Cyberinstruments via Physical Modeling Synthesis: Compositional Applications

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ABSTRACT

This paper details compositional approaches in music for cyberinstruments by means of physical modeling synthesis. Although the focus is on compositions written with the models simulated by the digital waveguides, modal synthesis and mass-spring-damper algorithms, music written with other modeling techniques is also reviewed.

A physical model is a computer simulation of a sonic object (whether it be a musical instrument, an environmental phenomenon or an everyday object) based on understanding and implementation of the sound production mechanism. Physical modeling synthesis is an excellent vehicle for conceptualizing and incorporating the reality of physical sounding objects such as musical instruments into computer-mediated artistic production [1,2]. What differentiates this technique from other syntheses is the fact that physical modeling simulates the mechanics of sound production, while other techniques (e.g. additive, subtractive and FM syntheses) focus on modeling the acoustical properties of the signal as heard and recognized by the listener [3]. Derivation of the models from physics ensures that their perceptual identities and behavior are retained under a variety of conditions.

The purpose of this article is to examine how cyberinstruments of the physical modeling type were used in music compositions [4]. In each section we focus on a particular kind of cyberinstrument. We recognize three categories of cyberinstruments: extended, hybrid and abstract cyberinstruments. The extended cyberinstruments are simulations of existing physical instruments. Besides pure replication, they enable augmentation of the instruments' parameters beyond the limitations of their physical origins. Hybrid cyberinstruments are typically combinations of the properties of two or more existing instruments, such as the *blotar* [5] and *ublotar* [6], which combine the properties of flute and guitar. Abstract cyberinstruments are structures inspired by physical laws, yet without equivalence in the physical world. Table 1 displays the basic topology of cyberinstruments created by means of physical modeling.

Certain cyberinstrument types are often associated with a particular method of physical modeling. While *extended* cyberinstruments are frequently modeled by means of *digital waveguide synthesis*, simulation of *hybrid* cyberinstruments is efficiently realized using *modal synthesis*. *Abstract* cyberinstrument designs are facilitated using a *mass-spring-damper* algorithmic approach. There are also a number of exceptions, which suggest that all classes of cyberinstruments can be realized by techniques other than those assigned in our categorization.

The following sections treat each kind of cyberinstrument in turn, describing modeling approaches and presenting compositional examples. We also provide a sampling of compositions written with cyberinstruments. These are compositions known and accessible to the authors—the catalog is not to be considered comprehensive.

Composing with Extended Cyberinstruments

Extended cyberinstruments enable parametrical expansion of existing music instruments beyond the limitations of the physical world. While manipulating extended cyberinstruments, the composers have generated novel timbres and conceived an augmented sonic reality.

Origins

Most probably, the first cyberinstrument was the physical model of a vocal tract proposed by J. Kelly and C. Lochbaum [7]. Max Mathews used this cyberinstrument in the composition *Bicycle Built for Two* (1960). To create a futuristic effect and celebrate emerging modeling possibilities, Stanley Kubrick included the song, performed by the dying computer HAL, at the end of his film *2001: A Space Odyssey* (1968).

Hiller and Ruiz Algorithm

The behavior of vibrating objects such as strings can be modeled as a mass-spring system archetype. This behavior is expressed mathematically through difference equations, which in turn describe the behavior of digital filters needed for the synthesis. Solving the difference equation for strings plucked and struck at different places allowed Hiller and Ruiz to simulate the vibrating string with a series of masses and springs [8].

In *Corda di Metallo* (The Metal String, 1997), for string quartet and electronics, Michelangelo Lupone composed with a model of the bowed string designed by Marco Palumbi and Lorenzo Seno. The model is based on Hiller and Ruiz's algo-

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An on-line database of compositions written with cyberinstruments by physical modeling synthesis along with other information concerning the topic can be accessed at <www.cybermusik.net>.

rithm. Lupone controlled the following bowed string parameters: bow position, velocity, force, string dampening, length and material density [9]. *Corda di Metallo* presents a communication between the physical and cyber strings. Such oscillation is reflected in the formal design of the piece. Sections performed by cyber strings follow sections performed by the string quartet. Either the cyber string retains the parametrical behavior of the physical string instrument or its registers and gesture envelopes stretch to unreal dimensions. Lupone blended the bowed string model sounds with the vocal samples in his later composition *Canto di Madre* (The Mother's Song, 1998).

