Recursive Digital Fabrication of Trans–Phenomenal Artifacts

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Abstract: The concept of a trans–phenomenal artifact arose from a project to digitally fabricate a series of bells, where each bell is shaped by the sound of the previous bell. This paper describes the recursive process developed for fabricating the bells in terms of generic stages. The first bells fabricated with this process raised the question of whether the series would converge to a static attractor, traverse a contour of infinite variation, or diverge to an untenable state. Reflection on these early results encourages further development of the recursive fabrication process, and lays groundwork for a theory of trans–phenomenal artifacts.

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1. Introduction

Digital fabrication is typically considered a one-way process, from the digital to the physical object. But could the process be considered as a transition between different states of the same artifact? The difficulty is that the 3D structure of a physical object is static, frozen in time. It cannot morph in response to changes in parameters like a digital structure can. However there is an aspect of every physical object that is temporal and dynamic — the sounds it makes. Physical acoustics are influenced by shape, size, material, density, surface texture and other properties of an object. Larger objects produce lower pitched sounds, metal objects are louder than plastic, and hollow objects produce ringing sounds. The acoustic properties of an object may be analysed with spectrograms and other signal processing techniques. A spectrum contains all the information required to re-synthesise the sound from simple sine tones, and this is the theoretical basis for the electronic music synthesizers. Could the spectrum recorded from a sounding object also contain the information to reconstruct the object that made the sound? This speculation lead to the idea to digitally fabricate an object from a sound recording. A sound could then be recorded from the new object. What would happen if another object was then fabricated from that sound? This recursive process of digital fabrication would generate an interleaved series of shapes and sounds shown in Fig. 1.

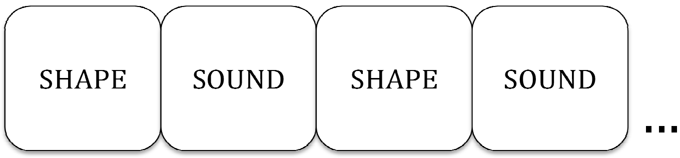


Fig. 1. An interleaved recursive series of shapes and sounds.

The rest of this paper describes experiments that explore this idea. The background section describes related concepts of synaesthetic transformation in painting, music and sculpture. It also describes previous work on sculptural 3D representations of music, and the digital fabrication of acoustic phenomena. The following section describes a first experiment to digitally fabricate a bell. This is followed by an experiment that develops a recursive method for generating a series of bells in which each bell is shaped by the sound of the previous bell in the series. The process is broken down into stages with parameters that can be adjusted to explore the space of possible outcomes. The discussion reflects on the results of the experiments, identifying theoretical issues and directions for further research.

2. Background

Wassily Kandinsky's invention of abstract painting was inspired by the abstract structure of music, and in his writing he refers to the synaesthetic composer Alexander Scriabin's 1915 score for *Prometheus: a Poem of Fire* which included a colour organ that projected arcs and waves of colour onto overhead screen in time to the music. The first abstract paintings in Australia were also inspired by music. Roy de Maistre's painting *Rhythmic Composition in Yellow Green Minor* featured in a controvertial exhibition in Sydney in 1919 (Edwards 2011). His interest in relations between sound and colour may have been inspired in part by his attendance one year beforehand at recitals on the colour organ by Alexander Hector in 1918. De Maistre developed a formal Colour Sound theory in studies such as *Rainbow Scale D# minor–F# minor*, and his works were popularly known as 'paintings you could whistle'. Some of his other musical paintings include *Arrested Phrase from a Haydn Trio in Orange-Red Major*, *Colour Composition Derived from Three Bars of Music in the Key of Green*, and *The Boat Sheds, in Violet Red Key*.

