes must be restated and reapplied wherever they recur. Moreover, if musical fragments are to be specially treated, based upon features relating to their derivation, then this

too must be tracked by the composer since it may not be readily apparent from the resultant material itself (Crochemore, Iliopoulos, and Pinzon 2001).

Yet further, while music is naturally experienced in a "left-to-right" fashion, it is not necessarily composed in this way. While it is true that some composers speak of a spontaneous vision of a work (Sloboda 1985), that "simply" requires transcription, others (Spiegel 1988) describe detailed, iterative, evolutionary processes, in which the composition develops from possibly incomplete sketches in different musical dimensions, and at different levels of abstraction.

The representation of tangled, multi-dimensional, polyarchic relationships is difficult, and generally not explicitly represented in computer music systems. However, recent developments in computer software, collectively termed Aspect Oriented Programming (AOP), seek to address similar types of problem that exist in software. In particular, AOP approaches aim to help manage the separation, encapsulation and subsequent merging together, or *weaving,* of the implementations of separately specified areas of interest or *concern*. Modern object-oriented approaches to software design and implementation (Meyer 1997) (Rumbaugh et al. 1991) represent a natural evolution of the module paradigm suggested by Parnas (Parnas 1972), enabling application domain and design concerns to be represented as *classes* which encapsulate both data *and* the operations that may be performed upon that data. Even so, certain areas of interest, or *concerns,* remain difficult or impossible to encapsulate as classes (Hürsch and Lopes 1995). From one perspective, the fields and methods defined within a class might be further grouped in terms of the concerns that they address and the implementation of a given concern might involve a number of methods and fields that extend across multiple, possibly unrelated, classes. Moreover, multiple concern implementations may incorporate common code fragments that themselves have no natural class association. Typical Object-Oriented approaches therefore impose a decomposition scheme that is not sufficiently general to enable separation of concerns. This has been dubbed "the tyranny of the dominant decomposition" (Tarr and Ossher 2000). At another level of abstraction, certain programming concerns relate to particular events that occur within the execution of a program. For example, a "tracing concern" which outputs diagnostics that trace entry into selected methods typically requires tracing implementation to be restated in every method of interest.

These complementary viewpoints identify that certain concerns tend to be *scattered* across multiple, possibly unrelated, classes and intertwined or *tangled* with other concern implementations. Since such concerns cannot be localized and encapsulated using the prevailing decomposition, they are said to be *crosscutting*.

In this paper, we introduce an experimental object-oriented software system, called AspectMusic, which adapts ideas from AOP in order to realise an Aspect Oriented Music Representation (AOMR). AOMR aims to provide a general approach to the separation, organization and composition of musical concerns from both of the viewpoints outlined above.

Symmetric and Asymmetric Composition of Concerns

Approaches to AOP are diverse. Some, such as Aspectual Components (Lieberherr, Lorenz, and Mezini 1999) apply to specific programming concerns while others, such

as AspectJ (Xerox 1998-2002), Hyper/J (Tarr and Ossher 2000) and Caesar (Mezini and Ostermann 2003) aim to address more general separation of concerns issues. General-purpose approaches broadly adopt one of two paradigms, namely *symmetric* or *asymmetric*. The following paragraphs briefly outline these approaches. In each case, the reader is directed to the references for further detail.

Asymmetric approaches, such as AspectJ (Xerox 1998-2002) and AspectS (Hirschfeld 2002), consider the augmentation of a base decomposition, which is typically a standard OO-decomposed program, with crosscutting concern implementations. In AspectJ, the best-known example of this approach, the base decomposition is a normal Java program. Crosscutting concern implementations, generically termed *advice*, are associated with well-defined points, termed *joinpoints*, in the static or dynamic structure of the base decomposition. Typically, joinpoints are at method calls and variable assignments. Particular joinpoints of interest are specified as *pointcut* expressions and advice may typically be run *before*, *after* or instead of (*around*) the joinpoint. In this way, asymmetric approaches, in general, enable standard programs to be non-invasively augmented with separately encapsulated crosscutting concern implementations.

