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2aAAa4. The raw and the cooked in architectural acoustics
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Whereas the 'raw' experience of live sound events is often quite far removed from the 'cooked' auditory imagery that is presented when live acoustical events are amplified by a sound reinforcement system, there are many audio signal processing tools that can be applied in the attempt to simulate the more natural auditory characteristics of live ('unplugged') musical performances. This paper builds a discussion of perceptual results of modern acoustical treatment and sound reinforcement technology based upon notions from Lévi-Strauss regarding what modern culture does to the 'raw' to make it 'cooked'. A key concept in evaluating the quality of a sound reinforcement system is that of the standard of reference against which the perceptual results can be compared. As there is no shared opinion nor well-established optimal acoustical character for a space upon which some consensus could be built, the question presents itself again and again. This paper will address related issues of reference, preference, and adequacy in sound reinforcement.

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INTRODUCTION

The ‘raw’ experience of live sound events in a performance space can be contrasted with the modified experience that is available when modern acoustical treatments and sound reinforcement technologies are employed. From the perspective of a cultural anthropologist, this contrast parallels a structural contrast between the raw foods readily provided by Nature and the cooked foods that result when those raw foods are transformed through human cultural practices such as roasting or boiling. This paper builds a discussion of auditory perception in modern performance spaces upon this Structuralist approach that was introduced in the 1960s by Claude Lévi-Strauss in his analysis of the culture of South American Indians (Lévi-Strauss, 1964). In fact, the superficial structures that he identified in culinary practices were used to deepen our understanding of human culture by opening a window into the mythology of South American Indians. Likewise, the current paper relies upon such structural contrasts to delve more deeply into the mythology underlying what modern audio and acoustical technology does to the human experience of live sound events in a performance space (i.e., what is done with the “raw” auditory imagery to create “cooked” auditory imagery)\(^1\).

To begin with, we could (and will) set up a straw man that is easy to tear down, but looks as if it might provide a useful perspective on the classification of auditory experience given live sound events, those raw versus those cooked. Let’s tentatively define a “raw” auditory image as the perceptual result of listening to naturally occurring sound events in natural environments. Although this might seem the quintessential definition of a “raw” auditory image, it is too extreme in its exclusion of anything touched by human culture. So what would musical purists recommend as the standard of reference, to serve as a more adequate definition of “The Raw?” Would it be an unamplified musical performance (on an acoustical instrument) in an enclosure of conventional shape (such as a shoebox-shaped concert hall)! And if we wanted to capture that raw experience in an audio signal that could be reproduced elsewhere, what would the purists choose to do? Assuming they wanted the most accurate re-creation of the live experience, they might argue for capture using a binaural microphone system coupled with a matched headphone reproduction, but this typically provides an unnatural experience that fails to qualify as a proper reference for comparison, particularly due to the difficulty of dealing with listener head movements. Without a head-tracking-based technology to update a synthetic reconstruction, they might be tempted to ask listeners to stabilize their head position and orientation by biting down firmly on a stationary ‘bite-bar.’

In contrast, stereophonic loudspeaker reproduction doesn’t have the same problem, since signals reaching the listener’s ears do change in response to head motion; however, if conventional stereophonic loudspeaker reproduction is employed, the listening experience will be far-removed from that available in the original performance space. In fact, there is disagreement regarding what sort of microphone system is expected to produce the most natural sounding reproduction. For example, one might conclude that coincident pairs of microphone capsules (located at a single point) produce the clearly superior result, as did Stanley Lipshitz (1986) in his paper that asked the question, “Are the Purists Wrong?” Nonetheless, the classically opposed alternative of spaced omnidirectional capsules produces stereophonic loudspeaker imagery that is often preferred (and in fact, was preferred by the colleague that Stanley Lipshitz acknowledges in his 1986 paper for “many stimulating discussions on this topic and for help with the recording experiments” (Vanderkooy, 1985). This controversy underscores the difficulties we are likely to face when we attempt to determine what the most natural goals would be for live performances spaces: Most specifically, we might ask what the reference experience should be, against which we might compare the auditory imagery that results when modern acoustical treatments and sound reinforcement technologies are employed. Perhaps we will be forced to give up entirely on the notion of a standard reference, and adopt instead the more pragmatic notion of optimizing auditory imagery according to listener preference? This may in fact be the means enabling us to attain our goals in improving the material (structural) form of performance spaces, while allowing us to further enhance acoustical performance through the creation of ‘fictional’ room responses using in situ combinations of microphone arrays, signal processing, and loudspeaker arrays.

