Digital Design In Architecture:
First Light, Then Motion, and Now Sound

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If we restricted our idea of architecture to only the traditional and static description of visual space and form, we might not be considering significant characteristics of the places we are designing. If, however, we accept even a limited definition, as stated by LeCorbusier, that “architecture is the masterly, correct, and magnificent play of masses brought together in light”, we would at least be forced to consider the dimension of time as the ever-changing daylight modifies the way our creations are perceived. However, neither the built nor the natural environments are silent. Sound affects the way we feel about certain events and places, and in turn, places we create can modify or influence the way we hear sounds. As computers become more audio capable, we can expect changes in the ways that architects plan, design, and present their projects. Issues of both objective and non-objective sound can become significant factors throughout the building delivery process. As the visual sophistication and acoustic expectations of society rise because of the ubiquitous power of electronic multimedia — as well as “cross-media” applications (film, video, television, and scientific visualization) — it is inevitable that the architectural design and presentation processes reflect these changes.

Introduction

A brief survey of magazine advertisements shows that audio capable computers are now the “computer of choice” for mass market retail purchases and are quickly finding their way to the homes and offices of the general public. As affordable desktop computers become even more powerful and the level of audio capability increases, we have the opportunity to give both designer and client more information with which to make decisions during the building delivery process. The computer with multimedia capabilities can have an impact on the design process by providing both objective data and subjective influence.

In the pursuit of Architecture, we are concerned with (or should be concerned with) the sensory impact of our work. We can both see and touch the results of our efforts. But Architecture involves more; the design of interior and exterior environments includes consideration of both ambient and specific sounds. The quality of sound as perceived within any space is affected by variables which are undeniably architectural in nature: the volume of the space, the geometry of the space as well as the objects within it, and the nature of the finish materials present. All of these variables are, in some way, measurable and therefore lend themselves to a computational analysis of their interaction with sound waves. The complexity of aural analysis notwithstanding, architects have long understood the importance of acoustics in their designs. The increasing use and availability of computing power will soon permit the architect to include the evaluation of acoustic parameters as part of the design process in a matter comparable to the study of lighting, energy efficiency, and structure.

Architects, however, must also deal with issues that extend beyond the quantifiable. Discussions

Several architects are now redefining the profession as: inclusive, responsive, cooperative, and embracing the complex realities of relating the natural and man-made worlds. Pliny Fisk offers an instructive example. His Center for Maximum Potential Building Systems near Austin, Texas has been tackling the problem of responsive, involved architectural practice for several years. In his pursuit of problem definitions and problem resolutions, nothing is considered
of buildings frequently include words such as "spirit", "image", and "character". If we assume that these qualities must be taken into account during design, we must also assume that there is value in communicating this information to others (and to ourselves) during the design process. Music, speech, background sounds, etc. are all part of the environments we create and influence the character and mood of the place. Furthermore, as individuals become used to being "entertained" (interactively and/or passively), they are more likely to expect sounds to be part of the "presentation package" they see prior to deciding the fate of any particular project. A culture of people accustomed to television will more likely respond to presentations that make sophisticated use of audio and visual stimuli in a manner similar to that used in contemporary art, entertainment, advertising, and education. Just as renderings allow the architect to communicate a visual picture of the character of a place (accurate to the extent the architect chooses), sounds may soon accompany animated or serial presentations that communicate additional perceptual qualities.

The following represents "educated speculation" about the potentials and possibilities of integrating acoustic analysis and sound into the building delivery process.

Audio Capable Computers

Audio capable computers must have a variety of characteristics if they are to be useful for both objective analysis and non-objective sound integration.

In order to be able to manipulate acoustic data within an architectural model, the computer must be capable of creating, storing, and displaying the physical information of the three-dimensional model itself. Furthermore, the processing speed must be sufficiently high to perform both graphic and analytic calculations with enough speed so as not to inhibit the design process it is supposed to help. (The recent history of CAD/graphics has shown that if designers need to wait for what they perceive to be an excessive amount of time for information, they will find other ways to get the data — or do without it altogether.) Three-dimensional data must also, of course, be capable of being displayed both graphically and aurally.

