INRIA, Evaluation of Theme
Embedded and Real-time Systems

Project-team MuTant

24-25 March 2016

Project-team title: Synchronous Real-time Processing & Programming of Music Signals

Scientific leader: Arshia Cont

Research center: Paris

Common project-team with: IRCAM, CNRS & UPMC

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1 Personnel

Personnel (2012)

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors	1		1		2
CR (2) / Assistant Professors		1			1
Permanent Engineers (3)					0
Temporary Engineers (4)					0
PhD Students				2	2
Post-Doc.					0
Total	1	1	1	2	5
External Collaborators					
Visitors (> 1 month)					

(1) "Senior Research Scientist (Directeur de Recherche)"
(2) "Junior Research Scientist (Chargé de Recherche)"
(3) "Civil servant (CNRS, INRIA, ...)"
(4) "Associated with a contract (Ingénieur Expert or Ingénieur Associé)"

Personnel (24-25 March 2016)

	Misc.	INRIA	CNRS	University	**Total**
DR (1) / Professors	1		1		2
CR (2) / Assistant Professors		1			1
Permanent Engineers (3)					0
Temporary Engineers (4)		1			1
PhD Students		1		4	5
Post-Doc.					0
Total	1	3	1	4	9
External Collaborators					
Visitors (> 1 month)					

Changes in staff

DR / Professors	Misc.	INRIA	CNRS	University	total
CR / Assistant Professors					
Inria Starting Positions					
Research Engineer		1			1
Arrival		1			1
Leaving		1			1

Comments: INRIA ADT Engineer Thomas Coffy joined the team for the development of *AscoGraph* on 09/2012 and left the team on 12/2014 for the embedded software industry.

Current composition of the project-team (24 March 2016):

- Arshia Cont, Professor at IRCAM (Team Leader)
- Jean-Louis Giavitto, Professor at CNRS
- Florent Jacquemard, Assistant Professor at INRIA

Current position of former project-team members (including PhD students during the 2012-16 period):

- Arnaud Dessein (former PhD student), Post-doc at University of Bordeaux (2015), Post-doc at York University (2013-15).
- José Echeveste (former PhD student), Post-doc at Collège de France (with Gérard Berry) since 2015.

Last INRIA enlistments

None

Other comments:

The INRIA Engineer, Thomas Coffy, entered the team in September 2012 (ADT Contrat) for two years and his contract was further extended from September 2014 for an additional year. He left the team by the end of 2014 to join the embedded software industry.

2 Work progress

2.1 Keywords

Audio Modeling and Processing, Engineering of Interactive Systems, Signal Analysis, Programming Languages, Synchronous Languages, Embedded systems/CPS, Verification, Music, Art.

2.2 Context and overall goal of the project

The premise of the research program of MuTant is centered around two disjoint themes of *Real-time Machine Listening* and *Synchronous and Timed Real-time Programming* in *Computer Music* whose strong coupling and union (as opposed to an intersection) has become a necessity in music practices associating computers and human on stage. The team was initially motivated by large adoption of *Interactive Music Systems* by the international community, whose aim is to provide temporal scenarios describing real-time interactions between computer environments and human musicians (in forms of programs or augmented music scores), and employ them in real-time on stage where fault-tolerance and time-correctness is a major issue. State-of-the-art systems are often seen in two major categories: (1) *Compositional* environments whose aim is to provide rich languages and data-structures for the programming/structuring phase of a music composition which are not necessarily real-time; and (2) *Performative* environments that are inherently real-time and provide the back-bone of any music performance. Current practices has shown the limitation of the existing gap between the two categories, and the MuTant team-project positioned itself at the very onset to bridge-in this gap by providing tools that are both expressive and rich in the programming/composition phase; and guarantee performance/real-time interactions despite all the variations inherent in musical interpretation.

The major incarnation of our research is the award winning *Antescofo* language and real-time system, deployed since our inception in major international festivals with more than 100 known repertoire pieces regularly played throughout the world. *Antescofo* is joint coupling of a real-time machine listening (See Section 2.4) and a DSL and Real-time Language (See Section 2.5), that allows users to program complex temporal and interactive scenarios involving strongly timed patterns in a dedicated language/environment and to make sure that, simply said, what they see/hear is what they have programmed despite system/user errors and high variability of the environment. Antescofo real-time language and system has documentation partially contributed by its users which spans more than 200 pages[1].

Besides the Antescofo system, the team has deployed efforts in fostering each objective scientifically and independent of the goals prescribed by the software and its users. This has led to the development of new *Real-time Machine Listening* mechanisms as well as contributions to the field of verification and test on dynamic setups and work-flows such as those observed in Music which are detailed in the upcoming sections.

2.3 Objectives for the evaluation period

In the initial proposal for the MuTant team-project, we identified 2 main objectives:

- Objective 1 - Machine Listening: Including real-time machine listening algorithms such as event-detection, real-time audio-to-score alignment and musical parameter estimation, and symbolic rhythmic quantization described in Section 2.4.

- Objective 2 - Synchronous and Real-time Programming for Computer Music: Including the design and development of the Real-time Antescofo language and system with its subsequent challenges described in Section 2.5; and Verification and Test procedures for Mixed scores described in Section 2.6.

2.4 Objective 1 : Machine Listening

When human listeners are confronted with musical sounds, they rapidly and automatically find their way in the music. Even musically untrained listeners have an exceptional ability to make rapid judgments about music from short examples, such as determining music style, performer, beating, and specific events such as instruments or pitches. Making computer systems capable of similar capabilities requires advances in both music cognition, and analysis and retrieval systems employing signal processing and machine learning.

Machine listening in our context refers to the capacity of our computers to understand "non-speech sound" by analyzing the content of music and audio signals and combining advanced signal processing and machine learning. The major focus of MuTant has been on Real-time Machine listening algorithms spanning *Real-time Recognition Systems* (such as event detection) and also *Information Retrieval* (such as structure discovery and qualitative parameter estimation). Our major achievement lies in our unique Real-time Score Following (aka Audio-to-Score Alignment) system that are featured in the Antescofo system (cf. Section 3.2). We also contributed to the field of On-line Music Structure Discovery in Audio Processing, and lately to the problem of off-line rhythmic quantization on Symbolic Data.

2.4.1 Personnel

Permanent members: Arshia Cont, Florent Jacquemard
Ph.D. students: Philippe Cuvillier (since 2013), Arnaud Dessein (defended 2012), Maxime Sirbu (since 2015)
Engineer: Adrien Ycart (for Rhythmic Quantization, since September 2015)

[1]See http://support.ircam.fr/docs/Antescofo/AntescofoReference.pdf.

2.4.2 Project-team positioning

MuTant is among very few teams that focus on *Real-time* Machine Listening of Music Signals, where most existing teams (such as INRIA METISS and PANAMA teams) focus on Information Retrieval from large databases with off-line (access to future) algorithms. The literature on Incremental and Real-time machine listening is thus sparse and mostly application oriented.

MuTant is a founding member of the *Brilouin National Workgroup on Geometric Science of Information* together with THALES Radar and LIX labs which quickly became an international workgroup and led to the organization of the first International Conference on the topic in GSI at École des Mines (150+ participants). The group exists today and refer to us regularly for scientific organizations.

On the topic of Score Following (or real-time audio-to-score alignment) MuTant possesses the state-of-the-art both in terms of performance (evaluated by the large adoption of Antescofo by the community and the MIREX Evaluation Campaign) and scientific approach. Whereas most approaches to Music Information Retrieval and Audio Analysis focus on cleaning data before entering probabilistic models, MuTant chose the inverse approach at the onset. We leave the uncertainty of the environment where it is and address it in our intelligent systems. This approach, while mathematically cumbersome, has allowed us to extend and deploy our software in real-world situations and with the cheapest and most common Observation Front-ends in Signal Processing communities. We maintain continuous interactions with experts in the field such as Roger Dannenberg (Carnegie Mellon) who we invite regularly for our PhD juries; and our scientific approach has been adopted by several institutions such as Tokyo University (See Collaborations below), UCSD (through Shlomo Dubnov), and UC Berkeley's CNMAT.

We are regularly called by colleagues in other fields, especially Machine Learning teams at INRIA, for our expertise in the field of Machine Listening and Audio Analysis in Real-time.