\(^1\) The perspective taken here employing the ‘Raw versus Cooked’ distinction was generated in direct response to an invitation to contribute to a special session at the International Congress on Acoustics 2013, the joint ICA/ASA/CAA meeting held in Montreal 2-7 June 2013. This was an invited paper for a session hosted by Architectural Acoustics, joint with Psychological and Physiological Acoustics and Signal Processing in Acoustics. The session, entitled ‘Adapting, Enhancing, and Fictionalizing Room Acoustics,’ had the following brief description: ‘Rooms, systems, and techniques for adapting, enhancing, and fictionalizing acoustic performance through audio and architectural acoustics.’
To continue along this line of thinking, it will be useful to inquire into the prevalent mythology underlying such issues in architectural acoustics, particularly in the case of spaces designed to support live performance, since such cases define a category of built structures that have inspired a great deal study. More specifically, we want to expose here the myths that have developed in explaining how spatial material form and modern audio technology contribute to desirable acoustical conditions for human experience of live sound. We use the term ‘myth’ here to denote ‘a fiction or a half truth, particularly one that is associated with an ideology,’ which is a use that is consistent with the inspirational approach taken by Uttal (2003) in his writing on the ‘sources of artifacts and misconceptions in scientific psychology.’ In fact, it is particularly in regards to the connection between architecture in the physical domain (material forms and acoustical responses) and the associated psychological responses (perceptions and preferences) that unscientific beliefs have developed which are most open to criticism as ‘myths.’

While it is usually beneficial to explode such myths, there is often practical and valuable knowledge embodied therein, such as in the folkways underlying native culinary practices (e.g., preparing meats by roasting, smoking, boiling, etc.). That is, there is often apt knowledge embodied in analogous myths underlying architectural acoustic research and practice. It is important to note that this knowledge might be overlooked if researchers were to allow an exclusively scientific bias to color their appreciation of real-world complexities. In fact, a critical perspective such as that taken in ‘The Raw and the Cooked’ might reveal as much about the culture of research on architectural acoustics as it could about currently prevalent myths themselves. Indeed, Lévi-Strauss was most deeply criticized for his attempt to promote his theories without adequate empirical foundation. In fact, the theories he proposed were difficult to test, as pointed out by the analytic anthropologist Edmund Leach, a foremost authority on the Structuralism of Claude Lévi-Strauss. In a most readable book on the subject, Leach (1996) attempts to show what is most useful in what Lévi-Strauss has written, advertising its importance while exposing its weaknesses (interested readers might consult this ‘Modern Masters’ book originally published in 1970, now in its fourth edition with new Introduction, Notes, and Guide).

In this paper we will inject into a relatively broad discussion of architectural acoustic research some thoughts about employing contemporary generative architectural design practices, which can include iterative phases of parametric design and evaluation via acoustic simulation (for an example of such an endeavor, see Reinhardt, Martens, and Miranda, 2012). Parametric design that is applied in the context of acoustic simulation allows for the refinement of acoustical performance via listener experience, and can support parallel variation studies in multiple domains, evaluated particularly via visualization and auralization (as defined in Kleiner, et al., 1993). This work, taking place in the context of contemporary computer acoustic simulation of spaces, enables an interdisciplinary collaborative design process between architectural and acoustic designers, whereby different configurations can be explored, and proposed designs changed according to acoustic preferences in the early stages of their development.

