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Four Decades of Music Research, Creation, and Education at Padua's Centro di Sonologia Computazionale

Abstract: Research in computer music at the University of Padua, Italy, began in the early 1970s and was formalized in 1979 by establishing the Centro di Sonologia Computazionale (CSC). Since its foundation, CSC has established itself as a leading research center in the field of computer music. This article describes the scientific and musical research activities of the center and of the composers and members who worked in association with it in its first four decades. The center's historical background with its musical and scientific precursors is also chronicled, as are important events at CSC. An outline of its scientific research activity is then traced, with aspects of the technical details in its different areas of activities, showing the distinctive research ethos and the changing priorities of the center. Research from the 1970s is also included, as it led to the foundation of the CSC. Moreover, selected musical works, representative of CSC works from historical and scientific points of view, are described. Finally, perspectives for future developments are discussed.

> *Do you have it well calculated?*
> —Teresa Rampazzi, speaking to students on their music

Music composers discovered the potential of digital technologies and adopted the computer as a natural evolution of the analog instruments that had been developed since the 1940s in broadcast radio stations. In university research centers, composers could learn computer science as well as music, and engineering students could participate in musical projects (Manning 2004).

Since the early 1970s, a group of researchers and musicians has been working in Padua, Italy, on computer music. In 1979 these activities were formalized in the establishment of the Centro di Sonologia Computazionale (CSC) of the University of Padua.

Thanks to a close collaboration among experts in different disciplines (including information engineering, computer science, archival, acoustics, physics, materials science, mathematics, musicology, psychology, and philosophy), it was possible to create an interdisciplinary group. As an example, CSC today includes a composer, an archivist, two performers, a musicologist, eight computer engineers, and a materials scientist (http://csc.dei.unipd.it/people). The CSC group has achieved international recognition, and has come to be part of the contemporary music scene, with over two thousand scientific publications (there is an up-to-date repository of CSC publications in the Research Padua Archive, https://www.research.unipd.it, where one can search by author's name or by keywords) and more than two hundred important computer music productions (see http://csc.dei.unipd.it/multimedia-works). Activities at CSC can be grouped into four main areas: scientific research, music research, production and performance of music works, and education and dissemination.

One of CSC's basic principles was that it would not interfere with the aesthetic form of the composition; instead, it would give the artists' intentions innovative technological support (made ad hoc, if and when needed), striving for optimal musical results. Scientific and musical research are considered to be of equal value at CSC: A composition would be treated similarly to a scientific publication (or patent) and it would not be excluded on the basis of the composer's affiliation or musical style, as long as serious planning and a professional realization of the work were assured. This approach also derives from the fact that CSC Board is composed of computer scientists who are more interested in

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the advancement of research, both in music and in science, than in the affirmation or continuation of the work of any single "maestro." In this sense, many composers from different backgrounds and aesthetics were able to work well in Padua, always finding an open and flexible environment capable of satisfying different musical needs. The only requests made of musicians interested in collaborating with CSC were that they be composers or researchers in the field of experimental art music working with computers, and that they bring contributions and new ideas. For this reason, the musical works produced at CSC use the computer in different ways, including sound synthesis, assisted composition, audio processing, live electronics, and 3-D tracking of human motion.

A first reflection on the history of the CSC was discussed by Canazza, De Poli, and Vidolin (2013), published on the occasion of an exhibition, organized by the University Museums Center, on the activities of CSC. The exhibition retraced Padua's creative role in musical research, from medieval precursors to the experiments of the second half of the 20th century at the CSC. We believe that, four decades after the founding of the CSC, there is enough distance in time to discuss its history in relation to the evolution of computer music. This reflection leads us to think about new possibilities for future research developments, while being well aware of CSC's past.

This article is organized as follows: The section on Historical Background introduces the previous musical situation in Italy, the musical and scientific CSC precursors in Padua, and the main events of CSC history. The section Scientific Research at CSC accounts for the distinctive research ethos and changing priorities of the center and then documents the technical details of research grouped by areas: sound processing for music, expressiveness and well-being, and musical cultural heritage. The third section, Music Research at CSC, considers some achievements in music production and describes several important musical works along with their motivation and technological innovations. Finally, the Conclusion and Future Perspectives casts a look at CSC's visions of the future, built on the basis of its history.

Historical Background

The roots of music research in Padua date back to the 14th century, with the development of written music and musical symbols. The composer and theorist Marchetto da Padova (b. 1274?, fl. 1305–1319) pioneered these developments and his arithmetic- and geometry-based studies were a significant step in the development of Western music notation. Mathematical studies are also at the core of Giuseppe Tartini's (1692–1770) theories. He discovered a *terzo suono* (combination tone), which he heard when two different notes were played together loudly on a violin. His work was devoted to linking physics to a musical and metaphysical theory.

When the first instruments able to generate new sounds appeared, composers and musicians enthusiastically welcomed this revolution. In Italy, the pioneering phase of electronic music was characterized, from the 1950s to the 1980s, by the Studio di Fonologia Musicale della RAI in Milan and by the composers who operated there (Novati and Dack 2012). In Italy during the 1960s, electronic music took place in small private studios where, according to the aspirations of the artistic avant-garde of the time, a patient work of experimentation was carried out on the sonic possibilities of electronic instruments, trying to lay the foundations of a new musical language.

In the 1960s, computers were not widespread in Italy and were mainly used in the economic and administrative fields and in a few research centers. A systematic study of the use of computers for musical purposes started in 1969 at the initiative of Pietro Grossi, a composer at the Centro Nazionale Universitario di Calcolo Elettronico of the Italian National Research Council, located in Pisa (Giomi 1996), where several interactive systems for automatic composition—often governed by pseudorandom processes—were designed. The underlying principles of his work were real time, interaction, and automation. The compositions produced were defined as musical processes with continuously and instantaneously changing sonic results that often attest to Grossi's relative lack of interest in

(a) (b)

Figure 1. The group Nuove Proposte Sonore (NPS): Teresa Rampazzi (a), and Rampazzi talking with Alvise Vidolin (left, in white) and Giovanni De Poli (b). (Photographs by Luciano Menini, Padua.)

timbre; instead his focus was on the main points of the compositional procedures and on automated ideas.

Electronic Music in Padua: "Well-Calculated Music"

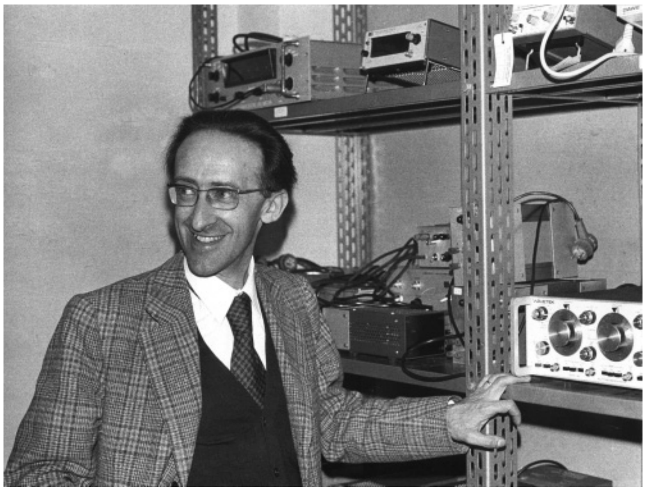
In the 1950s and 1960s the first musical and scientific steps of those who can be considered the mentors of CSC trace back to Teresa Rampazzi (1914–2001), one of the relatively few female electronic music composers, and to Giovanni Battista Debiasi (1928–2012), an electronic engineer.

Rampazzi (see Figure 1a) was an electronic music pioneer in the Italian artistic scene (Zattra 2003). Together with Ennio Chiggio she founded the group Nuove Proposte Sonore [New Sound Proposals, NPS] in Padua in 1965. Chiggio was part of Gruppo N, a group that applied kinetics to visual art. The theoretical assumptions were based on Rampazzi's total faith in electronics: As she considered electronics a sign of the times, and its potential worth studying, she often posed the unusual question to her students about their music, "Do you have it well calculated?" The NPS Group's research dealt with the timbre and density of sound objects and with tracks of different levels of complexity that explored acoustic phenomena. The goal was to carry out a rigorous study and a systematic analysis of the sounds produced by electronic instruments, in a research perspective initially not aimed at the production of musical works, but leading later to the musical synthesis of different electronic techniques. In 1972, Rampazzi donated her equipment to the Conservatory of Music "Cesare Pollini" in Padua, which was one of the very first Italian conservatories where electronic music classes were taught, just after Florence. Even when the NPS Group stopped its activity, however, Rampazzi continued to produce works with synthesizers, and, later at CSC, with computers.