Our recent work on Rhythmic Quantization and Symbolic Transcription is relatively new and it is still early to position the work. However, the team collaborates with Algomus Group at Univ. Lille I and Univ. de Picardie Jules Verne, Amiens on Computational Music Analysis.

2.4.3 Scientific achievements

Real-time Audio-to-Score Alignment. This is a continuation of prior work of team-leader[2] which proved the utility of strongly-timed probabilistic models in form of Semi-Markov Hidden States. Our most important theoretical contribution is reported in [35, 36] that introduced Time-coherency criteria for probabilistic models and led to general robustness of the Antescofo listening machine, and allowed its deployment for all music instruments and all setups around the world. We further studied the integration of other recognition algorithms in the algorithm in form of *Information Fusion* and for singing voice based on Lyric data in [41]. Collaboration with our japanese counterparts led to extensions of our model to the symbolic domain reported in [46]. Collaboration with the SIERRA team created a joint research momentum for fostering such applications to weakly-supervised discriminative models reported in [45]. Our Real-time Audio-to-Score alignment is a major component of the Antescofo software described in Section 3.2.

[2] Arshia Cont. A Coupled Duration-Focused Architecture for Real-Time Music-to-Score Alignment. IEEE Transactions on Pattern Analysis and Machine Intelligence, Institute of Electrical and Electronics Engineers, 2010, 32, pp.974-987.

Online Methods for Audio Segmentation and Clustering. To extend our listening approach to general sound, we envisioned dropping the prior information provided by music scores and replacing it by the inherent structure in general audio signals. Early attempts by the team leader employed Methods of Information Geometry[3], an attempt to join Information Theory, Differential Geometry and Signal Processing. We were among the first teams in the world advocating the use of such approaches for audio signal processing and we participated in the growth of the community (cf. Section 3.6). A major breakthrough of this approach is reported in [8] and the PhD Thesis [2] that outline a general real-time change detection mechanism. Automatic structure discovery was further pursued in a MS thesis project in 2013 [82]. By that time we realized that Information Manifolds do not necessarily provide the invariance needed for automatic structure discovery of audio signals, especially for natural sounds. Following this report, we pursued an alternative approach in 2014 and in collaboration with the INRIA SIERRA Team [75]. The result of this joint work was published in IEEE ICASSP 2015 and won the best student paper award [24]. We are currently studying massive applications of this approach to natural sounds and in robotics applications in the framework of Maxime Sirbu's PhD project.

Symbolic Music Information Retrieval and Rhythm Transcription. Rhythmic data are commonly represented by tree structures (rhythms trees) due to the theoretical proximity of such structures with the proportional representation of time values in traditional musical notation. We are studying the application to rhythm notation of techniques and tools for symbolic processing of tree structures, in particular tree automata and term rewriting.

Our main contribution in that context is the development of a new framework for rhythm transcription [88, 55] addressing the problem of converting a sequence of timestamped notes, *e.g.* a file in MIDI format, into a score in traditional music notation. This problem is crucial in the context assisted music composition environments and music score editors. It arises immediately as insoluble unequivocally: in order to fit the musical context, the system has to balance constraints of precision and readability of the generated scores. Our approach is based on algorithms for the exploration and lazy enumeration of large sets of weighted trees (tree series), representing possible solutions to a problem of transcription. A side problem concerns the equivalent notations of the same rhythm, for which we have developed a term rewrite approach, based on a new equational theory of rhythm notation [38, 42, 43].

2.4.4 Collaborations

We initiated a collaboration in 2014 with the SIERRA Team at INRIA specialized in Machine Learning techniques and on the topic of unsupervised and online joint segmentation and classification of Audio Signals. A Masters student was jointly supervised by Arshia Cont and Francis Bach [75], that led to a *Best Paper Award* in the prestigious IEEE ICASSP 2015 Conference[24].

MuTant and SIERRA collaboration was further pursued by the teams' PhD students and led to a novel Weakly-supervised discriminative model for audio-to-score alignment and a joint publication in 2016 [45].

We hosted a Post-Doc, Eita Nakamura from Tokyo University, in our team for 3 months on the topic of Symbolic Score following which led to a joint publication in 2015 [46].

[3] Arshia Cont, Shlomo Dubnov, Gérard Assayag. On the Information Geometry of Audio Streams with Applications to Similarity Computing. IEEE Transactions on Audio, Speech and Language Processing, Institute of Electrical and Electronics Engineers, 2011, 19 (4), pp.837-846.

We have regular exchanges with Prof. Masahiko Sakai, of Nagoya University, on problem related to the theory of term rewriting and applications to rhythm notation. On the later problem, and more generally problems regarding the music notation and symbolic MIR, we also collaborate with the Algomus group in Lille (computational musicology), in particular Slawek Staworko from the Links team (currently on leaves at Edinbourg), the GRAME in Lyon, in particular Dominique Fober (dynamic visual representation of musical data) and the team of Philippe Rigaux at CNAM (music scores digital libraries).

2.4.5 External support

The relevant contracts for this objective, detailed in Section 4, are scholarships from UPMC University and a late funding from PERSU Sorbonnes-University to extend our general listening algorithms to Robotics.

2.4.6 Self assessment

For Machine Listening involving Real-time Audio Analysis, we worked on two scientifically similar and coherent domains but different application wise. For Score Following, we have proven that we can deal with highly uncertain data from the environment for real-time recognition and decoding when a structured prior (such as music score) is available. The Segmentation and Clustering work mentioned above aims at extrapolating this application to more general sounds and with less prior information. Up to late 2013 we believed that methods of Information Geometry with strong time-awareness (in terms of time-series) could address such problems. We stopped this and reverted back to extending more traditional approaches in 2014. Applicability of this approach to real-data is currently under study.

We should now extend our studies to other application domains with strong involvement of "Time" as a first class citizen for our Audio Listening approach. Late 2015 we started porting the general approach to mini-computers (Raspberry PI, UDOO) and acquired a POPPY Robot (INRIA Bordeaux) to study other structured temporal interactive scenarios in collaboration with the Flowers Team (Bordeaux). We should pursue this study and propose general-purpose libraries that are programmable by non-experts. This is clearly a lack in Audio and Music Processing application where an equivalent of *OpenCV* is missing and the combination of two themes in MuTant can clearly contribute to this lack.

2.5 Objective 2 : Synchronous and Timed Real-time Programming for Computer Music

The research presented here aims at the development of a programming model dedicated to authoring of time and interaction for the next generation of interactive music systems. Study, formalization and implementation of such programming paradigm, strongly coupled to recognition systems discussed in the previous section, constitutes the second objective of the MuTant project.

The tangible result of this research is the development of the Antescofo system (cf. sect. 3.2) for the design and implementation of musical scenarios in which the human and computer actions are in constant real-time interaction. Through such development, Antescofo has already made itself into the community; it serves as the backbone of temporal organization of more than 100 performances since 2012 and used both for preexisting pieces and new creations by music ensembles such as Berliner Philharmoniker, Los Angeles Philharmonic, Ensemble Intercontemporain or Orchestre de Paris to name a few.

2.5.1 Personnel

Permanent members: Jean-Louis Giavitto, Arshia Cont
Ph.D. students: José Echeveste (Defended 2015), Julia Blondeau (since 2015)
Engineer: Thomas Coffy

2.5.2 Project-team positioning

Antescofo is the unique computer music programming environment that proposes a strong coupling between a listening module operating in real-time (cf. 2.4) and a *strongly timed programming language*. It corresponds to a paradigm shift in the field of mixed music defined as the association in live performance of human musicians and computer mediums interacting in real-time.

We have close collaborations with PureData (M. Puckette, San Diego Univ.) and Max/MSP (Cycling'74) development teams. Contrary to these systems, we face the explicit representations of time (sample-synchronous) and predictable mechanisms for controlling time at various timescales (temporal determinism) and across concurrent code modules (time-mediated concurrency).

Compared to programmable sequencers (esp. Iscore, INRIA project Poset, Bordeaux; the Haskore or Euterpe projects in the Haskel ecosystem), the Antescofo DSL offers a rich notion of time reference and provides explicit time frame for the environment with a comprehensive list of musical synchronization strategies.