**THE RAW AND THE COOKED**

A number of bullet points will orient the reader to the Lévi-Straussian ‘bricolage’ approach that is taken in the organization of this paper:

1. The ‘Raw versus Cooked’ distinction is employed here as a handle on understanding the techniques for adapting, enhancing, and fictionalizing acoustic performance through generative architecture design
2. Many researchers and practitioners have intuitions about what will work best, but few have formulated experiments with the explicit intention of testing their theories and intuitions. Therefore, a scientific approach to the work is promoted.
3. Working on parametric generative architectural design may be thought as a means to quantify the process whereby the artifact has come to embody the knowledge gained as a result of ‘research through design.’
4. Auralization, or the synthesis of audible scenes from computer models, provides a ‘shortcut’ in the collaborative design process, such that acoustical performance becomes integrated into the design process.
5. Emphasis is placed on the creation of unique performance spaces that are nonetheless functional, with acoustical properties serving as the driver for aesthetic exploration in architectural design.
6. In contrast to an engineering approach to problem solving, which most often proceeds from goals to means, this paper follows 'bricolage' approach (Levi-Strauss, 1962) in which available materials are juxtaposed in order to solve new problems.
Architectural Design Overview

Within the field of generative architectural design practices, parametric design provides a language that is apt to approximate formations and variations through numerical descriptions and solution solvers. It thus empowers a potential strategic development of acoustic performance by way of interaction, whereby – instead of feedback on acoustic performance given after completion of design - both generative design and acoustic analysis are linked in an iterative cycle, and thus enable a ‘reverse engineering’ process. Instead of post-optimisation (through sound reinforcement or material treatment providing corrective absorption, reflection, etc.), generations of design solutions can be developed through continuous information flow between the design of a space, and the acoustical effects resulting from its spatial form. In fact, this interdisciplinary exchange between parametric design and acoustic simulation models dependencies between spatial formation, acoustic behaviour and the auditory perception of the space. Furthermore, applied as a driver for design decisions between generative design and acoustic simulation, this reverse engineering can lead to a different understanding of spaces for the temporal arts, by which purely structural or aesthetic decision processes are significantly informed of the actual spatial acoustical behaviour. By identifying spatial formations effective for acoustic performance and a rewarding spatial perception, the design process, acoustic analysis and auralization thus can jointly improve sound in relation to the structure, space and audience.

While all acoustical spaces influence our auditory spatial perception (most often unconsciously), spaces specifically designed for the temporal arts are dependent on the designer’s understanding of relationships between geometry and acoustical performance, of predicted speech intelligibility, and of the soundscape unfolding for the spectator. Classical spaces for the temporal arts (theatres, concert halls, stages) often follow predetermined typologies that have been acoustically tested over centuries. They are culturally refined through critical listening experiences over generations, and may be well ‘cooked’ through a process of error identification and correction. Yet in a contemporary realm of novel architectural paradigms enabled by computational design software, these familiar spatial typologies are traded for speculative architecture approaches. Generative design offers a tight control of temporal parameters, force flow, structural deformation, material agencies, and spatial behaviour. In bubbles, domes, fluid spaces and complex curved structures, usually a catenary logic is applied to solve structural affordances of the architectural building envelope, whereby processes of self-regulation and optimisation enable structures to respond to both internal and external force flows. An acoustic optimisation is usually performed at the end of a design process, by introduction of absorbing materials or amplification instead of geometrical optimisation using acoustic simulation as an integral part of the design process. In this manner, the novel architectural paradigm potentially repeats previously known conditions and experiences, or deploys design methodologies that make use of heavily ‘cooked’ approaches: experiences that refer to the techniques applied to enhance performance capacities, such as multichannel microphone-based reinforcement, or absorption and diffusion structures. While this restricts spatial vocabulary somewhat, it also prevents the creation of new acoustic generators, the spaces that reverberate sound and affect differently, thereby limiting a future sonic knowledge that might come into existence.

In contrast, this research is focussed upon the genuine acoustic performance that arises through raw architecture approaches. ‘Raw’ in this context may be argued to refer to spaces in which the original ‘raw’ spatial characteristics and properties (material, structure, dimensions and so forth) support the sonic behaviour of a space, providing an aural architectural experience that is the result of space itself, and devoid of secondary acoustical-treatment-based affordances (e.g., absorption or diffusion). The collaborative dialogue between structure, material, geometry and spatial acoustic effects can be significantly supported by auralization-based acoustical forecasting, proceeding iteratively to provide feedback on further generative design stages. The research methodology for the field discussed here applies such an iterative design logic by shortcutting parametric design variations with their acoustic simulation and subsequent auralization (see Vorländer, 2008). While it is admitted that the handling of curved surfaces continues to be difficult for most auralization software (for background on this issue, see Dalenbäck, 1993), we have successfully used such software to prune from a solution set a subset of design options using curved surfaces, both
as interior additional treatment, and constituting novel building forms, have been tested through computational acoustic analysis techniques suitable for the prediction of sound concentration. This research addresses the acoustic properties of such complex curved geometries in the context of performance spaces, and examines the ways in which acoustical performance can become a main driver for design decisions. In effect, the resultant acoustic behaviour can act as a critical factor for decisions relating to parametrical variations of geometry, structure, and aesthetics.