The McIntyre, Schumacher and Woodhouse Algorithm

Self-sustained oscillators can be also modeled with the McIntyre, Schumacher and Woodhouse algorithm. This methodology centers on detailed examination of time-domain behavior of sounds. Coupling nonlinear exciters with linear resonators facilitates simulation of such systems as woodwinds, bowed strings and pipes [10].

Chris Chafe used this technique to model the bowed cello [11]. Chafe designed a cello-like synthesizer that combines a number of bowed string instruments. The synthesizer facilitates control over five performance parameters: string length, bow velocity, force, contact position (affecting loudness and tone quality) and string dampening.

In *Transect* (1999), Chafe used the cyber cello to extend the sonic capabilities of the physical instrument. Further expanding the cello identity, Chafe fused the extended cyberinstrument with a model of the vocal tract. Emergent sound, the result of this cross-synthesis process, carried the sonic, although not physical, features of both parents [12].

Karplus-Strong Algorithm

In 1983, Karplus and Strong proposed an effective algorithm to model plucked string and drum synthesis [13]. First, a wavetable is filled with random values. Subsequently, the values are read and sent out to a modifier (e.g. a low-pass filter). The algorithm contains a loop that is completed when the data is fed back to the system and re-read after a certain delay. This process is continuously repeated at audio speeds. The resulting sound resembles the timbre of plucked strings. Jaffe and Smith expanded the Karplus-Strong algorithm by adding all-pass filters to the loop and improving the filters proposed by Karplus and Strong. Their refinements included improvement of tuning, better control for tone decay time and loudness, spectral shaping of the initial "plucked" sound, variation of tone loudness in relation to its bandwidth, variation of the character and number of attacks, glissando and slur, simulation of the sympathetic string vibrations, simulation of a stiff string and simulation of a moving pick [14].

Jaffe used the extended Karplus-Strong algorithm of plucked strings in his compositions *May All Your Children Be Acrobats* (1981), *Silicon Valley Breakdown* (1982), *Telegram to the President* (1984), *Grass* (1987) and *Racing against Time* (2001), as well as in other pieces. The composer focused on extending the timbral possibilities of the string model while preserving its sonic identity. Additionally, Jaffe used the cyberinstrument to simulate performance modes such as extremely rapid tempi and register changes impossible to accomplish on the physical instruments.

Jaffe structured *May All Your Children Be Acrobats,* for computer-generated tape, eight guitars and voice, as a dialogue between physical and cyber guitar strings. Although continuously stretching the timbral, pitch and rhythmic possibilities of the guitar performance, Jaffe strove to retain the field of recognizable sounds [15].

Silicon Valley Breakdown, for tape, is scored for a symphony of plucked string cyberinstruments, including piccolo, mandolin and deep bass strings the size of the Golden Gate Bridge. Augmentations of the string's identity are very subtle. Jaffe smoothly transitioned between the sound of physical strings and extended sonorities marked with impossible detuning, performance velocity, articulation, distortion effects and length of resonant decay, which spanned from a fraction of a second to approximately half a minute. Timbrally coherent, *Silicon Valley Breakdown* may entice the listener to believe that there in fact physically exists such a multi-string instrument.

Tempo perturbation added a complexity to the performance, such that it would be impossible for real performers to reproduce the piece. This "impossibility" technique implies a characteristically digital augmentation, clearly paralleled with Colon Nancarrow's acoustic works.

Digital Waveguides

Julius Orion Smith III proposed modeling with digital waveguides as a novel approach to physical modeling [16–18]. Digital waveguide synthesis focuses on modeling the medium in which the waves propagate. A pair of digital delay lines simulates sound waves traversing the resonating medium in opposite directions. Interaction of the traveling waves causes resonances and interferences related to the dimensions of the medium [19]. Strings and tubes may be considered such media. If the previous implementations considered the ideal string, in which no losses occur, digital waveguides take into account these losses by means of low-pass filters in the system. Digital waveguides offer a finer level of accuracy in modeling certain vibrating objects. Further, compactness of this synthesis facilitates efficient real-time implementation of the models. In general, systems with quasi-harmonic spectra, such as vibrating strings and air columns, are suitable for efficient modeling by one-dimensional waveguide techniques, while inharmonically behaving sonic objects are more efficiently modeled with 2D waveguide meshes, modal synthesis techniques or a combination of 1D waveguide and modal techniques called "banded waveguides."