Towards Computer Music in Padua

Research on music technology at the University of Padua dates back to the late 1950s, when Debiasi (see Figure 2) developed a working photoelectric organ in which oscillations were produced by a rotating disk with slits that periodically modulate the light reaching a photodiode. The different envelopes of each harmonic and organ stop were produced by modulating the light intensity through a sliding window (having the shape of the envelope contour) and by controlling the light on/off transients (Debiasi 1959).

Figure 2. Giovanni Battista Debiasi in his laboratory in the early 1970s.



Research on speech synthesis began in the early 1960s at the initiative of Debiasi. At that time the most common approach was frequency-domain simulation of the phonation process by time-varying filters, such as the vocoder. Computers had very limited computing power and memory space, however. Thus, Debiasi's approach was concatenative synthesis in the time domain. Debiasi's idea was to develop a text-to-speech synthesis for the Italian language by experimentally identifying a minimum set of elementary speech segments (phonemes or parts of phonemes) which, when appropriately recombined, allowed the synthesis of any message, keeping intelligibility as the main goal. From this point of view, prosodic factors (intonation, accent, and duration), emotional content, and speaker identification became secondary. Therefore, for the languages for which these factors are not essential for the purposes of intelligibility, it was possible to normalize the intensity, duration, and pitch of the various segments, which entails a reduction in their number, a simplification in their search and, subsequently, in the rules of the text-to-speech conversion (Francini, Debiasi, and Spinabelli 1968). The realization of such an approach required the development of a special computer system, and this led to the birth of computer music research in Padua.

Development Steps and Education

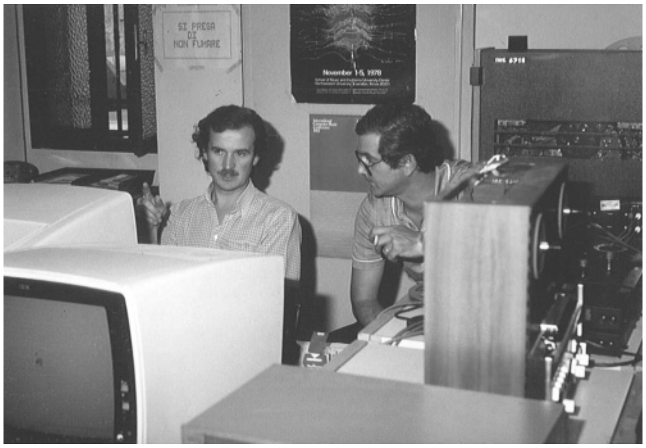
Research in the field of computer music at the University of Padua started in 1972 with a Master's thesis by Giovanni De Poli on score coding, at the initiative of a group of researchers and musicians as an expansion of Debiasi's research on speech synthesis (Dashow et al. 1978).

The activities were first hosted by the university computing center Centro di Calcolo di Ateneo (CCA). The possibility of making use of rooms, machines, and computer facilities at the CCA (at that time directed by Carlo Panattoni) without constraints granted great freedom to the researchers and the musicians involved in CSC, who could then devote their time to explore and experiment with new and innovative research paths.

Soon Padua University signed formal cooperation agreements with the Conservatory of Padua (in 1974), thanks to Rampazzi, professor of Electronic Music from 1972 to 1979, and with the Conservatory "Benedetto Marcello" in Venice (in 1976), thanks to Alvise Vidolin, professor of Electronic Music from 1976 to 2009, allowing musicians and students to use the university computer music system and to regularly attend the laboratory to realize music compositions.

The University of Padua formally instituted CSC in 1979 as a joint collaboration of the Institute of Electrical Engineering, the CCA, and the Faculty of Engineering. The founding members were Debiasi (director until 1981), who—often ahead of the international scientific community—carried out research in several fields, from speech and music synthesis to preservation and restoration of cultural musical heritage; Graziano Tisato (director from 1981 to 1991, see Figure 3), researcher on speech and on sound analysis and synthesis; De Poli (director from 1992 to 2015, seen in Figure 1), interested in algorithms for sound modeling, expressiveness in music, and preservation and restoration of audio documents; and Vidolin (artistic supervisor at CSC since its inception, Figure 1, and a distinguished computer music designer and live electronics performer [Zattra 2018]). De Poli and Vidolin were also former members of the NPS Group. From 1991 until 1992, Stefano Merigliano, director of the

Figure 3. Graziano Tisato (left) and Gian Antonio Mian at the ICMS console.



CCA, was also appointed as CSC director. Sergio Canazza (see Figure 4) has directed CSC since 2015. He carries out research in affective multimodal human–computer interaction (HCI) and computer science for musical cultural heritage.

Since 2009 the cooperation of CSC with the Conservatory of Padua has been strengthened by the creation of the Sound and Music Processing Lab (SaMPL, see www.facebook.com/SaMPL-151443791562594). Directed by Nicola Bernardini, professor of Electronic Music at the conservatory, SaMPL combines artistic and scientific components and offers advanced teaching. It is the first *living lab* dedicated to music and musicians. A living lab is a concept that can be defined as a user-centered, open-innovation ecosystem, often operating in a territorial context (e.g., in a city or larger metropolitan area, or extending to a larger region), integrating concurrent research and innovation processes within a partnership between businesses, citizens, and government (Almirall and Wareham 2011).

Until 2003, CSC labs were hosted in several rooms in the CCA building. This was necessary in the early years of CSC, because only one computer dedicated to music existed in Padua, an IBM System/7, and it was installed in the CCA building. In 2003 CSC moved its labs to the Department of Information Engineering (DEI) and it has been officially part of the DEI department since 2009. At the time of writing, it includes a laboratory for Computer Science for Musical Cultural Heritage (director: Canazza); a laboratory for Multimodal Interaction for Learning and Well-Being and Computational Creativity (director: Antonio Rodà); a laboratory for Musical Production (director: Vidolin and Canazza); and an archive of audio tapes, electronic equipment (often originally designed and realized in CSC), correspondence, manuscripts, books, and scientific articles (manager: Canazza).

Education

The participation of the Faculty of Engineering in CSC was underscored by the institution of a computer music course (active since the academic year 1978–1979, one of the earliest such courses worldwide). The course evolved with different names and programs, keeping up with the state of the art of international computer music research:

- 1978–1990: Musica all'Elaboratore Elettronico, as part of the Master's program in Electronic Engineering curriculum;
- 1990–2005: Sistemi di Elaborazione per la Musica;
- 2005–2019: Informatica Musicale; and
- as of the current academic year (2019–2020): Computer Engineering for Music and Multimedia, within the Master's program in Computer Engineering.

In addition to the computer music course, scientific education was ensured through supervision by PhD students and by the presence of visiting students from European partners and students enrolled in the Erasmus exchange program.

Special importance has been given to teaching to ensure the dissemination of competencies developed through production and research activity. Such activity moves in two directions: one for musicians who want to familiarize themselves with new techniques of composition and performances, and the other for students from STEM disciplines who want to specialize in the field of computer music.

In the 1970s, the only possibility of practicing computer music was to attend institutions where large computer systems were available. To this purpose, agreements with the Conservatory of Padua were signed. Music students could familiarize

Figure 4. CaRo 2.0 system wins Rendering Contest (Rencon), Stage II, 2011. Announcement by contest co-organizer Mitsuyo Hashida (a) and reaction from the audience (b) showing, from left to right, Antonio Rodà (applauding), Sergio Canazza (arm raised), and guest musician Davide Tiso (standing), who was also a team member.