In contrast, symmetric approaches, such as Multi-dimensional Separation of Concerns (MDSoC) (Ossher and Tarr 1999) implemented by Hyper/J (Tarr and Ossher 2000), consider the construction of software systems from separately specified components, *units*, that each address just one concern. In MDSoC, these components are organised into a multidimensional structure called a *hyperspace*, in which each named unit is associated with a dimension name, and the name of a concern within that dimension that the unit relates to. Broadly speaking, using an MDSoC approach, software systems are composed by specifying those dimensions and concerns that the resultant system should contain.

As noted in (Harrison, Ossher, and Tarr 2002), no single composition method is suitable for all requirements., therefore symmetric and asymmetric approaches should be regarded as complementary.

AspectMusic Overview

AspectMusic is an object-oriented, experimental implementation of an AOMR, written in VisualWorks Smalltalk (Goldberg and Robson 1989). The system consists of two interrelated components, HyperMusic and MusicSpace that respectively implement Symmetric and Asymmetric composition approaches.

HyperMusic provides a framework for abstracting, organising and representing musical ideas. Using HyperMusic, the user defines musical materials and transformational processes, which are then organised according to user-defined criteria into a hyperspace. Declarative specifications are used to compose new material from the components in the hyperspace. These new components may themselves be added to the hyperspace and thus the hyperspace becomes an evolving repository of compositional ideas.

MusicSpace allows components from HyperMusic to be arranged in time, in a similar manner to a MIDI sequencer. However, the key feature of MusicSpace is that it enables the music to be dynamically modified, based upon context, using an approach

that is similar to asymmetric AOP. In particular, modification strategy implementations may be modularized, and associated with particular dynamic musical conditions in terms of pointcut-like events that must be satisfied in order for the strategy to be applied.

In order to link the two approaches, the construction of materials using HyperMusic is audited through a "Composition History" that is associated with each symmetrically composed element. This history is available to MusicSpace. Thus for any musical event in MusicSpace, it is possible to determine not only its current state, but also how it has been derived. In the remainder of this paper, we describe the symmetric and asymmetric components of AspectMusic in greater detail.

Symmetric Composition of Musical Concerns using AspectMusic

The Symmetric Composition (HyperMusic) component of AspectMusic provides an extensible framework that supports the definition, organisation and combination of musical fragments. HyperMusic is heavily influenced by the notion of Hyperspaces (Ossher and Tarr 1999) and the Hyper/J^{TM} (Tarr and Ossher 2000) implementation of hyperspaces for the Java programming language. The principal class structure of HyperMusic is shown in Figure 2.
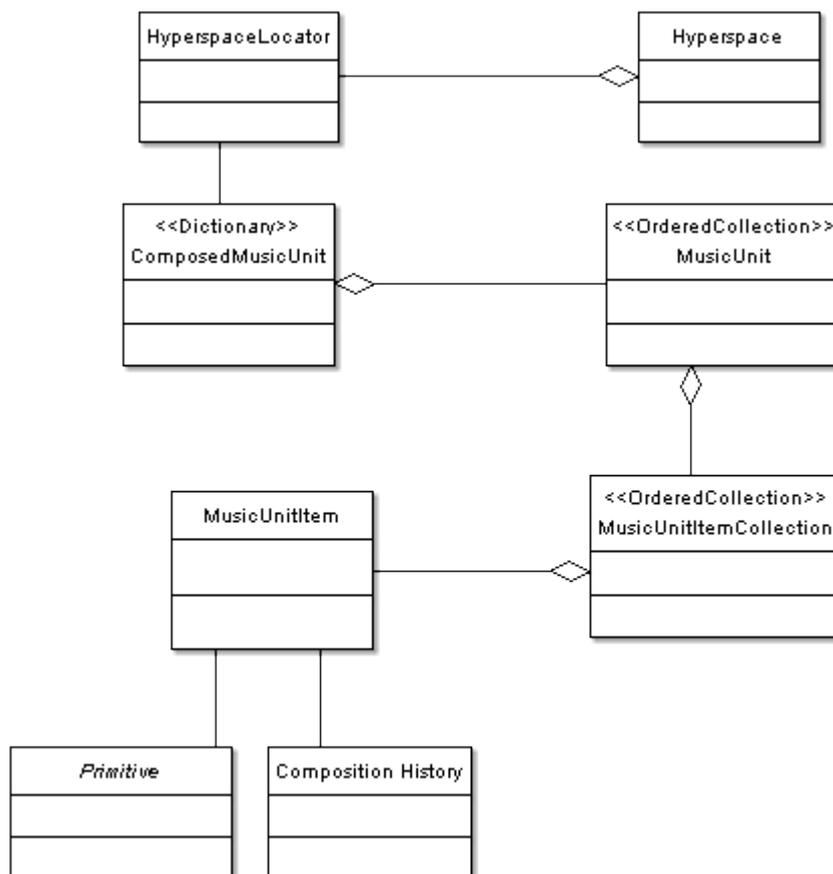
Figure 2. HyperMusic Class Structure