Empirical Study of Listener Experience Related to Architectural Acoustics

We approach the problem of design and evaluation of performance spaces for human listeners from a multi-disciplinary perspective that is described briefly in the following conceptual overview. First and foremost, we are motivated by the important goal of providing a scientific basis for improving acoustical quality and character of a performance space that is founded upon empirical data; however, our motivation is geared towards meeting the informational needs of designers of those spaces in the interest of more adequate acoustical specification. We regard such acoustical specification as most useful if the employed physical measures have been validated as predictors of auditory attributes through systematic tests using human listeners. We are engaged in an experimental research program to answer key questions regarding what physical measures best predict subjective results, and we expect the results of our studies to inform those who currently are involved in the acoustical design of performance spaces, but also those engaged in the retrofitting of existing spaces for improved acoustical support and sound reinforcement. We intend to provide a scientific basis for design of performance spaces by breaking the problem down into a number of more manageable sub-problems, each of which addresses questions about observed data in one of four domains, the architectural, the acoustical, the sensory, and the affective. Our greater interest, then, will be the examination of the relationships between empirical data from these four domains, as illustrated in the diagram found in Figure 1.

FIGURE 1. Diagram showing the four domains with which the current research is concerned (denoted by the terms contained within the four red rectangular boxes) and the associated quantitative data that are typically collected within each domain (the term for which appears in the ‘callout’ above each red rectangular box). Note that stimuli within the two domains on the left are specified in terms of physical data (as indicated in the upper-left blue trapezoid), while psychological data are produced when phenomena in the two domains on the right are observed (as indicated in the upper-right blue trapezoid). The yellow arrows between the rectangular boxes are labeled according to the name given to the relationships between data in each domain, which relationships are the focus of empirical data analysis.
While the ultimate goal of applied research in Architectural Acoustics described here is in the design of performance spaces and systems for human listeners, it must be stated up front that there is a great deal to be learned about relations between variations in material forms in the Architectural Domain and system responses in the Acoustical Domain. We have recently begun a program of research into generative architecture via an interdisciplinary exchange between parametric design and acoustic simulation (Reinhardt, Martens, and Miranda, 2013). This work has involved the strategic development of temporary dynamic material structures that can be manipulated through variations of spatial formation in both digital models and in practical installations for real-world applications in existing performance spaces. Acoustical rendering, as we intend it here, refers to any method by which material form may be related to acoustical response. Modern auralization techniques allow this rendering to be done in via software (as more comprehensively explained in Vorländer, 2008), which begins with digital models of performance spaces (similar to models used in graphical visualization). Alternatively, the acoustical rendering can be enabled via a miniature analog model of a performance space, or any other comprehensive or hybrid approach that aims to create plausible responses at a listener’s ears. Indeed, we are agnostic with regard to how the acoustical signals reaching the listener’s ears are generated, since head tracking-based binaural resynthesis from responses measured in the built environment can be interchanged with computer synthesized acoustical responses with confidence that listening results can be cross-validated (see Olive and Martens, 2007).

Phenomena in the Acoustical Domain that are associated with sound transmitted in live performance spaces naturally give rise to a variety of responses in the Sensory Domain. These two domains, represented by the middlemost red boxes in Figure 1, are connected via a yellow arrow labeled ‘Psychoacoustical Scaling’ to imply that a mathematical relationship between acoustical data and psychological data is desired. Of course, what constitutes the appropriate psychological data can be interpreted quite broadly, but here we focus upon only those sensory experiences about which listeners may reasonably reach consensus regarding readily identifiable auditory attributes (see Kim and Martens, 2007). Given a set of magnitude estimates, or other ranking or rating data, on each of a number of presumably relevant sensory attributes for a collection of stimuli, it is natural to imagine that a prediction of reported preferences data for those same stimuli might be derived using multiple regression of some other multivariate analysis. Of course, it is worth asking whether introducing such a complex model is really necessary here (and it should be admitted that there is no certain answer to this question at present).

