

## Entagogy: Developing a Systems-Theoretical Framework for Autopoietic Co-Construction Between Learners and AI in Posthumanist Education

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### Abstract

This article introduces Entagogy, a posthumanist, systems-theoretical framework for AI-integrated learning that addresses conceptual gaps left by traditional paradigms such as pedagogy, andragogy, and heutagogy. Drawing on Luhmann's theory of structural coupling, Entagogy reconceptualises the interaction between the Human Cognitive System (HCS) and the AI Semantic Subsystem (AISS) as co-autopoietic, mutually adaptive, and structurally coupled processes occurring within an entangled Zone of Proximal Development (e-ZPD). Entagogy's novel contributions include (i) the introduction of a measurable Coupling Index and clearly defined mechanical thresholds of adaptivity, latency responsiveness, and governance permeability, that determine when genuinely recursive and co-constructive learning emerges; (ii) the elaboration of the Entagogy Stack, an integrative schema connecting computational substrates, interface semantics, exogenous perturbations, and institutional policy; and (iii) a methodological roadmap structured around four analytical lenses: scenario-based reasoning, learning-analytics trace ethnography, longitudinal mixed-methods inquiry, and comparative multimodal analysis. The article explicitly addresses limitations, including systemic risks associated with digital inequality, bias propagation, and ethical oversight. Ultimately, Entagogy equips researchers, educators, and policymakers with actionable theoretical constructs, robust validation criteria, and equity-driven governance recommendations, guiding the development of ethically grounded, adaptive, and inclusive AI-enhanced learning environments.

**Keywords:** Developing Frameworks, Systems Theoretic, Autopoietic Construction, Educational AI Learners, Post-Humanities

### 1. Introduction

The rise in understanding of posthumanism's distributed agency within a Luhmannian system has recently rendered traditional frameworks of pedagogy, andragogy, and heutagogy insufficient, particularly in the context of contemporary learners operating within increasingly complex AI-mediated environments (Luhmann, 1997; Barad, 2007; Haraway, 2016; Agonács and Matos, 2019; Blaschke, 2021; Holmes et al., 2019). As AI moves from peripheral tool to central partner in education, existing theories, grounded firmly in anthropocentric models,



struggle to adequately capture or explain the mutually transformative interplay between learners and intelligent systems (Fawns, 2022; OECD, 2023).

While posthumanist educational theory challenges and expands the theoretical and epistemological framework through decentralising human agency and incorporating non-human actors (Burriss and Leander, 2024; Morales and Zarabadi, 2024; Cadman, Tanner and Pang, 2025), the insights of developmental psychology; Piaget's cognitive stages, Vygotsky's Zone of Proximal Development, and Bloom's taxonomy, require revisitation and reassessment in light of contemporary empirical evidence highlighting developmental asynchronies (Vygotsky, 1978; Bloom, 1984) exacerbated by AISS technologies.

Building upon Latour's sociomaterial symmetry, which dissolves the binary separation between human and technological actors, the insights of postdigital scholarship, highlighting technology's embeddedness in everyday educational infrastructures (Bayne and Jandrić, 2020; Bozkurt, 2024; Weich and Macgilchrist, 2023), and posthumanism's critical decentering of the human learner, we argue that AISS-mediated learning inherently constitutes a reciprocal entanglement of adaptive human and machine agencies. Such an entanglement, operationalised within an expanded, entangled Zone of Proximal Development (e-ZPD) where AISS dynamically scaffold learning not just by responding to learner input, but by evolving alongside it, fundamentally surpasses the explanatory and operational reach of established educational paradigms (Vygotsky, 1978; Fawns, 2022).

This paper proceeds by critically examining the existing theoretical landscape that leads to and informs Entagogy. The Literature Review begins by tracing the evolution of educational theories from traditional teacher-led paradigms (pedagogy) through to learner autonomy (andragogy and heutagogy) (Hase and Kenyon, 2000; Moore, 2020; Loeng, 2023; St Clair, 2024, Holt & Harris, 2025), identifying the inherent limitations each faces within AI-mediated contexts. While heutagogy's focus on self-directed learning represents a significant shift in framework, it lacks the conceptual apparatus to capture the complex, recursive interactions enabled by AISS systems.

