A Short History of Digital Sound Synthesis by Composers in the U.S.A.

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Abstract: A new technology for music has emerged with unprecedented speed. Just over forty years ago, the first digitally-produced sounds gave pioneering composers from around the world a taste of vast new possibilities. Numerical experiments with sound became a logical extension of compositional interests that were pushing the boundaries of timbre, perception, new instruments and performance techniques, organization and paradoxically, indeterminism. At several centers including a small number in the U.S. interdisciplinary teams combined composition with research in musical acoustics, psychoacoustics, and artificial intelligence. Their musical works provide a timeline of progress in sound synthesis.

1. Introduction

To describe the past four decades in a nutshell, we see composers, scientists, and engineers working to develop a new musical medium; exploring the fabric of sound and sound perception; and pushing a new technology's scale and capabilities rapidly towards the practical and effective. Briefly looking forward another stretch of time, this same description might apply to music made using direct stimulation of auditory sensations in the brain. Far fetched? Brain imaging techniques that are central to perceptual studies suggest such a possibility. *Magnetoencephalography* (MEG) shows promising temporal and spatial resolution for music, perhaps foreshadowing the analytic side of this futuristic medium. And its synthetic reverse, *transcranial magnetic stimulation* (TMS), though still quite course, has been used to induce certain non-auditory effects. Electrical stimulation of the inner ear is already in prosthetic use. In time, consequent technologies may lead to an *evoked music* (I'm just hoping for early work on the problem of loudness control).

Presently, about sixty sites are equipped for MEG analyses and a handful for experimentation with TMS. My prediction is that just as with digital sound synthesis over forty years ago, at some point an observed auditory pattern will be synthetically induced and from then a new medium for composers will be born. Rewinding to 1965, there were likewise only a few sites equipped with computers and the necessary digital audio converters for sound acquisition and playback, but the promise was already apparent when a "Portrait of the Computer as a Young Artist" was published:

> Today, scientists and musicians at MIT, Bell Telephone Laboratories, Princeton University and the Argonne National Laboratory are trying to make the computer play and sing more surprisingly and mellifluously. As a musical instrument, the computer has unlimited potentialities for uttering sound. It can, in fact, produce strings of numbers representing any conceivable or hearable sound… Wonderful things would come out of that box if only we new how to evoke them.
>
> [Pierce 1965]

The timeline of compositions below follows the development of synthesis algorithms along such a track, citing several examples of new techniques which replicated observed patterns and musical signals, and which were rapidly incorporated in composers' work. The compositions described are the fruits of research into new materials: they engage the listener in a completely illusory world which could only have been achieved with digital tools.[1]

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[1] Listening to the accompanying, brief musical excerpts and explanatory sound examples will enhance an appreciation of the timeline (total duration is about 20 minutes). Each work constitutes a waypoint in a list that is much longer than

Composers were immediately attracted by a general-purpose machine which by itself prescribes no particular musical style, but which must be fed models and insights to produce results. Solutions which seem logical to us with hindsight were gained through key advancements in the understanding of the materials and nature of music. “Musical Sounds from Digital Computers” in the contemporary music journal, Gravesaner Blätter, closed with:

> The Future of Computer Music
>
> Man’s music has always been acoustically limited by the instruments on which he plays. These are mechanisms which have physical restrictions. We have made sound and music directly from numbers, surmounting conventional limitations of instruments. Thus the musical universe is now circumscribed only by man’s perceptions and creativity.
>
> [Mathews 1962]

And more from Pierce’s “Portrait:”

> The computer is a great challenge to the artist. It enables him to create within any set of rules and any discipline he cares to communicate to the computer. Or, if he abandons discipline, he may leave everything to chance and produce highly artistic noise.

This is an attempt to portray the rapid progress and excitement which began to fill that vast potential enabled by digital tools.

2. Modeling

For many disciplines, music included, the digital computer has enabled the age of modeling. The arsenal of techniques for numerical simulation of natural phenomena (including for example, behavior of a trumpet) continues to expand with addition of new models expressed as algorithms and / or data sets from analysis. In all forms, they can be studied under different hypothetical conditions, from the plausible to the extreme.