Fig. 2. Rhythmic Composition in Yellow Green Minor

In 1993 the Australian coder Kevin Burfitt released the open source music visualization program Cthuga that was the forerunner of the visualization plugins in media players such as iTunes, Windows Media Player and VLC today (Music Visualization 2013). Music visualizations map the loudness and frequency spectrum of sound into 3D graphics and image effects. The peer competition within the Cthuga community, and the ongoing commercial competition between large companies has resulted in high production values and well developed aesthetics in music visualizations.

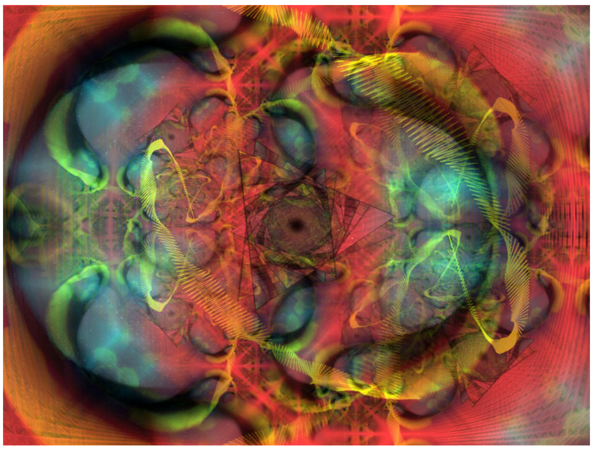


Fig. 3. Music Visualisation from MilkDrop

Computer programs have also been used in the inverse transformation from graphics into sounds. The UPIC program, developed by algorithmic composer Iannis Xenakis in 1977, allowed waveforms and volume envelopes to be drawn on a computer screen with a tablet to be electronically synthesized. HighC, shown in Fig. 4, is a graphic music creation tool modeled on UPIC that is available for download at http://highc.org/.

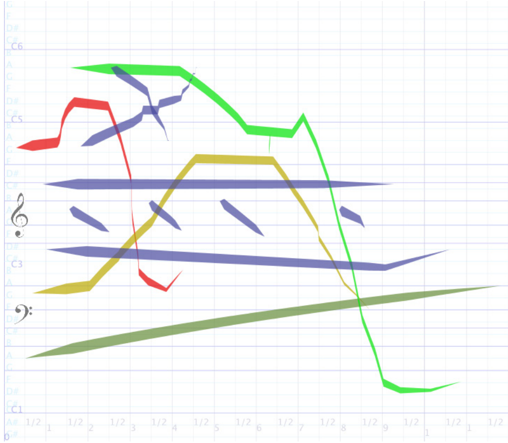


Fig. 4. Graphic Music composition using HighC.

The representation of sound in visual form is extended to three dimensions in the Sibelius Monument created by Finnish sculptor Eila Hiltunen in 1967 to capture the essence of the music of the composer Jean Sibelius. The unveiling of the sculpture constructed from more than 600 hollow steel pipes welded together in a wave-like pattern sparked debate about the merits of abstract art that resulted in the addition of an effigy of Sibelius.

Fig. 5. Sibelius Monument in Helsinki.

Digital fabrication provides a new way to create physical objects from sound. A search for 'sound' in the Shapeways.com community for digital fabrication returns a set of 3D models titled 12Hz, 24Hz and 48Hz (shown in Fig. 6) constructed from images of vibrations on the surface of water (Shuuki 2012).

Fig. 6. 48Hz sound vibration in water.

A further search for 'music' on *Shapeways* returns several flutes, pan-pipes and whistles that may be fabricated in either plastic or metal. There is also a wind-chime fabricated in glass or ceramic. These examples show the potential to use 3D CAD tools and personal fabrication services to custom design sonic objects and acoustic structures.