One-dimensional digital waveguides have been used to model vocal tracts [20], bowed strings [21], woodwind instruments [22,23], piano [24], singing corrugated tube [25] and other instruments. Objects with a few inharmonic modes were modeled using banded waveguides. Examples of such models include resonating percussion bars [26], musical

Table 1. Basic topology of cyberinstruments created by means of physical modeling.

Instrument type	Modeled object	Novel timbre results from
Extended	Existing instrument or sonic object	Extending the instrument's parameters
Hybrid	Two or more existing instruments or sonic objects	Blending multiple instruments together
Abstract	Abstract instruments or sonic objects described by terms such as masses, springs and dampers	Combining physical agents of sound production such as masses, springs and dampers

saw [27], Tibetan bowl [28] and glass harmonica [29]. Modeling highly inharmonic structures is not usual in waveguide methodology, yet Serafin, Huang and Smith proposed a banded waveguide mesh to model bowed cymbals [30].

S-Trance-S (2001), *S-Morphe-S* (2002) and *That Which Is Bodiless Is Reflected in Bodies* (2004) are compositions by Mathew Burtner that use waveguide models designed by Stefania Serafin [31]. In *S-Trance-S,* for metasaxophone and electronics, the identity of the virtual bowed string is distorted and mixed with the sonorities of an acoustic saxophone [32]. At moments, the string timbre completely dissolves into an abstract electric mist.

The cyber Tibetan bowl is tapped and blown by soprano saxophone in *S-Morphe-S.* The composer widened the instrument's sonic identity while reshaping its natural gesture envelope. The composition begins with sustained bowl sonorities and proceeds to a saxophone and bowl duet, in which the bowl augments the sonic space as the resonating cavity for the saxophone signal. Blending of the physical and cyber sonorities is followed by the instruments' registral separation, in which the saxophone part floats above the resonating bowl.

In *That Which Is Bodiless Is Reflected in Bodies*, the composer focused on the exploration of beating—the characteristic Tibetan bowl sonic quality. The extended cyberinstrument enabled the composer to generate beating in a multitude of spectral variations and rhythms. The composition investigates the notions of distortion, polymetrical pulse and textural transformation in the cyber bowl. The composer augments the sonic space through subtle detuning, pitch bending and registral expansion of its 8-channel spatially distributed body.

Chris Chafe explored the sonorities of the cyber bugle and Perry Cook's "hoseplayer" waveguide brass model [33] in an improvisation-based composition *El Zorro* (1991). With Greg Niemeyer, Chafe also designed *Oxygen Flute* (2001), an interactive real-time computer music environment. The work utilizes digital waveguide models of four 9,000-year-old Chinese bamboo flutes from the Jiahu archeological sites [34]. While the flutes' timbral qualities remain preserved, *Oxygen Flute* augments the notion of an instrument and performance. The visitors' breathing directly excites the extended cyberinstruments. As the viewers enter the space, the carbon dioxide levels in the greenhouse increase. The sensors detect the level changes and send the information to enliven the cyberinstruments.

Ping, also created by Chafe and Niemeyer, is a network environment, which involves a series of the cyber-plucked strings parametrically expanding and contracting. Like *Oxygen Flute*, *Ping* (2001) expands the notion of the performance space. The installation's Internet connections are constantly reforming, with multiple physical destinations, and the communication between the locations excites the cyber strings. The mapping of these Internet contacts to the cyberinstruments defines the composer's extended sonic space.

Ted Coffey used physically modeled glass harmonicas [35] in *Armonica Lullabies* (2004), for stereo tape, *Koans,* for video and sound (2004) and other works. In *Armonica Lullabies,* the composer reached into the virtual sonic space while engaging the extended cyberinstrument in delicate augmentation of the sampled harmonica's timbral properties.

Achim Bornhoeft employed a waveguide model of a plucked string in *Virtual String* (1997), for tape. The cyber string was implemented in the graphical user interface vstring, which allowed the composer to manipulate string tension, stiffness, dampening, excitation type and position, virtual pickup position and frequency response. Sounds of simulated strings with unnatural physical measurements and behaviors expand Bornhoeft's sonic space, yet the space remains informed about the sonorities of the original physical instrument [36].