(a) (b)

themselves with computer music by attending courses at the Conservatories in Venice and Padua in which the CSC facilities were used for practice, thus introducing them to a research and production environment rich in stimuli. In the 1980s, with the development of personal computing, it was necessary to acquaint musicians with new techniques of composition and performances. A series of summer schools (1983–1989), structured in independent and intensive teaching modules, were organized. Moreover, wide-ranging meetings were arranged, in which both composers and researchers presented their most recent works. Introductory seminars and broad overviews of topics of general interest were organized for a less-specialized audience.

CSC organized numerous international conferences, including the 1982 International Computer Music Conference (ICMC) in Venice and the 2011 Sound and Music Computing Conference (SMC) in Padua.

Scientific Research at CSC

Although CSC was not formally established until 1979, research at the University of Padua from the 1970s is included in this section because the important achievements in the decade led to the founding of the CSC. The long-term idea was to create an interdisciplinary space where scientific and musical expertise could meet to achieve a constant application of knowledge developed by theoretical research to music production and, conversely, to stimulate scientists to investigate and formalize issues that arose from the musical experimentation and creative utopias of composers.

During these years, CSC research moved in several directions, pushed by the advancement of technology and knowledge and by researchers' curiosity. It should be mentioned that many of these activities reflect trends in the international field of computer music and are not necessarily specific to CSC. The evolving foci are listed here by the decade when they became key issues, but they should not be intended as limited to specific years, as their importance outlasted any single decade.

In the 1970s particular attention was paid to acoustic aspects, and the aim was to generate any type of sound by a computer, with little regard for interactivity. The initial approach was complementary to that followed in Pisa: Whereas the focus there was on algorithmic composition and randomness, in Padua the focus was on sound quality and determinism. Over the years, the study of sound and, above all, of sound production with new methods has become a focal point of attention for researchers and musicians. This considerable interest is reflected in the name of CSC and in those of several computer music centers that were created around the same time.

In the 1980s work at CSC moved towards basic scientific research. The focus in this decade was on instrumentality, i.e., allowing interaction in real-time processing and the categorization of sound classes by new synthesis algorithms and perceptual timbre spaces.

In the 1990s the new focus was on the exploration of expressiveness and performance. The goal was to overcome the rigidity typical of early computer music, to render the many expressive nuances introduced by a performer while playing a piece of music.

At the end of the 1990s, international computer music research evolved into the broader field of sound and music computing, incorporating nonmusical areas related to research on sound (Bernardini and De Poli 2007). An important new theme in the decade beginning in the year 2000 was preservation of musical cultural heritage, in particular for art forms in which technology had played an important role, such as electronic and computer music (in which composers had worked directly with magnetic tape) or interactive multimedia installations. It was motivated by the awareness of the technological obsolescence and the historical importance of the music works realized at CSC.

In the 2010s interaction studies opened up important new societal fields of research, such as inclusive systems dedicated to learning for people with special needs, using modeling for tracking of human motion and nonverbal 3-D sounds as a preferred communication channel.

In retrospect, the evolving research trends can be summarized as:

1970s: systems for sound synthesis,
1980s: instrumentality,
1990s: expressiveness,
2000s: musical cultural heritages, and
2010s: inclusive interaction.

Sound Processing for Music

The focus of CSC research in sound processing proceeded in different directions: speech analysis and synthesis, development of computer music systems, algorithms for sound modeling, timbre spaces, and spatial audio.

Systems for Computer Music

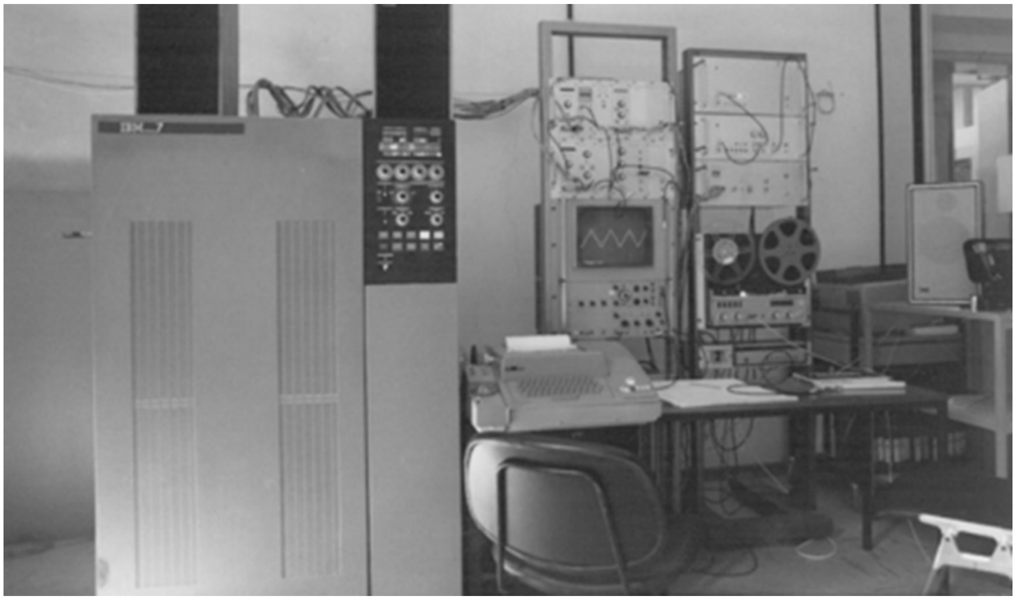
In the 1970s the first research objective of CSC was to develop a system for computer music that would provide researchers the opportunity to operate in an integrated manner both at the score level and at the sound level. The first musical sounds that could be heard at CSC in the beginning of 1974 were a melody played by an organ simulation.

The main concern was to create a complete system, easy to use and flexible in application, for producing music with the equipment of CCA, an IBM mainframe connected to an IBM System/7, for high-quality, four-channel digital-to-analog conversion. Figure 5 shows the system for speech and music research in 1979. For batch synthesis, the Music V and Music 360 programs were used (Dashow et al. 1978). Languages for encoding traditional scores alphanumerically and for computer-aided composition were developed.

Graziano Tisato created the Interactive Computer Music System (ICMS) in 1976 for interactive synthesis (Tisato 1976). The system operated in a multiprogramming environment, and its principal purpose was to develop a single environment suitable for the processing of any sound source, be it acoustic or synthesized, vocal or instrumental. It provided real-time synthesis, editing and mixing of selected musical material, reverberation and spatial distribution on four channels, linear predictive coding (LPC) sound analysis, and synthesis using any sound source as the stimulus. Particular care was given to HCI through easy commands and graphic visualization. This allowed ICMS to provide an easy introduction to computer music, particularly for nonspecialists.

The system was successfully used in the production of many musical works, for acoustic and psychoacoustic research, and for educational purposes. The sound analysis system provided a deep understanding of the acoustics of multiphonics on woodwind instruments, an experimental performance technique developed in the 20th century in

Figure 5. Hardware and software systems used by CSC in 1979 for recording, sound synthesis, and music processing. (Photograph by Luciano Menini, Padua.)



which several tones are produced at once by using special fingerings and particular embouchures.

Speech Research

Research on speech synthesis in the time domain required a dedicated computer system for an optimal selection of the time segments. As the memory space to store the segments was both expensive and limited, considerable effort was devoted by Mian, Mildonian, and Offelli (1973) to extract the smallest possible number of speech units from articulated speech. For each isolated vowel two units were needed, the first containing the initial transient and part of the steady state, the second containing the remaining part of the steady state and the final transient. For consonant-to-vowel groups one unit was used for consonant-to-vowel transition, and the second unit was the same as the second unit in the isolated vowels. Almost all isolated consonants required a unit but very few groups, like some diphthongs, required specific pairs of units. The system synthesized clearly intelligible speech, albeit with a robotic quality (Francini, Debiasi, and Spinabelli 1968). The system was later expanded for German, Greek, and Serbo-Croatian languages (Stathopoulou, Kokkinakis, and Mian 1980).