Neale McLachlan used a CAD package and computer modeling to design a set of 200 harmonically tuned bells for the Federation Bells installation in Melbourne in 2000, shown in Fig. 7. He identified the geometric factors that influence the harmonics as wall thickness profile, wall curvature, conical angle, the circumference of the opening rim, the thickness of the rim, and the overall width and height of the bell (McLachlan 1997). Bells are complex 3D shapes that flex in 3 dimensions, and they are much more difficult to tune than one-dimensional wind or string instruments. Tuning a bell was traditionally done by skilled craftsmen who manually lathed the thickness profile of a cast bell. Due to the high costs of casting bells in the modern era, McLachlan manufactured CAD bells by pressing sheet metal, which had the advantage of very consistent geometry. The fixed thickness required tuning of harmonics by shaping the wall curvature, rather than lathing the thickness (MCLachlan 2004).

Fig. 7. The Federation Bells in Melbourne.

Advances in digital fabrication technology have brought new materials, such as stainless steel, bronze, silver, titanium, glass, and ceramics. The introduction of metal shaping technologies in the iron and bronze ages resulted in the invention of bells, gongs, singing bowls and other resonating musical instruments. Could the introduction of metals in digital fabrication herald a new era of sounding objects that could not be arrived at by manual crafting?

3. Digital Fabrication of a Bell

This section describes an experiment to extend previous work on CAD bells by digital fabrication, with a view to more complex sounding objects in the future.

Digital fabrication places constraints on size, thickness and level of detail, depending on the material. The *Shapeways.com* service constrains stainless steel to a maximum bounding box of 1000×450×250mm, wall thickness of 3mm, and detail of 0.6mm. This is quite limiting but does allow for the fabrication of small bells.

A bell shaped 3D mesh was constructed from graphic primitives using the processing.org open source environment for graphic programming. The outer hemispherical shell with diameter 42mm and height 34mm was duplicated, scaled and translated to make an inner shell. The rims of the outer and inner shells were 'stitched' together to make a watertight shape. A handle was added so the bell could be held without being damped. The digitally constructed bell, shown in Fig. 8, was saved as a CAD file in STL format.

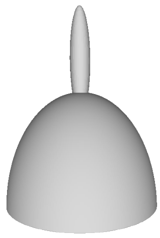


Fig. 8. Graphic rendering of the CAD mesh of Bell00.

The CAD file is limited to 64MB and the polygon count to less than 1,000,000 for uploads to the *Shapeways* site. The high resolution mesh was reduced in size and count by merging close vertices in the Meshlab open source system for editing unstructured 3D meshes (http://meshlab.sourceforge.net/). The mesh was then checked to be watertight and manifold using the Netfabb software for editing and repairing 3D meshes for additive manufacturing (http://www.netfabb.com/). This carefully prepared CAD file was then uploaded to *Shapeways*, and fabricated in stainless steel with bronze colouring, to produce the first prototype of a digitally fabricated bell shown in Fig. 9.

Fig. 9. Digitally Fabricated Bell.

When the bell was tapped with a metal rod it produced a ringing tone. The sound was recorded at 48kHz sampling rate with a Zoom H2 recorder in a damped room. The recorded waveform in Fig. 10. shows that it rings for about 1s.

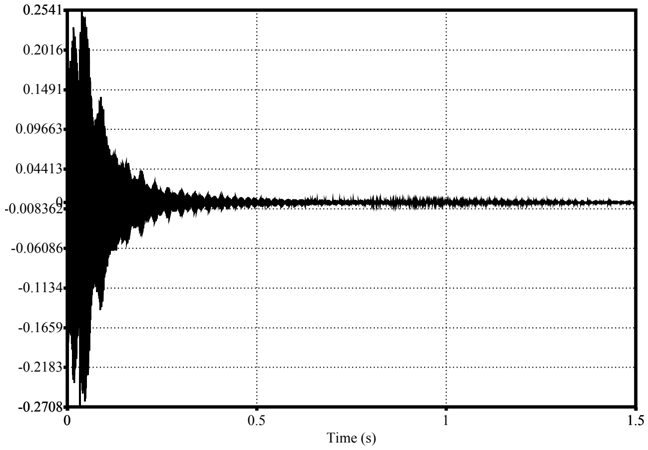


Fig. 10. Waveform of Bell 0.