We share with ChucK (CCRMA, Stanford), one of the most advanced proposition in the field of Live Coding, the handling of time as a denotable entity in a framework subsuming the time-triggered and the event-triggered frameworks but we cared less about audio processing for the first stage of this project, and focused on tackling temporal expressiveness of the language and its correctness with higher levels of musical and interactive control.

In addition to the realm of audio and music programming, it is worthwhile to provide context for this work with respect to synchronous languages. We exchange regularly with G. Berry (CHRONOS network, post-doc of J. Echeveste) and the PARKAS project team [23, 74]. Antescofo shares the synchrony hypothesis but differs from the event-driven and synchronous reactive languages by its handling of duration and a notion of tempo extending the language to time-driven computations. These continuous notions are not adequately addressed by current frameworks for hybrid systems, since there is no continuous formalization (*e.g.* ODE) of the musician behavior at score level. Our application domain requires dynamic constructions while verification is a lesser concern. As a consequence, our work perspective is shifted towards expressiveness in the specification of musical entities and the synchronization of asynchronous processes with "variable speed" rather than strong safety properties.

2.5.3 Scientific achievements

Multiple Times. Audio and music often involve the presence and cooperation of multiple notions of *time*: an ideal time authored by the composer in a score and also a performance time produced jointly by the performers and the real-time electronics; where instant and duration are expressed both in physical time (milliseconds), in relative time (relative to an unknown dynamic tempo) or through logical events and relations ("at the peak of intensity", "at the end of the musical phrase", "twice faster"). The specified temporal relationships span and link several timescale from tens of milliseconds and smaller (one audio sample) to more symbolic timescales (fractions of seconds and above for musical events to piece organization).

Antescofo is the first languages that addresses this variety of temporal notions, relying on the synchronous approach for the handling of atomic and logical events and an anticipative notion of tempo for the handling of relative duration [32, 66]. A first partial model of time at work in Antescofo (single time, static activities) has been formalized relying on parametric timed automata [9] and constitutes the reference semantics for tests (cf. section 2.6). A denotational semantics of the complete language (multiple times and dynamic constructions including anticipative synchronization strategies) has been published in [3].

Human-Computer Synchronizations. Antescofo introduces the notion of temporal scope to formalize relationships between temporal information specified in the score and their realization during a performance [31]. A temporal scope is attached to a sequence of actions, can be inherited or dynamically changed as a result of a computation. A synchronization strategy is part of a temporal scope definition. They use the performer's position information and its tempo estimation from the listening module, to drive the passing of time in a sequence of atomic and durative actions. Synchronization strategies have been systematically studied to evaluate their musical relevance in collaboration with Orchestre de Paris and composer Marco Stroppa. Anticipative strategies enable handling of uncertainties inherent in musical event occurrence, exhibiting a smooth musical rendering whilst preserving articulation points and target events [53].

Temporal Organization. Several constructions dedicated to the expression of the temporal organization of musical entities and their control have enriched the language from the start of the project. These construction have been motivated by composer's research residences in our team: representation of open scores (J. Freeman); anticipative synchronization strategies (C. Trapani); adaptive sampling of continuous curve in relative time for the dynamic control of sound synthesis (J.-M. Fernandez); musical gesture (J. Blondeau); first class processes, actors and continuation combinators for the development of libraries of reusable parametric temporal behaviors (M. Stroppa, Y. Maresz); *etc.*

The reaction to a logical event is a unique feature in the computer music system community [47]. It extend the well known `when` operator in synchronous languages with process creation. Elaborating on this low-level mechanism, *temporal patterns* [40] enable expression of complex temporal constraints mixing instant and duration. The problem of online matching where the event are presented in real time and the matching is computed incrementally as well, has received a recent attention from the model-checking community, but with less constrained causal constraints.

Embedding Audio Processing. Audio processing has been integrated in the Antescofo language. Started in 2014, this extension aims at providing sample-accurate control and dynamic audio graphs directly in Antescofo. Currently, FAUST (through a native embedding of the in-core compiler) and a few specific signal processors (notably FFT) can be defined. The tight integration enable specification of multiple-timed signal processing in conjunction with control programs. One example of this integration is the use of symbolic curve specification to specify variations of control parameters at sample rate, a task whose correctness in real-time is not at the scope of competing systems. Our approach has proven to provide such mechanisms at a lower computational cost; for example a factor of two in the *remaking* of Boulez' piece *Antheme 2* compared to the original version with the audio effects managed in Max. We will further pursue such optimizations while extending sample accuracy, by developing a type-system to preserve block computations in case of preemptive audio processing [77].

The reduced footprint enable the embedding of an *Antescofo* engine with internal audio processing on Raspberry PI and UDOO nano-computers (early results are reported in [20]).

Visualization and Monitoring of Event-driven and Time-driven Computations. The authoring of complex temporal organization can be greatly improved through adapted visual interfaces, and has led to the development of *AscoGraph*, a dedicated user interface to Antescofo. Ascograph is used both for edition and monitoring interface of the system during performances [30]. This project was held from end 2012 to end 2014 thanks to Inria ADT and ANR support.

An information visualisation perspective has been taken for the design of timeline-based representation of action items, looking for information coherence and clarity, facility of seeking and navigation, hierarchical distinction and explicit linking [28]. One of the problem was to minimize the information overload for the presentation of the nested structure of complex concurrent activities. We frame the problem of mapping actions with temporal relationships in a 2D space as a strip packing problem, with the additional constraint that the (horizontal) time coordinates of each block are fixed. We proposed novel algorithms of various complexity for automatic arrangement and efficient automatic stacking of time-overlapping action blocks, estimated their packing performance and provided a mathematical proof of their time-coherency during their real-time animation [27].

2.5.4 Collaborations

Miller S. Puckette is a professor of computer music in University of California San Diego (UCSD) and creator of Max and PureData real-time programming environments for interactive arts. He has been visiting MuTant regularly and contributed to the team's knowledge of multimedia realtime scheduling challenges and paradigms and collaborated with the team on the new audio processing engine for embedded nano-computers.

We also collaborate with Gérard Berry at Collège de France for the formalization of the language semantics and on the reactive programming of musical web applications.

We collaborated with the Parkas team on an implementation of a fragment of Antescofo's reactive engine in the synchronous-reactive language RML [23, 74].

We have a long standing interaction with people at GRAME, Stefan Letz and Yann Orlarey for the Faust embedding and on real-time audio implementation, as well as Dominique Fauber for the visual representation of musical data. These collaborations have been supported by the ANR project INEDIT. Our interaction with the third INEDIT partner, David Janin and the POSET INRIA team at LaBRI, focused on formal representation of musical sequences.

Grig Burgioglu is a PhD student, external member of the project, based at the University of Bucharest. We collaborated on the design of Ascograph.

We exchange regularly with Camilo Rueda (Univ. Javeriana-Cali, Colombia)on Concurrent Constraints Programming Calculi applied to musical problems. Visit between the teams have been funded by the FORCES INRIA associate team.

Several of our Ph.D student and internship visited the team of Edward Lee at Berkeley, David Wessel at CNMAT (Berkeley), Jaroslaw Kapuscinski at CCRMA (Stanford) and Roger Dannenberg at Carnegie Mellon.

We organized yearly public seminars by experts in the field to scientifically position our approach with regards to state-of-the-art in Real-time Multimedia Computing that are available online: `http://repmus.ircam.fr/mutant/rtmseminars`.

2.5.5 External support

The relevant contracts for this objective, detailed in Section 4, are: ANR INEDIT, ANR EFFICACe, ANR SynBioTIC.

2.5.6 Self assessment

The design of the Antescofo DSL clearly benefits of a strong and continuous involvement in the production of world-class composer pieces and their continuous recreation throughout the world. These interactions motivate new developments, challenge the state of the art and in return, opens new creative dimensions for composers and musicians. The maturity of the system is assessed by the generalization of its use in a large proportion of Ircam new productions, and its use outside Ircam all around the world (Brasil, Chile, Cuba, Italy, China, US, etc.). If the heavy software developments may hinder the publication of the results, we advocate the specificities of a research methodology at the heart of advanced applications, hand in hand with composers. Antescofo enjoys an active community of 150 active users: `http://forumnet.ircam.fr/user-groups/antescofo/`

We believe that the concepts and tools developed here face requirements that are characteristics of an emerging class of cyber-physical systems where safety is less critical than bold temporal interactions in complex interactive scenarios. From this perspective, we believe the design of the Antescofo DSL has an interest that exceeds the computer music application domain, for example for the declarative control of robot immersed in human environment, and domotics applications.