A system for the automatic translation from any Italian text into naturally fluent speech was developed in the 1980s. It was built up around a phonological processor, which mapped the phonological rules of Italian into prosodic structures, and around a synthesizer that processed and joined LPC-coded diphones, derived from the previous research on concatenative speech synthesis. This repertoire of diphones resulted in an interesting possible application: using this set, with its well-known timbral characteristics, as a spectral vocabulary for controlling musical sound synthesis (Mian and Tisato 1986). This study of the voice culminated in research on overtone singing that investigated the virtuosic technique of a singer able to emphasize some upper harmonics while holding the fundamental frequency constant, thus creating a two-voice texture (Tisato and Ricci Maccarini 1991).

Sound Modeling

With the increased availability of personal computers in the 1980s, scientific research at CSC was oriented towards digital signal processing and to the analysis and synthesis of musical sounds, with the dual goals of supplying composers with new timbres, on the one hand, and of developing efficient algorithms for low-cost computer music systems, on the other. In the early years of computer music, the ambition was to enable the generation of any sound that the human ear can hear through digital means. It was soon clear, however, that any sound can be reproduced by sampling, but that new sounds can be created as far as an explicit computing procedure (a synthesis algorithm) can be described. This idea greatly encouraged the study of new algorithms (and models) for sound synthesis and their subsequent utilization in creating music.

A sound-synthesis algorithm can be thought of as a digital model for the sound itself; it can be used for representing and generating a whole class of sounds, depending on the choice of control parameters. The idea of associating a class of sounds with a digital sound model is in complete accordance with the way people tend to classify natural musical instruments according to their sound generation mechanism. The structure of the algorithm gives an identity to the sound class. The degree of compactness of a class of sounds is determined, on the one hand, by the sensitivity of the digital model to parameter variations and, on the other, by the amount of control necessary for obtaining a certain desired sound (De Poli 1983; Borin, De Poli, and Sarti 1997).

Various synthesis techniques modeling the audio signal were investigated, in particular, frequency modulation with phase or frequency series modulators (De Poli 1983) and special functions for waveshaping synthesis (De Poli 1984). De Poli collaborated with Aldo Piccialli of the University of Naples in working on time-domain algorithms for sound synthesis. Different strategies were proposed to bring methodologies and techniques of digital signal processing into the context of granular synthesis. With this goal in mind, they developed several techniques for waveform design and transformation (pitch-synchronous granular synthesis) to produce sounds with time-varying formant regions (De Poli and Piccialli 1991).

At the end of the 1980s, the increased computing power promoted a shift of focus in synthesis techniques from signal modeling to sound source modeling, i.e., to the development of models of physical sound production mechanisms (physical modeling synthesis), rather than the simulation of the sound itself (Pope 1992, 1993).

At the time, sampling synthesis applications were limited by storage costs, thus the physical model approach offered new perspectives on sound generation. In this case, the class of sounds that could be produced was much more limited (it is a characteristic of the mechanism to be modeled by the algorithm) but the degree of difficulty involved in generating the control parameters was quite modest, as it corresponded to physical parameters that had an intuitive counterpart in the experience of the musician. The basic advantage was that source models were naturally dynamic, with behaviors similar to the modeled objects, and they reacted directly to users' actions, thus having potential applications in HCI and in the synchronization of audio and visual synthesis. Moreover, they could be used with parameters unusual in musical practice. These models could also be used to develop new structures inspired by—but not directly related to—physical models of real objects. Using this method, the experience gained in simulating traditional instruments could be useful to develop new synthesis algorithms (De Poli 1996).

To experiment with the effectiveness of this approach, researchers at CSC initially studied efficient algorithms for the simulation of specific musical instruments and the main mechanisms of sound excitation. Research on synthesis with physical modeling continued with the definition of the concept of a generalized exciter and resonator as a unifying element. This structure inspired the realization of most of the classical mechanical and fluid dynamic exciters of musical instruments, and of pseudophysical exciters (Borin, De Poli, and Sarti 1992).

Computational delay-free loops often occur in physical modeling synthesis. This issue was addressed and two novel methods were devised: the K-method (which used geometric transformations of nonlinearities and algebraic transformations of equations in the time domain, cf. Borin et al. 2000), and a generalization of the formalism of the wave digital filters applicable to nonlinear elements (Sarti and De Poli 1999). This latter proposal was well matched with the waveguide models that were widespread at that time in musical instrument simulations (and remain in use today).

Timbre Research

Another focus of CSC research was directed at investigating the physical and perceptual relationships that exist among sounds and explaining the main factors that differentiate timbres. A more effective sound generation could thus be obtained. Researchers at CSC used acoustic analysis methods derived from digital signal processing (such as mel-frequency cepstral coefficients, see De Poli and Prandoni 1997) and from computational auditory models (such as the classical auditory model, cf. Cosi, De Poli, and Lauzzana 1994) with an advanced physical model of the cochlea (Balliello, De Poli, and Nobili 1998) to obtain relevant parametric representation. Then, low-dimensional physical timbre spaces, which preserved the perceptual topology of musical timbres, could be obtained by means of self-organizing map neural networks and multivariate analysis: Different sounds were distinguishable and, at the same time, similar sounds were close together. These physical timbre spaces supported the importance of the features of the steady-state portion when evaluating timbre quality and confirmed the importance of the attack for recognizing sounds (Cosi, De Poli, and Lauzzana 1994; De Poli and Prandoni 1997).

Spatial Audio

For reverberation, circulant feedback delay networks (CFDNs) were studied as a generalized model of a resonator. The main advantage of physical modeling techniques, namely, the availability of physically meaningful parameters such as size, absorption, damping, diffusion, etc., is retained with CFDNs. At the same time, the CFDN model was sufficiently general that it could be used as instrument resonator, postprocessing filter, or reverberator (Rocchesso and Smith 1997).

Research activity at CSC included the development of innovative techniques for spatial audio synthesis with particular attention to binaural audio synthesis and real-time audio rendering. Spagnol, Geronazzo, and Avanzini (2013) analyzed the contribution of the external ear in relation to specific and individual head-related transfer functions and modeled the physical features that had a perceptual interest for vertical localization of sound. Efficient real-time algorithms were developed for spatial sound rendering for a coherent simulation of complex multisource acoustic environments in which the spatial positions of both the listener and the sound source were expected to move dynamically.

As an example of nonmusical application of research on sound, microphone array systems with variable geometry were specifically designed for both the monitoring of urban environments for homeland security and for performer-tracking systems for live electronics (Salvati and Canazza 2013).

Expressiveness and Well-Being

Expression is an essential aspect of music performance. Moreover, understanding and modeling expressive content and emotion communication is important in many engineering applications. Thus, human expression and expressive behavior have become a domain of intense scientific study, as has their application in the field of HCI. The following sections present CSC research in this area.

Modeling Expressive Music Performance

The interest in comprehending how musical sounds are articulated in a musical context directed some research groups towards the field of affective computing and, in particular, to analysis and modeling of music performance. As a consequence, in the 1980s computational models of music performance started being developed, for example in Sweden (Sundberg, Askenfelt, and Frydén 1983).

In this context, CSC changed the focus of its research to study how different expressive intentions could be communicated by the performer to the listener, and introduced models to explain how to modify the performance of a musical piece to convey a particular expressive intention. Canazza et al. (2000) analyzed many musical performances played with different expressive intentions, and looked into the relationships between measurable parameters and intentions, to understand what strategies performers employed.

These analyses led to the development of computational models for rendering and processing expressive content in multimodal interactive systems (Canazza et al. 2000, 2012). The CaRo model, developed by Canazza and Rodà (and named after them), allows the performer to gradually modify the expressive content of a performance, both at the symbolic and at the signal level, smoothly morphing between performances with different expressive content and adapting the expressive character of the audio to the user's needs (Canazza, De Poli, et al. 2015).

Understanding Expressiveness

Music experience can be described from many complementary points of view. Different perspectives may be suitable for different applications and contexts: For example, emotional aspects of musical experience could be useful in affective HCIs, sensory-motor aspects could be useful in direct interaction and manipulation of contents, psychological aspects of cross-modal experience may reveal mechanisms concerned with synesthesia, and so on.

