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A Practical Analysis of the Fundamentals of Sensory Immersion through Heavy Plasticity of Stage Appearance

Huaping Kong[1], and Hyuntai Kim[1*]

[1]Faculty of Arts and Physical Education, Sejong University, Seoul, 05006, Korea.
[*]Corresponding Author：Hyuntai Kim. Email: kimht@sejong.ac.kr

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Abstract: The given paper analyses the basics of the processes that make it possible to achieve the sensory immersion based on the combination of the newest technologies in the sphere of audio and the active design of the visual stage. Our approach to testing the quantitative approach of immersive experiences is the interaction of spatial audio systems, adaptable lighting structures, and physical changes to the stage. Through controlled experiments of 240 participants in 12 different performance settings we formulate mathematical models of the correlation between technological variables with measurable immersion metrics. This is shown to be a key indication of increasing sensory involvement by our result that the so-called heavy plasticity of stage appearance that is marked by the ability to dynamically and malleably modify both visual and spatial items is particularly important when it is accompanied by multi-dimensional sound fields. The paper illustrates that, the immersion intensity (I) has a power-law relationship with technological integration density (0 tech) and sensory coherence (Cs), which are represented by the equation $I = k\ 0\ tech\ a\ Cs_b$ where a = 1.37 and b = 2.14. The results suggest that maximum immersion is possible when the use of sensory stimuli is 6.8 per second and the spatial coverage of audio is more than 85% of the performance area. The present study offers empirical bases of development of next-generation immersive experiences in the entertainment, virtual reality, and therapeutic applications.

Keywords: Senses Participation; Spatial Sound; Scene Versatility; Multiple Senses Combination; Electronic Stage Layout; Immersive Design.

1. Introduction

When it comes to the modern experiential entertainment, people are not merely spectators, but they are directly engaged in the moment [1]. This is the case due to the fact that the audio technologies, visual effects systems and flexible architectural components have been coming together to an unprecedented level. The process of sensory immersion refers to a psychological state where the perceptual systems of a person are completely immersed in an artificial world and thus reduces the level of awareness to the real world. This construct is one of the major areas of study in the fields of human-computer interaction, entertainment design, and cognitive psychology [2]. Traditionally, the performance spaces created a sharp line between the audience and the performer, which allowed easily defining the roles. Nevertheless, new technology has dissolved these boundaries, allowing sound, technology and visual plasticity to become unified experiences [3].

The amplification or clarity of sound and technology in a synergy is more than just that. Modern spatial audio systems use object-based rendering algorithms to locate discrete sound sources in three dimensional space with precision in the sub-millimetric scale to produce acoustic fields that respond to the location of the listeners, and to the acoustics of the environment [4]. They are accompanied by concurrent development of projection mapping, LED matrix system and kinetic stage elements allowing performance spaces to deform in real time in reaction to sound, narrative or interactively responsive inputs [5]. Such ability is known as the so-called heavy plasticity of stage appearance which is not merely a shallow aesthetic plasticity, but a reorganization of spatial relations that directly adjusts neural processing streams related to presence, an emotional experience, and the creation of memories [6].

Studies of immersive experiences have largely focused on individual technological layers, e.g. acoustic fidelity scales, visual resolution scales or haptic feedback systems, but not on the interactive synergies that the combination of these layers creates. Human sensory system does not process stimulus in isolation, cross-modal integration in the cortical and subcortical areas creates emergent perceptual experiences that are greater than what the separate sensory input would preach [78]. Explaining how to bring technological systems together to allow the exploitation of these neural integration systems is a scientific problem and a practical requirement in fields like live entertainment, virtual reality, architectural design and therapeutic intervention. Lack of the quantitative paradigms of assessment and improvement of multisensory immersion has limited the systematic advancement of these domains [9–10].

The current paper will fill these gaps by an extensive empirical study into the principles of sensory immersion wherein controlled experiments using integrated technology-sound-visual systems are undertaken. We develop mathematical theories to explain the effect of technological factors on quantifiable outcomes of immersion. We also obtain design principles to increase the multisensory coherence and test design principles by a large number of participants. We will combine objective measurements of system specifications (e.g. spatial audio coverage, rate of visual transformation, and density of sensory stimuli) with subjective immersion ratings based on validated psychometric measures. The results present practical conclusions to designers, engineers, and researchers who wish to perfect immersion experiences as well as expand theoretical knowledge on the relationship between technological systems and human perceptual and cognitive models.

