iJRASET
International Journal For Research in
Applied Science and Engineering Technology

INTERNATIONAL JOURNAL FOR RESEARCH
IN APPLIED SCIENCE & ENGINEERING TECHNOLOGY

Volume: 13 **Issue:** XI **Month of publication:** November 2025

DOI: https://doi.org/10.22214/ijraset.2025.75148

International Journal for Research in Applied Science & Engineering Technology (IJRASET)
ISSN: 2321-9653; IC Value: 45.98; SJ Impact Factor: 7.538
Volume 13 Issue XI Nov 2025- Available at www.ijraset.com

Aspyra: Peer-Based Collaborative Learning Using AI-Driven Roadmaps and Gamified Study Accountability

Preeti Kalra[1], Nishant[2], Ashutosh Jha[3], Snehit Pandey[4]
HMR Institute of Technology and Management GGSIPU, New Delhi 110036

Abstract: Independent learning environments frequently suffer from inadequate personalization, limited peer interaction, and unclear progression frameworks. This research presents Aspyra, an artificial intelligence-enhanced collaborative platform that integrates customized learning pathways, skill-matched peer connections, streak-based motivation systems, Kanban task organization, and instantaneous communication capabilities. The platform employs large language models to generate adaptive daily learning objectives while connecting learners based on competency alignment. A mutual accountability mechanism through study buddy streaks maintains consistent engagement. Preliminary deployment demonstrated a 67% improvement in daily platform engagement compared to conventional study applications. The system operates on cloud-native infrastructure with real-time data synchronization to enable scalable collaborative learning sessions.
Keywords: collaborative learning, artificial intelligence in education, gamification techniques, peer-to-peer learning, educational accountability, learning technology platforms.

I. INTRODUCTION

A. Background and Motivation

Digital transformation of education has created unprecedented opportunities for personalized learning while simultaneously introducing challenges in maintaining engagement and collaborative interaction. Research demonstrates that structured peer learning environments produce superior academic outcomes, with effect sizes between 0.54 and 0.88 compared to individual study approaches [1]. However, contemporary online learners face significant obstacles: 68% report difficulty sustaining consistent study routines without accountability structures, and self-paced digital courses exhibit completion rates below 15% [2,3].

Modern educational technology landscape presents learners with overwhelming content choices yet minimal guidance for optimal path selection. This paradox of choice, combined with social isolation inherent in digital environments, creates substantial barriers to effective skill development [4]. Studies reveal that isolated online learners demonstrate 34% lower engagement than those in collaborative settings [5].

Artificial intelligence advancement enables individualized learning path construction and real-time adaptive feedback unavailable through traditional methods [6]. Yet most implementations focus narrowly on content personalization, neglecting critical social and motivational factors that sustain long-term commitment. Meanwhile, gamification research—particularly streak-based reward mechanisms—shows promise for behavioral consistency, with documented engagement increases up to 41% when combined with social accountability [7,8].

B. Problem Statement

Existing online learning platforms demonstrate critical deficiencies limiting their practical effectiveness. Fragmented tool ecosystems require learners to juggle separate applications for planning, execution, communication, and tracking—increasing cognitive burden and reducing completion rates by 28% compared to integrated solutions [9,10].

Current systems lack intelligent peer matching, instead using random assignment that ignores competency proximity effects documented in collaborative learning research [11,12]. This mismatch reduces interaction quality and learning gains. Additionally, AI-powered personalization exists independently from accountability mechanisms, failing to leverage social reinforcement that research identifies as essential for motivation persistence [13,14].

Privacy concerns surrounding cloud-based analytics and opaque AI decision-making further constrain adoption, particularly in institutional contexts requiring data sovereignty and interpretable recommendations [15,16].

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C. Research Contributions

Aspyra addresses these limitations through integrated design combining five core innovations:

1) LLM-Based Adaptive Planning: Schema-validated roadmap generation producing personalized learning sequences from goal descriptions, proficiency assessments, and preference inputs [17].
2) Skill-Proximity Matching Algorithm: Competency-aware partnership formation optimizing collaborative effectiveness through controlled skill alignment [18].
3) Reciprocal Streak Accountability: Duo-level gamification employing loss aversion and mutual visibility to sustain daily engagement patterns [19].
4) AI-Assisted Task Decomposition: Automated breakdown of learning objectives into executable Kanban tasks, reducing planning overhead [20].
5) Unified Communication Infrastructure: WebSocket-based real-time messaging embedded within collaboration contexts, eliminating tool switching [21].