The concept of the performer's expressive intentions was extended beyond emotions by including labels with sensorial connotations, which are frequently used in music performance. Music performances played to convey expressive intentions suggested by sensorial adjectives (bright, dark, light, heavy, soft, hard, and natural) were rated by listeners on a series of continuous verbal scales used to characterize sensorial qualities the listeners felt when the stimulus was expressed. The listeners' ratings were analyzed by means of multivariate techniques. Two quite distinct expressive factors were observed, one related to the kinetic parameters and the other related to the energy of the pieces (Canazza et al. 2003).

Traditionally, the analysis of musical expression is based on measurements of the deviations of acoustic parameters with respect to the written score. Based on that assumption, researchers at CSC investigated the most relevant score-independent audio features describing expression in music performance at different time scales (e.g., from simple sounds to music as a structured organized events). These audio features could be used to retrieve expressive content from audio data and to design search engines for music information retrieval (Mion and De Poli 2008).

Sensory-Motor Expressiveness

The emerging view was that experiences of music are multifaceted, of different kinds, or possibly consisting of interacting qualities, aspects, and dimensions. From a technological point of view, the understanding of metaphors used to describe different aspects of music (affective, sensorial, or physical) supported the development of new applications for interaction with musical content. The relations between acoustic cues and metaphors could be used to develop systems for the automatic generation of metadata. Action-based metaphors could be used to enhance the interface of devices using gestural interaction with musical content, such as portable music players or musical video games (De Poli et al. 2017).

To understand sensory-motor expressiveness without using verbal labels, Mion, De Poli, and Rapanà (2010) focused on the associations between (1) emotional and sensory expressive intentions and (2) human movements, from the point of view of an action–reaction paradigm. Three clusters of stimuli were found: happy/light, sad/calm, and hard/angry/heavy. The same patterns were also found in a previous study (Mion and De Poli 2008) when acoustic cues were used to group music performances inspired by different emotional and sensory expressive intentions. These results supported the hypothesis that the three clusters corresponded to different expressive categories that could be characterized both from an acoustic and from a perceptual point of view.

Murari et al. (2015) used the semantic differential approach with nonverbal sensory scales taken from the visual, gustatory, haptic, and tactile domains to study cross-modal associations. The results showed that sensory scales provided an alternative understanding of the musical experience, since they index different aspects of the musical experience not accessible to natural language and could provide fruitful results in the fields of cross-modal associations and synesthesia.

The important role of valence and arousal dimensions in representing and recognizing emotions in music is well established. There was less evidence for the contribution of secondary dimensions such as potency, tension, and energy. By perceptually clustering real-world musical recordings, constrained on modality and tempo, Rodà, Canazza, and De Poli (2014) could identify computable musical features that can be related to the potency dimension, to use them in automatic recognition or classification tasks.

Multimodal Interaction for Learning and Well-Being

Today, educational materials need to be more than just pages full of content, noninteractive videos, or purely text-based communication. Although acceptable in the past, they are no longer engaging for students, in particular for those with severe disabilities who attend public schools. We feel that it is possible to tackle this issue using interactive multimodal environments at school, offering teachers a simple yet innovative tool to manage lessons.

In our opinion, inclusive learning for participants with disabilities is one of the most important and urgent aims in the new millennium. Since the 2010s, CSC has been developing interactive applications based on large-scale responsive environments and user-friendly involvement with expressive behavior (for teaching music or for tuition of the visually impaired), emphasizing the added pedagogical value of fun and competition. Experimental results showed a great user engagement and a satisfying amount of successful results in formal task activities (Zanolla et al. 2013; Mandanici, Rodà, and Canazza 2017; Mandanici et al. 2018).

Musical Cultural Heritage

The last four decades at CSC have seen the realization of many musical works. As a result, the problem of preserving these works for posterity arose. In the 1990s, in the international field of computer engineering for musical cultural heritage, digital restoration of audio documents increasingly drew attention and many different solutions were proposed for the application of digital processing techniques to this field, a trend probably derived from the glamor of the (seemingly) unlimited potential of the new digital media for music (e.g., DAT, CD-A, or DVD-A) and new recording tools. Researchers at CSC took a step forward and addressed the problem of improving existing algorithms, not only for simple denoising, nor purely for the aesthetic of digital silence, but rather to tackle the issue in terms of computational efficiency and quality of results, and extending their applicability to sounds and music that have been relatively neglected, such as electroacoustic and computer music (Canazza, De Poli, et al. 2010). This has been an immensely challenging task, considering CSC's particular computer music production, in which there are so many sound objects with an energy distribution on the frequency domain similar to that of noise recordings of concrete sounds, or synthesized by noise generators, or obtained by cut-and-paste operations from magnetic tape (Canazza and Orcalli 2001; Canazza and Vidolin 2001).

The methodology used at CDC identified a number of possible goals to audio restoration: (1) intelligibility recovery in speech recordings; (2) speaker recognition; (3) adaptation to current aesthetic tastes (in artistic fields: concerts, CD-A production); and (4) retrieval of historical information (e.g., using tape noise to recognize the original studio equipment used in the historical recordings, cf. Canazza and Vidolin 2001).

Preservation and Enhancement of Musical Cultural Heritage

Millions of hours of recordings of music, sounds, voices, and evidence of past life are being lost. The erosion of collective memory is due to the intrinsic physical and chemical instability of audio media, which results in a short life expectancy (LE) from only few years to, at best, a few decades. This is in sharp contrast to the LE of the materials used in other artwork, such as paintings or sculptures, in which degradation is measured in centuries or millennia.

The preservation of the musical works at CSC corresponded to specific studies on each work, which meant a precise philological research on the compositional processes. In this sense, in the 2000s the CSC research on the preservation and restoration of audio documents evolved and combined information engineering with musicology and philology to meet the needs of today's society, for which everything needs to be stored, browsable, and available by "anybody, anytime, and everywhere" (Canazza, Camurri, and Fujinaga 2010; Canazza, De Poli, and Mian 2010; Canazza 2012; Bressan and Canazza 2013). This implied the definition of new strategies for data storage and the study of new techniques for content search (e.g., query by humming) in data mining, as well as listening strategies appropriate to each situation (e.g., the living room, the concert hall, or headphones connected to a Walkman or an iPod).

An innovative and philologically informed methodology for the conservation, restoration, and critical editing of sound documents (in particular, speech archives and electroacoustic audio documents) has been defined, and has already been applied in international research projects funded by large archives (e.g., the Luigi Nono Archive, Centro Studi Luciano Berio, Paul Sacher Stiftung, Verona Arena, and the Scuola Normale Superiore in Pisa). Taking advantage of an interdisciplinary team consisting of musicologists and information engineers, CSC's methodology accounts for the cultural context in which the document has been produced, while preserving it within an infrastructure adequately equipped and with devices developed as needed (e.g., functioning, professional playback equipment, compatible with the format of the documents to remediate; analog-to-digital converters; precision incubators for thermal treatment of magnetic tapes; etc.; for details, see Fantozzi et al. 2017).

In parallel to a thorough and rigorous philological attention, a methodology with a high degree of automation necessary for the massive preservation task has been defined, thanks to artificial intelligence software tools specifically developed for discontinuity detection and equalization recognition, and to the systematic review of chemical-mechanical analyses to identify the most suitable treatment for the carrier (Bressan et al. 2016).

Today, the typical scenario in a music library is as follows: The scholar interested in studying a piece will be given a digital copy on compact disc, or on an MPEG-3 player. In both cases the rendering is, at the very least, unfaithful to the peculiarities of the analog original, and it is also incomplete, as the copy does not give the access to ancillary information from the original computer music analog tape, such as pictures of the annotations (marks and writings by the composer or by technicians), splices, chemical corruptions, and the color of leader tape often used also for identifying the lead-in and tail-end sections of musical piece sections (Pretto et al. 2018). Commercial software packages that reflect some characteristics of analog players (e.g., gramophones) exist, but the virtualization is incomplete and inaccurate. At CSC, application software has been designed and developed for several platforms (tablet, smartphone, and Web-based) to recreate the experience of the original analog equipment. For each piece of music the apps show a rich set of metadata, both textual (for instance, author, year, or country of origin) and multimedia (e.g., pictures of the original media or a video of the original tape synchronized to the audio). The virtual devices on the app are controlled using a skeuomorphic user interface that reproduces the behavior of a real device in detail (Canazza, Fantozzi, and Pretto 2015).