Audio (or "sound") boards continue to simultaneously gain features and drop in cost. As with video cards, each level of hardware sophistication services some specific area of the computer-use spectrum. Low bit, low resolution boards may be acceptable for voice annotation (for use in correspondence with a remote consultant or client, voice descriptions of vendor supplied information, etc.) but greater capability is necessary for more demanding applications and complex sound manipulation.

Sampling Rate

An audio board should be capable of sampling from 6 or 8 kHz to 44 kHz [WALKENBACH 1992] (in this instance, sampling is a time value which refers to the frequency with which a recording device "listens to" the audio source.) Voice annotation will record acceptably ("telephone quality") at 11.025 kHz. Quality comparable to that heard on the radio would be sampled at 22.05 kHz. For faithful recording of musical tones, sampling can approach the quality of an audio compact disc at 44.1 kHz. Some boards boast a sampling rate of 48 kHz, called "DAT quality." At 48 kHz, audio reproduction is, in theory, beyond the range of discernment by human ears. However, some audio systems make use of this quality to create an "ambiance," something of a tactile stimulation through resonances in nearby objects or even one's skeletal structure [SUTHERLAND 1993]².

Bit Resolution

While sampling rates as an input consideration may be roughly analogous to the dots-per-inch capability of image scanners, the concept of bit resolution in audio cards shares closer ties with the bit designation of video cards. Just as 16-bit capability on a video adapter exponentially surpasses 8-bit capability (65,536 colors versus 256), 16-bit audio capability is superior to 8-bit capability ("CD quality" versus "business quality"). Worth noting are technological advances said to improve the quality of 8-bit sound (in some ways, a distant cousin to dithering) and the existence of a rarely used 12-bit...
sound compromise [Sutherland 1993]. Nevertheless, 8-bit sound adapters are rapidly becoming obsolete.

Other noteworthy features appearing on audio cards are on-board DSP and on-board compression. On-board DSP, or digital signal processor, works like a co-processor to help speed tasks and expand capability. The upgradability of the DSP will be an issue to those who want access to emerging developments, i.e., reverberation, delay, and voice recognition. Because CD quality recordings will consume memory at a rate of about 10 MB per minute, the availability and quality of on-board data compression will be a crucial concern to most users.

**Audio Output**

The number and quality of the speakers and the environment in which they are used represent a significant component of audio capability. The perception of the audio hardware is only as good as the quality of the output device. The presentation of high-quality audio images through low-quality speakers is tantamount to the display of data-rich, graphically sophisticated video images on substandard monitors. In short, any of the links which make up an audio presentation - input, resolution, storage, or output - has the potential to weaken the whole. The quality of audio output, while relevant for all types of acoustic simulation and evaluation, may be most critical when considering non-objective sound. An objective analysis of any proposed acoustic environment usually includes numeric data as part of the information being evaluated. Aural information that one hears through the computer is subject to the idiosyncrasies of an individual's ear and represents only a portion of the analysis. However, because non-objective sound depends exclusively on individual perception, the audio output may be the only means by which information is transferred and therefore becomes a critical component in communication.

**Objective Sound**

The current state of architectural acoustics research suggests that architects may soon be able to manipulate sound in computer aided designs in a way comparable to the manipulation of light. There are a variety of algorithms being designed, written, and revised to achieve both accuracy and reasonable computation time to analyze acoustic performance of proposed spaces. Applications have tested the viability of available packages [Turner and Hall 1990]. A number of analytical packages are commercially available and some designers are writing their own. Most, however, do not utilize the audio capabilities of computers; feedback is provided to the user graphically and/or numerically.

The idea of computer models for acoustical study is not new. Some literature on the subject dates back over 25 years [Krokstad, Steren, and Sondel 1968]. However, the recent availability of relatively cheap computing power has spurred a fairly active period of development. There are currently two popular approaches to the development of room acoustics computer models: image source algorithms and ray-tracing algorithms.