Drawing on Latour's notion of sociomaterial symmetry, which erases the binary between human and technological actors, and on postdigital perspectives that highlight the infrastructural entwinement of education and technology, we argue that AISS-mediated learning represents a reciprocal entanglement of adaptive human and machine agencies, revealing the insufficiency of existing binary educational models that highlight the inseparable infrastructural relationship between learners and digital technologies. These insights culminate in a synthesis underpinned by Luhmann's systems theory, particularly the concepts of autopoiesis and structural coupling, to establish a coherent theoretical rationale for Entagogy (Luhmann, 1997; Steiner-Khamsi, 2021; Vanderstraeten and Rudolph, 2020).

Grounding the Neologism: Etymology of Entagogy The term Entagogy is formed by blending: "Ent-" from *entangle*, itself rooted in Latin *tangere* ("to touch"), suggesting mutual interweaving and non-linearity. "-agogos" (Ancient Greek ἀγωγός), the same root as in pedagogy, andragogy, and heutagogy, meaning "leader," "guide," or "conductor." Together, Entagogy literally conveys "guiding through entanglement." The neologism captures the paradigm shift from solo self-direction (heutagogy) to co-adaptive learning where human and non-human agents entwine their developmental trajectories. By echoing established -agogies while signaling a qualitatively new form of guided learning, Entagogy stakes its claim as the next evolution in educational theory.

## 2. Literature Review

### 2.1. From Pedagogy to Heutagogy: A Critical Diachronic Analysis

The genealogy of learner autonomy in Western educational thought can be read as a progressive loosening of teacher control (pedagogy), a negotiated redistribution of responsibility to adult learners (andragogy), and, most recently, an aspiration toward full learner self-determination (heutagogy). A closer examination, however, reveals conceptual and empirical fissures that become acute once artificial-intelligence systems enter the instructional ecology (Loeng, 2023; Agonács and Matos, 2019; Harris and Holt, 2024). Tracing this conceptual trajectory from pedagogy, through andragogy, to heutagogy reveals not only progressive emancipation from instructor-led educational practices but also exposes critical theoretical and empirical limitations. These limitations become especially pronounced when examined within the context of emerging artificial intelligence (AI)-mediated educational environments.

Pedagogy, historically dominant in formal education, privileges instructor authority in determining curriculum content, pacing, and methods of assessment, thereby relegating learners to dependent, largely passive roles (Loeng, 2023). Classical pedagogical models operate on assumptions of externally motivated, experience-poor learners whose educational outcomes depend heavily on explicit knowledge transmission (St Clair, 2024). While the progressive pedagogical movements spearheaded by theorists such as Dewey sought to enhance learner engagement through problem-centred inquiry and experiential relevance, these efforts did not entirely dismantle the hierarchical, teacher-centric foundations inherent in traditional pedagogy (Loeng, 2023). The persistence of pedagogical norms, particularly in formal institutional contexts, continues to reflect deeply entrenched epistemological assumptions about the nature and locus of educational authority (St Clair, 2024; Harris, 2024)..

In contrast, the emergence of andragogy, notably advanced by Malcolm Knowles (Knowles et al., 2005), constituted a significant reorientation toward learner-centred instructional design (St Clair, 2024; Loeng, 2023). Andragogy introduces a structured model predicated on six foundational assumptions regarding adult learners: the necessity of understanding the rationale behind their learning ('the need to know'), a self-directed self-concept, extensive and formative life experiences, readiness to learn driven by real-life tasks, problem-centred learning orientation, and intrinsic motivation. These assumptions collectively reposition the role of the instructor from authoritative disseminator of knowledge to facilitator of learning processes, employing mechanisms such as negotiated learning contracts and collaborative objective-setting (St Clair, 2024). However, despite its significant influence across multiple educational and training domains, andragogy faces critiques regarding conceptual ambiguity, primarily arising from its initial dichotomisation against a reductionist view of pedagogy (Loeng, 2023). Additional empirical critiques emphasise a paucity of rigorous evidence demonstrating andragogical superiority over alternative models (St Clair, 2024), alongside theoretical critiques highlighting its limited responsiveness to broader socio-cultural and structural inequalities.