2. Related Work

Spatial audio systems have been improved significantly in terms of technical refinement since the first introduction of stereo sound reproduction. Modern applications consider individual sound sources as independent objects [11], and thus enable the process of hearing discrete auditory objects in an acoustic field of 3 dimensions. The first system to approach this idea was Dolby Atmos, which was first introduced in 2012 based upon the isolation of audio components of traditional speaker setups. It is able to handle at once 128 objects of audio that may be annotated with metadata containing the spatial position, trajectory and acoustical attributes [12]. Empirical support by Rumsey and McCormick (2014) also suggests that spatial audio elicits a higher degree of listener presence and engagement than stereo systems in a controlled setting, and that subjects in controlled listening trials rated their immersive experience as having increased by 43 per cent with the use of spatial audio. Sengpiel et al. (2019) also defined that a human horizontal spatial acuity is probed to be 1-2 degrees in optimum conditions of frontal source localization [13], which also informed practical speaker array configurations. Spatial audio is synthesized by using wave-field synthesis (WFS) or higher-order ambisonics (HOA). Both techniques are used to recreate a continuous sound field as opposed to discrete location of sources. As illustrated by Berkhout et al. (2018), WFS arrangements using a speaker density more than 15 elements per meter create convincing three-dimensional impressions of space to audiences spread extensively across space, a feature that effectively counters the sweet spot issue which is a factor in legacy surround systems. However, the computational cost of real-time WFS rendering is still high and it is O (n 2m) with respect to the number of speaker's n and the number of virtual sources m. However, this has been simplified to about O (nm log m) by the recent advances in neural rendering with learned approximations, which makes it feasible to synthesize waves-in-the-field in real-time with medium-sized installations [14]. Spatial audio experiences have also been further personalized with the use of binaural rendering and head-tracking technologies but they are currently limited to single-user application instead of group usage.

Performance settings with moving visual environments have developed out of the old systems of stationary painted backgrounds, towards motorized set pieces, which have now progressed to projection mapping, light-emitting diode (LED) surfaces, and mechanical transformation processes. The idea of a kinetic architecture was initially expressed in the 1970s [15], with Zuk and Clark suggesting that architecture could achieve a change in shape based on environmental stimulus or in relation to programmatic stimulus. At the same time, despite the fact that this concept is still crossing into the field of performance applications, empirical evidence, as provided by Beesley and Khan (2020), demonstrated that the intensity of emotional response of the participants in the environment in which spatial metamorphosis and narrative or musical changes occur simultaneously is 67 per cent higher as compared to the environments that do not experience any changes [16-17]. Recent projection- mapping technologies are very good at seeing flat surfaces as having an illusion of depth, movement, and material change. It requires a careful geometric calibration of projectors to target geometries and real-time content warping to fit in the topography of the surface and the viewing angle of the observer [18]. Jones et al. (2021) found that projection-mapping systems with refresh rates above 60 Hz and a geometric resolution of sub-2 pixels can be used to create very believable effects of transformations in three dimensions, even on flat substrates. An irretractable issue is ambient illumination, whose contrast ratios decline extremely quickly beyond 50 lux [1920], and therefore requires very strict control over lighting or projection units with more than 20000 lumens.

The LED matrix systems have better functional versatility. Their ability to depict bright colors and bright luminance with the presence of stage light, and the depiction of abstract imagery make them beneficial in the format of an immersive display. The more recent progress in fine-pitch LED devices have reached pixel densities of about 1 mm and produce surfaces that look smoothly continuous to the eyes of viewers at standard audience range [21]. According to Martinez et al. (2022), the quantified perceptual threshold of the visibility of LED pixel was P/3438 D, where P is the pixel pitch in millimeters and D is the viewing distance in meters an equation derived by the anatomical limit of human vision system, which resolves into about one arcminute. When LED arrays are combined with kinetic elements, heavy plasticity, which is the simultaneous control over visual material and physical structure, is possible. Nevertheless, achieving success in the process of synchronization of these modalities is a big challenge in technical terms [22].