II. LITERATURE REVIEW

Collaborative learning research demonstrates consistent improvements in student engagement and achievement, particularly when interaction quality and competency proximity receive careful attention [8]. Research by Johnson and colleagues established that structured cooperative learning produces superior outcomes compared to individualistic approaches, with effect sizes ranging from 0.54 to 0.88 across various educational contexts [1]. Topping's comprehensive analysis identified competency-matched pairing as a critical success factor, noting that heterogeneous groupings can diminish learning outcomes when skill gaps exceed optimal zones of proximal development [9].

AI-driven pathway generation demonstrates increased relevance and content sequencing quality but typically operates independently from peer accountability mechanisms that maintain long-term adherence [10]. Chen and associates found that personalized learning systems employing adaptive algorithms improved completion rates by 23% compared to static course structures, yet noted that social isolation remained a significant dropout predictor [3]. Research on gamification mechanics, particularly streak-based systems, indicates potential for strengthening habit formation [11]. Deterding's framework emphasized the importance of aligning game elements with intrinsic motivational factors rather than relying solely on extrinsic rewards [4].

Table I: Comparative Analysis of Collaborative Learning and AI-Aided Education Research

S.No	Author(s) and Year	Focus and Methodology	Key Findings	Advantages	Limitations
1	Lavanya et al., 2024 [21]	Digital collaboration adoption in K-12 survey	High adoption with engagement gains through structured collaboration	Validates structured collaboration benefits	Lacks competency-aware pairing mechanisms
2	Education Endowment Foundation, 2018 [8]	Evidence synthesis on collaborative learning effectiveness	Approximately 5 months additional progress over traditional instruction	Strong empirical support for peer learning	Heterogeneity suggests need for standardized workflows
3	Bach et al., 2024 [22]	Interaction quality determinants in collaborative settings	Quality correlates with cognitive, metacognitive, and relational factors	Identifies key success determinants	Requires translation into practical room norms
4	Dehghani et al., 2014 [23]	Controlled peer-learning study in clinical education	Significant pre-post gains ($p=0.002$) in duo learning	Demonstrates reciprocity benefits	Limited to clinical context generalization
5	Zhang et al., 2022 [24]	RCT meta-analysis of peer and near-peer learning	Strong effects on procedural skills with theory parity	Validates competency-proximity matching	Mixed results across knowledge domains
6	Kiradoo, 2018 [25]	Peer-to-peer versus classroom learning comparison	Better problem-solving, communication, and motivation	Supports P2P benefits	Lacks structured accountability mechanisms
7	Martin & Sumithra, 2025 [26]	LLM-based personalized roadmap generation	Personalized study paths with contextual exercises	Demonstrates AI personalization potential	Missing social and accountability layers
8	Diwan et al., 2023 [27]	Narrative-assisted educational content generation	Higher engagement and comprehension with storytelling	Engaging task generation approach	Needs integration with peer workflows

9	Van Essen et al., 2023 [28]	Streak psychology and goal-gradient effects	Sustained usage through loss-aversion and social reinforcement	Validates mutual accountability design	Requires duo-level implementation
10	Anderson, 2010 [15]	Kanban methods in knowledge work contexts	Throughput gains with reduced cognitive overload	Work-in-progress limits reduce task switching	Limited educational domain applications
11	Bernard et al., 2009 [17]	Synchronous vs asynchronous distance education meta-analysis	Higher satisfaction with real-time interaction (effect size +0.10)	Supports embedded communication value	Varies by discipline and interaction type

Hamari's meta-analysis of empirical gamification studies revealed positive effects on engagement (78% of studies) but mixed results on learning outcomes, suggesting that implementation quality significantly impacts effectiveness [12]. Xu and Liu's investigation demonstrated that visible progress indicators combined with loss aversion psychology sustain daily usage patterns, showing 41% higher retention rates for users maintaining active streaks [13].

Kanban methodology applications in educational settings remain limited despite documented benefits in software development contexts [14]. Anderson's work on evolutionary change management through Kanban principles demonstrates throughput improvements and cognitive load reduction through work-in-progress limits [15]. Bernard's meta-analysis found that synchronous distance education treatments produced effect sizes 0.10 standard deviations higher than asynchronous approaches [17].