Structuring in HyperMusic

Fundamental to HyperMusic is its ability to support the separation and combination of musical ideas from discrete musical dimensions. In this context, a musical idea is generalized as an indexed collection of events relating to the same musical dimension, where each event may contain multiple elements organised into discrete voices. For example, a monphonic rhythmic idea might be expressed as a sequence of events where each event contains a single object representing relative onset time and duration. A sequence of chords, on the other hand, might be expressed as a sequence of events, in which each event contains pitch value representations distributed across multiple voices.

In HyperMusic, MusicUnits (MUs) represent discrete musical ideas in a single musical dimension, organized as an ordered collection. Each element of the ordered collection within a MU contains an ordered collection (a `MusicUnitItemCollection`) of `MusicUnitItem` objects that wrap user-defined objects representing musical information. The index value of a `MusicUnitItemCollection` relates to a discrete voice. Conceptually, the wrapped objects each pertain to the same musical *type*, such as pitch, rhythm, or dynamic information. However, HyperMusic does not prescribe the types that may be represented, neither does HyperMusic mandate that all wrapped objects within a MU are of the same class. For example, a pitch MU might contain `MusicUnitItems` that wrap a mixture of object types that represent pitch as, say, MIDI pitch values (0-127), symbolic values such as 'C#4', or frequency values.

Complete musical ideas are typically formed from multiple musical dimensions. A melody, for example, may be viewed as being formed from pitch and rhythm. In HyperMusic, MUs of different types are aggregated into Composed Music Units (CMUs), represented by the class `ComposedMusicUnit`, in which each component MU is identified by the name of the type it represents.

To illustrate the structure of CMUs, a simple musical fragment and a schematic representation of the HyperMusic objects involved in a CMU representation of the fragment are shown, respectively, in Figures 3 and 4.
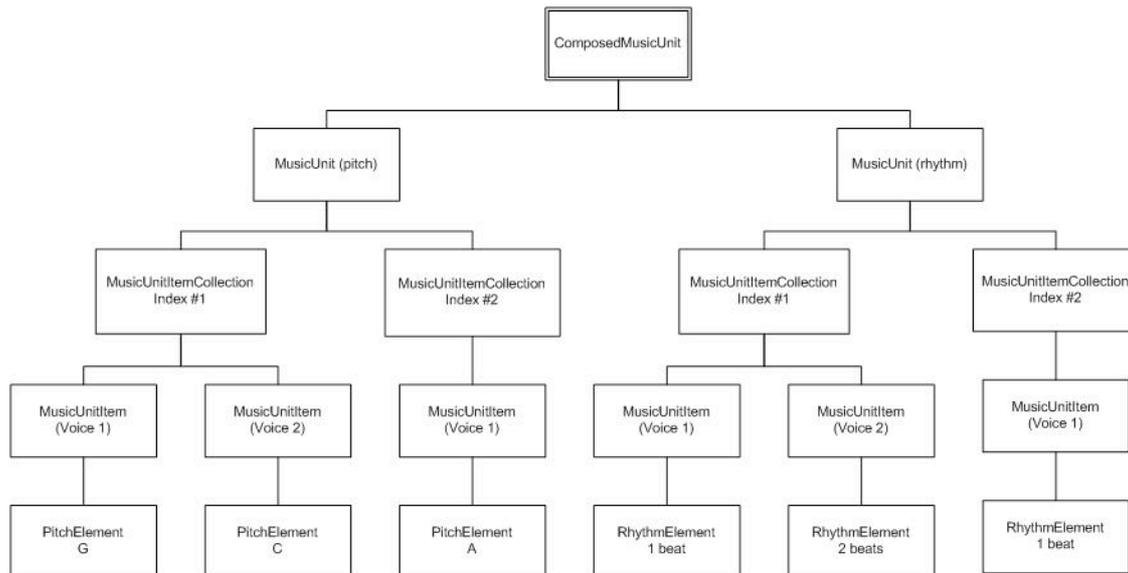

