Modelling in Audio: Physical, Phenomenological, and Mimicry

EXE Consulting

05 August 2024, 23 September 2025

This is a Rough Draft

The subject of this note is modelling in audio applications such as computer-based instruments and effect processors, in particular three types of modelling: physical, phenomenological, and mimicry. The audience for this note includes many different types of programmers and users, but more specifically anyone who believes that real-time, computer-based instruments and effects utilize physical modelling. A major point of this note is that there is little to no physical modelling being done in the world of real-time audio plugins, and the scope of this note is limited to explaining this point by means of giving descriptions of each of the three types of modelling.

Mimicry is very simple: Something makes a sound. Another thing that is of completely different construction ideally makes a sound that is indistinguishable from the original. Birds of certain species, for example, "hear" an original sound and figure out a way to replicate that sound after trial and error. Mimicry involves no modelling because there is no one-to-one match of internal components of the two different sources of sounds. Mimicry is a type of pattern-matching, strictly limited to matching input and output, no matching whatsoever of internal states. For the remainder of this note, the proposition that "no matching of internal states" means "no modelling" is accepted as self-evident, leaving only two types of modelling to be discussed.

It should help to recognize that the best model of something is a literally exact copy of that something, and nothing less. Mimicry is about as far away from this ideal as one could possibly get.

Physical versus Phenomenological

Distinguishing between these two types of modelling is important for a number of reasons, among which is that ignorance of the differences could lead to bad investments, wasting of time, promising projects being cancelled due to such ignorance, and so on. People could wrongly believe that we've already reached the end of the road, whereas we are currently very far from it.

Physical modelling is based on solving, for example, partial differential equations in three-dimensional space along with the associated boundary and initial conditions. The partial differential equations to be solved are based on physical "laws," for example the conservation of linear momentum, which itself can be thought of as a consequence of something that is even more fundamental, such as the required properties and various symmetries of three-dimensional space. (For example, Noether's Theorem "states that every continuous symmetry of the action of a physical system with conservative forces has a corresponding conservation law" [3].)

Phenomenological modelling is based on the observed results of physical systems governed by physical "laws," not upon the "laws" themselves.

It is probably fair to say that a number of computer-based instruments and effects are "based on physics," but this phrase is as loose a description as Hollywood's "based on real events," which is more of a denial than a confirmation. "Based on real events" means not truly real. Similarly, phenomenological modelling is not truly physical modelling, but the latter term is very often misused as a description of software that is actually the former. It is no exaggeration to say that this misuse is rampant.

Once upon a time, I created several room acoustics modelling programs that 1) Solved the 3-D acoustic wave equation for regular 3-D structures such as parallelepipeds; 2) Simulated the absorption of acoustic energy as time progressed. The first part was physical modelling, involving the solution of a 3-D partial differential equation along with boundary and initial conditions. The second was phenomenological modelling because I imposed functions of decreasing amplitude over time on top of the solution for the wave equation. The first is based on equations derivable from physical "laws" (for example conservation laws of energy, mass, momentum, etc.) while the second is based on the observed result of physical systems governed by physical "laws," not upon the "laws" themselves. Absorption of acoustic energy occurs due to many different mechanisms, for example, the induced vibration and rotation of molecules in the medium and in the layers of the boundaries of a structure. None of this was modelled in any detailed way whatsoever. There was not one iota of code that simulated the induced vibration of molecules. The phenomenon or result of decreasing sound was modelled mathematically, crudely, and very inexactly, but nevertheless sounded realistic to me and others.

Some people in audio like to say: "If it sounds good, then it is good." As a claim whose scope is limited to judgment about the artistic merit of a piece of work, there is little if any harm done by accepting this widely appealing claim, or perhaps more accurately this widely appealing sentimental definition of goodness; however, similar-sounding claims "If it sounds good, then it must be correct," "If it sounds good, then the internal details don't matter," and other similar claims have no basis in fact. There are far too many counterexamples to accept these latter claims as anything other than sheer nonsense.

Phenomenological models tend to take their lead from "If it sounds good, then it is good" types of claims, whereas physical models tend to take their lead from very fundamental and widely applicable principles.