Heutagogy further expands learner autonomy, conceptualising the learner as entirely self-determined, responsible not only for learning strategies but also for defining educational objectives and evaluating outcomes (Hase and Kenyon, 2000). Central to heutagogical theory is the emphasis on developing learner 'capability'; the ability to adapt competencies flexibly to novel and unpredictable contexts, achieved through continuous double-loop reflection (Blaschke, 2021). While conceptually innovative, heutagogy confronts substantial empirical and practical constraints: evaluations indicate limited institutional adoption, fragmented implementation practices, and challenges in scalability and assessment (Moore, 2020;

Blaschke, 2021). Consequently, despite its aspirational appeal, heutagogy has not been uniformly successful in supplanting earlier paradigms in widespread educational practice.

Significantly, each of these paradigms - pedagogy, andragogy, and heutagogy - presume human-centred agency and self-regulation within clearly delineated human-learner or instructor-learner relationships. The introduction of artificial intelligence (AI) into educational contexts disrupts this assumption by incorporating non-human, adaptive agency directly into instructional processes. Intelligent Tutoring Systems (ITSs), for example, utilise real-time learner modelling, adaptive curriculum customisation, and sophisticated feedback mechanisms, establishing bi-directional metacognitive interactions between learners and AISS (Alkhatlan and Kalita, 2018). Such interactions transcend the limitations inherent in traditional human-led frameworks, offering scalable personalisation and real-time adaptation at levels unattainable by purely human instructional models (Alkhatlan and Kalita, 2018; Bloom, 1984; Harris and Holt, 2024). As AISSs become more sophisticated, the inadequacies of heutagogy, predicated as it is on the assumption of entirely human-managed self-direction, become increasingly evident (Fawns, 2022).

These limitations point to a deeper epistemological fault line: pedagogy, andragogy, and heutagogy each presuppose a unidirectional or self-contained human agent; whether teacher-led, self-regulated, or self-determined. None of these models accounts for the recursive, co-adaptive agency introduced when artificial intelligence enters the learning ecology not as a neutral instrument but as an active participant.

To theorise this mutuality, we must turn to frameworks that treat human and non-human actors not as binaries but as dynamically entangled (Bayne and Jandrić, 2020; Bozkurt, 2024; Burriss and Leander, 2024). Actor-Network Theory's symmetry principle, postdigital scholarship's insistence on already-embedded infrastructures, and posthumanism's distributed agency all find a formal grammar in Luhmann's systems theory, where learning systems are autopoietic ensembles and the human/AI relationship is maintained through structural coupling, reciprocal irritations that allow each subsystem to change while preserving its own operational boundary (Luhmann, 1997; Vanderstraeten and Rudolph, 2020; Cadman, Tanner and Pang, 2025; Harris, 2024).

## 2.2. Entangled Learning

Latour's Actor-Network Theory (ANT) (Latour, 2005) dismantles the human-versus-machine binary by granting technological artefacts symmetrical footing with people; agency, in this view, is an emergent property of the relations that bind actors together. Postdigital scholars extend this insight: Bozkurt (2024) and Weich & Macgilchrist (2023) show that those actor-networks are never neutral plumbing but deeply sociopolitical infrastructures whose code, data flows and business logics pre-shape what learning can become. Posthumanist work, from Barad's onto-epistemology (2007), to Morales & Zarabadi's relational ethics (2024), and Fawn's entanglement (2022) pushes this still further, insisting that knowledge itself is produced within material-discursive entanglements rather than simply transmitted across a network (Holt and Harris, 2025).

Yet describing the mesh of actors and their politics is only half the task; we must also explain how such heterogeneous elements stabilise long enough for learning to occur. Here Luhmann's social-systems theory supplies the needed dynamism. By conceiving humans and technologies as operationally closed systems that nevertheless remain *structurally coupled*, Luhmann shows how recursive irritations can generate durable meaning without collapsing difference. Entagogy therefore inherits Latour's symmetry and the postdigital/posthumanist critique, while using Luhmann's notions of autopoiesis and structural coupling to model how learner and AI co-evolve within an 'entangled' Zone of Proximal Development.