Imitative synthesis of musical sounds is an old tradition and spans the major epochs of technologies, including mechanical organs with *stops* like the *vox humana*, or analog electronic synthesizers with *patches* like the instruments played on Wendy Carlos’ album *Switched on Bach*. A newer technology often invites its usage for imitation of the sound of an earlier technology. This cascade leads right to the present were we can even hear digital software imitating analog hardware imitating mechanically-produced sound.

Models employed in the compositions cited below fall into five general categories:

- subtractive acoustical models (beginning with source / filter vocal simulations)
- additive acoustical models (recreating Fourier analyses)
- impulsive linear physical models (beginning with plucked string simulations)
- self-sustained physical models with acoustical feedback (electric guitar simulations with feedback)
- self-sustained physical models with nonlinear excitation (beginning with simulations of bow, reed and air jet)

In each case, a good dosage of acoustical theory and analysis of existing instruments provided the platform upon which the modeling approach was developed.

2.1. Acoustical

Acoustical models involve spectral (frequency domain) descriptions of patterns of air pressure variation radiated by the modeled instruments. The most common is based on Fourier analysis in which an acoustical wave, picked up by microphone, is analyzed to give an accurate portrait of its time-varying spectral components. Identical components are generated digitally and become sound again via loudspeaker. Ideally, if the signal can be adequately analyzed, the resulting model will enable high quality *resynthesis*, as well as a large set of transformations.

Acoustical models can also be based in analysis of hearing, supplying those cues known to envoke a particular musical or auditory sensation. Such sounds might not be based in the real world at all, and are instead formulated from psychoacoustical principles or paradoxes.

2. 2. Physical

Physical models describe the vibrating mechanisms of (instruments and other) sound sources. Analysis and synthesis is either in the time domain, in terms of mechanical or fluid dynamics, or in the frequency domain, as mixtures of distinct modes and regions of vibration.

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what is represented. Many others (in the U.S. and internationally) have contributed to the medium and their music could be included, but then this wouldn’t be a short history.

Dynamics-based modeling has not yet gained a general-purpose analytic method. Synthesis models are constructed by capturing "first principles" of a physical system and then refining the model by addition of physical details that are perceptually significant. The resulting sonic advantages, particularly with regard to transients and long-term laws (e.g., connected note transitions, turbulence or timbre control spaces), often remain outside the present powers of analysis for acoustical models.

A very young field at the moment ties physical modeling in with research in hearing: are there effects similar to those in acoustically-described perceptual illusions that can be expressed in terms of the physics of the sound source itself? If so, this may lead to a new class of physical models rooted in sensation rather than real-world simulations.

3. Bell Labs Experiments

The very first examples of digital sound synthesis were created alongside research in speech technology. Though the computer hardware was the same, new software was needed to meet the requirements of musical sound generation and organization. An anthology, *The Historical CD of Digital Sound Synthesis*, has preserved several of the earliest works for listening along with writings about the art and technology.

The original approach to non-speech synthesis consisted of juxtaposing periodic *waveforms* which were essentially digital versions of audio function generator tones common in analog signal laboratories. These would be familiar from oscilloscope observations, eg. sinusoid, square, triangle, sawtooth, etc. The same technique persists today under the name *analog synthesis* in current digital synthesizers. It is a special case of *wavetable* synthesis in which a single period of a sound is looped repeatedly at the pitch rate. A given note consists of one or more layers of such waves whose amplitudes and frequencies are controlled by *envelopes* changing through time.

Making astonishingly rapid progress, models borrowed from analog practice were quickly replaced in less than a decade by methods for acoustical analysis and synthesis. Precise envelope control of spectra opened up a world of experimentation with natural instruments and auditory illusions.

3.1. (1957) **Guttman's *Silver Scale***

The original musical example to be produced by controlling the motion of a loudspeaker with numbers alone represents a great technical step. It required development of software with musically-useful frequency and dynamic ranges and that handed over to the machine a certain amount of sonic detail. Without the latter, the composer would be lost in a sea of numbers. It marks the beginning of a medium in which software is divided into two layers, one for the generation of sounds as notes (coded as sound-producing subroutines) and the other a list of the notes to be played (as calls on the subroutines). Since then, almost ubiquitously, the parameters compiled into note lists have indicated timing, pitch, loudness, and aspects of timbre.