2.6 Objective 3 : Semantics, Verification and Test of Mixed Scores

We address the questions of *functional reliability* and *temporal predictability* in score-based interactive music systems such as Antescofo. On the one hand, checking these properties is difficult for these systems involving an amount of human interactions as well as timing constraints (for audio computations) beyond those of many other real-time applications such as embedded control. On the other hand, although they are expected to behave properly during public concerts, these systems are not safety critical, and therefore a complete formal certification is not strictly necessary in our case.

Our objective in this context is to provide techniques and tools to assist both programmers of scores (*i.e.* composers) and the developers of the system itself. It should be outlined that the former are generally not experts in real-time programming, and we aim at giving them a clear view of what will be the outcome of the score that they are writing, and what are the limits of what is playable by the system. To help the development of Antescofo, we have built a framework for automated timed conformance testing.

In both cases, it is important to be able to predict statically the behavior of the system in response to every possible musician input. This cannot be done manually and requires first a formal definition of the semantics of scores, and second using advanced symbolic state exploration techniques (model checking).

2.6.1 Personnel

Permanent members: Jean-Louis Giavitto, Florent Jacquemard
Ph.D. students: Clément Poncelet (Since 2013)

2.6.2 Project-team positioning

The use of formal methods for verification and testing is a new research area in the field of computer music, and MuTant is a pioneer team on this topic. The team PoSET (resp. David Janin) studies formal models (based on inverse monoid theory) able to represent the triggering, synchronization, mixing and transformation of temporal media streams of different natures. Camilo Rueda (Univ. Javeriana-Cali, Colombia) and Myriam Desainte-Catherine (PoSET) develop various formal models of interactive scores (based on Concurrent Constraints Programming Calculi, Petri Nets or Timed Automata) and applied to automated verification of correctness and compiling into various targets for real-time perfomance. One can also mention collaborations between the group of Sanjit Seshia and David Wessel (UCB) on controller synthesis techniques in improvisation systems, and other works on formal models of improvisation by the team of Shlomo Dubnov at University of California San Diego.

As far as we know, no methods have been proposed for the analysis or verification of other DSLs for music real-time programming such as ChucK or Supercollider. Some tools exists for automating the test of interactive systems such as MAX MSP through assertions, but they do not offer procedures for generating test data.

We have collaborations with teams working on the verification and testing of real-time systems and synchronous languages (see paragraph below). Note however, as explained above, that our case study, which is very particular in the field of realtime systems, and our objectives differ significantly from those teams.

2.6.3 Scientific achievements

Models and Semantics of Mixed Scores. We are studying models providing operational semantics for the scores written for the system Antescofo. As described above, every such score contains some instrumental (input) and electronic (output) parts, and we have attached a particular attention to the high level constructions for describing the interactions between both parts, and for specifying strategies to adapt to timing deviations of musicians and to handle errors in input.

In [9] we sketch the real-time features required by automatic musical accompaniment seen as a reactive system and model formally, as a network of parametric timed automata, the behavior of the system Antescofo for playing a given score. The model is used both to give semantics of an *ideal performance* (when the musician respect exactly the timing values specified in the score) and of an *actual performance* (a musical interpretation of the score), just by defining various instantiations of the parameters. We establish a first simple result stating the determinism of the accompaniment for any interpretation.

In a next step, we have proposed an ad hoc medium-level Intermediate Representation (IR) [72], in the form of FSM extended with timings, input and output messages, process creation (alternations) and call to external blocks of code. This model is the base of the work presented below.

Timed Static Analysis of Robustness of Mixed Scores. It is well known that all musician performances will differ from one to another. Therefore assessing the behavior of interactive music systems like Antescofo in order to prevent unwanted outcomes requires to check its response to any possible performance, a challenging task.

With Léa Fanchon [81], and in collaboration with the LSV (ENS Cachan), we have been working on a module for timing analysis of Antescofo's scores with the aim of exploring symbolically the possible behavior of authored scores with respect to all possible deviations in human musician performance. For this purpose we have considered [39] parametric models and the good parameters problem, which consists in inferring a set of timing parameter valuations (in the form of *linear constraints* representing performances here) which guaranties a good behavior of the system on the score analyzed (typically, the property that the events follow the same ordering as during the ideal performance). This method has been applied to Antescofo in order to provide the authors with feedback on the robustness of the score they are writing with respect to the environment's (musician's performance) temporal variations, and indications about the critical regions of the score.

Model Based Testing Framework. Conformance testing consists in checking whether a black box implementation under test behaves correctly with respect to a formal model specifying the expected behavior of the system. In the context of the Phd of Clément Poncelet, we have developed a framework for addressing this problem in the case of Antescofo playing a given score, with of focus on the timed behavior of the system. Our framework [85, 84, 50, 49, 13] makes it possible to automate the following main tasks:

1. generation of relevant input data for testing (*i.e.* artificial performances),
2. computation of the corresponding expected output, according to a formal specification of the expected behavior of the system on the given score,
3. black-box execution of the input test data on the system under test,
4. comparison of expected and real output and production of a test verdict.

The input and output data are timed traces: (sequences of timestamped discrete events). The score given to Antescofo can be seen as a description of the timed behavior expected form the system during a music performance. Based this assumption, we have developed an approach for *model based testing* where a score is compiled automatically into a formal model of the system's behavior, in the IR mentioned above. This permits us to propose a fully automatic test method which is in contrast with other approaches generally requiring experts to write specification manually.

We have implemented several tools for Tasks (3) and (4), see corresponding to different boundaries for the implementation under test (black box): *e.g.* the interpreter of Antescofo's synchronous language alone, or with tempo detection, or the whole system [50].

The main challenge in task (1) is to cover enough significant cases of performances in order to be gain some insurance on the behavior of the system on the given score. We have implemented offline and on-the-fly approaches for this problem.

The **Offline testing procedure** [49, 13] uses a translation (assuming restrictions) of our IR models into timed automata with inputs and outputs, and on tools of the Uppaal suite. In this approach, the construction of a relevant test suite (task (1)) is reduced to a model-checking problem delegated to Uppaal. For the sake of exhaustiveness, it follows coverage criteria referring to the model (such as the number of states or transitions visited). The above task (2) is also performed in Uppaal, by simulation.

In the **Online testing procedure**, the generation of test data and its execution is performed on-the-fly. The advantage over offline techniques is that only low memory resources are needed (sometimes at the price of exhaustiveness). Online testing frameworks such as Uppaal Tron have shown to be inadequate to our case study because scores contain time values measured in number of beats relatively to a tempo that can change over time – a feature unsupported in Tron.

We have developed an ad hoc procedure for online test generation and execution for Antescofo. It is based on a Virtual Machine, developed for this purpose, which executes the IR models generated from scores. This work is in submission, on invitation, to a special issue of Science of Computer Programming (long version of [49]).

2.6.4 Collaborations

The group of Ch. Kirsch (Salzburg University and UC Berkeley) and MuTant are settling a long term project on Rigorous Engineering of Interactive Multimedia Systems. We have collaborations and student exchanges supported by PHC Amadeus LETITBE,

We also have collaboration and student exchanges with Marielle Steolinga (Twente University) on the problems of model-based testing and probabilistic models in this context.

We have collaborations with the team PoSET on formal musical representations, supported by the ANR project INEDIT, in particular David Janin, Myriam Desainte-Catherine, and Jaime Arias. We have also interactions with the two latter regarding recent work that they are conducting on timed automata modeling and verification with Camilo Rueda (Univ. Javeriana-Cali, Colombia) and on model-based testing with Antoine Rollet (team Formal Methods at LaBRI).

We have collaboration with Laurent Fribourg and (LSV, ENS Cachan) Étienne André (LIPN, Paris 13) on the problem of synthesis of good parameters (in parametric timed automata models) and also interactions with Patricia Bouyer, Nicolas Markey (LSV axe VASCO, ENS Cachan) and Ocan Sankur (now in SUMO team) on the evaluation of robustness of real-time systems.