Preservation of Historical and Modern Instruments

There are several different kinds of musical instruments, each with peculiarities that need to be preserved and communicated. All of them share a common characteristic, however: To be understood, they must be played. Other multidisciplinary work carried out at CSC in the field of computer engineering for musical cultural heritage concerned the enhancement of modern electrophonic instruments (e.g., Studio Fonologia Musicale della RAI di Milano, see Canazza et al. 2011) and of historical musical instruments (e.g., a pan flute, cf. Pretto et al. 2020). At CSC, a methodology to develop a multimedia installation that communicates and enhances both acoustic and electrophonic instruments by considering their cultural context has been defined. Multimedia installations could be a valid means to provide interaction with artifacts, which are usually not touchable nor playable in museums. The interaction model used to provide access to the general public is based on multisensory interplay (visual, auditory, and tactile) that includes both contextual information and a virtual counterpart of the artifact. The methodology includes an adaptation of "design thinking" for interactive museum installations and a deeply interdisciplinary matching design process (Pretto et al. 2020).

Preservation of Interactive Multimedia Installations

Born in the first decades of the 20th century, installation art has been able to foresee the potential of new media, and it has largely explored their possible applications. Today, the impact of installation art on contemporary artistic production is acknowledged worldwide. The deep interconnection with technology is taking its toll in terms of fast obsolescence, however, which may soon become an irreversible loss. At CSC such new challenges raised by interactive multimedia installations with respect to preservation have been studied. Not only do installations change over time, but they also change according to what happens in the surrounding environment. The variations in time may be programmed to occur automatically, or they might require an external event (most commonly, a user action). Variations with respect to time and interaction introduce some of the most complex issues in the preservation of interactive multimedia installations. They are not completely new for CSC, however, as they had already been raised by musical "open works" such as *Scambi* (1957) by Henri Pousseur (Canazza and Dattolo 2009).

Time is a crucial factor also in the sense that multimedia installations are characterized by an LE that is significantly lower than that of other cultural materials. Interactive multimedia installations are affected by a short LE in different ways. From least to most serious, these are: degradation of physical elements, degradation of hardware and software (i.e., the hardware itself, software environments, file formats, and programming languages), and loss of knowledge about the setting (LE may even coincide with the duration of the exhibition).

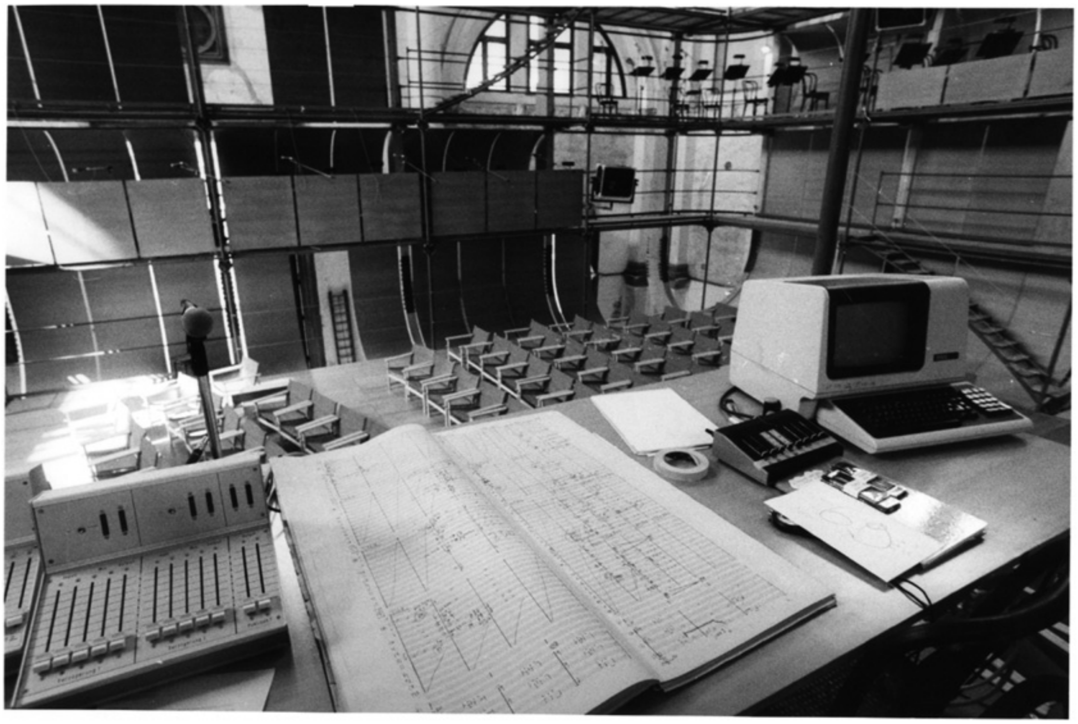
The CSC model for the preservation of interactive multimedia installations (cf. Bressan and Canazza 2014) provides different approaches to maintaining the object we wish to preserve: documentary, aesthetic (to recreate the original experience, to "feel it again"), sociological (to reflect what the installation meant to the people of the era and how it was perceived), and reconstructive (to replicate the work as faithfully as possible).

Music Research at CSC

With the emergence of live electronics (Manning 2004, ch. 8) now used in a large music repertoire all over the world, a new professional figure with dual training, with both a musical and a scientific background, became necessary. At CSC, a close cooperation between the electronic music class at the Conservatory of Padua and the degree program in computer engineering at the University of Padua led to the successful teaching of many musician-engineers: Scientists, researchers, and technicians continue to collaborate with artists using the new art-science-interaction laboratory and CSC know-how as a support for the innovation of expressive forms in music, music theater, and interactive multimedia arts.

In addition, CSC aims to promote and encourage the production of works that use computer systems to control and to create music, especially projects that use technologies developed in its laboratories. It has also developed new interfaces to play instruments, necessary to control musical timbre

Figure 6. The musical space designed by Renzo Piano in 1984 for Luigi Nono's Prometeo. *The VT100 terminal of the computer Digital PDP-11, which controlled the 4i System, is in the foreground. Potentiometers are used for gesture control. (Photograph by Graziano Arici, Arles.)*



and the virtual space, stimulating the interest of many composers who believe that the traditional keyboard is not suited to simultaneously control multiple parameters, synthesis algorithms, and sound spatialization.

In the 1980s CSC, together with the Institut de Recherche et Coordination Acoustique/Musique (IRCAM) in Paris and the Laboratorio per l'Informatica Musicale della Biennale (LIMB) in Venice, developed the 4i System, designed by Giuseppe Di Giugno. The system is based on digital processors for live electronics with four DACs, two ADCs, and a control interface for performance parameters (Vidolin 1997). This system was used to move sounds in space in one of the most important musical works of the second half of the 20th century, Luigi Nono's *Prometeo*. Figure 6 shows the choir and orchestra arrangement in the original musical space designed by Renzo Piano for the performance at the Venice Biennale in 1984.

Several artists work on musical projects at CSC and are stimulated by the permanent collaboration with CSC researchers, thus having the opportunity to organize concerts. In fact, CSC organizes concerts open to the general public, presenting experimental and research-related musical and multimedia projects. Such concerts mainly take place in the Conservatory of Padua's auditorium, but CSC is also equipped for different venues (e.g., the Padua Botanical Garden) with a number of art and music organizations.

Works

A complete list of musical works produced at CSC is available at http://csc.dei.unipd.it/multimedia-works.

Many electroacoustic works were realized in the 1970s by the CSC historical composers. Two examples are "With the Light Pen" (1976) by Rampazzi and Paolo Balladore and "Whispers Out of Time" (1976) by James Dashow.

"With the Light Pen," for ICMS, premiered June 1977 in Bourges, France, where it was awarded a Special Mention in the International Electroacoustic Music Competition. It is available on CD (Rampazzi 2008).

"Whispers out of Time" had its premiere March 1976 in Rome, as part of the Beat '72 festival, and won First Prize in the analog electronic music category at the 1977 Bourges International Electroacoustic Music Competition. It is included in on a CD (Dashow 1995)

In the following, some representative works, noteworthy from historical and scientific points of view, are highlighted, ranging from the 1980s to the 2010s.

