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UNFOLDING THE POTENTIAL OF COMPUTATIONAL MUSICOLOGY

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Abstract: This paper addresses current chances and challenges in computational musicology. Computational musicology is a genuinely interdisciplinary research area that requires the contribution of questions, methods and insights from both musicology and computer science. This paper demonstrates how computational approaches to musicological questions generate new perspectives for musicology. In turn, computational musicology has the potential to become an indispensible partner for computer science in Music Information Retrieval. We argue that, for unfolding the potential of computational musicology, the full interdisciplinary enterprise has yet to be realized and we discuss examples of promising collaborative directions.

1 INTRODUCTION

Morehen & Bent (1979) raised the confident expectation that computational approaches in musicology will become a "respectable" and "widespread" academic discipline. However, Cook (2005) characterized the relation between computer science and musicology as it has developed over the intervening decades as a rather long moment of opportunity that has not yet led to fulfilling the promising potential of this relation.

In this paper we discuss both current chances and challenges in computational musicology. Computational musicology is a genuinely interdisciplinary research area that requires the contribution of questions, methods and insights from both musicology and computer science. Within this interdisciplinary setting, the investigation of musicological questions with computational approaches generates both new perspectives on old problems, and new questions formulated in the context of musicological research.

Computational approaches to musicological research have led to increasing efforts towards the formalization and empirical testing of musicological knowledge. This has contributed to the greater visibility of musicology within other scientific disciplines (Honing, 2006b). Furthermore, due to the explosion in music digitization over the last decades, the new research area of Music Information Retrieval (MIR) has evolved, which designs methods to retrieve music from large data-bases using musical "content" rather than meta-data (Downie, 2003). Many computational models for music have been developed within MIR. However, both the potential of these models to contribute to musicology and the potential of musicology to contribute to building models have not yet been fully exploited. We show that computational musicology has the potential to become an indispensible partner for computer science in enriching the current data-driven approaches in MIR by knowledge-based alternatives (De Haas & Wiering, 2010).

This paper discusses two important aspects of the potential of computational musicology: section 2 demonstrates its ability to open up new perspectives and questions in musicological research, and section 3 its potential as an interdisciplinary connection between musicological knowledge and computational modelling in MIR.

2 NEW PERSPECTIVES FOR MUSICOLOGICAL RESEARCH

Though the potential of the computer to contribute to musicological research had been envisioned in the 1950s, the first computational projects with an academic aim in music started in the 1960s. Heckmann (1967) expected that the use of computers within musicology would open up entire new research areas, since the computer allows to process huge amounts of information that are difficult to oversee for a human being. Thus, the computer might assist, for instance, in finding musical patterns in thousands of musical pieces. As Huron (1999a) argued, computational approaches have the potential to turn musicology into a data-rich field, which "provide greater power for hypothesis testing" than data-poor fields, which musicology traditionally has belonged to. Musicologists anticipated "colossal returns" from computational approaches and made "sweeping plans for an information revolution" from the 1960s onwards, as documented by Hewlett and Selfridge-Field (1991).

However, during the 1980s scepticism spread with respect to computational approaches to music. Many different aspects contributed to this development. One problem was that existing music theories could hardly be implemented right away, since they were not formalized enough in order to be translated into a computer program. As Vercoe (1971) stated, "we seem to be without a sufficiently well-defined 'theory' of music that could provide that logically consistent set of relationships between the elements which is necessary in order to program". Hence, achieving far-reaching results through computational musicology turned out to be way more difficult than anticipated in the 1960s.

The end of the 20th century witnessed a rapid increase in digitization of music, such that finally large collections of digitized music became available. This created the possibility and need to develop computational models in order to research these huge amounts of digitized musical data. Accordingly, many different computational approaches for very different musicological questions have been developed since then. In this section we give an overview of what new perspectives have opened up through computational musicology on genuinely musicological questions.

Musicology as an academic discipline is subdivided into many different subfields of research, along with different conventions in different countries about what research areas belong to musicology. For instance, for British and Australasians, "musicology" is an inclusive term, subsuming music theory and ethnomusicology, while in North America, historical musicologists call themselves "musicologists" and distinguish themselves from ethnomusicologists and music theorists (see Cook, 1998). In this paper we use the term "musicology" in the most inclusive way, hence not as a demarcation from music theory or ethnomusicology. In the following section we specify for five different areas within musicology, which are music theory and analysis, historical musicology, ethnomusicology, cognitive musicology, and musical performance research, the contribution of computational approaches to research questions in these areas.