3.2. (1961) **Hal's Tune**

Mathews arranged *Bicycle Built for Two* using waveform techniques and J. Kelly's vocal tract analog speech synthesis approach (a physical simulation of the shape of the vocal tract using a series of continuously changing digital filters). The resulting performance became a well-known performance of the traditional song having been incorporated by the creators of the movie, *2001: A Space Odyssey*. Hal, the computer, sings this excerpt as his memory is removed bit-by-bit.

3.3. (1963) **Ferretti's *Pipe and Drum***

An advanced example of synthesis is Ferretti's *Pipe and Drum*. The remarkable musicality of this short composition demonstrates the composer's interest in carefully mimicking human performance. Instrumental sounds were created by building up layers of waves, different mixtures occurring note-to-note within the same instrument with an ear for performance practice.

3.4. (1968) **Risset's *Computer Suite from Little Boy***

The precision of digital techniques opened up a world of illusions in which acoustical elements could be manipulated to devise sounds based on models of what is heard and how it is heard. Three classes of synthetic sounds were explored in Risset's work at Bell: instrument simulations, paradoxical illusions and novel structures tailoring timbre to harmony and scale. Underlying the three were new digital analyses of natural instrument tones, studies of hearing, and possibilities of adapting spectra to theories of harmony. Timbral mixtures were structured from these specifications (additive synthesis) and the recipes were shared with others [Risset 1968]. Some recreate analysis data exactly where others are data reduced, primarily specified as algorithms that reproduce relationships observed in the data.

Long understood as a mathematical concept, spectral decomposition of a waveform into its component frequencies became practical with the advent of digital signal processing. The principle states that any complex wave, like that produced by a musical instrument, could be represented as the mixture of individually specified partial tones (the sinusoidal components of Fourier analysis). As the waveform changes through time, which is characteristic of natural sounds, so do the frequencies and amplitudes of these elemental components. The decomposition operates analogously to a prism in which a color mixture is split apart by the bending properties of different wavelengths. Because natural sounds are time-varying, techniques were developed to observe these changes at fine time scales, particularly the *phase vocoder* [Portnoff 1976].

Paradoxical tones are possible by eliciting conflicting perceptual cues. Tones that slide forever downward in pitch or that seem to follow a descending scale while becoming higher are demonstrated in *Computer Suite from Little Boy*. One recipe specifies an endless glissando (*Shepard ton*e) comprised of 10 harmonic partials fading in and then out imperceptibly, as they traverse a down-sloping pitch glide.

Risset simplified the great burden of data required for strict resynthesis of instrument tones by identifying aurally significant details. Traits relating spectral behavior within a note or across an instrument's gamut of pitches or dynamic levels were coded as rules.

> Computer studies (through analysis of the real sound and synthesis of various simplified models) demonstrated that, rather than being associated with a given set of physical parameters (e.g., a given spectrum), a given timbre can often be related to some property, some law of variation, some relationship between the spectrum and other parameters.
>
> [Risset 1985]

His recipes for trumpet tones specified increases in higher spectral components related to increases in loudness and were an early success that encouraged further work in synthesis-by-rule.

4. Frequency Modulation Synthesis

Time-consuming and expensive calculations were required for these early runs of analysis and synthesis. Component-by-component additive techniques compounded the wait by requiring large numbers of digital oscillators, each in itself a signal to be calculated independently. A spectrally-rich note that might comprise forty components would take forty times as long to calculate as a single wavetable oscillator. In a musical texture with several voices plus artificial reverberation, the turn-around time for a small passage would be hours. Often followed by a trip with the data over to another lab having the digital-to-analog converters (through the snow…). These rigors are now mostly forgotten.