Luigi Nono: Prometeo

Nono's *Prometeo: La tragedia dell'ascolto*, for vocal and instrumental soloists, choir, orchestra, live electronics, and 4i System, was commissioned by the Venice Biennale and the Teatro Alla Scala in Milan. Computer production was by Sylviane Sapir, Vidolin, and Mauro Graziani, and the work had its premiere 25 September 1984 in Venice, in the Chiesa di Santa Lorenzo. The score and several recordings are available (Nono 1985, 1995, 2018).

Prometeo is one of the most important musical works of the second half of 20th century in which technology has a mandatory and dominant role. The composer renounced the traditional scenic elements, costumes, and theatrical actions of the opera to focus the audience's attention wholly on the music. The work was presented in an acoustic environment designed for the music by the architect Renzo Piano: a wooden structure containing musicians and audience for an immersive experience in a world of sounds, favoring the vertical dimension (see Figure 6). (For more details about Nono's work and, in particular, *Prometeo*, cf. De Benedictis and Rizzardi 2018). For the occasion, CSC developed custom real-time digital synthesis performing environments, played live at the premiere in Venice. By means of the 4i System, a timeless, mobile, and distant chorale was performed and a sweet, iridescent B flat, simultaneously monodic and polyphonic, hovered progressively in space in constantly changing timbral-harmonic structures (Vidolin 1997).

Salvatore Sciarrino: Perseo e Andromeda

Perseo e Andromeda (1989) is an opera in one act by Salvatore Sciarrino, for four voices and synthetic sound, with a libretto by Jules Laforgue. Commissioned by the Staatstheater Stuttgart, the computer production was realized by Vidolin and Paolo Zavagna. The premiere took place 27 January 1990 in the Staatstheater Stuttgart. The score and a recording are available (Sciarrino 1990, 2001).

Perseo and Andromeda is one of the first works in the history of musical theater using no traditional acoustic instruments. All the sounds are performed live by two musicians using a network of four computers running software for live electronics developed by CSC (see Figures 7 and 8). Particularly innovative was the technique of sound generation based on subtractive synthesis, transforming white noise into a vast palette of noises and melodic gestures through the judicious use of dynamic filtering. It was not intended as an adaptation to new media, but Sciarrino meant to design it with computers, creating a particular surreal alienation, inseparable from the fantastic dimension of such music (Vidolin and Zavagna 1990, note that although the text is in Italian, it includes the entire Music V code). Inseparable from the electronic part, the vocal part was entrusted to four traditional singers: soprano, mezzo-soprano, baritone, and bass, with the curious feature that Perseo's part is portrayed by the two lower voices, who always sing as a duo (Vidolin 1997).

Carlo De Pirro: Il Caos delle Sfere

Il Caos delle Sfere: Anche Tu Musicista con 500 Lire (The Chaos of the Spheres: You, Too, Can Be a Pianist for 500 Italian Lira, 1998–1999) is an installation for electronic pinball and Disklavier. Computer production was by Paolo Cogo and Nicola Orio, and the work premiered 9 June 1999 in the Biennale dei Giovani Artisti di Europa e del Mediterraneo (Biennal of the Young Artists of

Figure 7. The orchestra in Perseo e Andromeda *by Salvatore Sciarrino. Two musicians, Vidolin (left) and Paolo Zavagna, playing a network of four computers. (Photograph by Horst Huber, Stuttgart, 1991.)*

Europe and Mediterranean) in the Mattatoio del Testaccio in Rome.

A real electronic pinball machine controlled an automatic performance played on a Disklavier (see Figure 9). The installation was based on the popular pinball game "Creature from the Black Lagoon." This was one of the first pinball games to use the concept of different game levels in which the player needed to achieve a number of goals to go on to the next level. This kind of interaction introduced a large amount of unpredictability in the resulting sounds. The composer's idea was to avoid a one-to-one mapping between the objects hit by the ball and the generated sound. Moreover, the composer decided that a proficient player should be rewarded with a more interesting and complex performance than a less skilled player. To this end, the amount of interaction varied according to the progress through the game: As the player reached higher levels, the performance generated on the Disklavier became more complex and virtuosic. The game started with automatically generated sequences, partly controlled by the user, depending on the kind of targets being hit. To monitor the game, with its levels and targets, CSC developed a custom electronic circuit that sent data from the pinball machine's switches and lights to the computer through a parallel port. The software component was programmed to play, generate, and modify melodic sequences according to the composer's indications. The result was sent to the only sound source, the Disklavier, using the MIDI port (Bressan et al. 2009).

Giorgio Battistelli: The Embalmer

The Embalmer (2001–2002), a comic chamber monodrama, is based on a text by Renzo Rosso and featured Ian McDiarmid as speaker. William Kerley directed the stage production, and the computer

Figure 8. From sketch to code in Perseo*: excerpt from composer's sketches (a); the same passage at page 65 of the score (b); block diagram of one voice from the passage (c); and the final Music V source code (d).*

Figure 9. Carlo De Pirro's Il Caos delle Sfere*. An electronic pinball machine controls an automatic performance played on a Disklavier. Hardware and software developed at CSC.*