Juraj Kojs has composed a number of works with digital waveguides, such as *Garden of the Dragon* (2003), *Three Movements* (2004), *Air* (2006), *Concealed* (2006), *En Una Noche Oscura* (2006), *In Secret* (2006) and *To Where He Waited* (2006). Musical instruments, everyday objects and musical toys suggested actions to which various extended cyberinstruments responded. The cyberinstruments expanded the musical space while timbrally enhancing their physical counterparts, participating in a creation of hybrid analog-digital instruments and providing a resonant space for the performance given on the physical instrument. The compositions engaged extended cyberinstruments, such as the singing tube [37], bowed string [38], fujara [39], Tibetan bowl [40], bowed bar [41], flute [42] and 2D mesh [43].

Paul Lansky utilized a waveguide model of the slide flute [44] in *Still Time* (1993–1994) and Sullivan's physical model of a plucked electric guitar string [45] in *Things She Carried* (1997). Furthermore, a number of digital waveguide Synthesis ToolKit (STK) implementations can be heard on Lansky's *Music Box* CD (2006). *In F* uses clarinet, mandolin and saxophone models. Other pieces on the CD, such as *Composition Project for Seniors* and *A Guy Walks into a Modal Bar,* engaged the modal bar designed by modal synthesis.

Lansky was primarily involved in stretching the cyberinstrument's parameters to unrealistic dimensions and, by doing so, producing vast-sounding cyber landscapes in *Still Time.* Lansky invites the listener to actively inspect the cinematic, flowing soundscape and reflect on it.

The listener may observe intertwining streams of natural and synthetic identities as they are presented through uncluttered structures arriving from a variety of proximities.

SonoMorphis (1998) is an interactive 3D installation designed by Bernd Lintermann (graphics) and Torsten Belschner (sound). The sonic part utilizes waveguide models of pipe and string (with 16x Yamaha VL70-m). Both graphics and music mutate while interacting with the system. The visuals are based on extracted natural patterns. Both visuals and sounds are transformed to unrealistic ones as the user interacts with the system [46]. Visual materials, shapes and spatial positioning of the objects are mapped to the timbre and pitch of the extended cyberinstruments. Additionally, the visuals dynamically control sound spatialization in real time. Through this cross-modal approach, Belschner achieved sensible augmentation of the instrumental identities.

Juan Reyes used digital waveguide models in *Straw-berri* (1997, flute and plucked string models), *Wadi Musa* (2001, clarinet model), *ppP* (2001, piano model), *Freddie the Friedlander* (2004, bowed string model) and *Fuxing* (2006, pipa model). In *ppP,* for piano and electronics, Reyes used the virtual piano to extend the sonic possibilities of the physical instrument while simulating the effects such as detuning and retuning of the strings, generating extreme pitch fluctuations, expanding the instrument's registers and modifying the natural envelope of the struck-string gestures. Complementing relationships between the physical and extended cyberinstruments fuels a sinuous augmentation of the piano sonic space.

Physically Informed Stochastic Models

Perry Cook developed the Physically Informed Stochastic Event Modeling (PhISEM) technique, which is based on pseudorandom organization of small sound particles [47]. The algorithm is based on Newtonian equations that explain motion and collision of point masses. Statistical principles of particle collision in a shell are applied to shakers such as maraca, sekere and cabasa. Percussive instruments with larger numbers or resonances, such as tambourine and sleigh bells, may be also modeled using the PhISEM algorithm. Individual partials are modeled with digital filters, whose resonant frequencies are replaced by another frequency located in close yet random proximity to the principal resonance every time a collision occurs.

Juan Reyes scored *Wadi Musa* (2001) for *quenas* (Andean flutes), cello, clarinet waveguide model, and stochastic models of maracas. Reyes extended Cook's PhISEM model of maraca [48] by customization of gourd-resonant filter coefficients, shaking rate and energies with the Common Lisp Music (CLM) program [49]. The program reads and executes the score with pre-specified parameters. Derived from the model of a maraca, a cabasa, guiro, tambourine and wind chimes provide continuously changing rhythmic patterning in the composition. Reyes was primarily concerned with augmenting the sonic properties of the physical instruments.

Dan Trueman utilized Cook's PhISEM models in *Lobster Quadrille* (1999). The composer controlled the models with the Bow-Sensor-Speaker-Array (BoSSA) system [50]. Cyber bamboo wind chimes were used in *Wind in Hands, Water in Feet* for dancers and electronics, in which the instrumental timbres are extended to simulate the water-like sonorities. The dancers, equipped with sensors (accelerometers) on their feet, then activate the instrument as if interacting with the cyber water. The composer augmented the instrumental space of the bamboo while transforming it into the sonorities of the flowing water [51].