Figure 3. A simple music fragment

Figure 4. Schematic of a CMU representing the fragment shown in Figure 2.

Combining CMUs

CMUs are designed to be combined together, in various ways, to form new CMUs that represent new musical material. We adopt the AOP term *weaving* to describe these combination processes. HyperMusic supports the, musically fundamental, notions of sequential and parallel weaving. However, it is easy to extend the system to support other kinds of weaving corresponding to any method through which two CMUs can be combined, for example, to weave appoggiatura or acciaccatura (Honing 1993) configurations. It is important to note that CMUs are not constrained to be "complete"; While clearly, for final realization, CMUs must contain all required musical elements in all required dimensions, at any intermediate stage, a CMU may be incomplete in terms of the types that it contains (vertically), and the number of elements in each type (horizontally). Since there is no implied correspondence between arbitrary groupings within each type, CMUs are able to support tangled inter-dimensional relationships.

Sequential Weaving.
When two CMUs are woven in *sequence*, notated as the binary operator '+', those MUs with identical type names are concatenated. If an MU type appears in only one of the woven CMUs, then it is concatenated with an empty MU. Thus, the set of MU types contained in the resultant CMU is the union of the set of MU types of both the combined CMUs. Usefully, this means that if, say, a CMU containing only a pitch dimension is sequentially woven with a CMU containing only rhythm, then the resultant CMU contains the pitch sequence in *parallel* with the rhythm sequence.

Parallel Weaving
When two CMUs are woven in *parallel*, notated as the binary operator '|', the `MusicUnitItemCollections` that exist at the same index in MUs of the same type name are merged together, allowing, for example, the formation of chords. Like sequential weaving, the resultant CMU contains the union of the set of MU types of both combined CMUs.

Transformations

In the foregoing sections we have described the representation of musical data within the CMU model. However, musical composition often involves the algorithmic transformation or generation of musical material. The CMU model supports these requirements by enabling transformational or generative code, generically termed *transformations*, to be placed in the special CMU type `#Transform`. Like other types, the `#Transform` type is represented by a `MusicUnit` structure, enabling ordering to be represented. A common use-case might be to construct CMUs that contain just one or more transformations. However, as we will demonstrate later in this paper, the open-ended nature of the CMU structure means that the approach also naturally supports CMUs that contain both transformational code and other musical information.

Combining and Executing Transformations

While, like other types, the `#Transform` type is a MU, the semantics of non-sequential weaving are not defined. Consequently, `#Transform` is *always* woven sequentially. However, simply weaving transformations into a CMU does not cause the transformations to be applied. Rather, transformations are executed by *evaluating* the CMU. This approach enables sequences of transformations to be constructed, and allows the user to specify when these transformations should be applied. Evaluation, notated as the unary operator `@`, causes all transformations in a CMU's `#Transform` MU to be executed, in index order, and for a resultant CMU to be produced that contains no `#Transform` type. A CMU without a `#Transform` type is said to be *final*, and the result of evaluating a final CMU is the CMU itself.