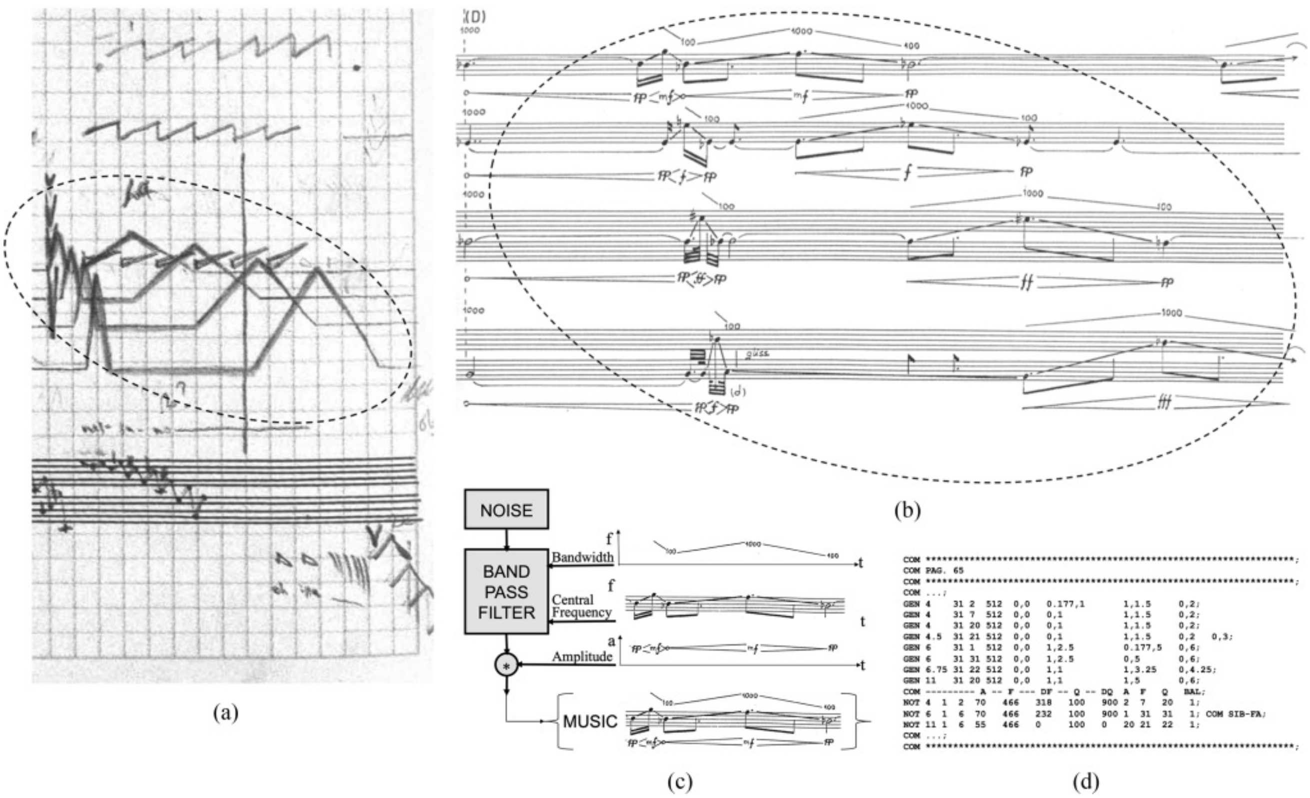


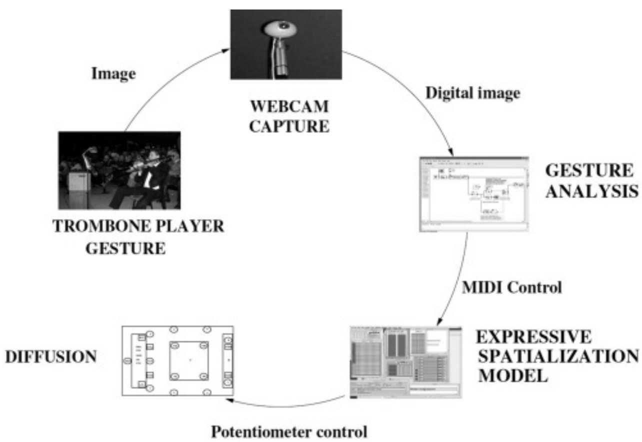
Figure 8

Figure 9

realization was by Vidolin and Davide Tiso (Figure 4b). The work saw its premiere perforamnce 7 October 2002 in the Almeida Opera, London. The score is available from Ricordi (Battistelli 2013a) and a recording is on the Stradivarius label (Battistelli 2013b).

The musical theatricality of the lyrics is mapped into acoustic events by real-time processing of the sounds of the live show, using CSC-developed software for live electronics. At the premiere in 2002, the performance took place in two halls simultaneously. The actor, a live instrumental ensemble, and live electronics were in the first hall. The sounds in that hall were electronically processed and then diffused over loudspeakers in the second hall. These transformations were carried out by means of motion-capture techniques, developed by CSC, to transform the instrumental ensemble music and the voice in real time, tracking the movements which were taking place on the scene. These processed sounds were played and spatialized

Figure 10. Expressive gesture and sound interaction in Adriano Guarnieri's video opera Medea. *The trombone player's gestures, captured by a digital camera, are analyzed and mapped onto spatialization software.*



in the second room following a slow evolution that started with a faithful sound reproduction of the show and finally reached a terrific simulation of the evaporation process (Vidolin 2002).

Adriano Guarnieri: Medea

Loosely based on the tragedy by Euripides, *Medea* (2002) is a video opera in three parts for video sequences, soloists, chorus, orchestra, and live electronics, in which the sound direction becomes almost visual, and the spatial sound seems to alternate between close-ups and overviews. Computer production was by Bernardini and Vidolin, and the premiere took place 18 October 2002 at the PalaFenice in Venice.

The Medea myth, represented by three female voices, merged with the play of the dynamics of sound in space. The sounds produced by the singers and orchestra were picked up by 68 microphones, processed by the live electronics software, and finally diffused over dozens of speakers spread throughout the audience. The sound movement in the room, moreover, was controlled in several different ways (e.g., by musicians' gestures) and reinterpreted in real time by live electronics software (Bernardini and Vidolin 2003, see also Figure 10 for a schematic example of how this was done for the trombone part). This work is one of the greatest artistic studies in expressive gesture and sound interaction, a domain born in the late 1990s.

Nicola Sani: Chemical Free(?)

Nicola Sani's *Chemical Free(?): Un Viaggio nel Microcosmo della Materia* (2014–2015) is a multimedia work. It was premiered 5 October 2015 in the Venice Biennale. Computer production was by Vidolin and Luca Richelli. The work is available on DVD (Sani 2015).

Chemical Free(?) is structured as three movements of about 15 minutes each, played without interruptions. The movements are connected by segments of acousmatic music. Each movement has a specific protagonist instrument, which becomes the leading actor: "There Is So Much Space Down There" (Richard Feynman) for double bass; "No Landscape" (Mark Rothko) for piano; "More Is Different" (Philip Warren Anderson) for hyperbass flute.

The three soloists were placed in three fixed positions, with the double bass placed on the right of the stage, the piano on the left, and the hyperbass flute at the center. The musicians were illuminated by a spotlight only when playing. The three instruments were used as sound generators, each using extremely suggestive and innovative performance techniques, real-time audio processing, and sound spatialization. The live electronics were applied to the three instruments in a multichannel spatialization system. In particular, the motion capture system PhaseSpace was applied to the hyperbass flute and to the piano (see Figure 11). Developed at SaMPL and CSC, the motion-capture and signal-processing software allowed the musicians' gestures to be captured by light sensors and used to transform their musical sound in real time.

Conclusion and Future Perspectives

Since its foundation in the 1970s, CSC has established itself as one of the world's leading research centers in the field of computer music. Its researchers achieved many important scientific and musical results, often attracting the attention and collaboration of musicians, including some of the most innovative and internationally recognized.

Figure 11. Motion capture system PhaseSpace applied to the piano, played by Aldo Orvieto, in Chemical Free(?) *by Nicola Sani. (Photograph by Andrea Graziani, Padua.)*

If the current "Industry 4.0" revolution emphasizes the transformation of factories into Internet of Things—enabled intelligent structures that use cognitive processing and interconnection via cloud servers, "Industry 5.0" (or, as it is sometimes called, "Society 5.0") is predicted to focus on the return of human minds into the industrial context (Nahavandi 2019). Although robots are excellent for manufacturing standard products in standardized processes, customizing each individual product can present a challenge where robots need guidance. It is therefore essential to maintain human contact within the production: Automation can be exploited to the maximum potential only when there is a spark of human creativity that influences the processes. In this situation, humankind and machine complement each other, and humanity is empowered and can use collaborative robots (or "cobots") as multifunctional tools.

CSC is striving to be a leader in this trend, taking advantage of the fact that music is a transcultural language. Currently, the CSC visions are to facilitate (1) the inclusion of people with special needs (e.g., multimodal interaction for learning and well-being, acoustic analysis for safety and security in the workplace) and (2) dialogue among different cultures and populations (production of new cultural events, computing and cultural heritage, preservation and enhancement of audio documents, and computational creativity).

To achieve these visions, CSC continues to push forward various activities, including:

1. Involving researchers in the development of new musical ideas, at the same time involving musicians as sources of creativity in scientific research.
2. Inspiring new generations of students, researchers, and artists, empowering them to become mature scholars able to work in a human-centered organization, with a greater emphasis on the team acting together for shared purposes. Dissemination and teaching activities include the Computer Engineering for Music and Multimedia course, supervision of PhD students, and participation in events aimed at bringing researchers closer to the general public, e.g., the European Researchers' Nights.
3. Stimulating technological transfer into the business world, thanks to the CSC spin-off AudioInnova (of which Sergio Canazza is one of the founding members and current CEO, see: https://www.audioinnova.com/en). AudioInnova is one of the European leaders in the field of computer science for musical cultural heritage. It concluded a number of projects of massive preservation of audio documents, including the Archive of Teatro Regio, in Parma, Italy; the Archive Vezzani in Reggio Emilia, Italy, and several archives of speech documents. AudioInnova is also a leader in the field of technologically enhanced learning environments for inclusion (e.g., Board on Air https://www.boardonair.eu, a technologically enhanced learning environment that is based on a lightboard for easily creating and streaming effective videos and lessons and that applies the paradigm of "enactivity" to the learning process, involving the entire sensory sphere). AudioInnova was founded in 2013, thanks to CSC's having twice won the Italian business plan competition Start Cup.
4. Patenting new products. Two patents have already been obtained at CSC: a pedal

resonance effect simulation device for digital pianos, and a hardware/software instrument for the structural control of wooden poles used in the field of safety and security in the workplace (De Poli et al. 1998; Biasutto et al. 2016).

CSC's future goals are to remain a place able to attract scientists and artists who want to carry out research, music productions, and teaching activities, and to collaborate with other organisations, both at a national and at an international level.

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