**Image Source Method**

Several different researchers have described the image source algorithm [Kirszenstein 1978, Borish 1985, Lee and Lee 1988]. The algorithm works by tracing sound image sources back from a receiver position. This method has proved to be impressively accurate, since energies and reflection times are calculated with floating point precision. However, the technique is painstakingly long on computation time. Many image sources must be calculated, only to have most of these rejected because they are not visible to a particular receiver position (Figure 1). In theory, the ratio of visible sources to invisible ones can be as high as 10 [Vorländer 1989]. Because of the exponential nature of calculating air positive reflections, air researchers using the algorithm have had to truncate the length of the impulse response relatively early. For example, for an initial impulse response duration of 400 ms, a room with 30 walls and a volume of 15000 m³ would require 10 wall reflections for a reasonable level of accuracy. The computation time would require some 10000 years on an old IBM-AT compatible computer [Vorländer 1989]. These constraints limit this

"out-of-bounds". His group has no problem imagining ways in which to use computers, because, in their practice, they are asking important questions. In challenging themselves they challenge our view of the profession and our view of the role of computers in that profession. Viewing the profession with these new glasses, we can now raise some questions and engage in speculations on what computers are or could be.
technique to very specific cases which include: very short impulse responses, a small number of walls, or simple rectangular rooms where the visibility test can be omitted. Note also that the image source method relies on specular surface qualities.

Figure 1: Image Source Method. The listener volume actively seeks and calculates all possible sound images. In most cases, however, the majority of the images will be discarded because they are not visible to the listener.

Ray-Tracing Method

The earliest computer models use some variation of the ray-tracing algorithm. The algorithm works by the radiation of sound "particles" omni-directionally from a source. Each particle carries with it a certain magnitude of energy. As these particles encounter obstacles, usually walls, some amount of energy is absorbed and the remainder is reflected to wall after wall until the rays reach a receiver position. Arrival times and final energies are recorded to construct the sound intensity and reverberation time (Figure 2). While the accuracy level is not as high as with the image source algorithm, the computational times are considerably less. The 30 wall example described above would require a shortened amount of computer time: approximately 12 hours on the same IBM-AT [Vorländer 1989]15. The ray-tracing method also has the added feature of being able to account for diffuse reflections from a rough surface, something that the image source method cannot do. A documented problem with at least one variation of the ray-tracing variations is that the spreading of rays as they grow farther from the source, a simulation of energy reduction through the atmosphere, can cause rays to just miss a receiver volume [Vian and Van Maeke 1986]12.

Figure 2: Ray-Tracing Method. As rays travel, some amount of sound energy is absorbed by walls and fixtures while the diminished remainder is reflected. The listening volume passively waits for the rays to arrive, then records sound energy levels and time of arrival.

The evolution of these sound propagation models continues to push them toward a finer form of acceptable accuracy and computational times. A ray-tracing algorithm for fitted workshops, dubbed the RAYSCAT model [Onset and Barby 1988]13, has scored very high in a testing of several different algorithms [Hodgson 1990]14. A hybrid approach has been proposed in which ray-tracing finds only visible image sources before handing over computation to an image source algorithm [Vorländer 1989]15. Cones, instead of rays have been proposed to rectify the just-miss possibility of the classic ray-tracing algorithm [Vian and Van Maeke 1986]16.

Other have suggested adding a reverberation "tail" to either the image source or ray-tracing method to handle the exponential factors involved [Laude and Vian 1990, Jacob, Birkle, and Ickler 1990]17, 18.

Howard's End

critical thought

collaboration

ACADIA 1994
Limitations

The current acoustical computer models attempt only to measure steady state and transient sound propagation within empty or fitted spaces. This will account only for airborne sound energy propagated and received within the same space. Profoundly absent is analysis of impact noise and the analysis of the ability of a material to transmit sound energy (Figure 3). Impact sound analysis, for example, would allow for the study of footstep noise through a floor structure into connected spaces. Related to the study of impact sound is the phenomenon by which airborne sound energy is transmitted through a wall, floor, or ceiling only to become airborne sound again in an adjacent space. (In some building types - especially multi-family housing which is not always subjected to rigorous acoustic analysis during design - sound transmission through barriers has an enormous effect on the comfort of the space for its inhabitants.) Note that the current algorithms that provide for fitted spaces consider only the sound energy reflected from those fittings and not the sound energy transmitted through them. In order to do a complete and meaningful acoustical analysis, an architect must be aware of the total, albeit complex, interaction among these different types of sound energy. As the technology now exists, the only beneficiaries will be architectural firms specializing in the design of concert halls, auditoriums, and other such spaces concerned chiefly with initial impulse airborne sound propagation.