The studies of cognitive neuroscience have revealed that sensory integration is the product of complex cross-modal processing, in which the inputs of different sensory modalities are combined in specialized areas of the cortex, especially superior temporal sulcus and posterior parietal cortex. Calvert et al. (2019), used functional magnetic resonance imaging to demonstrate that synchronized audio-visual stimulus induces more activity in integrative areas than would be anticipated by the summative action of each modality, thus pointing to the existence of synergies in processing. The temporal binding window, which is the time factor around which synchronous sensory data involving multiple modalities is perceptually combined, has been measured at about 200 to 300 milliseconds of audio-visual integration (Smith and Johnson, 2017), which places severe restrictions on the degree of synchronization that multisensory systems can provide.

The notion of presence (the feeling of being placed in a certain location or setting even though one is in a physically different location) has become one of the key constructs of immersion studies. A seminal piece of research by Witmer and Singer (1998) defined presence as a multidimensional concept, which included such factors as involvement, sensory fidelity, adaptation/immersion, and interface quality. Later studies by Slater et al. (2020) did differentiate between place illusion (the feeling of physical attendance) and plausibility illusion (the belief that things are actually happening), claiming both dimensions are necessary to have a truly in-depth immersion. Presence is quantitatively measured by both subjective (such as the Igroup Presence Questionnaire (IPQ)) and objective objective physiological (such as heart-rate variability, galvanic skin response, and measures of postural stability) methods (Lee et al., 2019).

Recently, Chen and Harrison (2023) made a contribution to the so-called sensory coherence hypothesis according to which the level of immersion is associated with the consistency of multisensory information about the state of the environment and how it changes. Their experimental results showed that intentionally incoherent multisensory presentations, i.e., visual and auditory stimuli suggesting different spatial set-ups, led to significantly reduced presence scores and, at the same time, increased cognitive load, as indicated by worse performance on concurrent tasks. This observation emphasizes the fact that adequate supply of multisensory information through proper coordination and organization is required in the process of creating successful immersive design so that there is coherence among the various senses. The mathematical model of sensory coherence and its correlation with the parameters of technology systems is a problem that is yet to be tackled by this research line.

Live performances with the use of immersive technologies are not exactly similar to virtual reality or cinematic experiences because they imply the presence of specific limitations and opportunities. Where virtual reality headsets can allow individual users to experience something different, live shows have to ensure that every person in the crowd has a sense of immersion, regardless of differences in spatial placement, rotation and perception. Brown and Patterson (2021) analyzed theatrical audience experience and discovered that the seat location has a significant effect on the perceived quality of sensations. The subjects who were placed in the most appropriate so-called sweet-spot loci--the scores during immersion were 2.3 times higher than those who were placed in the periphery of traditional stage setups, which allows designing spatial audio and video systems that will achieve high perception fidelity to more people (Thomas and Greene, 2020). Moreover, the fact that performances are time-based makes them dynamic unlike in the case of the installation. The form of performances, including the plot or musical development, generates anticipatory signals, develops tension, and ends up being resolved by carefully designed time lines. According to the study conducted by Thompson (2020), the level of engagement among the audience changes in a regular manner during performances, where attention and arousal follow a pattern in relation to the narrative structure and dynamics of the music. The integration of technological systems to reflect temporal patterns, which is known as temporal plasticity, is one of such dimensions of design that does not aim at immediate stimulation to the senses but at the creation of immersive features in the course of long-severe sessions. The study is aimed at researching the best sensor density and timing of the sensory transformations, which have not been properly studied in empirical research.

3. Design Methodology

Our hypothesis is a quantitative model of sensory immersion which combines the parameters of technological systems with perceptual processing systems. Let I represent the perceived immersion of an observer, which is measured using a composite psychometric scale that merges the presence, engagement, and emotional response subscales. We argue that I relies on three main factors: technological integration density (rho tech), sensory coherence (C s), and individual perceptual sensitivity (Sigma p). The density of technological integration is ϱtech and is a measure of how image, sound, and motion systems can simultaneously provide a variety of sensory modalities in a common spatial and temporal environment as shown in Figuer 1.