We have frequent interactions with the Uppaal team, in particular Kim Larsen, Alexandre David, Marius Mikucionis (Aalborg University) about testing real-time systems with the tools of the Uppaal suite.

2.6.5 External support

The relevant contracts for this objective, detailed in Section 4, are: ANR INEDIT, ANR EFFICACe, and PHC Amadeus LETITBE.

2.6.6 Self assessment

Our applications of formal methods for verification and testing to interactive music systems are amongst the first work of this kind in the field of computer music. Following the two observations that (*i*) the case study is difficult (strong constraints on timings, multiple timelines, importance of human interaction), and (*ii*) the application is only weakly critical, we have oriented our studies less towards qualitative verification problems (yes/no answer) and more towards quantitative evaluations (like a measure of robustness), inference of parameters (inverse problems) or inference of constraints. Our goal is therefore essentially assistance to developers.

In this context, an integration of our tools into the graphical environment Ascograph could be very useful, and remains to be done. For instance, the timeline-based visualization of input events (piano roll), extended with an editor, could be helpful in a task of generation of test cases (artificial performances). Moreover, graphical representations of formal models like timed automata, such as in Uppaal editor, could help decluttering the representation of reaction items [28, 27].

A conclusion of our work on model-based testing is that, because of the specificities of our case study (in particular the multiple time lines), it turned out to be both simpler and more efficient to design new ad hoc models and solutions rather than reusing more general techniques and tools.

3 Knowledge dissemination

3.1 Publications

	2012	2013	2014	2015-16	**Total**
PhD Thesis	1			1	**2**
H.D.R (*)		1			**1**
Journal	4	4	1	2	**11**
Conference proceedings (**)	3	10	8	14	**35**
Book chapter		2	1		**3**
Book (written)					**0**
Book (edited)	1	2	1		**4**
Patent					
General audience papers	3	1	1		**5**
Research report	1	3	2	6	**12**
Total	**13**	**23**	**14**	**23**	**73**

(*) HDR Habilitation à diriger des Recherches
(**) Conference with a program committee

During the evaluation period, members of MuTant published in the following international journals (highlight):

1. IEEE Signal Processing Letters, [8]

2. Journal of New Music Research, [13]

3. Journal of Discrete Event Dynamic Systems, [9]

During the evaluation period, members of MuTant published in the following highlighted international conferences:

1. *International Computer Music Conference*, 6 publications, *1 Best Presentation Award*: [30, 31, 39, 50, 83, 53]

2. *IEEE International Conference on Acoustics*, Speech and Signal Processing (ICASSP), 2 publications, 1 Best Paper Award, both jointly with SIERRA Team: [24, 45]

3. *International Symposium on Principles and Practices of Declarative Programming (PPDP)*: [40]

4. *ACM/SIGAPP Symposium On Applied Computing (ACM SAC)*: [49]

5. *EMSOFT*, 1 joint Publication with PARKAS: [23]

3.2 Software

3.2.1 Antescofo

Antescofo is a modular polyphonic score following system as well as a synchronous and timed programming language for musical composition. The system allows for automatic recognition of music score position and tempo from a real-time audio stream coming from performer(s), making it possible to synchronize an instrumental performance with computer realized elements. The domain specific language within Antescofo allows flexible writing of time and interaction in computer music.

Software Developments. The system appears as an external module for Max and PureData (Pd) audio programming environments and is available on Mac, and also on Linux (Pd version) and Windows (Max). A standalone offline version exists and is used for tests and the simulation mode in Ascograph.

Antescofo base code represents more than 70 000 `C++` locs. The current version (v0.9) is the third major rewriting since 2012. A challenging constraint is to maintain upward syntactic and semantic compatibility for the existing Antescofo repertoire, despite the drastic language evolution.

To face the production constraints (Antescofo is used in numerous concerts outside IRCAM) the system is tested before each major release (cf. sect. 2.6) and users have access to a bug tracking system.

Distribution. The system is distributed as binary software packages on the IRCAM Forum site. The Max version on Mac is available by subscription. All other versions (PD target and Linux or Windows environments) are freely available. About two official versions are released per year. Beta versions are available for advanced user through the project forge.

The documentation includes an extensive user guide and reference manual (200 pages long), and several examples and tutorials, including the /emphremake of *Anthèmes 2* an emblematic mixed music piece by P. Boulez, showcasing the software's latest developments. Users outside IRCAM may interact through a dedicated user group.

Diffusion. Each new version is uploaded more than 300 times through the forum (total of 3K downloads since 2012). The system is mature and robust enough to be used outside IRCAM, in the creations of new musical mixed pieces or the recreation of old repertoire by composers such as Pierre Boulez, Philippe Manoury, Marco Stroppa, Emmanuel Nunes, Jonathan Harvey, among many others, and for their live performances by various music ensembles such as Los Angeles or Berlin Philharmonics in international art venues.

Antescofo is teached outside IRCAM through dedicated seminars and workshops (Shangai, Stuttgart, Buenos Aires, Athènes, Sao Paulo, Séoul, Cali…). The first Antescofo user's workshop has been organized in November 2015 in Paris.

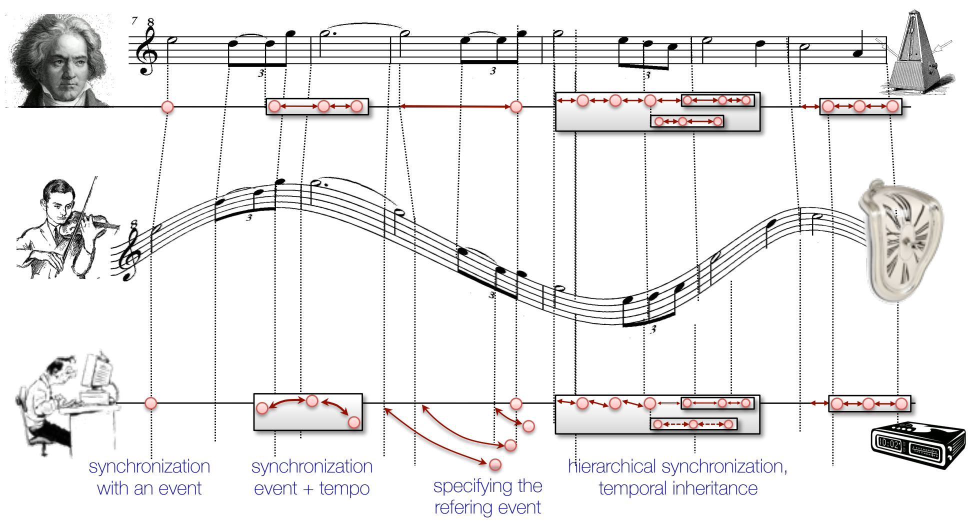

Figure 1: Authoring time and interaction in mixed music.

Antescofo has been popularized by several presentations in the general media by team members, and also by journalists and users themselves (cf. Section 3.6).

Several online videos illustrate the variety of system utilization: piano/video synchronization, adaptive karaoke, automatic accompaniment, ASA 2014 Concert (demonstration concert of the Acoustic Society of America, the trumpet player is R. Dannenberg, one of the father of automatic accompaniment; Antescofo won the best presentation award), rhythmic canon by composer C. Trapani (ICMC best presentation award), coupling with face tracking and embedded audio processing, student project by C. Kirsch at Univ. of Salzburg. Other examples are available from the Antescofo project pages.

Positioning. Antescofo is a unique software of its kind providing a joint coupling of a Real-time Score Following (Machine Listening) and a Real-time DSL for Computer Music. Competing software provide one aspect and never both. On Score Following aspect, our software has participated in the International Music Information Retrieval Evaluation Exchange Campaign and its results has never been beaten since 2012. Moreover, we provide the only software capable of decoding highly polyphonic recognition in noisy environments. In the language counterpart, ChuCK (developed in Stanford) is a DSL that provides Synchronous Constructions for Music Composition. However, ChuCK is made only for "Live Coding" paradigms and thus not useful for interactive setups with human musicians and thus not comparable. A detailed comparison in this regard can be found in [3].

3.2.2 Ascograph

The Antescofo programming language can be extended to visual programming to better integrate existing scores and to allow users to construct complex and embedded temporal structures that are not easily integrated into text. This project is held since October 2012 thanks to Inria ADT and ANR support. In 2015, AscoGraph's User Interaction was redesigned as reported in [27, 28].