The spectrogram, in Fig. 11, shows partials at 2971, 7235, 13156, 20359 Hz. The first rings for ≈1.2s, second ≈0.75s, third ≈0.5s and fourth ≈0.2s. The temporal development of these partials produces the timbral 'colour' of the bell. Although the partials are not harmonic, the bell does produce a clearly pitched tone.

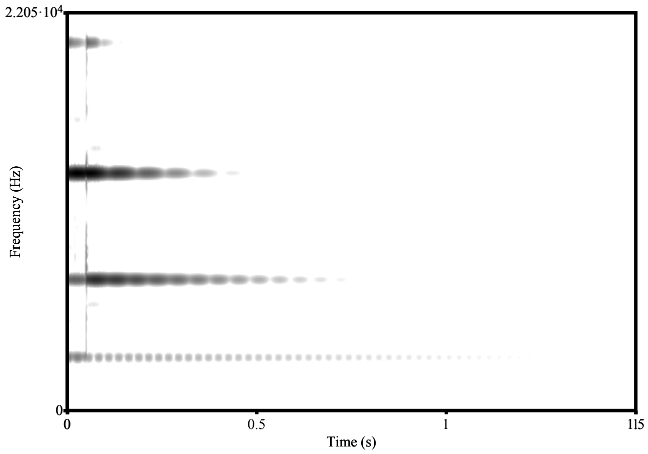


Fig. 11. Spectrogram of Bell 0.

The Long Term Average Spectrum (LTAS) is a 1D summary of the spectrogram. The LTAS in Fig. 12, shows the peak amplitude for the four main partials, along with the four main regions of resonance that produce the ringing timbre of the bell.

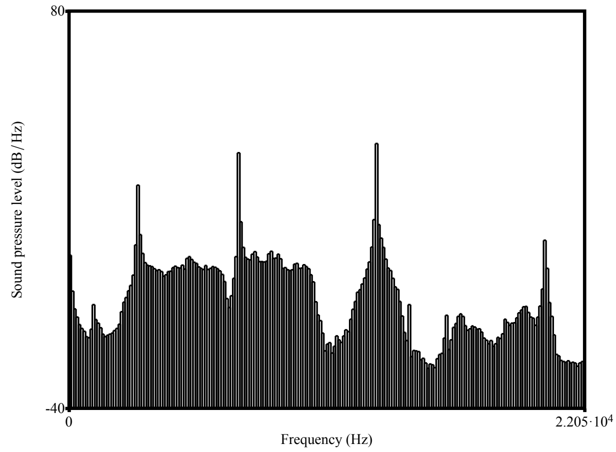


Fig. 12. Long Term Average Spectrum (LTAS) of Bell 00.

The prototype demonstrates that a bell can be digitally fabricated, and opens the door to more complex acoustic objects that cannot be manufactured or made manually.

4. Recursive Bells

This section presents an experiment to design of a recursive series of bells where each bell is shaped by the sound of the previous bell in the series.

The stages of the recursive process are shown in Fig. 13. The process begins with the CAD file specifying an initial bell, labeled as BELL 0. The CAD file is fabricated as a physical shape, SHAPE 0, which is the stainless steel prototype bell constructed in the previous section. The sound of SHAPE 0 is generated by tapping the bell, and recorded as SOUND 0. This sound is then transformed into PROFILE 1 by a process labeled XFORM. Then PROFILE 1 is added to BELL 0 and the new CAD file is fabricated as SHAPE 1, which is the next bell in the series. SOUND 1 is then recorded by tapping SHAPE 1, and XFORMed to create PROFILE 2, which is added to BELL 0 to create the second recursive bell. This recursive process can be repeated ad. infinitum to produce a series of interleaved SHAPES and SOUNDS generated from each other.