Organising and Combining CMUs

CMUs represent musical raw data, and transformational processes. However, CMUs are of limited value in themselves. Rather we want to be able to organise CMUs according to our own ontology, and by combination, to construct new CMUs by reference to this organisation. The organizational structure of HyperMusic, like that of MDSoC, is the *hyperspace.*

Dimensions and Concerns

In the hyperspace model presented in (Ossher and Tarr 1999), units are organised according to the dimension and concern to which they relate. In this context, dimension and concern are arbitrary textual names whose purpose is to represent an organisational structure that transcends the explicit structure of the software itself. In object-oriented software, for example, while a *class* may represent a prototypical object that exists within some universe of discourse, the field contained within the class, and the operations that may be performed on instances of that class, may conceptually pertain to different functions or concerns of the system. Moreover, the operations that pertain to a given concern may exist in multiple classes. Thus, because the dominant, class-based, decomposition of object-orientation does not support such a partitioning, it is not easily possible to identify and reason about only those parts of the class graph that relate to a particular concern.

There are many established musical representations, each with their own musical ontology and consequently there is no clear analogue of a "dominant decomposition" in music. Nonetheless, music can be considered in terms of independent perceptual dimensions (Loy and Abbott 1985) pitch, rhythm, dynamic and timbre. We may also consider music in terms of aggregates of a single dimension, such as melodic themes,

cells, tone rows, harmonic progressions, rhythmic motifs, or more abstractly, arbitrary parameters, and their evolution through generative, transformational and combinatorial processes throughout a given musical work. We argue, therefore, that from many purposes it is useful to consider each newly generated musical structure as serving some identifiable compositional purpose that can be attributed to some dimension and concern within the work. For example, different melodic fragments might be used in an antecedent / consequent relationship, themes might be associated with extra-musical events in similar ways to Wagner's use of the Leitmotiv and so forth.

Hyperspace and Hyperslices
In HyperMusic, a hyperspace is a data structure that maps between co-ordinates, consisting of the triplet of *dimension* name, *concern* name and *unit* name, and CMUs. Thus the hyperspace, represented by the `Hyperspace` class is an organised repository of musical and transformational fragments represented as CMUs.

A *hyperslice* is an abstract slice through a hyperspace, defined by a partial specification of the co-ordinates of CMUs of interest. For example, we might be interested in any CMU in the "Themes" dimension, or any CMU in a concern whose name begins with "Ostinato".

Combining CMUs
The purpose of organising CMUs into a hyperspace is to facilitate their subsequent composition into new CMUs. The specification of such a composition, represented by an object of the `HypermoduleSpecification` class, contains three key attributes, namely one or more *hyperslice specifications,* a *composition expression* and a *composition relationship specification.*

Composition Expressions
A *composition expression* specifies the hyperspace coordinates of those CMUs that are to be woven, and the weaving operations that are to be performed on these CMUs in order to generate a new CMU. Typical weaving operations, as described previously, are sequence (`+`) and parallel (`|`). Additionally, the composition expression may cause the evaluation of CMUs, using the unary operator '`@`'. Within the composition expression, CMU coordinates are specified In the form `dimension;concern;unit`, where `dimension`, `concern` and `unit` are regular expressions.

For example, consider the following various weavings of two CMUs, A and B, which exist in the C concern of dimension D. Assume that A and B each contain some musical information in the `#pitch` dimension, and that A also contains a transformation T that transposes pitch up by one semitone.

| CMU A			CMU B	
MU Type	Content		MU Type	Content
#pitch			#pitch	
#Transform	T			

The composition expression `D;C;A + D;C;B` causes `A` and `B` to be sequentially woven, resulting in a CMU whose content is the pitch component of `A` followed by the pitch component of `B`, and that also contains the transformation `T`.

MU Type	Content
#pitch	
#Transform	T

The expression `@D;C;A` results in a CMU that contains the pitch component of `A` that has been transposed up by one semitone, due to the evaluation (`@`) of `T`. The evaluation also causes `T` to be removed from the resultant CMU.