2.1 Computational approaches to musicological research areas

2.1.1 Music theory and analysis

From the beginning of computational musicology in the 1960s, the analysis of musical pieces with the help of the computer formed a central topic in computational musicology. For instance, a bibliographical project on 16th century French chansons (Bernstein & Olive, 1968) rapidly turned into an analytical project, as argued by Morehen & Bent (1979), since music analytic approaches turned out to be necessary in order to be able to recognize similar patterns within different chansons. The recognition of a lack of formalized analytic approaches within musicology within the context of computational approaches in the 1970s led to increasing efforts on the formalization of music theories underlying music analysis. Basic music theoretic terms, such as scale, chord, or tonality, need to be redefined in order to be applicable to computational music analysis (see, e.g. Honingh and Bod (2011) for a computational model on scales).

A prominent example of linking music theoretic concepts to concrete analytic procedures for musical pieces is the development of computational approaches to tonality. For instance, Longuet-Higgins (1962) developed a computational approach for determining the tonality of a musical piece based on the music theoretic notion of the *Tonnetz*. The *Tonnetz*, a two-dimensional pitch space representing abstract tone relations, has firstly been developed by the Leonhard Euler and later used by Arthur von Oettingen and Hugo Riemann in order to display tonal relations (e.g. the relations between different chords). Longuet-Higgin's approach was further developed in Chew's (2000) Spiral Array model, which has been applied to questions such as the determination of stable tonal areas vs. areas of tonal modulation, segmentation of musical pieces and similarity assessment based on tonality. Tonal relations belong to the most widely studied musical characteristics in Western classical music. However, abstract tone relations (such as chord sequences considered to be prototypical, e.g. certain cadence types) as studied in music theory are often difficult to link to the concrete tone relations occurring in musical pieces. Computational models of tonality, based on abstract tone relations and applied to digitized musical pieces, provide the link between theoretic concepts of tonality and their application to 'real-world' music.

Another prominent area of computational approaches to music analysis is the study of rhythm and meter. While Riemann (1903) predicted that the study of rhythm and meter would form a major topic in 20th century musicology, de la Motte-Haber (1968) stated that this expectation had not been fulfilled. However, within computational approaches, rhythm and meter became indeed one of the most prominent research areas. A major topic is the automatic detection of the metric structure of musical pieces, based on rule-based approaches (Temperley, 2001), on probability approaches (Raphael, 2001) or on the detection of pulse patterns (Volk, 2008a). Studies of the tonality of musical pieces have long distinguished between areas of stability and change both on large scale pitch information (e.g. main sections) and small scale pitch information (e.g. short chord progressions). By contrast, the metric structure of a musical piece as given by the time signature is often considered a more static musical characteristic. However, the application of the model of Inner Metric Analysis by Volk (2008a) has demonstrated that time information in music fluctuates between persistence and change as well, such that the metric structure of a piece arises from different hierarchical levels.

In the area of melody analysis, Huron (1996) tested the musicological hypothesis that most melodies follow an arch-shape, using the Humdrum-Toolkit (see e.g. Huron, 2002). His analysis of 6000 melodies, containing 36000 phrases, from the Essen Folksong collection (http://www.esac-data.org/) is an example on how computational methods enable the testing of implicit knowledge of musicological experts through a data-rich approach. Without such a rigorous test it remains an open question whether expert knowledge is rooted in a biased perspective on the musical material. Huron's analysis confirmed the hypothesis of the melodic arch for the melodies in the Essen Folksong collection

Computational musicology has helped linking abstract music theories with concrete, operationalised analyses of musical pieces; has helped to explicate and verify implicit musicological knowledge, and opened up new perspectives on the musical material in areas of music analysis that have received less attention within musicology. Moreover, we will show in section 3 that the results of computational musicology in the area of music analysis are of crucial importance for MIR.

2.1.2 Historical musicology

The goal of historical musicology is to understand musical works in their historical context. Traditionally, the focus in historical musicology has been on 1) how compositional methods and musical style have developed and 2) the biographies of composers, with a minor role for performative and socio-economic aspects. Historical musicology used to have the underlying agenda to show how over time the ideal of the musical work as an autonomous, timeless aesthetic creation emerged. Modern, 'critical' approaches have generally claimed the opposite, namely that musical creations are first and foremost to be explained from their contexts. The new emphasis on subjectivity and originality in research however, was achieved at the expense of evidence-based, incremental and collaborative research approaches. It is now generally recognized that this new emphasis is also a weakness. We believe that data-rich computational approaches can remedy this, as we will argue in section 4.