Kojs' *Revelations* (2005), for circular toys, resonant plates and electronics, primarily explored the sonorities of physical toys and cyber percussion instruments. Plastic superballs, glass marbles and metal Bocci balls were used to control cyber maracas, guiro and bamboo wind chimes. Bouncing, rolling and scraping the circular toys against the resonant plates excited unrealistically shaped cyber shakers. To complement the scraping of a physical rubber ball against hard surfaces, MAX/MSP implementations of the bowed percussion bar physical model developed by Georg Essl and Perry Cook [52] and a friction-bowed string model designed by Stefania Serafin [53] were employed in *Revelations*. The models contributed to the timbral and temporal augmentation of the quickly decaying scraping gestures of the physical plates (particularly the plastic ones). Mixed analog-digital resonating structures resulted from the combination of physical scraping excitation and reverberation of extended cyberinstruments.

Hybrid Instruments

As mentioned in the introduction, although digital waveguides and mass-spring-damper algorithms can be used to simulate hybrid cyberinstruments, modal synthesis is predisposed for such a design. Conversely, modal synthesis was applied to extended cyberinstruments (squeaking door and singing wine glasses [54] and some percussive cyberinstruments [55]). In his composition *Erba near che cresci segno nero tu vivi* (1999), Mauro Lanza utilized modal synthesis forms implemented in the MODALYS software. Lanza designed a set of percussive extended cyberinstruments and combined them with the sound of a soprano voice.

The hybrid cyberinstruments present an amalgamation of multiple cyberinstruments within one unit. The cyber hybrids inherit the timbral characteristics of both parents, the dominance of which depends on the parametrical alignment. Intrinsically, the hybrids initiate novel timbres existing solely in cyberspace.

Modal synthesis is based on the proposition that any sounding object can be deconstructed into a set of vibrating substructures, such as bridge and body in the case of the violin [56]. After excitation, each substructure produces well-defined modes of vibration. Each mode is represented by its modal data, consisting of frequency, dampening coefficients and shape variables. Such modal data may represent structural elements such as violin bridge, body, string, acoustic bell or timpani membrane. The resulting simulation sums up the elements of all modes involved in the synthesis. As opposed to a mass-spring approach, modal synthesis allows flexibility in reorganizing the substructures of the instrument in order to modify its physical and thus sonic characteristics. MOSAIC is a virtual workbench designed by Jean-Marie Adrien and Joseph Morrison, which allows the user to assemble modal substructure objects into musical instruments [57]. Thus, the model is constituted as a collection of mechanical and acoustic resonant structures that vibrate and interact under various excitation conditions. Adhering, striking, bowing and plucking may connect the elements. In some design situations, however, such as in reed and bow connection, it is difficult to decide on efficient control values. Similarly, debugging and control of spectral features of actual sound remain problematic [58].

Hans Tutschku used hybrid cyberinstruments by means of modal synthesis in *Eikasia* (1999). *Eikasia,* for 8-channel tape, was written with MODALYS, a new generation application of the previously described MOSAIC, which was developed at IRCAM. In the composition, Tutschku explored the resonances of rectangular and circular plates mixed with the spectra of low piano tones. Most interestingly, the composer created hybrid cyberinstruments while dynamically fusing multiple plates of different spectral characteristics. Parametrical combination and oscillation between the multiple parental models resulted in creation of cyber plate-like hybrids transpiring into the "intermediate states" [59].

Designing hybrid cyberinstruments by means of digital waveguide synthesis, which combines excitation of one instrument with the resonator of another, is an uncommon phenomenon. Dan Trueman and Gary Scavone involved hybrid cyberinstruments in their compositions. Trueman used the *blotar,* a hybrid cyberinstrument combining properties of flute and Charles Sullivan's electric guitar models, in the improvisational contexts [60]. Novel timbres emerge with the parametrical oscillation between the flute and guitar identities, depending upon the prevalence of electric guitar or flute parameters in the synthesis. Scavone proposed and compositionally implemented two cyber "blown strings" in his *Air Study I* (2002).