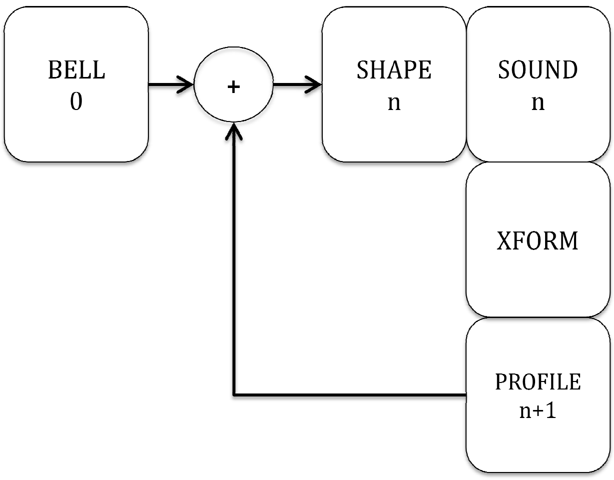


Fig. 13. Recursive fabrication process.

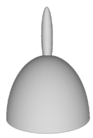
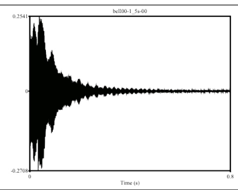
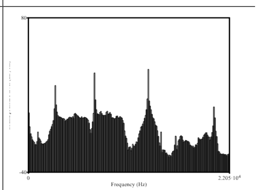
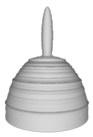
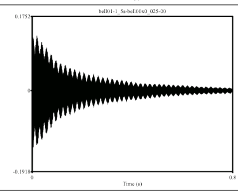
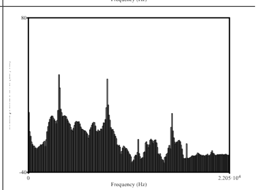
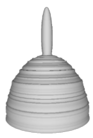
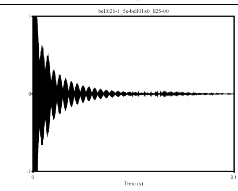
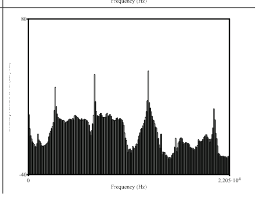
4.1. XFORM

The XFORM is a mapping from sound into a thickness profile that can be added to a bell shape to change the sound it makes.

The LTAS analysis of the prototype bell captures timbral features in a 1 dimensional format that can be used to algorithmically construct a thickness profile as a 3D quad mesh. The LTAS has low frequency and high frequency ends that could be mapped onto the bell shape in two different directions. The physical acoustics of vibration mean that lower frequency resonances are produced by larger objects, and higher frequencies by smaller objects. This led to the decision to tonotopically map the low frequency end of the LTAS to the large circumference at the opening rim, and the high frequency end to the smaller circumferences towards the crown.

The first experimental series of bells generated using this XFORM is shown in Table 1. The first row shows the CAD rendering of the basic bell, a photo of the first prototype fabrication, the waveform of the sound it produces when tapped, and the LTAS profile with 4 partials. The second row shows Bell 1, with thickness PROFILE 1 constructed by XFORM from the LTAS of Bell 0, and fabricated in stainless steel. The waveform rings for ≈1.5s, and the LTAS shows 3 partials that produce a higher pitch, but lower timbral brightness. The third row shows Bell 2 shaped by the XFORM of LTAS 1, and constructed in stainless steel with gold colour. Bell 2 rings for 0.75s, but has only two main partials. The pitch is higher than Bell 0 and lower than Bell 1, and the timbre is brighter than either.