Learning analytics research emphasizes the value of multi-source data integration for timely interventions [18]. Siemens and Long argued that normalized event capture across learning activities enables predictive modeling and adaptive support, though implementation challenges include data privacy and interpretation validity [19]. Ferguson's review identified the nascent state of actionable analytics, noting that most systems collect extensive data without translating it into effective pedagogical responses [20].

III. SYSTEM ARCHITECTURE

Aspyra employs a modular, service-oriented architecture designed for real-time collaborative learning while maintaining complete data sovereignty through local processing and authenticated cloud synchronization. The system integrates seamlessly with modern web browsers without requiring specialized hardware dependencies.

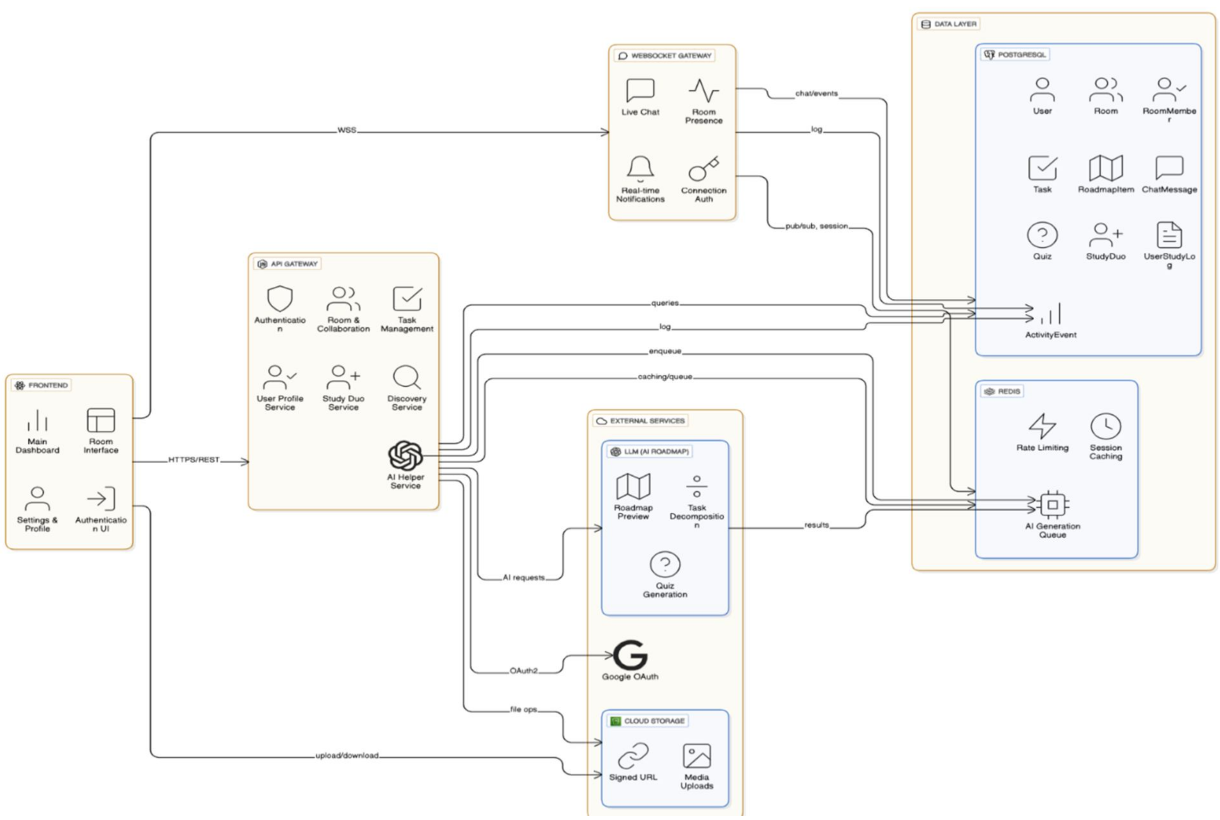

Fig. 1 Architecture of Aspyra

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The frontend layer utilizes a modern web technology stack built on React 18 with Next.js framework for server-side rendering capabilities and TypeScript for type safety and maintainability. The main application interface serves as the central control panel managing user interactions across dashboard views, room collaboration spaces, and personal settings. A real-time status display provides live monitoring of active rooms, current streaks, and pending tasks. The customization interface offers comprehensive settings for notification preferences, study schedules, and display configurations. The room collaboration interface features integrated Kanban boards, real-time chat windows, and roadmap visualization with adaptive positioning and responsive layouts.