Abstract Cyberinstruments

Mass-spring-damper algorithms excel in the simulation of the abstract cyberinstruments. CORDIS-ANIMA is an audiovisual environment [61] that epitomizes implementation of modeling by combining masses, springs and dampers. These agents can be connected in a linear network. A conditional link may introduce nonlinear behavior to the system. While CORDIS simulates the sounds of music instruments, sonic objects and natural phenomena such as moving sand dunes [62], ANIMA allows modeling of the visual component. GENESIS is a compositional environment in which the CORDIS principles were recently implemented [63].

Tutschku used GENESIS in his *Resorption-Coupure* (2000). In *Resorption-Coupure*, a bow-like object, friction objects and hammers excite abstractly defined resonating structures. Tutschku constructed the piece by conscious alternation between the perceptual recognition and nonidentification of sonic objects. This process is reflected in the use of the abstract cyberinstruments (somewhat resembling string-like metal objects) and physical-world sounds (whispering and breathing).

Claude Cadoz exemplified creative work with CORDIS in *pico. .TERA* (2002) for quadraphonic tape. In this composition, Cadoz restricted himself exclusively to implementation of physical models. Cadoz suggested that instruments, performers and conductor, as well as resonant performance space, can be simulated by means of physical modeling [64]. Cadoz constructed *pico. .TERA* as a net of hierarchical relationships between the involved agents. The agents interact and exchange function during the composition. For example, a cyberinstrument may "play" a model of an instrumentalist when appropriate interaction is initiated. The abstract cyberinstruments are designed as elastically connected bridges, soundboards and other parts. These cyberinstruments are inherently responsive to modifications, thus facilitating myriad abstract sonic identities.

A number of composers, such as Hans Peter Stubbe, Ludger Bruemmer, Giuseppe Gavazza, Periklis Douvitsas and Frederic Curien, have worked at the Association pour la Creation et la Recherche sur le Outils d'Expression (ACROE) center to compose music with GENESIS. While some of them use the abstract cyberinstruments in concert works (Stubbe), others have incorporated the cyberinstruments in multimedia (Bruemmer, Gavazza) and theatrical contexts (Douvitsas). GENESIS is an exciting and sophisticated compositional environment that will increase in popularity with real-time implementation and distribution on common platform computers.

Conclusion

The above examples demonstrate ways in which composers have utilized physical models to extend the sonic possibilities of existing instruments (extended cyberinstruments), create merged identities (hybrid cyberinstruments) and generate novel vibrating structures (abstract cyberinstruments).

Composers have increasingly favored real-time implementation of cyberinstruments through physical modeling. This trend has been facilitated by emerging software such as Synthesis ToolKit [65], Pure Data [66], and Max/MSP [67] with PeRColate—the free external library of physical models [68] and ChucK [69], to name a few.

Waveguide synthesis seems to represent the prevailing approach in the current trends due to its compact and efficient implementation, which makes it particularly suitable for real-time use. Many composers have explored perceptual ambiguity when extending the timbres of an existing instrument while retaining its identity (extended cyberinstruments). Others have focused on distorting such identities by creating cyber hybrids. Abstract cyberinstruments, suggested by Borin in 1992, have been recently developed and established as sonic entities with strong, however abstract, identity attributes.

References

1. G. Borin, G. De Poli and A. Sarti, "Algorithms and Structures for Synthesis Using Physical Models," *Computer Music Journal* **16**, No. 4, 30–42 (1992).

2. J.O. Smith III, "Physical Modeling Using Digital Waveguides," *Computer Music Journal* **16**, No. 4, 74–91 (1992).

3. V. Valimaki and T. Takala, "Virtual Musical Instruments—Natural Sound Using Physical Models," *Organised Sound* **1**, No. 2, 75–86 (1996).

4. The present article builds on work previously outlined in C. Chafe, "Case Studies of Physical Models in Music Composition," paper read at International Congress on Acoustics, Kyoto, Japan (2004).

5. D. Trueman and L. DuBois, "PeRColate" (2005), <music.columbia.edu/PeRColate>; discusses Version 0.9b5.

6. V. Stiefel, D. Trueman and P. Cook, "Re-coupling: the uBlotar Synthesis Instrument and the sHowl Speaker-feedback Controller," *Proceedings of the International Computer Music Conference* (2004).

7. J. Kelly and C. Lochbaum, "Speech Synthesis," *Proceedings of the Fourth International Congress on Acoustics* (1962).

8. L. Hiller and P. Ruiz, "Synthesizing Sounds by Solving the Wave Equation for Vibrating Objects," *Journal of the Audio Engineering Society* **19** (1971) pp. 463–470, 542–551.