Table 1. Recursive series of bells 0, 1, 2.

n	SHAPE *n*	BELL *n*	SOUND *n*	LTAS PROFILE *n*+1
0				
1				
2				

4.2. Profile weighting

Bells 1 and 2 look and sound more similar to each other than expected. The weighting of the shape profile relative to the bell template can be adjusted in the mesh generating program. The ability to alter this weighting has been added to the process diagram as a parameter labeled T in Fig. 14.

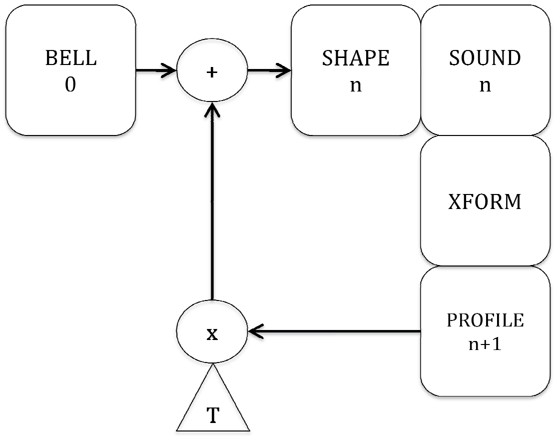
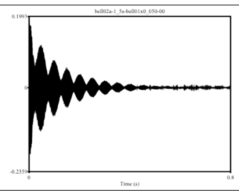
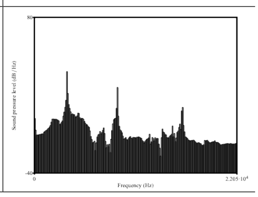


Fig. 14. Process with profile weighting T.

The next experiment tested the effect of varying parameter T on the sound of Bell 2. An alternative Bell 2+ was fabricated with T double the previous level, thereby doubling the geometric effect of the PROFILE generated from the sound of Bell 1. The results in Table 2, show an amplitude modulation in the ringing sound that is heard as a tremolo effect. There has also been an increase in the frequency of the two main partials. Bell 2+ is distinctly different in timbre from Bell 2, and Bell 1.

Table 2. Bell 2 with doubled parameter T.

n	SHAPE 2+	BELL 2+	SOUND 2+	LTAS PROFILE
2				

This result suggests that increasing T may generate more variation in the series of shapes and sounds. To explore this further the value of T was raised to 3x and used to generate the next bell in the series. The CAD rendering of Bell 3++, shown in Fig. 15. has wide flanges that indicate that raising T too high could transform the geometry beyond the point where it will function as a bell. On the other hand, these flanges may introduce unusual timbral effects, such as tremolos and vibratos, that are not heard in conventional bells. At this stage the bell has not been fabricated and the experiment is still work in progress.

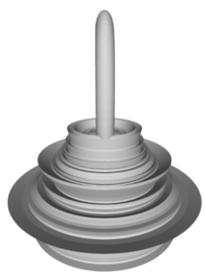


Fig. 15. CAD rendering of Bell 3++

4.3. Material

The Bells in the experiments have so far been fabricated in stainless steel. However, other materials, such as ceramic and glass, also have good acoustic properties. The recursive generation process is updated with a stage for materials in Fig. 16. What is the effect of using these materials on the acoustics of the bell?

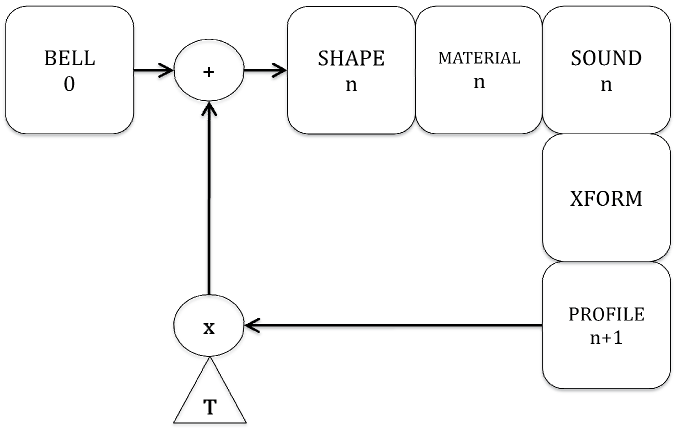
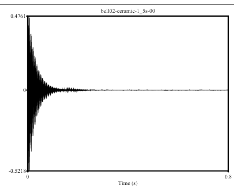
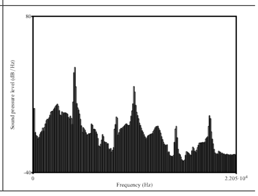