### 2.3. Luhmann's Systems Theory and Educational Contexts

Niklas Luhmann's systems theory provides a rigorous and compelling framework for understanding contemporary educational environments, particularly those integrated with artificial intelligence (AI). Rooted in the concept of autopoiesis, Luhmann conceptualises social systems, including educational systems, as self-producing entities sustained through internal communications rather than direct external inputs (Vanderstraeten, 2019; Harris, 2023c). These communications do not merely convey information but are the essential operations through which the system continually recreates itself, ensuring both stability and adaptability (Vanderstraeten and Biesta, 2006).

Central to Luhmann's theory is the notion of operational closure, whereby systems operate according to their internally established processes independently from direct external control. Nevertheless, this closure does not imply isolation; systems engage dynamically with their environments through structural coupling (Vanderstraeten, 2019). Structural coupling describes the reciprocal interactions and perturbations between systems, where each system influences and responds to the other without losing its operational autonomy or integrity (Vanderstraeten and Biesta, 2006).

In educational contexts enhanced by AI, structural coupling offers profound insights. Learners and AISS act as distinct yet mutually adaptive entities. Intelligent tutoring systems (ITS), for example, dynamically modify instructional strategies based on real-time learner inputs, such as performance data and affective responses, without surrendering their operational logic. Conversely, human learners reciprocally adapt their cognitive and metacognitive strategies in response to AI-generated feedback (Alkhatlan and Kalita, 2018; Harris and Holt, 2024). This mutual adaptation exemplifies Luhmann's concept of structural coupling, highlighting education as a complex, co-evolving ecology rather than merely a transactional space.

Luhmann defines education uniquely as a social system whose primary function is transformative, aiming to produce observable changes within learners to facilitate their participation in societal communication processes (Luhmann, 1997, Vanderstraeten, 2019). Unlike other societal systems, education does not primarily process communication for consensus or information dissemination but seeks targeted psychic transformations in learners, observable as skills and knowledge (Vanderstraeten and Biesta, 2006).

AISS intensify these interactions, forcing the educational system to recalibrate its internal communication processes continually. Thus, education systems, through the lens of Luhmann's theory, demonstrate robust adaptability, integrating technological advancements while preserving core operational boundaries (Holt and Harris, 2024).

### 2.4. Postdigital Thinking in Education

The postdigital condition represents a conceptual shift away from technological determinism and simplistic digital transformation narratives. It foregrounds a reality where digital and analog, biological and informational, technological and social are inseparably entangled in complex and evolving configurations (Bozkurt, 2024; Pasquale, 2015)). Within educational contexts, this perspective mandates a re-examination of pedagogical, epistemological, and ethical commitments.

Bozkurt (2024) characterises postdigital educational technology as a dynamic domain critically engaging with the assumptions underpinning educational technologies. Rejecting both technological determinism and instrumentalism, this approach views technologies as embedded socio-material agents influenced by cultural, social, and political contexts.

Consequently, educational technology is not neutral but actively shapes and is shaped by social structures and human practices (Bozkurt, 2024; Veale and Edwards, 2018)).

Weich and Macgilchrist (2023) further this critical stance by interrogating participation within postdigital education, highlighting the complexities of media integration and the power dynamics embedded within educational infrastructures. They propose viewing educational environments as 'media constellations', interconnected assemblages of materials, meanings, and power relations, rather than isolated digital artefacts. This aligns closely with systems theory, suggesting a complex interrelation of human and technological agents within educational systems (Weich and Macgilchrist, 2023).

Critically, postdigital theory demands reflexivity, urging educators and researchers to question who benefits from technological integration, who is excluded, and how educational practices are reshaped within these entangled environments (Weich and Macgilchrist, 2023; Bozkurt, 2024). These reflections are essential for designing ethical, equitable AI-enhanced learning environments.