Ascograph includes a timeline representation of the augmented score, a textual dedicated editor, graphical edition of curve and graphical representation of hierarchical temporal structures. All views are synchronized to maintain coherency through edition operations. Since 2015, Ascograph includes an advanced importer that translate Music-XML score representations into Antescofo programs. Ascograph includes also a simulation mode for Antescofo program making possible to evaluate actions offline.

AscoGraph is strongly connected with Antescofo core object (using OSC over UDP): when a score is edited and modified it is automatically reloaded in Antescofo, and on the other hand, when Antescofo follows a score (during a concert or rehearsal) both graphical and textual view of the score will scroll and show the current position of Antescofo. Ascograph is routinely used to monitor Antescofo during performance.

Diffusion. AscoGraph is released under Open-Source MIT license and has been released publicly along with the Antescofo software packages (see previous section).

3.2.3 Antescofo Test Platform

The methods for conformance testing of Antescofo on a particular score presented in Section 2.6 have been implemented in a platform used internally for the development of Antescofo, especially when a focus is needed on the timed behavior of the system. There are two main use cases: (*i*) Test of Antescofo on a given real score, in a context of the preparation of a concert. (*ii*) Test on toy scores in order to debug some particular feature of the system.

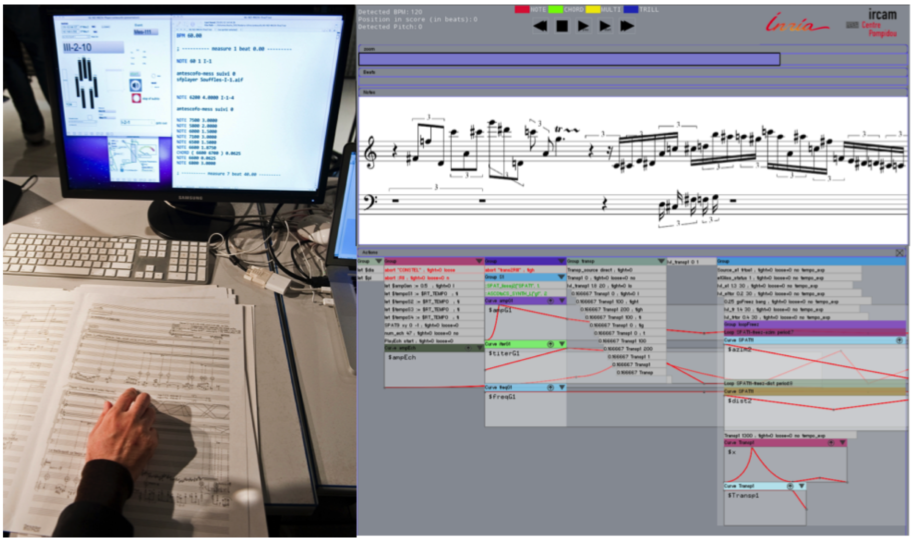

Figure 2: Antescofo and AscoGraph Screen Shorts (Nov. 2015).

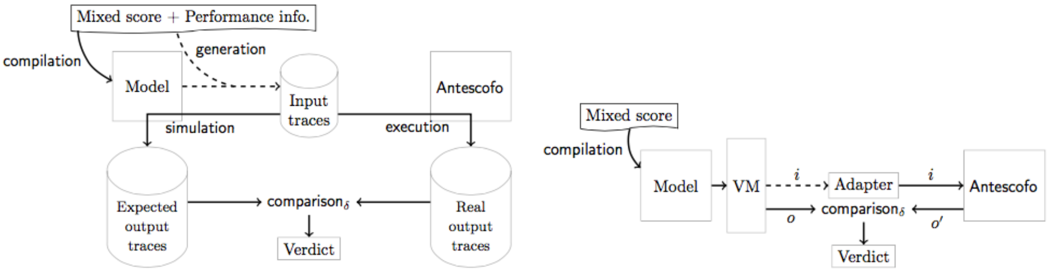

Figure 3: Offline and Online approaches for Antescofo Testing Framework.

Figure 3 displays the workflows for the two main approaches presented in 2.6; Several variants for test execution have also been developed.

Software Developments. Our test framework contains various independent modules (altogether 18 000 locs), such as: A frontend compiler of scores in Antescofo DSL into IR models, on the top of Antescofo Flex/Bison parser (13 000 C++ locs); Command-line tools and scripts for convenience conversion and comparison of timed input and output traces including an adapter for online workflow; Convenience Scripts for deployment of URRAAL Suite in our workflow; and specific adapter function for the Antescofo Standalone version. Documentations are provided to permit an easy use and understanding of the framework.

3.2.4 Rhythm Transcription in Open Music

We are developing a new system for rhythm transcription, following the approach presented in Section 2.4. Our system privileges the user interactions in order to search for a satisfying balances between different criteria, in particular the precision of the transcription and the readability of the music score in outcome. We have developed a uniform approach for transcription, based on hierarchical representations of notation of duration as rhythm trees, and efficient algorithms for the lazy enumeration of solutions. It has been implemented via a dedicated interface making it possible the interactive exploration of the space of

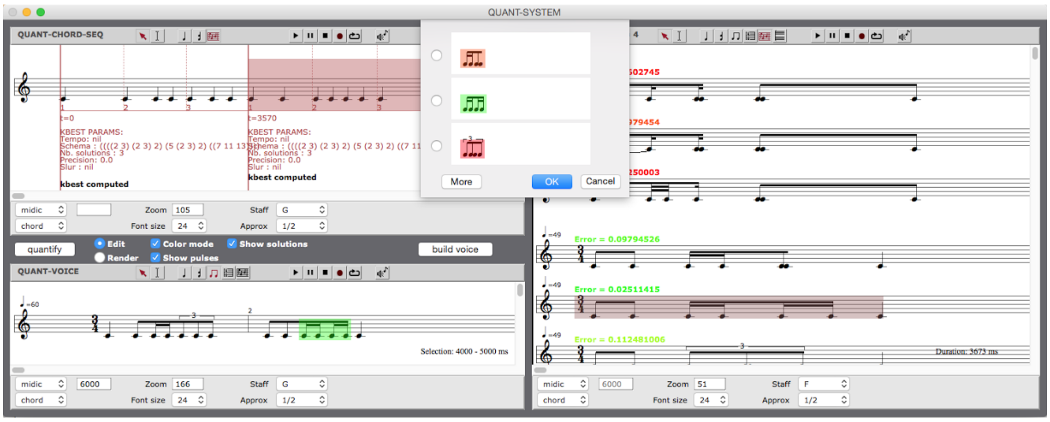

Figure 4: UI of our new Open Music Library for Rhythm Transcription.

solutions, their visualization and their edition, with a particular focus on the processing of grace-notes and rests.

Software Developments. Our transcription tool is integrated into the graphical programming environment OpenMusic, a state of the art system in computer assisted music composition developed at Ircam. It represents 7 000 Comon Lisp locs, including user interfaces components.

Distribution. Our system is released as a library of OpenMusic on the the Ircam's Forum. The sources are free and available under the GNU Public License (GPL). It is currently under evaluation in collaboration with composers at Ircam.

3.2.5 CHROMAX Spectral Delay

Chromax is a small sub-project of Antescofo used for real-time Generation of Frequency Templates destined for Real-time Processing of audio signals. It has been initially developed as external modules for the *Max* programming environment and since 2015 it is part of the *IRCAMAX* Collection for *Ableton LIVE* software used by over a million DJs around the globe[4]. Chromax is famous for its temporal organization and correct time-delivery of signals despite heterogeneous temporal patterns used in spectral processing as discussed in [34].

3.3 Valorization and technology transfert (Socio-economic impact and transfer)

- The Antescofo software in its current form described (cf. Section 3.2) has been largely used by the Computer Music community and subject to performances by famous music ensembles (Los Angeles Philharmonics, NYC Phil., Berlin Philharmonics, BBC Orchestra, Paris Orchestra, etc.) and in major world-class festivals (Edinbourg Festival, Paris Autumn Festival, Warsaw Autumn Festival, etc.); and many musicians around the world. This has led to general public awareness and considerable Press output for our team National Wise (Le Monde, Figaro, La Recherche, etc.) and worldwide (NY Times, BBC, Cuba Chronicles, Shanghai Times, etc.).