MU Type	Content
#pitch	

The expression `@(D;C;A) + D;C;B` results in a CMU containing the pitches of `A` transposed up by one semitone, followed by the (untransposed) pitches of `B`.

MU Type	Content
#pitch	
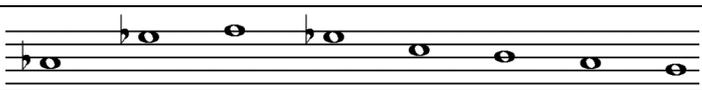
While specifying CMUs in terms of absolute hyperspace coordinates is clearly useful, greater expressive power is achieved from partial specifications using regular expressions. By default, CMUs are woven in sequence. So, for example, the composition expression `Intro;BassGuitar;Fragment.*` represents the sequential weaving of *all* CMUs whose name begins with `Fragment` and that exist in the `BassGuitar` concern of the `Intro` dimension, subject to the hyperslice constraints described below.

Hyperslice Specifications

In order to select CMUs for weaving, the CMU coordinates specified by a composition expression must be *matched* against CMUs that exist in the hyperspace. *Hyperslice specifications* within a hypermodule specification cause the search space to be refined by restricting matched names to those existing in the specified

hyperslices rather than the entire hyperspace. Hyperslice specifications may be expressed as regular expressions.

For example, given the following Hyperspace

```
Themes;Theme1;Opening1
Themes;Theme1;Closing1
Rhythms;Theme1;Original
Rhythms;Theme2;Original
Rhythms;Theme1;1stVariation
```

We can slice the hyperspace using hyperslice definitions such as

Hyperslice Specification	Slice Content
Themes;.*	Themes;Theme1;Opening1
	Themes;Theme1;Closing1

.*;Theme1	Themes;Theme1;Opening1
	Themes;Theme1;Closing1
	Rhythms;Theme1;Original
	Rhythms;Theme1;1stVariation

Rhythms;Theme1	Rhythms;Theme1;Original
	Rhythms;Theme1;1stVariation

Composition Relationships
Since composition expressions may specify CMU coordinates as regular expressions, it is possible for *multiple* CMUs to match the specification. A *composition relationship* specifies how this situation is managed.

There are two predefined composition relationships within HyperMusic, though it is possible to add new relationships as required. In the event of multiple matches for a CMU, the `overrideByName` relationship causes the last match found to be used. Conversely, the `mergeByName` relationship causes *all* matching CMUs to be woven in sequence. The results of the matching process are *always* returned in ascending ASCII order. Thus, in a hyperspace containing the following CMUs

```
Dim.Concern.Unit1
Dim.Concern.Unit2
Dim.Concern.Unit3
```

The regular expression `Dim;Concern;Unit.*` would be matched by all three CMUs. If the `overrideByName` relationship were used, then `Dim.Concern.Unit3` would be returned. If the `mergeByName` relationship were used, then a CMU formed by the sequential composition of `Dim.Concern.Unit1 + Dim.Concern.Unit2 + Dim.Concern.Unit3` would be returned.

Composition History
An important feature of music is that musical ideas evolve both inter- and intra-opus. The HyperMusic approach enables evolution to be defined declaratively as

hypermodule specifications that define the weaving or transformation of existing CMUs to form new CMUs. As part of the composition of CMUs, each `MusicUnitItem` is annotated with a "composition history" that provides an "audit trail" of the various weavings and transformations that have been performed and have caused the item to be in its present location.

Refactoring
Musical composition is obviously a creative and generally iterative process. As such, decisions that are made at some point in the process might be modified at a later point. For example, a CMU might be constructed as a single rhythmic figure `R`. At some later point, it might be decided that `R` can be usefully considered as two components, `R1` and `R2`, and that, `R1`, say, can be reused within the composition. We term this kind of adjustment as refactoring.