4.1. (1971) **Chowning's *Sabelithe***

Chowning discovered a means by which masses of spectral components could be very flexibly controlled with as few as two digital oscillators. Using one oscillator to rapidly modulate the frequency of the second, numerous *sideband* frequencies are produced. The effect occurs when frequency fluctuations become so fast as to change pitch vibrato into waveform distortion (by accelerating vibrato rate into the audio range, above 20 Hz. – which is how the phenomenon was discovered). The disposition and number of sidebands are specified by a small number of parameters pertaining to equations for frequency modulation (FM). The discovery provided a new technique for spectral synthesis which though it employed a wider paint brush than previous additive methods, was significantly more efficient. Some intriguing constraints were imposed on the relationships of spectral components and inspired further experiment with perception of timbre and salience of certain spectral cues.

Sabelithe demonstrated that laws of variation could be advantageoulsy employed with FM and that the rules themselves could be manipulated in the course of a piece by the composer. By trading off exact specificity (about each component) for the sake of computational efficiency, it became a matter of design to identify and render the most important aspects of a simulation. Chowning (a percussionist) demonstrated the salience of certain cues that create the illusion of a drum sound (non-harmonically tuned partials, exponential amplitude decay after the impulsive stroke, and decreasing bandwidth as a function of decaying amplitude) [Chowning 1973]. Moreover, as different models were compactly expressed in the sparse parameters of FM, timbre interpolations could be readily explored (cf. the change from percussion to trumpet in *Sabelithe*).

4.2. (1975) **Morrill's *Studies for Trumpet and Computer***

Naturally, several other musicians turned computer musicians have researched models of their own instruments. Composer / trumpeter Dexter Morrill, carefully analyzed details of trumpet phrasing building up rule-based algorithms for FM synthesis. A crucial amount of human-like imprecision was incorporated. His *Studies for Trumpet and Computer* added realism to a model that evokes lyrical phrasing [Morrill 1977].

5. Analysis / Resynthesis in Timbre Space

Where musical pitch, loudness and timing exist in continuous dimensions, instrumental timbres are discrete: there is no smooth change possible in traversing from the sound of an oboe to a flute. A perceptual study of orchestral tones [Grey 1975] described instruments as points inside a multi-dimensional acoustical space. Subjects were asked to rank similarities among pairs of tones from a set of sixteen identical pitches played on different winds, brass and strings. A statistical analysis of their responses suggested that three acoustical cues predominated (attack noise, brightness and harmonic coherence). These form the axes of a timbre space within which the discrete instrumental sounds are located.

By means of systematic interpolation along the dimensions of the analyzed space, cues could be smoothly altered creating *morphed* identities which lie between familiar points. For example, a new half-oboe, half-flute instrument can be found situated between the two known points.

More sophisticated alterations have become possible with improvements in the quality of acoustical models following those of the early phase vocoder analyses of the 70's. *Spectral Modeling Synthesis* (SMS) [Serra 1990] and other related systems afford finer temporal and frequency resolution including options for modeling of isolated noise components. Another advancement applies auditory models in which the analysis is tuned to respond with the ear's measured acuity. Data reduction and filtering according to perceptual importance has become a choice of front-end technique.

Timbre spaces are "zoomable" closed worlds in which instruments and their behavior are organized. A given space may describe an ensemble of timbres or the varied behavior of a single instrument. In the broadest definition, timbre space is a smoothly varying compass of timbres employed in a composition and independent of the particular technique use for synthesis (and whether structured via analysis or not).

5.1. (1975) **Dodge's *In Celebration***

Dodge set poetry to music by using the analyzed recording of a reading of *In Celebration* to provide all its musical materials. The resynthesis space was bounded by attributes of the linear predictive coding speech model (LPC). Edits that he could perform on the analyzed data included swapping voiced / unvoiced sounds, altering pitch contours, and time-base distortions.

> The situation of In Celebration is more closely related to a male actor's reading of the poem (albeit an actor who can extend his voice over five octaves, conjure up multiple copies of his voice at will, control the pitch and rhythm of his voice to an extraordinarily fine degree, and perform other vocal and musical tricks). The use of a single human voice as the foundation for all the sounds in the piece lends unity to the composition.
>
> [Dodge 1985]

5.2. (1978) **McNabb's *Dreamsong***

McNabb combined synthesis techniques and processed recordings to create a realm of extended identities and morphings.