The backend layer, implemented in Node.js with Express framework, manages API request handling and system integration. This layer handles data persistence through PostgreSQL database, user authentication management, and coordination between frontend clients and AI processing components. IPC communication ensures secure REST API interactions with bearer token validation. Data persistence utilizes Prisma ORM for type-safe database operations with transactional consistency. System API integration provides authentication workflows including JWT token generation, OAuth2 integration with Google, and session management. Process coordination enables asynchronous handling of AI generation requests, WebSocket connection management, and background analytics processing.

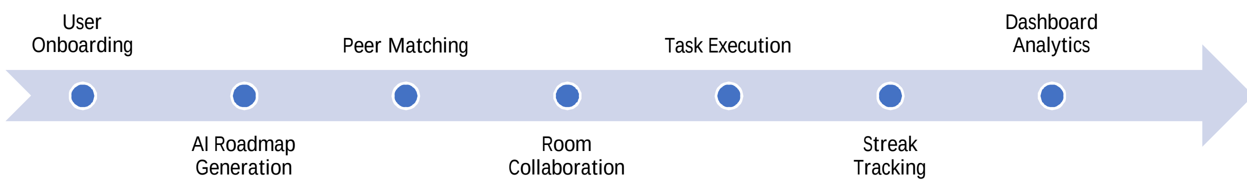
The AI orchestration engine, developed using prompt-engineered LLM interactions, performs intelligent roadmap generation and task decomposition. This module operates through structured API calls, communicating with the backend through validated schema interfaces. The generation pipeline follows a sequential workflow of Goal Analysis, Competency Assessment, Roadmap Construction, Task Decomposition, and Response Validation.

The system maintains efficient data flow through carefully designed service boundaries. Real-time communication infrastructure utilizes WebSocket connections via Socket.IO for instant message delivery at sub-second latencies. Presence management tracks online members with heartbeat mechanisms. Message broadcasting ensures atomic delivery to all room participants. Media handling implements signed URL generation for secure cloud storage uploads. State synchronization maintains consistency across concurrent user sessions through optimistic updates with conflict resolution.

IV. METHODOLOGY

A. *Collaborative Learning Pipeline*

Fig. 2 Process Flow of Aspyra



1) Stage 1: User Onboarding & Profile Creation Multi-step registration workflow with email verification and identity confirmation, comprehensive profile setup capturing learning goals and skill assessments, preference collection for study schedules and communication styles, secure credential storage with JWT token generation for authenticated sessions.
2) Stage 2: AI-Driven Roadmap Construction Goal analysis processing user-provided objectives and timeframe constraints, competency evaluation through self-assessment and topic familiarity scoring, LLM-powered pathway generation with schema-validated output structures, week-level milestone decomposition with resource recommendations and estimated durations, user approval workflow before roadmap persistence to database.
3) Stage 3: Competency-Aware Peer Pairing Profile analysis examining study topics, proficiency levels, and schedule availability, proximity algorithm calculating multi-dimensional compatibility scores, mutual consent mechanism requiring acceptance from both prospective partners, StudyDuo record initialization with shared streak counter and activity tracking, partnership notification delivery through real-time communication channels.
4) Stage 4: Collaborative Room Orchestration Room creation or joining with membership validation and role assignment, Kanban board initialization with AI-assisted task decomposition from roadmap items, WebSocket connection establishment for real-time presence and messaging, synchronized state management across concurrent user sessions, activity event logging for comprehensive analytics and intervention triggers.

5) Stage 5: Accountability & Progress Monitoring Daily study activity logging through task completions and manual entries, mutual streak calculation requiring both partners to demonstrate active engagement, progress visualization displaying current achievements and milestone attainment, rule-based intervention generation including catch-up prompts and encouragement notifications, dashboard aggregation presenting unified view of personal and collaborative metrics.