In its present form, HyperMusic does not contain any support for automatic refactoring operations. However, if we image the composition of CMUs being described as a sequence of weaving operations, then it is a simple matter to adjust this sequence such that `R` is described as being constructed from `R1` and `R2`, thus making `R1` and `R2` available within the hyperspace, but leaving all existing references to `R` intact.

Asymmetric Composition of Musical Concerns using AspectMusic

The HyperMusic approach to AOMR seeks to enable musical material, encapsulated as CMUs, to be represented, organised and woven together to form new material through declarative specifications. While it is possible to realise CMUs as, for example, MIDI sequences, the range of musical compositions that can be represented in this way is, naturally, limited.

MusicSpace provides an environment in which the events contained within CMUs may be arranged in time. In this respect MusicSpace resembles a typical MIDI sequencer. However the distinguishing feature of MusicSpace is its ability to enable music to be modified in relation to context through an approach that mirrors asymmetric aspects in software. The chief advantages of this approach are firstly that modification processes that occur at multiple locations, and are therefore crosscutting, can be modularized, requiring them to be stated only once. Secondly, aspects are non-invasive; there is no requirement to make any particular a priori arrangements within a CMU for aspects to be applied to the content of that CMU.

The MusicSpace approach enables compositional intent to be explicitly and declaratively expressed. For example, consider Beethoven's Sonata in C Minor (No 8 Op 13) "Pathetique". At bars 5-7 there is a fragment in which the theme is played *pp* and interspersed with *ff* interludes. We might suggest that Beethoven's structural plan was to have *pp* sections followed by *ff* sections, irrespective of what musical content these sections ended up containing. Alternatively, Beethoven might have considered that the *ff* markings were to be associated with the musical content of the interludes, irrespective of where they ended up. Perhaps, Beethoven wanted to accentuate those sections that were played in the lower registers, and so *ff* should be applied to any section in which all parts fell below middle C. From an analytical perspective this is

pure speculation, with some explanations being more plausible than others. Clearly, whatever the motivation, the resultant score would look the same, and the composer's intent has therefore been lost.

An example from a more contemporary genre might be to consider a section of a musical work containing pitch clusters that have been generated using a transformation based upon, for example, three parameters; mode, cluster size, and root. As part of this work, the composer wishes to reinforce particular pitches through doubling on another instrument, depending, say, upon the mode of the cluster in which they appear.

Using MusicSpace the special treatment of events, such as alteration of dynamic, or replication to a different instrumental part, may be separately, and reusably, encapsulated. Moreover, the compositional intent which associates such additional behaviours with specific conditions, which may include not only features of specific event, but also features of their derivation, may be declaratively specified.

MusicSpace Structure

A MusicSpace can be considered as a container for one or more named `MusicSpaceParts`. A MusicSpacePart is analogous to a part on an instrumental score, or a track within a MIDI sequencer, and contains CMUs arranged in time, with the restriction that CMUs may not overlap *within* a MusicSpacePart. The following diagram shows the basic structure of a MusicSpace that has been populated with two MusicSpaceParts, "Melody" and "Bass". The CMUs within a part may not overlap, however, CMUs may overlap between parallel parts. Note also that CMUs are not constrained to be contiguous within a part.

Melody	CMU1	CMU2		CMU3	CMU4
Bass	CMUA		CMUB	CMUC	

Joinpoints

As in software, some of types of crosscutting concern, termed *code-level crosscuts* (Bockisch et al. 2004), can be directly mapped to loci in the base decomposition. For example, referring to the logging example outlined earlier, it would be a relatively simple matter to automatically modify a program's source code by inserting logging calls into the methods of interest. This type of crosscut could be easily implemented, albeit the potential loss of traceability and intent, as a "search & replace"-style function operating on `MusicSpacePart` objects, for example, modifying duration to achieve articulation effects. However, *dynamic crosscuts* (Bockisch et al. 2004), whose loci can only be determined at run-time, present a potentially more useful class of crosscutting concern. In the case of logging, for example, we might be interested in logging a method A but only if it has been called by method B. Similarly, we might be interested in making particular notes in a given CMU staccato, but *only* when they are played at the same time as another CMU. In order to support dynamic crosscutting, the aspect model used in MusicSpace is *event-based*, conceptually resembling Axon (Aussmann and Haupt 2003) and the Event-Condition-Action (ECA) type "triggers" that are common in database applications. In order to generate joinpoint events, and process aspects, the MusicSpace is *compiled* against an `AspectManager` object, with which all required aspect objects have been registered.