Historical musicology has built an impressive infrastructure in the form of paper publications of source inventories, music editions and scholarly articles. Gradually, these are being complemented by digital resources, such as RISM A/II database of manuscript sources (http://opac.rism.info). Such digital resources are still disjunct and incomplete, but can serve as the basis for a comprehensive e-infrastructure for historical musicology.

Particularly interesting in this respect are initiatives to create digital scholarly editions of music in order to solve a number of issues that exist in paper editions:

1. Paper publications treat musical works as static entities, while they are now considered to be adaptable due to context requirements. Hence it is important to be able to include different historical versions of a work in one edition.
2. Different 'views' of the piece can be created, for example transpositions, renditions in different

notation styles or with different instrumental parts, or high-level overviews.

3. Digital editions can incorporate multimedia materials such as recordings and videos.
4. Digital editions can be conceived as collaborative, incremental editions, to which new materials, views and contextual information can be added.
5. The content of digital editions can be automatically searched and analyzed for scholarly, educational, performance and other purposes.

A digital musical edition is not a static product but an information base of source materials that can be used and enriched by researchers and performers (Wiering, 2009a). A good example of a state-of-the-art digital critical edition of music is CMME (Computerized Mensural Music Editing; www.cmme.org), containing vocal music from the Renaissance. It addresses issues 1 and 2 in particular. However, the concept of the digital scholarly edition of music is still immature; fully realizing it in all its implications is an important challenge as we will argue in section 4.

2.1.3 Ethnomusicology

Ethnomusicology is considered as the "study of social and cultural aspects of music and dance in local and global contexts" (New Grove Online). The term was introduced in the 1950s and replaced the older term of comparative musicology, which has been defined as the comparison "of tonal products, in particular the folksongs of various peoples, countries and territories" (Adler, 1885).

A central topic in ethnomusicology, in which computational approaches have been applied, is the study of folksongs that have been transmitted through oral tradition. Investigating large corpora of folksongs computationally dates back to the very beginning of computational musicology in the 1960s (see e.g. Suchoff, 1969). Since oral tradition introduces variation into folksongs, which leads to many different variants of one song, a typical topic in ethnomusicology is the classification of songs into tune families. Tune families consists of melodies that are considered to have the same historic origin. Different classification systems for folksongs have been introduced, such as Krohn's (1903) system of ordering songs according to their cadence tones. However, computational approaches allow the processing of much more complex information of the songs. For instance, Van Kranenburg's (2010) alignment-based computational model to the similarity of folksongs processes information regarding pitch, metrical structure and phrase structure of entire melodies. The model has been successfully used to retrieve Dutch folksongs hosted by the Meertens Institute that belong to the same tune family according to musicological experts. The notion of tune family at the Meertens Institute has hardly been formalized – yet the success of the computational model in Kranenburg (2010) to retrieve melodies belonging to the same tune family demonstrates that there is nevertheless a systematic approach that underlies the tune family concept.

The comparison of large corpora of folksongs from different geographic regions (e.g. Juhasz, 2006; Aarden and Huron, 2001) provides another example for data-rich approaches enabled through computational modelling. Unlike music theory, which concentrates on exhaustive analyses of single musical pieces, ethnomusicology is a data-rich field by definition. Computational approaches enable the quantification and evaluation of qualitative statements of ethnomusicologists, such as the list of typical changes introduced to folksongs through oral transmission as provided by Wiora (1941).

2.1.4 Cognitive musicology

The term cognitive musicology was coined by Laske (1988). Cognitive musicology "studies musical 'habits of mind' such that musical processes are of greater interest to the researcher than musical content" (Huron, 1999b). While a music theorist investigates complex relations between notes, chords and sections of a musical piece as notated in the score, the cognitive musicologist is more interested in how these relations are experienced within the listening process.

From its beginning in the 1970s, cognitive science was strongly connected to the study of the human mind through the computational paradigm. Computational models have contributed, for instance, to understanding the process of rhythm interpretation while listening to monophonic music (Longuet-Higgins & Lee, 1984), to understanding the human assessment of melodic similarity (Müllensiefen & Frieler, 2007) or to understanding segmentation processes in music (Cambouropoulos, 2001). Computational models enable the testing of basic assumptions of cognitive theories, which resulted, for instance, in a revision of 'innate' musical capabilities claimed by Narmour (1990), through a computational experiment by Pearce and Wiggins (2006). Computational models also allow the testing of assumptions underlying listening experiments, such as the revision of the role of pitch for meter perception in ragtimes investigated by Snyder & Krumhansl (2001) through a computational approach of meter induction by Volk (2008b).