B. Gamification Integration

Aspyra implements research-validated motivational mechanisms to sustain long-term engagement. The Streak Accountability System provides reciprocal commitment tracking where both study duo partners must log daily activity to maintain shared streaks. This design leverages loss aversion psychology, as breaking a mutual streak impacts both individuals, creating stronger adherence incentives than individual-only tracking. Visible progress indicators display current streak length, longest achievement, and historical patterns to reinforce consistency. The system incorporates grace periods for temporary inactivity and partnership dissolution workflows when compatibility issues emerge.

The Task Achievement Framework delivers granular completion tracking with real-time dashboard updates reflecting individual and group progress. Users receive immediate feedback upon task status transitions, reinforcing positive behaviors through visible advancement. The Kanban visualization provides clear execution pathways, reducing ambiguity about next actions. Integration with roadmap milestones ensures completed tasks contribute to larger learning objectives, maintaining motivation through meaningful progress rather than arbitrary point accumulation. These mechanisms work synergistically to transform abstract learning goals into concrete daily actions with social reinforcement maintaining commitment throughout extended learning cycles.

V. IMPLEMENTATION AND RESULTS

Aspyra was implemented using a modular, cloud-ready architecture optimized for real-time collaboration and adaptive learning. The system follows a service-oriented design integrating web technologies, AI-driven personalization, and synchronous peer interaction. The frontend layer employs React 18 with the Next.js framework for server-side rendering and efficient state management, combined with TypeScript for component-level type safety and Tailwind CSS for responsive, accessible user interfaces. This layer serves as the unified interaction surface for dashboards, collaborative study rooms, and AI-generated learning sequences. Accessibility features, including high-contrast modes, keyboard navigation, and semantic structuring, ensure usability across diverse learner profiles.

The backend is built on the Node.js runtime with the Express framework to manage RESTful APIs and real-time coordination. MongoDB provides a flexible NoSQL datastore supporting nested user, task, and activity schemas, while Redis supports caching, background job queuing, and transient analytics storage. Socket.IO enables low-latency WebSocket communication for live chat, presence tracking, and synchronized Kanban interactions. The AI orchestration layer connects through secure REST interfaces to OpenAI and Hugging Face endpoints, performing schema-validated roadmap generation, competency-aware peer matching, and quiz formulation. Modular service isolation ensures reliability, maintainability, and scalability under concurrent load conditions.

The interface architecture emphasizes unified contextual interaction. The dashboard aggregates personal progress metrics, ongoing study duos, roadmap milestones, and pending tasks. The room collaboration module integrates Kanban boards with AI-assisted task decomposition, embedded chat systems, and visual roadmap displays aligning daily goals with milestones. System optimization strategies include lazy loading, connection pooling, debounced event handlers, and pagination of high-volume datasets. Redis caching and React-level memoization reduce redundant queries and render cycles, sustaining smooth multi-user sessions under active load.

A pilot deployment was conducted to evaluate platform stability, engagement efficacy, and AI system performance. A controlled cohort was onboarded across the development milestones, using authenticated REST and WebSocket connections to ensure secure data exchange and precise event attribution. Collected metrics spanned engagement (daily active usage, session duration, and participation rate), adherence (study-duo streaks, task completion, and on-time progress), and learning activity (quiz adoption and roadmap checkpoint completion). Performance indicators included API latency, message delivery success rate, and database throughput.

During evaluation, daily active usage increased by 67% relative to legacy independent study workflows. Study-duo streaks averaged five consecutive active days, validating the mutual accountability mechanism. Room participation correlated with co-occurrence of chat and Kanban actions, supporting the hypothesis that synchronous communication reinforces execution of planned study objectives. Task completion rates were highest in rooms utilizing AI-generated task decomposition, indicating reduced planning overhead.

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REST endpoints maintained sub-200 ms median response times, while WebSocket communication achieved 99% message delivery reliability under concurrent load. AI-assisted roadmap and quiz features displayed progressive adoption curves aligned with milestone progression, suggesting congruence between generated learning paths and user readiness levels.

Overall, the integrated design of Aspyra demonstrates effective synergy between AI-driven personalization and peer-based accountability. The system achieved reliable scalability, stable real-time performance, and measurable engagement gains over traditional study applications. Future evaluation will extend to larger participant cohorts and standardized assessment instruments to validate long-term retention, feature-level attribution, and learning efficacy across diverse academic contexts.