[4] ProductURL:https://www.ableton.com/en/packs/ircamax-2/

- The team has advised several startup or companies in view of a possible integration of Antescofo's Automatic Accompaniment system and for their general workflow. Among them: MakeMusic (US) for their *SmartMusic* product; Qwant (that acquired a license); and several startups such as Weezic (France), Learnfied (Germany), AllegroIQ (China). Each case led to improvements and tests on real-world cases dealing with popular music or classical music used in education.

- **Collaboration with Paris Orchestra:** Following the Industry Award in 2013, we entered a collaboration with the famous Paris Orchestra with the aim of using their archives for Automatic Accompaniment ("Your child playing a Concerto with Paris Orchestra at home"). This led to the fine tuning of our system for highly polyphonic environments such as Piano and the behavior of the system as demonstrated in a public performance[5].

- **Antescofo Startup:** The team leader with two PhD students are creating a Startup around Antescofo to bring the product to greater public starting March 2016. The project was awarded the "Emergence Award" in 2015 that help emerging new technology companies to study the project and will be hosted by the French Incubator AgoraNov.

3.4 Teaching

(L3, 2012-2014) Arshia Cont, Audio Technology Review, 2h/week, 3rd year Bachelors, Conservatoire Nationale Supérieure de la Musique et de la Danse de Paris (CNSMDP), Métier du Son, Paris, France.

(M2, 2012-2013) Arshia Cont, Machine Learning for Music, 18h, Master ATIAM, UPMC, Paris, France.

Jean-Louis Giavitto has been invited to give a one week course on Spatial Computing at the University of Cali, Colombia (20 hours).

(L3 2014) Clement Poncelet, Environnement de développement, 40h, UPMC, Paris, France.

(L1, 2014) Clement Poncelet, Ateliers de Recherche Encadrée - ARE, 20h, UPMC, Paris, France.

(L3, 2014) José Echeveste, Structures discrètes, 30h, UPMC, Paris, France.

3.5 General audience actions

The Antescofo software developed and maintained by the team, has been featured in various prestigious international events with the following highlights:

- More than 100 world-class public performances around the world including: Antescofo premier with New York Philharmonics (June 2012), Lucerne Festivale (August 2012), Salle Pleyel (September 2012), Warsaw Autumn Festival (September 2012), Royal Albert Hall in London (August 2012), Vienna Festwochen (June 2012), Opéra Comique de Paris (June 2012), La Scala Opera, Berlin Philharmonics (March 2015), Barbican Center in London (May 2015), Royal Albert Hall in London, Warsaw Autumn Festival, and more.

[5]See https://youtu.be/A97lFbnqQRo

- Documentary film on Antescofo in honor of Gérard Berry (2014): https://youtu.be/he-BOMZhOWQ
- A documentary movie on Antescofo produced by INRIA (2013): https://youtu.be/ttKU1S2U2Yk
- French Popular Science Article: *Antescofo: Au plus près de la partition*, Science et Avenir, July 2012.
- French Popular Science Article: *L'ordinateur qui joue comme un musicien*, La recherche, June 2012.
- French Popular Science Web Article: *Antescofo à l'avant-garde de l'informatique musicale*, InterStices, November 2012.
- French Popular Culture Web Artciel: *Quand l'informatique maîtrise le temps de l'interprétation musicale*, France Culture Online, July 2012.
- French Popular Science Article on *Sous le signe du calcul*(with F. Reichenmann) in DocSciences, special issue on "Alan Turing : la pensée informatique" (DocSciences is a journal for college students published by the Rectorat de Versailles), June 2012. Published also on the InterStices web site, September 2012.
- French Popular Science Article on "Computer Assisted Music" in the review DocSciences, number 15, 2013.
- French Popular Science Article on Antescofo by Arshia Cont in the December 2014-January 2015 special out of series edition of "Dossier de La Recherche".
- MuTant team was featured in the 2nd edition of Made In France (MIF) Expo in the major Exhibition Hall in Paris (Porte de Versaille) with a dedicated stand for Antescofo with more than 3 million visitors during 3 days.
- Antescofo was featured by the French Ministry of Industry for a public talk and largely diffused video featuring the French popular singer Marlène Schaff from *The Voice* (2013)
- MuTant was featured in a public seminar in College de France invited by Gérard Berry (2013)
- Arshia Cont appeared in major TV, Radio and Press including: BFM Business TV (2015), BFM Business Radio (2014), Radio France (2013), Usbek et Rica Magazine (2014),
- Arshia Cont was invited to a *TEDx Talk* on "Machine Musicianship" (2014)
- Arshia Cont was invited to CNRS's Popular Event "Les Fondamentales" in Grenoble (2014)
- Jean-Louis Giavitto has co-animated the public discussion following the movie "Codebreaker: Alan Turing" with C. Villani and G. Berry at the Cinema Grand Action (2013)
- As the redactor-in-chief of TSI, Jean-Louis Giavitto has initiated a new section devoted to portraits and talking with french personalities in computer science. These articles are also published in the SIF journal (2013)

- MuTant was featured in the 2014 edition of the "Futur en Seine festival" in Paris and showcased collaboration with Orchestre de Paris in a public event.

3.6 Visibility

Prizes and awards.

- Antescofo has been awarded the Industry prize 2013 by the French Minister of Industry, for its R&D and upcoming industrial applications.
- Acoustical Society of America 2014 best paper award for students and young presenters [32].
- International Computer Music Conference (ICMC'14) best presentation award [53].
- Best Student Paper Award, IEEE 2015 International Conference on Acoustics, Speech and Signal Processing (ICASSP), in Machine Learning for Signal Processing Category [24].
- Best Student Paper award, International Symposium on Computer Music Interdisciplinary Research 2015 (CMMR) [54].
- Arshia Cont was awarded the 2015 French Ministry of Research's iLab Award (17th Edition) in the emergence category, which will culminate to the creation of a spin-off out of this technology.

Organization of workshops and conferences.

Jean-Louis Giavitto was co-chair of the Spatial Computing Workshop (SCW 2012, 2013, 2014) a satellite workshop of AAMAS [60].

Arshia Cont was co-organizer and scientific chair for the first International Conference on Geometric Science of Information 2013 which took place in École des Mines (Paris) in partnership with SEE, and THALES.

Arnaud Dessein and Arshia Cont have been the coordinators of the Brillouin Seminar series on Information Geometry on 2012 and 2013, in partnership with LIX and THALES.

Jean-Louis Giavitto organized jointly with Gérard Berry the *Réunion de l'intersection des applications des sciences on "Informatique et Musique"*.

MuTant team organized the First Antescofo user Symposium during Ircam Forum Workshops in 2015.

Editorial boards.

Jean-Louis Giavitto is the Editor-in-chief of TSI (Technique et Science Informatique), a french scientific journal published by Lavoisier and Hermes Science.

Program Committees.

Florent Jacquemard: International Joint Conference on Automated Reasoning (IJCAR'12), International Workshop on Trends in Tree Automata and Tree Transducers (TTATT'12), a satellite workshop of the 23rd International Conference on Rewriting Techniques and Applications (RTA'12), 6th International Symposium on Symbolic Computation in Software Science (SCSS'14), Journées d'informatique Musicale (JIM'14 and 16), Intl Conf. on Technologies for Music Notation and Representation (TENOR'15-16).

Jean-Louis Giavitto has been acting as PC yearly for various conferences including (highlights): Genetic and Evolutionary Computation Conference (GECCO), Information Processing in Cells and Tissues (IPCAT), IEEE International Conference on Self-Adaptive and Self-Organizing Systems (SASO), European Conference on Artificial Life (ECAL); and also (highlight) Intl Conf. on Technologies for Music Notation and Representation (TENOR'15), International Computer Music Conference (ICMC'15), among others.

Arshia Cont acts regularly as PC for Computer Music related conferences such as Sound and Music Computing (SMC), International Computer Music Conference (ICMC), Digital Audio Effects (DAFx); and signal processing conferences such as IEEE ICASSP, IEEE MLSP, and occasionally for ACM Multimedia and related.

Responsibilities in the scientific community.