> The basic intent was to integrate a set of synthesized sounds with a set of digitally recorded natural sounds to such a degree that they would form a continuum of available sound material. The sounds thus range from the easily recognizable to the totally new, or, more poetically, from the real world to the dream world of the imagination, with all that that implies with regard to transitions, recurring elements, and the unexpected. The essential sound elements in *Dreamsong* can be divided into five categories: simple FM, complex FM, sung vocal processing and resynthesis, other additive synthesis, and processed crowd sounds and speech.
>
> [McNabb 1981]

He found that correlated random spectral fluctuations across partials fused the them into coherent tones. The method imparts an altogether natural but highly data reduced way of controlling additive synthesis. Further experiments with vibrato were found to have a particularly strong effect on fusion.

5.3. (1981) ***Solera***

Like Dodge, I was interested in various kinds of freedom with data for resynthesis, in this case obtained from spectral analysis. I developed an ensemble of intrinsically related, though quite varied, timbres from manipulations of only the single bass clarinet tone analyzed in Grey's experiment. Simple alterations of pitch, harmonicity, duration, and bandwidth created a large palette of identities which were focused together in Solera (ranging from percussion and shakuhachi flute to new instruments with no reference to experience). It was conceived of as a closed space derived from limited acoustical transformations, or a sort of inverse timbre space.

5.4. (1984) **Schottstaedt's *Dinosaur Music***

FM synthesis is expandable into various topologies relating modulated (carrier) oscillators and modulators. Complex FM [Schottstaedt 1977] affords good independent control over acoustical cues like the ones identified by Grey. For example, one portion of an FM patch might be dedicated to attack noise and another to the modification of a particular spectral region. Popular patches like Schottstaedt's FM violin retain unexplored territories even after years. It is wide-open in terms of possible instrumental identities. The sole source of sound in *Dinosaur Music*, it occasionally plays with violin-like settings, at other moments it is taken along with the composer's imagination into unlabelled, orchestra-sized, spaces.

6. Waveguide Synthesis

One method for simulating the physical dynamics of a vibrating string or acoustic tube is based on *recirculating delaylines* [Karplus 1983]. In bucket brigade fashion, these copy their input signal to their output after a given interval that depends on their length. Providing a feedback loop back to the input causes the signal in the delayline to repeat at the delay (pitch) rate like a wavetable oscillator. With the addition of attenuation and low-pass filtering in the loop, excitations die away exponentially in a manner similar to real instruments. However, unlike the real system, this *lumped circuit* separates into separate units the source of pure delay and lossy effects, though the aggregate effect for generating a signal is the same [Smith 1992].

The technique simulates acoustical wave motion in one dimension. Surprisingly good approximations are possible since the dominant modes of strings and bores propagate along their length (which is proportionately much greater than their width). Refinements (e.g., a sitar's resonating strings) can be added as extra 1D side branches. Topologies with cross-coupling in two or three dimensions extend the approach to vibrating surfaces and volumes [Van Duyne 1996].

6.1. (1982) **Jaffe's *Silicon Valley Breakdown***

Simulated plucked strings are the principal sounds in Jaffe's composition *Silicon Valley Breakdown*. Another composer / musician interested in modeling their own instrument(s), he tailored the model for several variants of the plucked-string family, including physically-impossible extensions only appropriate as software (with super long and super short strings) [Jaffe 1983]. These waveguide models represent highly resonant physical systems that are passive, lossy and linear, meaning that energy must be put into the system for it to sound (by simulating a pluck) and that the ensuing vibrations will die out slowly as they dissipate (without any spectral distortion from non-linearities).

Physical models, in general, are characterized by their *articulatory* controls, the same controls that are familiar to players of the instruments. Sonic effects are governed by playing techniques. If a sound needs to be, for example, brighter or higher, or it squeaks, the change is made through a parameter that relates to the physical instrument:

musical - / acoustical	performer - / instrumental	model control parameter
pitch	string length	delayline length
brightness	pluck position	excitation comb filter
attack sharpness	plectrum type	excitation envelopes
sustain	finger damping	loop filtering

Given an adequate physical model, changes to its parameters will impart to the listener the expected timbre cues, automatically creating the corresponding acoustical changes.