The idea of extrapolating acoustical data from a three-dimensional model will necessarily require digital models constructed to more exacting specifications, since even the choice of caulking or flooring adhesive will have an impact on the acoustics of the space. Also, the assembly method of building components will be extremely important. However, in coming years, it is possible that 3-D objects will possess virtually all of the properties that belong to the real materials that they are intended to represent [Pupar, Dansah, and Baecker 1991]12.

Thus, beyond the visual attributes of the object (size, shape, color, texture, opacity), there will be acoustical attributes (density, rigidity, texture), physical attributes (mass, friction, gravity, structural

Figure 3: A visual representation of the acoustical transmission values for walls of varying construction. Note the unchanging impact transmission waves on the floor and side wall.

Design as Communication

Questions about design process or architectural educational and practice can be approached through a view of them as communication systems. The design process is better when people communicate more effectively with each other and with themselves; architectural education is better when we improve our skills of representation, critical thought, and collaboration; and the practice of
strength), thermal attributes (thermal conductivity), and even fire safety attributes (strength at high temperatures, smoke generation). As such, acoustics analysis may be an early step towards this goal.

The Next Step

Still to be developed in detail would be a package based on research into the integration of any of these methods into a 3-D design package that supports sampling of sounds, computational manipulation, and output through audio hardware. At some point, interrogative “hearings” should become available that rely on rapid analysis and output of acoustical data in a proposed three-dimensional model. Sound source data packets, which might include “orchestra,” “string quartet,” and “traffic,” would be chosen from libraries and placed within the model with a given magnitude and primary direction, much like the manipulation of light sources in visual rendering software. Similarly, a receiver volume would be placed within the model and oriented. Included in this complex manipulation of data will be the need to adjust variables in finish material, texture, and furnishings to study and hear the impact of design decisions. Aural analysis of buildings and spaces is already being researched by a variety of groups, including the Acoustics Research Group at the University of Florida which is expanding its interest to include behavioral impacts [Sieben 1994].

Finally, there is some question, as stated earlier, about the nature and quality of the output devices and the acoustic properties of the room (or place) in which the designer and clients sit while listening to and evaluating the acoustic feedback. Nevertheless, it is important that architects and researchers recognize the need and opportunity for expanding the accountability of design to include acoustical information. Much in the way graphic image sampling with computers allows us to quickly test formal ideas in site [Gold and Zelinka][2], the audio capable computers will ultimately allow us to test our designs against additional criteria.

Non-Objective Sound.

The use of audio capable computers will not be limited to objective and quantifiable acoustic analysis. Architects may find that adding non-objective background sound to design presentations enhances communication. Architects who see themselves as “purists” may be reluctant to appreciate the incorporation of sound that is not, at first glance, directly related to the design. However, as computing cost-to-performance factors continue to advance, a design presentation could easily produce many still images and lengthy, detailed animations. In many cases these will be expected or required by the client. Inevitably, computers-based sound will make its way into these presentations and a serious study on the melding of architectural images with non-objective sound will result. While this category of skill already exists in other disciplines that can easily be tapped by the architectural firm, responsibility will invariably move more and more “in-house” in the same way desktop publishing has changed the ways proposals and reports are prepared by businesses. Understanding the implication of non-objective sound in presentation will invariably become another skill in the architect’s repertoire.

To understand why non-objective sound will become part of a typical presentation in the future, one need only look at the history of music in silent film. In trying to explain the affinity between film and music, Kurt London, in his early study Film Music stated:

“The reason which is aesthetically and psychologically most essential to explain the need of music as an accompaniment of the silent film, is without a doubt the rhythm of the film as an art of movement. We are not accustomed to apprehend movement as an artistic form without accompanying sounds, or at least audible rhythms. Every film that deserves the name must possess in individual rhythm which determines its form. (Form is here taken in the widest sense as a ruling concept.) It was the task of musical accompaniment to give it auditory accentuation and profundity.”
[Prendergast 1992][2].

Howard’s End

Communication: Intrapersonal Interpersonal Extrapersonal Ecological

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Technological advances continue to make animations easier for the architect to produce, and as such, the representation of a design as a meaningful sequence of events becomes easier to communicate. As the proposed rhythm of a design becomes clearly apparent, music will no doubt find its way in as an enhancement to the message.