Given that we have incomplete understanding of the relationships between these domains, it is prudent to assume that we cannot ignore phenomena in the Sensory Domain, which the model presented in Figure 1 shows as intervening between the Acoustical Domain and the Affective Domain in which preferences are expressed as sentiments. Consistent with current convention (as explained in a reference text on psychometric theory by Nunnally and Bernstein, 1994), we regard such sentiments as directly representing the ground truth for the individual’s preference, although inconsistencies and contextual dependencies can be observed (see Martens, Marui, and Kim, 2006). Expressions of preferential sentiments can be contrasted in several ways with an individual’s perceptual judgments, which are more often treated as bound closely to stimulus parameters, and therefore may be regarded as correct or incorrect by the experimenter. Thus, while feedback often will be given to listeners regarding their correct ordering of stimuli along a sensory scale such as loudness, there is no correct ordering of stimuli along a preference scale, since the listener’s sentiments can clearly be influenced by factors other than the acoustical stimuli themselves. Idiosyncratic formation of preferential sentiments are typically assumed in most prediction models, which sentiments may combine details from recent personal experiences, or from immediate hedonic responses, and even from intellectual reflections on the state of the art. We could entertain more elaborate models, which might assign individualized evaluative weights to each of the assessed sensory attributes relevant to the formation of preferences (cf. Ando, et al, 1998), but the global model presented here suffices for the current methodological overview.

Most previous related studies of which the authors are aware generally have focused upon the attempt to relate directly a listener’s preferences for acoustical conditions to physical (acoustical) measurements made in the performance space. Although prediction equations can be made to fit such empirical data, the correlations between physical measurements and observed preference data can be quite low. In contrast, Martens, et al. (2007) took a more open-ended approach using qualitative descriptive analysis (Stone and Sidel, 2004), the results of which were analyzed to show how observed preferences may be related to auditory attribute ratings (i.e., ratings on derived sensory scales, anchoring adjectives for which were developed through a verbal elicitation process). We contend that attention to intervening sensory assessments may provide the missing piece to the puzzle posed for practitioners attempting to relate physical measures to preference data, such as sentiments expressed via preference choices.
Support for this contention can be found in Martens and Kim (2006), which study compared a variety of sound recordings made using multichannel microphone techniques, all of which produced quite acceptable multichannel reproductions of a set of piano performances captured in a relatively large hall. The success of these investigations relating preferences for multichannel sound programs to salient auditory attributes and binaural stimulus measurements give us confidence that these methods could be successful in acoustical investigations of performance spaces for a variety of other uses. Therefore, in addition to developing more valid physical measures, we are committed to experimentally identifying the most important auditory attributes that might predict preferences for performance space acoustics (this being the endeavor that is supported by ‘multivariate analysis’ in the above diagram, since such analysis focuses upon the many-to-one relations between two types of psychological responses, these being sensory judgments and preferential sentiments).

Simply put, our approach to ‘cooking’ the performance space acoustics is to follow a research plan based upon the assumption that the natural chain of observable phenomena, progressing from material form and acoustical system responses, mediated through the Sensory Domain, and finally observed in the Affective Domain. The unified mathematical treatment of data from all four domains enables the development of direct multivariate relationships between empirical data in each domain, potentially linking architectural practice with human affective responses (quantified as preference data). Perhaps the most important benefit of this work could be the delivery to designers of a greatly improved means for evaluating simulated spaces through physical analyses, thereby avoiding the expensive prospect of collecting many perceptual judgments and sentiments from groups of performers. Of course, in the case of the retrofitting of a performance space through acoustical treatment, it might be the actual physical measurements made in the space that are subjected to the same analysis. Furthermore, according to the overall scheme of such investigations, the scope of applicability of a set of developed prediction models may be extended through laboratory studies employing synthetic simulations that allow for the manipulation of virtual acoustic stimuli to produce variation in terms of those physical measures that have been established as predictors of preference. By collecting perceptual judgment data only for a purposefully designed set of stimuli, experimenters can ensure more efficient completion of their investigations, providing more comprehensive outcomes for a wider range of potential applications. Such an approach has been quite successful in studies concerned with sensory modalities other than audition, with particularly good examples found in Food Science, where it has long been common to emphasize the practical importance of such perceptually validated prediction equations (e.g., see Stone and Sidel, 1998).