6.2. (1997) **Lansky's *Things She Carried***

The plucked string model was inevitably extended to become a screaming electric guitar [Sullivan 1990]. The inclusion of simulated amplifier feedback and distortion resulted in the first instance of a self-sustaining model and that was employed by composers.

The strings of an electric guitar are forced by electroacoustical amplification so that the instrument becomes actively resonant. Options for significant non-linearities can be introduced in the amplification system. We've been listening to music with guitar feedback for more than fifty years and have gotten to know intimately the sonic behavior of chaotic dynamics as a result (long before its graphical counterparts were computed and displayed). The system exhibits these traits (e.g., sensitivity to initial conditions, harmonically-related bifurcation regimes on the path to chaos) because of chaos-inducing structures (e.g., feedback, scaling and non-linearity). Lansky's piece includes a particularly elegant example of the model deployed.

6.3. (1995) ***Push Pull***

Accurate time-domain simulations of mechanical self-sustained instruments were begun in the mid-70's leading to a unified model describing most families of instruments [MSW 1983]. Coupled to the same passive, lossly, linear resonant component (representing the string or bore) is a driving mechanism (the bow or reed) through which sustained external energy (the bow arm or breath) excites the system. The driving mechanism is inherently non-linear since energy admitted into the system must be gated in a pulse-like, periodic way (hence the stick-slip action of the bow or the in / out switching of reeds and jets).

Models of brass instruments, flutes, reeds and bowed strings are distinguished by their gating mechanisms and the paths connecting them to the linear (pitch entraining) element. In each of these algorithms, the non-linear mechanism acts on the instantaneous difference between the drive quantity (e.g., bow motion) and the returning acoustical wave (string motion under the bow). The product obtained adds to the wave motion already recirculating in the system.

Control parameters that are added for this class of algorithms are again physical in nature (bow velocity / force or embouchure / breath) and envelopes to mimic articulations can be developed by shaping them like the player [Chafe 1989]. Changes to the controls, like starving or exerting extreme values on an oscillation create familiar sounding timbre changes. P. Cook's *slide flute* with vortex noise enhancements [Chafe 1995] accompanies the electric cello in *Push Pull*. It was a fascinating medium for an attempt by the author to create a synthetic, phrasing-sensitive, musical personality [Chafe 1999].

7. Futures

The following remarks speak for themselves and are as apt today as when they were written four decades earlier (as closings to two extremely influential articles presenting digital music synthesis for the first time). To the International Congress on Acoustics in 1959, the Bell Labs team wrote:

> "Apart from its potential contribution to the structure of a composition, the principle feature of digital computer generation of music is its precise control of frequency, timbre, temporal sequencing within a single voice line, and temporal sequencing of multiple voices. At present, cost of computer time and inaccessibility to computer facilities may be deterring features. However, as computers become cheaper, faster, and more practical, we expect them to become important musical instruments which will provide a medium of great versatility for composers and other musicians."
>
> [Mathews and Guttman 1959]

An article in *Science* magazine brought these possibilities to the attention of the scientific community at large, including composers who became influential in its further course.

> The Future of Computer Music
>
> Computer music appears to be very promising technically. However, the method will become significant only if it is used by serious composers. At present, our goal is to interest and educate such musicians in its use. We believe that competent work in the field can benefit not only music but the whole field of psychoacoustics."
>
> [Mathews 1963]

The pursuit of synthesis is just one aspect. Artificial style, machine perception, real-time systems, signal processing, programming environments, standards and protocols, all have timelines that tell important stories about the state of the art. *Noise* is a term with which we often sweep under the rug phenomena which we hear but which remain outside powers of analysis. As new means of analysis develop, new musical models will continue to be excised from within "noisy" realms extending from the physical to Pierce's "highly artistic noise." New computer music compositions will continue to ride the edge arriving with and often ahead of these new disciplines.

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