As important consideration will be the ultimate relationship of the music to the design. Will the music simply serve as inspiration to the designer? Will the music help lend continuity to the images presented to a client or to fellow designers? Will the design and music be forever explicitly linked? (Helmut Jahn explicitly links movement, light, and music to create a “total environment” in the underground passage at United Airlines terminal at O’Hare Airport in Chicago.)

Perhaps more likely, the architect will simply view music as a way to enhance a presentation. The background music may be used to enhance, influence, and even manipulate viewers as it does in movies. (Imagine watching Elliot ride his bicycle into the sky in ET without the film’s soaring music.)

The type of sounds, and the integration with the “camera views” in an animation, can also affect the way a place is perceived. The shaky camera and staccato-like music at the beginning of the television show NYPD Blue is meant to give an impression of grit and toughness. Classical music being played while slowly panning across a New York City street would not convey the same intent.

Audio enhancements are not limited to music and they may include other sounds. The popular game SimCity 2000 by Maxis, Inc. has integrated synthesized sounds to simulate the building and destruction of a city including sounds of construction, traffic, and riots. There is even a spontaneous “parade” - complete with cheers - given to the mayor (player) of a successful city. Once a player decides to toggle off the sound, the game seems relatively empty. Similarly, animations showing a celebration in a grand space may subly (or not so subtly) convey the character of the place that the architect intends.

Orson Welles, in his critically acclaimed masterpiece Citizen Kane, pioneered the use of non-musical, non-objective sound in motion pictures. Very likely as a result of his experience in radio, Welles felt that, “...anything you could do to heighten the drama of a scene was worth doing and also of course the use of sound with the emphasis on its more dramatic content rather than its factual content was part of his concept.” Welles’ thinking was that sound could be used without reference to what was going on the screen.” [Prendergast 1992]22. Other worthy cinematic examples of the use of non-objective sound to enhance a message include Hitchcock’s The Birds and Friedkin’s The Exorcist. Although architecture does not usually strive for the extreme emotional response of these offerings, we can expect that architecture will not be immune to the influences that often result in the cross-referencing among seemingly dissimilar disciplines.

It should be noted that the idea of non-objective presentations is not a new one. Richard Norman, in his study of real and unreal color, cited the use of watercolor in architectural drawings at the École des Beaux-Arts during the nineteenth century. Although the watercolor renderings were not pictures of reality, they “succeeded in conveying the architectural intent of their creator...they existed in the unreal space between reality and the designer’s imagination.” [Norman 1991]23. Non-objective sound will very likely develop a similar vocabulary.

An interesting possibility worth mentioning is a relationship between music and architectural images that is somewhat reverse to those outlined above. Given the technology, it is entirely feasible that a computer compose music according to rule-based bit-mapped image analysis. By examining the use of color, value, tone, and texture, computer software may someday automatically compose a score for a given image or animation sequence. The generated music would provide us with another sensory aid we could use to understand the continuity or “rhythm” of the design (Figure 4).

Architecture becomes better with increased communication or sharing of tools among ourselves and other professions, and most emphatically when we change the image that we communicate back to ourselves about who we are.

The practice of design is concerned with at least four types of communication: **Intrapersonal** - communicating with oneself; **Interpersonal** - communicating with other people; **Extrapersonal** - communicating with computers
Figure 4: Three figures from a walk-through animation model at right. Software may one day analyze such animation sequences for progressive changes in features such as color percentages (first column), ratio of light to dark (second column), and number of edge boundaries (third column). Data would be interpreted into distinct sounds of varying pitch. Fed back to the architect would be a "musical score," an abstract tool intended to help achieve rhythm and harmony among all elements of an architectural event. (Images based on design competition entry of Michael Mezoller and Fred Travissano for IIT Student Center.)
Considerations and Conclusion

Whether audio capable computers are used for acoustical study of spaces, or as tools to add a non-objective sound ingredient, there are several issues that warrant attention.