9. M. Lupone, *Corda di Metallo* (1997), <www.crm-music.it/Corda%20di%20Metallo.html>.

10. M. McIntyre, R. Schumacher and J. Woodhouse, "On the Oscillation of the Musical Instruments," *Journal of the Acoustic Society of America* **74**, No. 5, 1325–1345 (1983).

11. C. Chafe, "Simulating Performance on a Bowed Instrument," in Max Mathews, ed., *Current Directions in Computer Music* (Cambridge, MA: MIT Press, 1989).

12. A linear combination of two models, this cannot be considered as an instance of a dynamically hybrid instrument. Cello and other excitations were piped into a vocal tract in place of the glottis.

13. K. Karplus and A. Strong, "Digital Synthesis of Plucked String and Drum Timbres," *Computer Music Journal* **7**, No. 2, 43–55 (1983).

14. D. Jaffe and J.O. Smith III, "Extensions of the Karplus-Strong Plucked String Algorithm," *Computer Music Journal* **7**, No. 2, 56–69 (1983).

15. R. Dal Farra, "An Interview with David A. Jaffe," *Journal of New Music Research* **22**, No. 4, 335–347 (1993).

16. J.O. Smith III, "Synthesis of Bowed Strings," *Proceedings of the International Computer Music Conference,* San Francisco (1982).

17. J.O. Smith III, "Techniques for Digital Filter Design and System Identification with Application to the Violin," Ph.D. thesis, Stanford University, 1983.

18. J.O. Smith III, "Physical Modeling Synthesis Update," *Computer Music Journal* **20**, No. 2, 44–56 (1996).

19. C. Roads, *A Computer Music Tutorial* (Cambridge, MA: MIT Press, 1996).

20. P. Cook, "Identification of Control Parameters in an Articulatory Vocal Tract Model, with Applications to the Synthesis of Singing," Ph.D. thesis, Stanford Univ., 1991.

21. S. Serafin, "The Sound of Friction: Real-Time Models, Playability and Musical Applications," Ph.D. thesis, Stanford Univ., 2004; Chafe [11]; Smith [17].

22. P. Cook, "A Meta-Wind-Instrument Physical Model, and Meta-Controller for Real-Time Performance Control," *Proceedings of the International Computer Music Conference,* San Francisco (1992).

23. G. Scavone, "An Acoustic Analysis of Single-Reed Woodwind Instruments with an Emphasis on Design and Performance Issues and Digital Waveguide Modeling Techniques," Ph.D. thesis, Stanford Univ., 1997.

24. J. Bensa, "Analysis and Synthesis of Piano Sounds Using Physical and Signal Models," Ph.D. thesis, Université de la Mediterranee, 2003.

25. S. Serafin and J. Kojs, "Computer Models and Compositional Applications of Plastic Corrugated Tubes," *Organised Sound* **10**, No. 1, 67–73 (2005).

26. G. Essl and P. Cook, "Measurements and Efficient Simulation of Bowed Bars," *Journal of the Acoustical Society of America* 108 (2000) pp. 379–388.

27. S. Serafin et al., "Analysis and Synthesis of Unusual Friction Driven Musical Instruments," *Proceedings of the International Computer Music Conference,* Göteborg, Sweden (2002).

28. S. Serafin, C. Wilkerson and J. O. Smith III, "Modeling Bowl Resonators Using Circular Waveguide Networks," *Proceedings of Conference on Digital Audio Effects* (DAFX-02), Hamburg, Germany (2002).

29. G. Essl, "Physical Wave Propagation Modeling for Real-Time Synthesis of Natural Sound," Ph.D. thesis, Princeton Univ., 2002; Serafin et al. [27].

30. S. Serafin, P. Huang and J.O. Smith III, "The Banded Digital Waveguide Mesh," *Proceedings of the Workshop on Future Directions of Computer Music* (Mosart-01), Barcelona (2001).

31. Serafin [21]; Serafin et al. [28].

32. M. Burtner and S. Serafin, "The Exbow MetaSax: Compositional Applications of Bowed String Physical Models Using Instrument Controller Substitution," *Journal of New Music Research* **31**, No. 2, 131–140 (2002).

33. Cook [22].

34. C. Chafe, "Oxygen Flute: A Computer Music Instrument That Grows," *Journal of Computer Music Research* **34**, No. 3, 219–226 (2005).