### An Example of Competing Paradigms for Architectural Acoustic Research

Two competing paradigms for architectural acoustic research, developed over the last 30 years, can be contrasted through a crystallized example (with apologies to those cited if this treatment misrepresents their positions). One might be associated with ‘The Raw’ in that it is more focused upon observing what occurs in existing performance spaces, and takes a less ‘manipulative’ approach. It is here associated with the early work of Yoichi Ando, a prodigious author and researcher, and is characterized by his work on concert hall experiences (Ando, 1983). An alternative approach was taken by Masayuki Morimoto which might be associated better with ‘The Cooked in that it is more focused upon experimental investigations that are more removed from existing performance spaces, and employing virtual acoustics for presenting stimuli in the listening laboratory.

Regarding his early efforts, Ando clearly expressed the hope… “that the theory of incorporating temporal and spatial values for both levels of global subjective preferences and individual preferences of sound fields can be generalized to blend nature, the built environment, and people” (Ando, 1998, p. x). Perhaps because he attempted to incorporate theories of brain function into his prediction model for global subjective preferences, readers hasty in their criticism of his work may have been tempted to throw the baby out with the bath water. For example, the importance of hemispheric lateralization of processing for temporal versus spatial information in listeners’ aural impressions of architectural spaces may be a bit too speculative. Such a loose interpretative approach to explaining human behavior in terms of brain research snacks of ‘Neuromythology’ (Hasler, 2010). However, looking back at what he attempted in the 1990s might lead to a new respect for his work on the goal to develop a quantitative prediction of preference for a performance space (in support of an optimal listening experience) that includes individual differences in the equation.
The related experimental work of Masayuki Morimoto (e.g., Morimoto and Pößelt, 1989) generally involved virtual acoustical manipulations (i.e., ‘cooking’), which is clearly in contrast to the methods of Ando, which focused primarily upon existing (i.e., ‘raw’) performance spaces. For example, in his early work on subjective preferences in concert halls, Ando (1983) shifted observations between receiver seating positions while testing the dependence of preference on acoustical parameters. Indeed, there seems to have been a clear bias towards examining behavior only in existing concert halls, which would force the experimenter to shift either source or receiver position in order to manipulate acoustical parameters. Therefore, Ando’s earlier work might be described as more in line with a research mode termed ‘naturalistic observation.’ While this may be regarded as providing greater assurance of ecological validity, it does not generally allow for independent (and especially not orthogonal) variation in selected acoustical parameters as does a virtual acoustical study, such as that of Morimoto and Pößelt (1989), which used digital delays for multichannel manipulation of early reflections, followed by diffuse reverberation generated by the YAMAHA REV 1 (arguably one of the best sounding digital reverberators of that era). What is lost in ecological validity here may arguably be justified by the claim that evidence for causal relations is only available through such experimental manipulation.

CONCLUSION

What leads researchers to believe in the correctness of their theories regarding what makes a performance space work well acoustically? Does their confidence stem from their critical listening experiences in a variety of performance spaces, or perhaps their belief based that is based upon the observation that some current experience compares favorably with some excellent previous experience an actual performance that is held as an internal reference? Perhaps it is more important to focus upon what is preferred, rather than limiting comparisons to an existing internal reference that might not be so optimal. Of course, just finding that one experience is generally preferred to another does not qualify the space supporting the preferred experience as an adequate or even acceptable space for critical listening. The current paper does not attempt to answer these difficult questions (despite the clear bias toward the more quantitative experimental approach). Perhaps the questions we ask are more important than the theories we construct?

It was one goal of this paper to examine the current state of architecture research, recognizing the value of differentiating between contending research paradigms. Many have reported success in the design of sensational spaces that are constrained in terms of structural affordances set by external or internal forces; however, these have not often been driven by the user experience that is desired for the space. The interdisciplinary approach proposed herein may allow acoustical properties to become an integral component in architectural design. Ultimately, it is hoped that the methodology proposed herein leads to a ‘closing of the loop’ in the architectural design process, so that the auralization experiences of designers will feed back on their manipulations of material forms and structures.

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