User Acceptance

Currently, there is still a doubt in the minds of many architects as to whether the computer can ever be used adequately as a design tool. There was, for example, an article published in the May 1994 issue of Progressive Architecture that has as its core a resistance to experiment with CAD/graphics and design. (It is a burden, the author feels, “that is unacceptable to most offices in today’s economy.” [Horowitz 1994]25. Many in the architectural profession still resist the computer altogether and seem vulnerable to the affliction of “social inertia.” [Kean 1981]26. Even though computers have now been used as a design tool in university based studies for over a decade, not all schools of architecture use the computer in a design studio context for graphic/visual input (which, presumably, is not dealing with new design criteria). This does not bode well for fast and easy acceptance of any audio board based technology. Now, with the consideration of sound, the computer appears poised to make available to the architect a technology which has no real precedent as part of the routine design and presentation process.

Client Acceptance

As proposed earlier, the expectations of the latest generation of architectural client will most likely undergo profound changes. The client base of the MTV culture may demand more gratifying sensory stimuli than did their predecessors [Leland and Peyer 1991]27. As such, this may be a case of architectural firms needing to keep up with cultural change, with the most successful firms providing that which a new breed of client finds most satisfying.

Obscuring of Design Intent

As with any new technology, the potential for misuse is always present. Audio technologies should not be allowed to obscure a design (eg., used to commit fraud); rather the purpose of the added audio must be to enhance the design to which it is attached. Misuse is a problem inevitable with inexperience. The successful firm will foresee these issues and adopt the technology only within carefully prescribed guidelines.

Abuse

Abuse is the intentional use of the technology irresponsibly or in bad faith. An example from current visual imaging technology would include the case of a designer who renders a proposed building exterior and finds that valid sun angles do not compliment the building façade. Rather than redesign the exterior, the designer can easily, and unscrupulously, present the building in an impossible sun angle (Figure 5).

Figure 5: Current imaging technology allows a designer to present his ideas in the best light, although not always a valid light. (Images based on design competition entry of Michael Menzler and Fred Travissano for NJIT Student Center.)

or other technologies; and Ecological - with the natural and man-made contexts of this world. All four types provide a fertile context for computer assistance to design.

As designers, we have two kinds of opportunities to communicate with ourselves. One is through memory, the other is in the form of messages formed outside ourselves. Interaction with memory is the substance of thinking, whereas
A similarly unethical modification will probably be very easy to apply to an acoustical analysis, with valid readings changed to falsely represent an ideal. Similarly, an architect’s integrity is put to the test when using non-objective sounds in presentations. In his essay on architectural ethics, Kim Dovey explores the systematic use of “distorted simulation” produced under the legal cover of “artist’s impression.” Mr. Dovey concludes, “It is a primary responsibility of the profession not only to capture the imagination of the community through architectural ideas, but also to ensure that the imagined future environment is delivered in reality.” [Dovey 1989]28 Historically, however, architects are optimists building for the future and, one hopes, have a tendency to behave ethically. For there to be any progress, one must assume that the technology will be put to good use.

Future Possibilities
The wide availability of audio capable computers will change the way that architects design and present their work. Sound boards and specialized software will be used both for acoustical analysis of computer models and for the integration of non-objective sound into design sessions and presentations. A client base defined by recent technological and cultural impacts will expect the effects of such new technology to be reflected in their communications with architects and will factor the aural criteria into account when looking at proposed designs. The successful architectural firm will respond positively to these changes.

Moreover, we must accept this new technology and the social issues attached to it with a responsibility appropriate to our positions as professionals. Because of the potential for abuse, particularly in the area of non-objective sound, it may be of value to establish guidelines to ensure that the public is served in good faith. While analytical software can be expected to conform to some level of accuracy, its utilization by the architectural community can be policed fairly easily by existing checks and balances. However, the same will not be true for non-objective sound. Since the very nature of non-objective sound is that it is subjective, it may take a while (and a few buildings and presentations) before the situation clears. Nevertheless, because technological capabilities increase, and because there will always be someone who will test the limits, architects and educators must prepare for the future now so that we are prepared to guide development in a way that ultimately benefits both the environment and the profession.

Notes
3 Sutherland, pp. 73-76.
the other form of intrapersonal communication results from interaction with an external message, these communications being intrapersonal in that the participation of other persons is not necessary. One model of this communication is diagrammed as a loop connecting external message, the senses, thinking, memory, and the forming of a new message. Each of the linkages in this loop