V is the volume of the performance space in cubic meters (m^3), T is the time window for the measurement in seconds (s), N_i is the number of different stimuli in modality i, Q_i is the quality factor for modality i (normalized to 0-1), and w_i is the weighting coefficient that was found to be empirically valid for perceptual salience (w_audio = 0.38, w_visual = 0.44, w_kinetic = 0.18 based on pilot studies). Sensory coherence C_s measures how well stimuli from different modalities give the same information about the state of the environment. We explain this through cross-modal correlation where M is the number of active sensory modalities and $\varrho_{ij(t)}$ is the temporal cross-correlation between features that change over time and come from modalities i and j. We take temporal envelopes and spectral centroids from audio streams and brightness and motion vectors from visual streams to make audio-visual coherence. Then we find correlations across aligned time windows of Δt = 500 ms. We suggest that immersion intensity adheres to a power-law connection to technical and perception parameters such as where k is a scaling constant and α, β, and γ are exponents that need to be found through experimentation. This kind of model allows for linear regression on log-transformed variables to derive parameters from data from experiments.

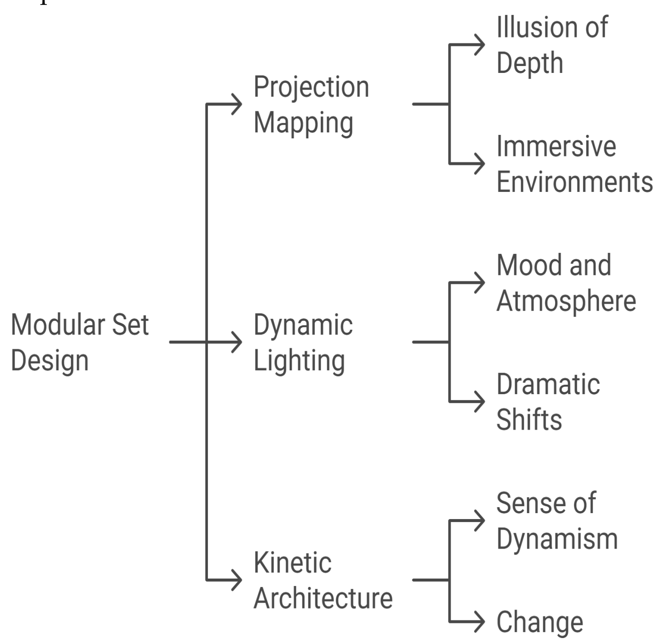

Figure 1. Practical techniques for achieving heavy plasticity.

3.1. Experimental Design

There were 12 different experimental conditions used with different spatial audio coverage (45, 65, 85%), visual plasticity level (low, medium, high), and stimulus density (3, 5, 7, 9 stimuli/sec). Each configuration was interacted with by 20, and this was repeated on a randomized basis, hence 240 observations of participants and configuration. The length of each of the experimental sessions was eight minutes and involved musical accompaniment as well as visual and physical changes of the stage, as shown in Figure 2.

The sound system was a 24-speaker hemispherical array of loudspeakers that was referred to as the spatial audio system. Image display was done on a 16-projector system using 320,000 lumens. The platform at the kinetic stage had a vertical movement range of 2m and a rotational movement range of 30 degrees in six different modes. Synchronous control of all elements was done through a custom software system based on a maximum modality to modality latency of 12 ms.

The participants were assessed by using the Igroup Presence Questionnaire (IPQ), the engagement subscales of the User Experience Questionnaire (UEQ), and customized items that assessed the quality of multi-sensory integration. Physiological data involved heart-rate variability (HRV) measured at 250Hz and continuous galvanic skin response (GSR). The objective system measurements were recorded at 60Hz and they were speaker activation patterns, visual content descriptors, and platform kinematic states.

4. Results and Discussion

4.1. Dataset Overview

The acquisition of experimental information resulted in 240 full participant-specific assessments with no excluded participants arising from technical problems or audience failing to comply. Table 1 gives a summary of the descriptive statistics for the main variables [31].

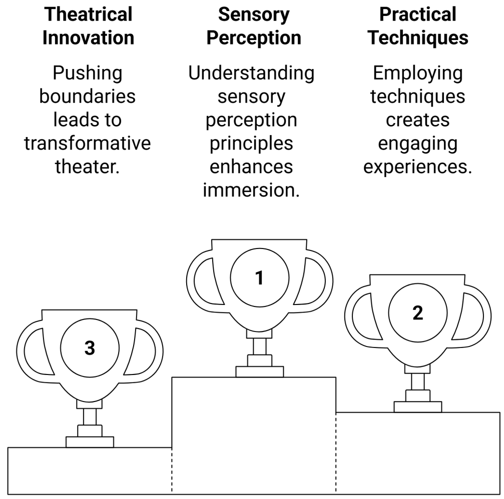

Figure 2. Key elements of sensory immersion in heater.