Arshia Cont is board member of ICMA (International Computer Music Association) since 2014,

Arshia Cont is a founding member of the *Brillouin International Workgroup on Geometric Science of Information* that led to the creation of the first GSI Conference in 2013 (2nd edition occured in 2015). URL: http://repmus.ircam.fr/brillouin/home

Arshia Cont is the director of Research/Creativity Interfaces at Ircam, in charge of coordinating scientific and artistic activities of the institution and dissemination of its software and community through Ircam Forum,

Jean-Louis Giavitto is in the management team of the GDR GPL (Genie de la programmation et du logiciel), responsible with Etienne Moreau of the "Languages and Vérification" pole of the GDR,

Jean-Louis Giavitto is an expert for the ANR DEFI projects and a reviewer for FET projets for the European Union,

Florent Jacquemard is member of the IFIP WorkingGroup 1.6 on Term Rewriting,

Florent Jacquemard participated in the selection committee to the 2013 recruitment campaign at the Inria center of Lille,

The three permanent members are regularly called for participation as examiner or reviewer in PhD defense (7 for Giavitto, 3 for Jacquemard, and 2 for Cont) and Habilitation juries (4 total).

4 Funding

4.1 Funding external to Inria

(k euros)	year1	year2	year3	year4
National initiatives				
ANR INEDIT	5.2	104.4	97.1	115
Industrial contracts				
QWANT	100			
Scholarships				
PhD, José Echeveste	35	35	35	
PhD, Philippe Cuvillier		35	35	35
PhD, Maxime Sirbu				35
Other external funding				
PERSU (Sorbonnes University)				80
IRCAM UPI [1]				30
Total	140.2	174.4	167.1	295

[1] IRCAM's internal call for "Innovative Project Unit".

4.2 Inria competitive funding

(k euros)	year1	year2	year3	year4
Scholarships				
PhD[2], Clément Poncelet		40	40	40
Pre-Phd[3], Philippe Cuvillier	40			
Technological development				
ADT [4]		55	55	
Total	40	95	95	40

[2] INRIA doctoral research contract (DGA/INRIA, doctorat Inria sur subvention).
[3] INRIA FRM Pre-PhD contract.
[4] Technological Development Action (ADT = Action de Développement Technologique).

National initiatives

INEDIT is an ANR project for the period 2012-2015, aiming to provide a scientific view of the interoperability between common tools for music and audio productions, in order to open new creative dimensions coupling authoring of time and authoring of interaction. The partners are the Grame (Lyon), and the LaBRI (Bordeaux). Arshia Cont was the coordinator of this project.

Efficace is an ANR Project for the period 2013-2016 exploring the relations between computation, time and interactions in computer-aided music composition, using OpenMusic and other technologies developed at IRCAM and at CNMAT (UC Berkeley).

SynBioTIC is an ANR Blanc project for the period 2010-2015 with IBISC, University of Evry, LAC University of Paris-Est, ISC - Ecole Polytechnique.

Arshia Cont was awarded the Sorbonnes University *PERSU Call*.

The MuTant team is also an active member of the ANR CHRONOS Network by Gérard Berry, Collège de France).

Industrial contracts

Qwant: Late 2011, the *Antescofo* core was licensed by the French Search Engine Company *Qwant* that saw an opportunity to commercialize a music service based on Antescofo's Automatic Accompaniment capabilities, offering an *Adaptive Karaoke* service targeting the greater public. This led to multiple tests and revisions of the Real-time Synchronisation services reported in [3, 53]. The company ran into financial difficulties and abandoned the contact after one year. This project led to collaborations with various artists from the popular culture and the French Industry Award for Antescofo in 2013. A public prototype of such usage was shown to the public in Summer 2015[6].

Associated teams and other international projects

LETITBE is Austria-French Partenariat Hubert Curient (PHC) Amadeus for the period 2015-2016 on Logical Execution Time for interactive and composition assistance music systems. The partners are MuTant/Ircam and U. Paris Lodron, Salzburg, Austria.

Other funding

PERSU is a funding by Sorbonnes University in Paris, for unfortunate twice admissible candidates of EU ERC call, awarded to Arshia Cont in 2015.

5 Objectives for the next four years

The team-leader, Arshia Cont, together with two PhD students, José Echeveste and Philippe Cuvillier, are co-finding a Startup as a Technology Spin-off to the Antescofo technology, with the help of INRIA, IRCAM and the French Government and Parisian Incubator AgoraNov. Their goal is to bring applications of Antescofo to the greater public in the Music Entertainment and Education industries.

Following INRIA Internal rules and as a consequence of the departure of the team-leader, the Team-Project will be stopped.

We however enlist some future directions that our ongoing scientific projects can take in the years to come:

5.1 Antescofo Real-Time System and Language

Antescofo system brings together state-of-the-art Real-time Machine Listening with a carefully designed DSL to allow specification of heterogeneously timed programs and their temporal guarantees in real-time performance/evaluation. It has been validated through various usages in world-class musical performance and also including mechanical device controls (such as lighting and robotic instruments). One reason for its success within the community is that the systems allows non-expert users to express their ideas using perceptual concepts (rather than pure mathematical concepts) and see/hear what they have

[6] Seehttps://youtu.be/gsYhDp2VXMo

written despite uncertainties in the environment. We believe that this approach can be extended to other application domains with strong involvement of "Time". One example is Robotics interactive scenarios which are currently limited to simple tasks. Another application domain would be interactive games and virtual reality. Each domain will bring in specific constraints triggering new challenges for our scheduling mechanisms. The Antescofo DSL in this respect can be further extended to an emerging class of Cyber-Physical Systems in complex interactive scenarios.

Similarly, we believe that the generalization of the Real-time Audio Listening in Antescofo (enhanced lately by Online Segmentation and Clustering) is in its infancy with great potential in many respects: The validity of our mathematical foundation and the utility of algorithms are to be explored in a large scale (ongoing through the PhD project of Maxime Sirbu); and the applications of such real-time approach should be further studied in other time-based scenarios such as Computational Auditory Scene Analysis. Synergies initiated lately with Machine Learning teams such as SIERRA should be pursued on this subject.

The development of the AscoGraph (cf. Sec. 3.2) for visualization of Antescofo programs proved to be both challenging and extremely important for users. Visualization of highly dynamic programs such as Antescofo brings in interesting questions for scientific visualization and Human-Computer Interactions that should be further pursued. Integration of Simulation and Test frameworks in a visual paradigm is also a common request from users.

5.2 Open Computer Audition Library

The Computer Vision community enjoys the existence of the *OpenCV* that basically synthesize machine learning algorithm for high-level use in real-time computer vision applications. No such library exist for Audio since it poses challenging problems for both machine learning and program synthesis. We believe that our team has a strong position, and gathers required talents, to tackle this problem.

5.3 Symbolic Music Information Retrieval

Florent Jacquemard has started collaborations (see Section 2.4.4) on the study, analysis and representation of music scores encoded in common Western notation. This notation is, since centuries, the primary channel to communicate, to exchange and to preserve musical works, and cannot be ignored when composers or musicians are involved. We aim at developing models and tools for analyzing and mining music scores, with application to digital humanities (computational musicology), digital music libraries management and music editors. Our primary concern in this context is the representation of timings (rhythm) in music notation. Besides the work on rhythm transcription presented in 2.4.3, our short term goals are to apply techniques issued from the theory of tree structured data processing to the MIR problem of query by tapping (in a single digital score or a corpus) and discovery of repetitions and score indexing.

Moreover, music psychology research has shown that the representation of durations by ratios in music notation is compatible with the human perception of time, and therefore the symbolic representations of rhythm notation could also be of interest for expressing timings related to human-machine interactions in programming languages.

5.4 Next Generation of Real-time Audio Systems

We should pursue our efforts on the embedding of audio processing in Antescofo (see Section 2.5.3), and the study of novel, adaptive and dynamic scheduling methods in this context. Following our first experiments with the embedding and on-the-fly compiling of Faust code and the intermediate representations designed for the purpose of model based testing, we want to developed a compiling approach for Antescofo language. This will include offline and online score analysis techniques, offline and online score compilation and scheduling, and real-time score execution. We have started a collaboration with the group of Christoph Kirsch (Salzburg University and UC Berkeley) on these topics.

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