There is a well-known book on the physics of musical instruments, [1]. I purposefully opened this excellent textbook randomly the other day to what turned out to be Section 16.4: The Regenerative Excitation Mechanism, page 516. There is a tremendous amount of information here about resonators of specific types, equivalent networks of admittances, and so on. A large number of approximations were made as the section proceeded. By the end of the section, a number of results were cited. I have no doubt that many users of audio plugins would conclude that this discussion is concerned with physical modelling. Then began the next part, Section 16.5 Rigorous Fluid-Dynamics Approaches. "As mentioned at the beginning of this chapter [16], the theory developed above is far from rigorous and includes many conceptual approximations. A rigorous theory should be based on the Navier-Stokes equations of fluid dynamics and must consider the vorticity field of a real fluid in the complex geometry of the instrument." The Navier-Stokes equations "represent the conservation of momentum for the three-dimensional flow of a Stokesian fluid" [2]. As implied above by mention of Noether's Theorem, conservation of momentum is a very fundamental concept in physics, not just a mathematical expression that a DSP programmer can conveniently use to approximate a particular phenomenon in a VST instrument or effect in real time.

Is the distinction clear? The discussion of Section 16.4 is a set of phenomenological models based on observations of results, while the statement at the beginning of Section 16.5 is a description of the minimum requirements of a basic physical model that has not yet been discussed.

Whenever one reads about "resonators," admittances," "waveguides," and the like, it is important to understand that these are abstract devices whose mathematical behavior can emulate phenomena of real instruments, but they are not actual physical devices. Now one can indeed have in one's possession a physical device that one might call a "waveguide." However, this unique physical thing has actual, unique physical dimensions, and is made of particular materials which have physical properties that depend on physics that goes down to the most fundamental things that we know about, far beyond the experience and knowledge of the vast majority of people who have ever lived or ever will live. The "waveguide" of a phenomenological model is typically a very simplified, approximate idealization of something that is actually an abstract concept that summarizes gross behavior that may be useful for producing something that some people may find to be an interesting sound to play around with. But confounding one or more digital "waveguides" with a real instrument like a real French horn is a serious mistake. It is not enough to kinda-sorta sound like a real French horn for a model to be considered a physical model as is done by some people in various videos, audio forum threads, and other media.

Let us now consider a real drum. How do you tune it? This is done, according to various videos and guides, by tightening the lugs on a drum in a particular order. How is this tuning done for various types of drum emulation software that claim to be physical models of drums? Do you actually have to pick up a wrench or other tool and tighten items displayed on the screen in a particular order? Or do you simply adjust a pitch-shifter until you like the sound? With a true physical model of a real drum, you would do everything with the physical model that you would do with a real drum. In contrast with this, and with a phenomenological model, you would, for example, take the mouse and move some emulated knob up or down, clockwise or counter-clockwise, etc. You just change the numbers of an abstraction. How do you change the skin on a real drum? You don't just take a mouse and rub it on the skin to change a number in the skin's memory, do you? Or select a radio button option on the side or bottom of the real drum? Isn't it true that you first have to physically remove the old skin, then carefully and forcefully place the new skin such that it seats properly, taking care to stretch it and so on? Is this also how drum plugins work? If not, then they are not truly physical modelling programs, instead phenomenological modelling programs.

Summary and Conclusions

Mimicry is not modelling at all. Phenomenological modelling is modelling of observed behavior. Physical modelling is simulating everything you would do with the real thing, no matter how unpleasant and time-consuming. Little to none of the latter is being done in the world of VST and other computer-based instruments and effects. There is a very long way to go, most likely forever, before this happens, especially in real time. The difference between phenomenological and physical modelling is widely understood and accepted in many technical fields, but there are unfortunate exceptions of fields full of people whose knowledge is quite deficient with regards to modelling. I sincerely hope that this note will improve the situation in audio, revealing the real potential of future modelling as well as the true and severe limitations of current technology.

[1] Neville H. Fletcher and Thomas D. Rossing. The Physics of Musical Instruments. Second Edition, Springer,1998.

[2] Jerald D. Parker, James H. Boggs, and Edward F. Blick. Introduction to Fluid Mechanics and Heat Flow. Addison-Wesley, 1974, page 89.

[3] https://en.wikipedia.org/wiki/Noether's_theorem