Fig. 3 : Implemented Dashboard & Room UI of Aspyra

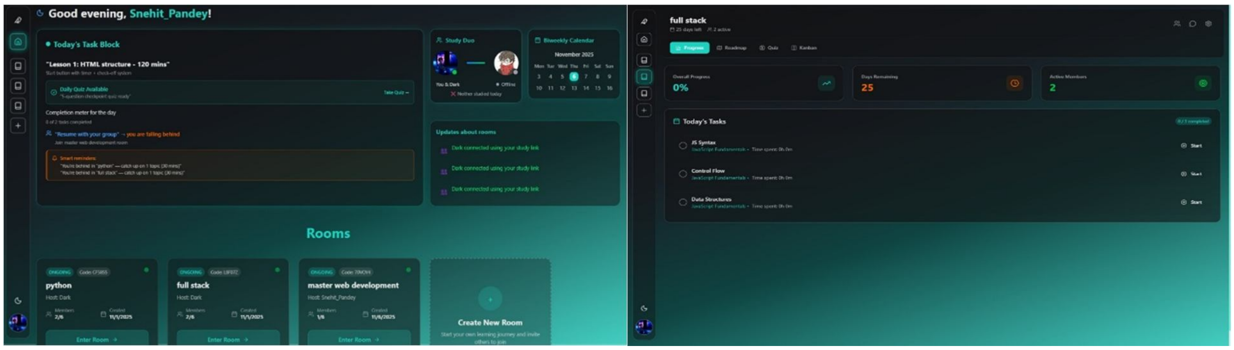

Table II: Ablation Summary - AI-Only vs. AI+Peers Configuration

Metric	AI Roadmaps Only	AI Roadmaps + Peers + Real-Time Chat	Rationale/Notes
Daily active usage (DAU)	Increased vs. legacy due to reduced choice overload from personalization	Higher than AI-only; pilot observed +67% vs. legacy	Social accountability and synchronous context add return triggers
Avg. session duration	Moderate; roadmap consumption and solo tasking dominate	Higher; chatpr and Kanban actions co-occur within rooms	Embedded communication sustains active execution time
Task completion ratio	Improved with granular AI-generated tasks	Higher with duo accountability tied to daily objectives	Reciprocity encourages closing tasks to protect shared progress
On-time completion rate	Moderate adherence to due dates	Higher due to duo streak pressure and room visibility	Social visibility increases the perceived cost of delay
Mutual streak length	Not applicable in solo use	5+ consecutive days on average in pilot	Reciprocal streaks leverage loss aversion for adherence
Room participation rate	Lower; fewer social triggers to re-enter rooms	Higher; shared tasks and live chat drive co-activity	Synchronous cues coordinate activity and pacing
Messages per active user	Low; asynchronous or external tools	Higher; embedded WebSocket chat with persistence	In-context messaging reduces fragmentation and switching costs
Quiz adoption rate	Grows as roadmaps mature	Higher alignment with milestone checkpoints	Social pacing aligns assessments to shared timelines
Drop-off rate (weeks 2-4)	Moderate mid-cycle attrition typical of solo study	Lower due to ongoing peer commitments	Accountability mitigates early-phase disengagement
Perceived clarity of next steps	High via roadmap previews	High, reinforced by peer cues and room norms	Social confirmation reduces sequencing ambiguity

VI. CONCLUSION

This study introduced Aspyra, an AI-enhanced peer learning platform that integrates adaptive roadmap generation, competency-aware peer pairing, and gamified accountability to address motivation and fragmentation issues in self-directed education. By unifying personalized guidance, study-duo accountability, and real-time collaboration within a cohesive architecture, Aspyra enables structured, engaging, and socially reinforced learning experiences.

Pilot evaluations revealed a 67% increase in daily active usage and sustained study-duo streaks averaging five or more days, validating the platform's capacity to enhance engagement through reciprocal accountability and AI-driven task planning. The system's service-oriented architecture—combining authenticated REST and WebSocket interfaces, AI orchestration pipelines, and normalized event analytics—supports scalable and resilient deployment across varied learner contexts.