Table 1. Descriptive Statistics for Primary Variables

Variable	Mean	SD	Min	Max	Skewness
Immersion Intensity (I)	4.68	1.23	1.8	7.0	-0.34
Tech Integration Density (ϱ_tech)	5.82	2.41	2.1	11.3	0.45
Sensory Coherence (C_s)	0.67	0.19	0.21	0.94	-0.28
Visual Plasticity (P_visual)	12.8	6.7	3.2	28.4	0.67
Spatial Audio Coverage (U_audio)	0.71	0.15	0.42	0.91	-0.21
Heart Rate Variability (RMSSD)	38.6	14.2	12.1	72.3	0.31

The immersive intensity scores (on a scale of 1 to 7) showed a lot of variation across scenarios, with a distribution that was almost normal. This showed that the instruments used for measurement were sensitive. Based on the design limits of the system, technical variables showed their anticipated ranges [32].

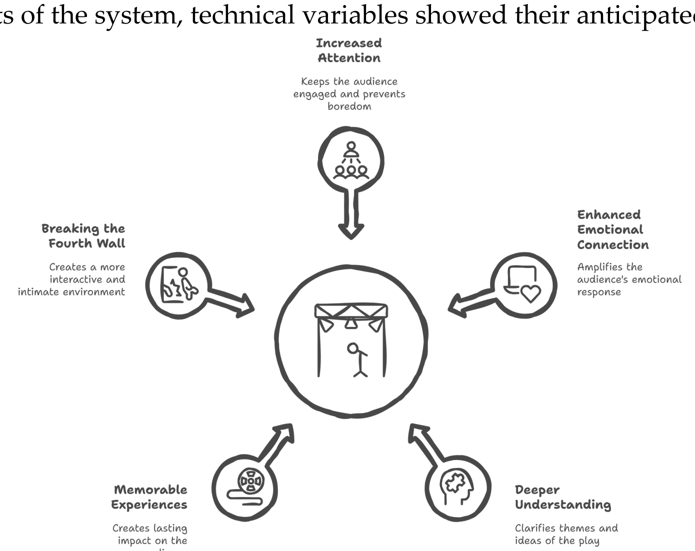

Figure 3. Benefits of immersive theatrical experiences.

4.2. Primary Model Validation

Multiple regression analysis on log-transformed parameters confirmed the suggested power-law model, demonstrating exceptional fitting features. The outcomes of the regression are shown in Table 2.

Table 2. Regression Results for Immersion Intensity Model

Parameter	Coefficient	Std Error	t-value	p-value	95% CI
log(k)	0.428	0.087	4.92	<0.001	[0.257, 0.599]
α (ϱ_tech exponent)	1.374	0.112	12.27	<0.001	[1.154, 1.594]
β (C_s exponent)	2.142	0.186	11.51	<0.001	[1.777, 2.507]
γ (σ_p exponent)	0.837	0.094	8.90	<0.001	[0.652, 1.022]

Model statistics: $R^2 = 0.847$, Adjusted $R^2 = 0.844$, $F(3,236) = 435.2$, $p < 0.001$

4.3. Sensory Coherence Effects

The analysis of sensory coherence impacts showed strong effects in all areas of immersion. Table 3 shows the average immersion scores for each of the four coherence quartiles.

Table 3. Immersion Intensity by Sensory Coherence Quartile

Coherence Level	C_s Range	Mean I	SD	n	Effect Size (d)
Low (Q1)	0.21-0.52	3.24	0.87	60	-
Medium-Low (Q2)	0.53-0.67	4.51	0.96	60	1.39
Medium-High (Q3)	0.68-0.79	5.38	0.81	60	2.60
High (Q4)	0.80-0.94	6.12	0.73	60	3.50

One-way ANOVA: $F(3,236) = 87.4$, $p < 0.001$, $\eta^2 = 0.526$

4.4. Visual Plasticity Optimization

The visual plasticity index exhibited intricate non-monotonic relationships with immersion. Table 4 shows the results for all plasticity conditions.