35. Essl [29].

36. A. Bornhoeft, *Virtual String* (1997), <www.achim-bornhoeft.de>.

37. Serafin and Kojs [25].

38. Serafin [21].

39. J. Kojs and S. Serafin, "The Fujara: A Physical

Model of the Bass Pipe Instrument in an Interactive Composition," *Proceedings of the International Computer Music Conference,* New Orleans (2006).

40. Serafin, Huang and Smith [30]; G. Essl et al., "Musical Applications of Banded Waveguides," *Computer Music Journal* **28**, No. 1, 51–63(2004).

41. Essl and Cook [26].

42. Cook [22].

43. Trueman and DuBois [5]; S. Van Duyne and J.O. Smith III, "Physical Modeling with the 2-D Digital Waveguide Mesh," *Proceedings of the International Computer Music Conference,* Waseda University, Japan (1993).

44. Cook [22].

45. C. Sullivan, "Extending the Karplus-Strong Algorithm to Synthesize Electric Guitar Timbres with Distortion and Feedback," *Computer Music Journal* **14**, No. 3, 26–37 (1990).

46. B. Lintermann and T. Belschner, "*SonoMorphis*" (1998), <111www.bernd-lintermann.de/SonoMorphis/index.html>.

47. P. Cook, "Physically Inspired Sonic Modeling (PhISM): Synthesis of Percussive Sounds," *Computer Music Journal* **21**, No. 3, 38–49 (1997).

48. Cook [47].

49. J. Reyes, "Composing for the Physical Model of the Maraca" (2001), <ccrma.stanford.edu/~juanig>.

50. D. Trueman, "Reinventing Violin" (1999), <music.princeton.edu/~dan>.

51. D. Trueman, personal communication, 2005.

52. Essl and Cook [26].

53. Serafin [21].

54. F. Avanzini, S. Serafin and D. Rocchesso, "Interactive Simulation of Rigid Body Interaction With Friction-Induced Sound Generation," *IEEE Transactions on Speech and Audio Processing* **13**, No. 5.2, 1073–1081 (2005).

55. Cook [47].

56. J.M. Adrien, "The Missing Link: Modal Synthesis," in G. De Poli, A. Picalli and C. Roads, eds., *Representations of Musical Signals* (Cambridge, MA: MIT Press, 1991).

57. J. Morrison and J.M. Adrien, "MOSAIC: A Framework for Modal Synthesis," *Computer Music Journal* **17**, No. 1, 45–56 (spring 1993).

58. Morrison and Adrien [57].

59. H. Tutschku, "Portfolio of Compositions," Ph.D. thesis, Univ. of Birmingham, 2003.

60. Trueman [51].

61. C. Cadoz, A. Luciani and J.L. Florenc, "CORDIS-ANIMA: Modeling and Simulation System for Sound and Image Synthesis—The General Formalism," *Computer Music Journal* **17**, No. 1, 19–29 (spring 1993).

62. A. Luciani, N. Castagne and N. Tixier, "Metabolic Emergent Auditory Effects by Means of Physical Particle Modeling: The Example of Musical Sand," *Proceedings of Conference on Digital Audio Effects,* London (2003).

63. N. Castagne and C. Cadoz, "GENESIS: A Friendly Musician-Oriented Environment for Mass—Interaction Physical Modeling," *Proceedings of the International Computer Music Conference,* Göteborg, Sweden (2002).

64. C. Cadoz, "The Physical Model as Metaphor for Musical Creation 'pico. .TERA', a Piece Entirely Generated by Physical Model," *Proceedings of the International Computer Music Conference,* Göteborg, Sweden (2002).

65. P. Cook and G. Scavone, "The Synthesis ToolKit (STK)," *Proceedings of the International Computer Conference,* Beijing (1999).

66. M. Puckette, "Pure Data," *Proceedings of the International Computer Music Conference,* Hong Kong (1996).

67. D. Zicarelli, "An Extensible Real-Time Signal Processing Environment for Max," *Proceedings of the International Computer Music Conference,* Ann Arbor, MI (1998); M. Puckette, "Max at Seventeen," *Computer Music Journal* **26**, No. 4, 31–43 (winter 2002).

68. Trueman and DuBois [5].

69. G. Wang and P. Cook, "ChucK: A Concurrent, On-the-Fly Audio Programming Language," *Proceedings of the International Computer Music Conference,* Singapore (2003).

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