When a MusicSpace is compiled, 'tick' events are generated and propagated to all `MusicSpaceParts`. These ticks, which by default are generated at a rate of 480 times per beat giving good resolution of n-tuplets, simulate the ticks of a clock source, such as a MIDI clock. However, it should be noted that, in the current implementation, ticks are not generated in real-time and therefore MusicSpace is not a live performance environment

MusicSpace Aspects

MusicSpace Aspects are implemented as standard Smalltalk classes that define crosscutting behaviour (advice), along with a representation of the conditions under which this behaviour is to be executed (pointcuts). An instance of each such class is registered with the `AspectManager` against which the MusicSpace is to be compiled.

At each clock tick, the contents of all `MusicSpaceParts` within the MusicSpace are queried to build a *context* that describes all the events that commence at the current tick value. This context includes all of the composition history that is associated with each event. The advice associated with a MusicSpace aspect is invoked if the current context, including temporal location, satisfies the pointcut expressions associated with the aspect. In general, an AspectMusic aspect may modify the content of the current temporal location by manipulating the events contained within the context. The advice may also modify future (or prior) events within the MusicSpace itself. Both *before* and *after* advice types are supported. *Before advice* is executed before the MusicSpace events contained by the current context is rendered into the resultant MusicSpace, enabling the advice to veto or modify the rendering of any component event of the context. *After advice* executes once this process has been completed, and therefore cannot modify the current event.

One of the perceived benefits, particularly of asymmetric Aspect Oriented Programming, is that pointcuts are defined declaratively. As MusicSpace is an object-oriented (Smalltalk) system, determining whether a pointcut is satisfied or not often requires procedural code that navigates and queries the object structures of the joinpoint context. These kinds of query may be arbitrarily complex and are, therefore, difficult to generalize in an object-oriented system. This kind of problem is, largely, more easily solved using logic programming languages, such as PROLOG. To support declarative pointcut queries, MusicSpace enables joinpoint contexts, including composition history, to be exposed as a set of AspectMusic logic predicates expressed in the PROLOG-like Smalltalk Open Unification Language (SOUL) (Gybels 2001). The symbiosis that exists between Smalltalk and SOUL enables expressions in either language to be evaluated from the other.

Rendering

The current implementation of AspectMusic enables MusicSpace instances to be rendered as MIDI sequences, by transforming information relating to pitch, rhythm and dynamic into MIDI events. This provides a convenient method of auditioning and visualising generated musical compositions using external MIDI tools. However, it should be noted that AOMR and AspectMusic systematically avoid any design bias or limitation towards particular rendering means such as MIDI.

Conclusions

In this paper we have proposed an approach to music representation which is particularly applicable to genres of music in which musical ideas across various musical and non-musical dimensions are merged together to form new musical elements resulting in tangled polyarchic relationships. We have described Aspect-Oriented Music Representation (AOMR), that draws from Aspect Oriented Programming in computer software, as a means to explicitly and declaratively support the organization and combination of musical and procedural elements separately from the musical material itself. AOMR supports the symmetric composition of musical materials, in which no one musical dimension is dominant, using a musical hyperspace as a dynamic repository of musical ideas. Moreover, AOMR does not limit the kinds of musical information that may be represented. AOMR also features an asymmetric, context-dependent, joinpoint interception model through which the selective modification of these materials is possible. Since the implementation of our AOMR system is open, the full expressive power of a general purpose programming language, in this case Smalltalk, is available within AOMR.

An AspectMusic tutorial is available in the Open University Department of Computing Technical Report TR2006/12, available at http://computing-reports.open.ac.uk/index.php/2006/200612.

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