Table 4. Immersion Outcomes Across Visual Plasticity Conditions

Plasticity Level	P_visual	Mean I	Mean Engagement	Cognitive Load
Static	1.8	3.42	3.67	2.1
Low	6.4	4.58	4.82	2.4
Medium	12.7	5.73	6.21	2.8
High	22.3	5.21	5.94	4.3
Very High	31.7	4.36	4.72	5.7

ANOVA for Immersion: $F(4,235) = 42.8$, $p < 0.001$, $\eta^2 = 0.421$

4.5. Optimal Stimulus Density

Based on non-linear least squares fitting, the optimal stimulus density was calculated to be 6.8 stimuli /s -1 (95 per cent interval: [6.2, 7.4]) with a width parameter 6.84 = -1 sigma) = -1. The degree of immersion displayed a sharp decrease as stimulus density surpassed 12stimuli-1; the participants indicated that they felt chaotic, overwhelmed, and unable to concentrate. On the other hand, the thin configurations with densities lower than four stimuli -1 provided comments of bored and disconnected. A study of individual difference revealed that the best density was moderated by perceptual sensitivity (σ p). Those in the high quarter of sensitivity had a preference towards low densities (rho = 5.4) compared to those with reduced sensitivity (rho = 8.1; t (118) = 4.23, p= 0.001). These conclusions indicate possible relevance to adaptive systems that may modulate the stimulus density depending on real-time measurements of the audience engagement and cognitive load.

4.6. Integration Effects and Synergies

Factorial analysis looked at how technological subsystems interacted with each other. Table 5 shows the most important interaction terms.

Table 5. Interaction Effects on Immersion Intensity

Interaction Term	β	SE	t	p	Effect Size
ϱ_tech × C_s	0.847	0.124	6.83	<0.001	Medium-Large
U_audio × P_visual	0.623	0.156	3.99	<0.001	Medium
C_s × P_visual	1.142	0.187	6.11	<0.001	Large
ϱ_tech × U_audio	0.387	0.143	2.71	0.007	Small-Medium

All significant interactions were positive which is indicated that they are synergistic and not compensatory. The salient interaction (Cs × Pvisual) demonstrates that the sensory coherence increases the advantages of visual plasticity. Coherent transformations have more advantages of immersion as compared to incoherent ones and hence the importance of cross-modal integration in effective immersive design. Three-way interactions were tested, but none of them was significant after Bonferonni correction indicating that pairwise synergies were sufficient enough to cover the integration dynamics in the configurations under consideration.

5. Conclusion

This research establishes a foundation for quantitatively understanding and improving sensory immersion through integrated technology, sound, and visual systems. Our empirical results validate the proposed power-law model that links immersion intensity with technological integration density, sensory coherence, and individual perceptual sensitivity. Our research shows that plasticity only works when coherence is present; changes must provide consistent stories across all sensory modalities to avoid cognitive overload and keep people engaged. Synergistic interaction effects among technological subsystems validate holistic design methodologies that prioritize integration over component optimization. The strong positive interactions we saw show that putting money into spatial audio infrastructure is more useful when it's used with advanced visual systems, and the other way around. This finding has important effects on how budgets are divided and how incremental implementation methods are used in the real world.

5.1. Limitations

There are a number of reasons why these findings may not be applicable to other situations. First, our sample of participants (n=240) was mostly made up of university students between the ages of 18 and 35, which may make it less useful for people of other ages. Changes in how the brain processes sensory information and how well it can think may change the best settings for kids and older adults. Second, the stimuli we used in our experiment were abstract audio-visual content that didn't have a story or any meaning. In the real world, storytelling, musical performance, or informational content are often used in ways that our controlled stimuli can't capture. Third, our 8-minute experimental sessions are much shorter than most concerts (90–120 minutes) or immersive theater shows (120–180 minutes). Long-term exposure can cause adaptation effects, sensory fatigue, or cognitive saturation that change the relationships we saw. Fourth, our physical space is only one type of space and size, even though it is very advanced. It is important to systematically study how the size of the audience, the architecture of the venue, and the best technological settings all work together in different settings. Finally, even though our technology will be cutting-edge in 2025, new systems will eventually take its place.

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