Cognitive musicology has contributed to testing the perceptual relevance of music theories; many computational approaches to the cognition of musical structures have subsequently been used for music analytic procedures (Temperley, 2001). This makes them especially relevant for research in MIR, as argued in section 3.

2.1.5 Musical Performance Research

The predominant focus of musicological research has long been the study of musical scores. By contrast, performance studies attempt to investigate the musical activity of performing, during which the performer needs to specify musical parameters that are not captured in the score (such as the exact tempo or loudness).

Hugo Riemann developed a theoretic approach to the relation between music analysis and performance based on the assumption that the performer has to convey the musical structure to the listener. For instance, Riemann (1905) suggested to shape the tempo of a musical piece in such a way that the duration of the upbeat is shortened and the duration of the downbeat lengthened in order to convey the position of the strong first beat in a bar to the listener. Fleischer-Volk (2003) has tested this strategy with a computational model that uses analytic weights gained from a computational analysis of the piece in order to generate an expressive performance. Using metric weights to shape the tempo in Riemann's manner led to a ridiculous result, since the strong first beat of the bar is played too early due to the shortening of the upbeat of the previous bar. Instead, inverting the strategy led to a reasonable performance. Hence, through this computational experiment Riemann's hypothesis was falsified. The computational modelling allowed a simulation of a complex process, namely the musical interpretation of a human pianist involving very different information, by constructing an artificial interpretation reduced to tempo based on only metric information.

A central topic in performance research is the comparison of different human performances of the same piece in order to investigate individual performance strategies. For instance, Goebl et al. (2004) introduced a visualization tool for performance patterns that allows switching between different performances of the same piece while visualising the timing and dynamic patterns. Cook and Sapp (2007) detected within a project on Mazurkas performances plagiarism within CD's recorded by Joyce Hatto. The comparison of performances of Schumann's Träumerei by Beran and Mazzola (1999) demonstrated that Cortot and Horowitz have opposite ways of shaping tempo: Horowitz puts high emphasis on local structures, while Cortot's performance have a high degree of four measure periodicities.

Computational approaches to performance research hence allow to test theoretical considerations on performance and to enrich the study of the musical notation by the study of the actual performance of the piece.

2.2 Summary on new perspectives

Computational musicology has opened up new ways of empirical evaluation for musicological concepts through computational experiments in many different research areas. This has helped to explicate implicit musicological knowledge, to formalize basic musicological constructs and to establish new research areas such as cognitive musicology and performance research. Moreover, computational models help connecting different subfields of musicology (see e.g. Volk, 2008b for connecting music analysis and music cognition). The increasing efforts in formalization and testing of musicological concepts are especially relevant for the application of these concepts within Music Information Retrieval, as discussed in the following section.

3 MUSICOLOGY AND MIR

Both the rise of the Internet and the World Wide Web, and the invention of the MP3 audio encoding gave an enormous boost to computational processing of music within the research area of Music Information Retrieval (MIR). The primary aim of MIR is to design methods to retrieve 'musical information' from large databases using musical 'content' rather than 'meta-data' (Downie, 2003). Typical tasks include genre classification, artist recognition, cover song retrieval, song recommendation and emotion recognition.

Since better understanding of music will lead to more robust and flexible music retrieval systems, computational models of 'musical content' are necessary to achieve high-quality retrieval methods. For developing these models, the contribution of musicology is of crucial importance. For instance, music theory and cognitive musicology provide concepts to describe musical structures and their human cognition. Furthermore, knowledge about the (ethnological) context of music is necessary in order to explain how music is used and which kinds of meanings are established within the relations between music and different 'audiences'.

However, although basic musical concepts – such as pitch, chord, meter, etc – are widely used, most studies in the field of MIR do not explicitly employ more elaborate musicological knowledge and models. This has various reasons. Firstly, most computer scientists contributing to MIR do not have a musicological background themselves. Secondly, it is hard to find ready-to-use models in musicological literature that are both adequate and implementable. In our vision, here lies an important task for computational musicology, namely contributing to the development of computational models of music that are employable within MIR-systems.