Fig. 16. Recursive process incorporating material

Bell 2 was re-fabricated in ceramic. This version of the bell is smoother and has less detail, as can be seen in Table 3.

Table 3. Bell 02 fabricated in ceramic.

n	SHAPE 2+	BELL 2 ceramic	SOUND 2 ceramic	PROFILE 3 ceramic
2				

Tapping the ceramic Bell 2 produced a short, sharp, high pitched, percussive sound very different from the ringing produced by the stainless steel version. The LTAS profile has 3 partials that look generally similar to previous bells. However the short duration makes it difficult to hear spectral details. The reduced detail of the ceramic fabrication effectively low pass filters the LTAS profile. Does this reduced detail have a perceptible effect on the sound the bell makes? This could be answered by fabricating a low-pass filtered version of Bell 2 in metal, and then comparing the sounds produced by the smoothed and original bells.

5. Discussion

The effect of varying the T parameter raises the question of whether the series will converge to an attractor shape, traverse a contour of endless variation, or diverge to a point of destruction? Is there a value of T on the boundary between convergence and divergence? Is the recursive process a random walk or does it have a trajectory of some kind?

If the series does converge, the bell will produce a sound that has an LTAS profile that is identical to its own thickness profile. The shape of this bell is a blueprint for the sound it produces, and the sound contains the blueprint for the bell that produced it. This attractor bell and its sound would be bilateral transformations of the same trans–phenomenal object. Does such an object actually exist, and can it be found with this process?

The XFORM mapping between the sound and shape in these experiments has been a simple mapping of LTAS to thickness profile. The decision to map the LTAS in one direction raises the question of whether mapping it in the opposite direction would make a difference. There are also other ways that features of a recorded sound could modify the acoustics of a bell. The audio waveform could be wrapped in a spiral down the bell shape, etching into the profile in a manner similar to a needle groove on a wax cylinder or record. The frequency axis of the 2D spectrogram could be assigned to the radial angles of the bell with the amplitude affecting the profile in the radial directions. Other kinds of timbral analysis could be used, such as mel frequency cepstral co-efficients (MFCC), or granular centroid, flux, kurtosis, and skew.

6. Conclusion

These experiments to generate a recursive series of bells and sounds have identified generic stages in a systematic process. The XFORM stage is a mapping between sound and shape. The T parameter controls the level of feedback in the recursive circuit, and the amount of variation in the shapes and sounds that are generated. This parameter may also affect whether the series converges, traverses a contour of variation, or diverges to destruction. The material has a significant effect on the acoustics of the object, and different materials may cause convergence to particular attractor nodes, for example the lack of detail in ceramic shapes and sounds may cause rapid degeneration to a singular point.

The bells in these experiments open the door to the design of more complex shapes than can be made with conventional manufacturing techniques. The geometry of acoustic shapes could be generated using a 3D fractal such as the Mandelbulb, or a rule based L system. These shapes can have complexity that is beyond the state of the art in acoustic simulation with finite element meshes. Digital fabrication allows rapid prototyping of physical objects that could allow research on the acoustics of shapes that are more complex than hitherto been possible.

These experiments have raised many theoretical questions to guide further experiments which are still in progress. Can the recursive process be used to find a trans–phenomenal artifact where the acoustic response contains the blueprint of the object that produced it? What new shapes and sounds will be generated through this process?

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