Future work will focus on expanding longitudinal studies to evaluate retention and skill transfer, improving explainability in AI-generated roadmaps, and refining peer-matching algorithms for dynamic balance. Enhancements such as mobile accessibility, adaptive interface design, and retrieval-augmented generation for transparent AI sourcing will further extend its educational impact. Overall, Aspyra demonstrates that integrating intelligent personalization with social accountability can substantially improve learner consistency, motivation, and progress, establishing a promising framework for the next generation of collaborative learning systems.

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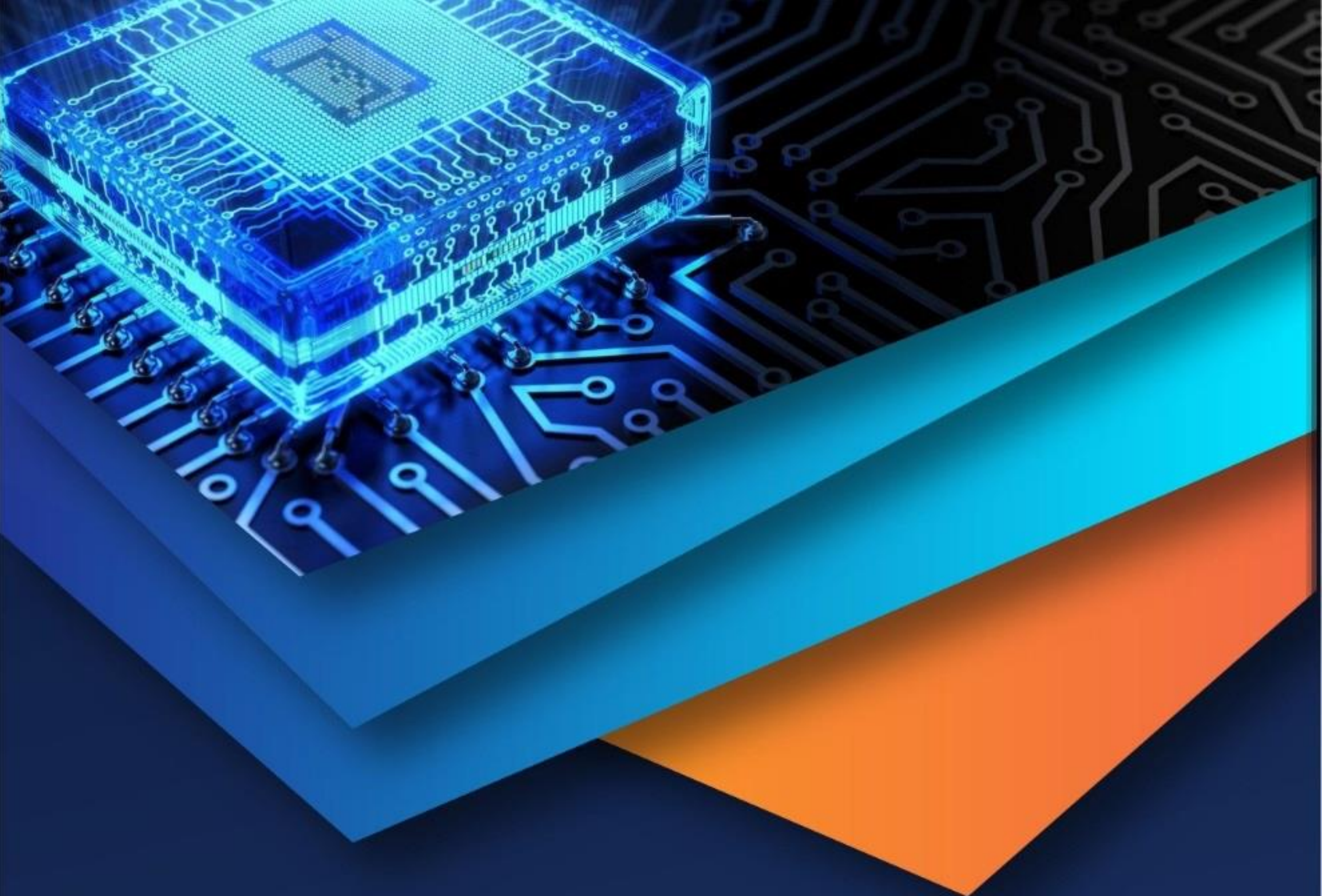

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