One specific aspect of MIR methodology that would benefit from a stronger contribution of computational musicology is the establishing and employment of so-called ground-truth data. For testing retrieval methods, the results of the methods are compared to an a-priori established set of results that is considered as the correct outcome (the 'ground-truth', or 'golden standard'). The quality of the method is indicated by the extent to which the method under consideration is able to *reproduce* this ground-truth data. However, a fundamental issue of this approach is the assumption that the correct outcome is known, which is often not the case. For example, for testing an algorithm of emotion recognition from audio signals, one needs a collection of audio fragments with corresponding 'emotions' as ground-truth. Assembling such a set is highly problematic as the question of how music and emotion relate is still a subject of debate. Hence, computational models of the relation between music and emotion can only be regarded as hypotheses. The results or predictions of such models have to be interpreted by music scholars, and the results of the interpretation have to be integrated in the ongoing domain discourse.

As a successful example of the creation of a musicologically informed ground-truth, we refer to an annotation method on melodic similarity of Dutch folk song melodies introduced by Volk et al. (2008). The annotation method allows to make implicit criteria for human perception of melodic similarity explicit and to study their relative importance. The criteria for the annotations were established together with the musicological specialists and the results of algorithmic processing led to reconsidering of the annotations (Van Kranenburg 2010, section 6.5). Hence, the ground-truth of the human similarity annotations was not considered as a static truth, but as a starting point of the investigation of melodic similarity. The computational modelling substantially contributed to evaluating and reconsidering the musicological insights.

In short, computational musicology has the potential to enrich MIR research with musicologically informed, implementable models of musical content and context.

4 CHALLENGES

Within the last 20 years, computational models have been successfully developed for very different fields within musicological research. Nevertheless, computational modelling does not yet belong to the every-day methods used by musicologists, as Cook (2005) envisioned it might be. He argues that the abundance of different computational tools with little consistence between them hampers their use for the "jobbing" musicologist. However, musicology itself is scattered into many subfields that are often rather disconnected from each other. As a result, designing and implementing computational approaches with a wide range of applications in a consistent manner remains difficult.

A major challenge for developing computational methods is the formalization of music. For algorithmic processing, musical data have to be formalized into appropriate data structures. Since such a data structure can be considered a model of the musical data, this formalization is a research topic in itself. Obviously, musicological knowledge is necessary to determine, in which way aspects of music can be described by formal models. In the area of music theory and analysis, complex musical phenomena have been deconstructed into different components through computational modeling, such as melodic, rhythmic or harmonic components. Through the computational modeling, these components have been described and anlyzed in unprecedent details. Yet, the musical structure of a piece is a complex entity arising from the interaction of these components. The integration of isolated components of music into a holistic model of musical structure through computational modelling is a challenge for future research.

In the area of cognitive musicology, many different computational models have been developed, often on related topics. The abundance of existing models on the same topic asks for the development of strategies for comparing and selecting models (see Honing, 2006a). As is the case for models concerning music analysis, developing cognitively relevant models of music comprising the complexity of different aspects of music, remains a challenge.

For ethnomusicology, computational models for tune families have bee successfully developed. Now the time is ripe to use them for investigating the process of oral transmission: what kind of transformations between songs occur most often? To what cognitive processes can these transformations be linked?

In the context of historical musicology, a major computational issue is to develop adequate representations of musical sources. Being *historical* sources, they are often context-dependent, incomplete, unclear, ambiguous or erroneous. It would be important to encode such problems as well as their possible solutions. (e.g, http://music-encoding.org/).

Significant amounts of musical works have already been encoded in various formats, maybe nearly enough to address contextualization. From a music-structural point of view, contextualization is a matter of shared high-level patterns between pieces. Such patterns include chord sequences, melodic motives, rhythmic structure, timing, ornamentation and instrument choice and are often the ingredients of musical styles.

Shared high-level patterns also play an important role in the generation of musical meaning. The ultimate challenge, and the one that links back to the goal of historical musicology to 'understand' music, would therefore be the modelling of musical meaning (Wiering, 2009b).

CONCLUSIONS

While important milestones have been achieved in computational musicology, the full potential of the interdisciplinary enterprise has yet to be explored. Computational musicology is not yet the widespread discipline envisioned by Morehen and Bent (1979). The majority of scientific research on music - among them computational approaches - is currently carried out outside of musicology departments (Parncutt, 2007). Cook (2005) argues that now the ball "is firmly in the musicologists' court". In order to unfold the potential of computational musicology, interdisciplinary collaborations between musicology and computer science need to be intensified, requiring initiatives from musicology to rise questions from their discipline that need to be modelled computationally. Moreover, musicologists substantially need to contribute their knowledge to developing the computational models, since existing musicological theories are often not enough formalized. In turn, this can strengthen the role of computational musicology as an indispensible partner for Music Information Retrieval.

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