## 2.5. Entangled Pedagogy: Integrating Posthumanist Insights

Posthumanist theory fundamentally challenges traditional conceptions of education that privilege human agency, cognition, and rationality. Instead, it advocates for understanding learning as inherently distributed and emergent, involving complex entanglements among humans, non-humans, technologies, and environments (Barad, 2007; Haraway, 2016). Central to posthumanist educational thought is the rejection of clear boundaries and hierarchies, such as learner/teacher, human/technology, and knowledge/ignorance, in favor of dynamic relationalities that are continually co-produced through material, discursive, and affective intra-actions (Barad, 2007).

Morales and Zarabadi's (2024) recent contribution to posthuman educational scholarship further advances this line of thought by introducing the concept of "agential cuts," derived from Barad's agential realism, agential cuts refer to the micro-level decisions and interactions that both distinguish and simultaneously create the entities involved, such as subjects and objects, through their intra-actions. These agential cuts highlight the moment-to-moment decisions and interactions that not only demarcate subject and object but also bring them into being through their intra-actions. This onto-epistemological framework, where knowledge and existence are mutually constitutive, positions educators and learners as nodes within fluid assemblages of human, technological, material, and affective agents (Morales and Zarabadi, 2024). Consequently, the posthumanist educator becomes less a transmitter of knowledge and more an active participant within a continuously emerging, co-constituted educational ecology.

Further enriching this perspective, Fawns (2022) proposes "entangled pedagogy," which moves beyond traditional binaries such as human/technology, emphasising that educational experiences are inevitably mediated through complex socio-material assemblages. His approach aligns closely with posthumanism's insistence on relational and ecological models of learning and knowing, foregrounding the role of infrastructural and technological conditions as integral, active, and inseparable from the educational process (Burriss and Leander, 2024).

These posthumanist insights mark a vital evolution in how education can be understood and enacted. Building upon the relational ontology articulated by Barad (2007) and further developed by Morales and Zarabadi (2024) and Fawns (2022), posthumanist theory situates AI not merely as a passive tool but as an active, adaptive participant in the co-constitution of learning. In this view, educational systems become sites of dynamic, reciprocal adaptation between human and non-human actors, where knowledge, identity, and learning processes are not linear or solely human-led, but fluid, distributed, and mutually emergent. This reconceptualisation invites a profound shift in educational design and research, suggesting that

any meaningful engagement with AISS in education must account for the onto-epistemological entanglement at its core

In sum, posthumanist educational theory, with its emphasis on relationality, distributed agency, and onto-epistemological entanglement, radically reframes the role of education in a world where human and non-human actors are deeply interwoven. Rather than offering a fixed blueprint for instruction, posthumanist perspectives open up new conceptual terrain for reimagining how learning unfolds within complex assemblages of material, technological, and affective agents. This view encourages the development of pedagogical models that can accommodate the emergent, co-constituted nature of knowledge production, and invites educational theorists and practitioners alike to consider frameworks that move beyond traditional human-centred paradigms. In this configuration, the ZPD is no longer a fixed span but dynamically stretches for both human and artificial participants, as each accesses real-time, contingent input precisely when needed. This reciprocal expansion, framed in terms of Balloon Theory (Holt, 2024) as the mutual inflation of cognitive boundaries, constitutes a live resolution of Bloom’s 2 Sigma Problem, as adaptive scaffolding yields personalised trajectories that exceed the gains of conventional instructional models (Holt, 2024; Vygotsky, 1978; Bloom, 1984).

## 2.6. The Entangled Zone of Proximal Development (e-ZPD)

Contemporary adaptive systems also compel a re-specification of Vygotsky’s (1978) Zone of Proximal Development (ZPD). In an entangled ZPD, guidance is no longer monopolised by a single ‘more-knowledgeable other’; instead, the guiding function oscillates moment-to-moment between human learner and artificial agent, depending on which sub-system currently possesses the richer anticipatory model of the next learning move (Alkhatlan and Kalita, 2018). Expertise thus becomes *situational* rather than positional, enacted through recursive hand-overs that are largely invisible to the learner.

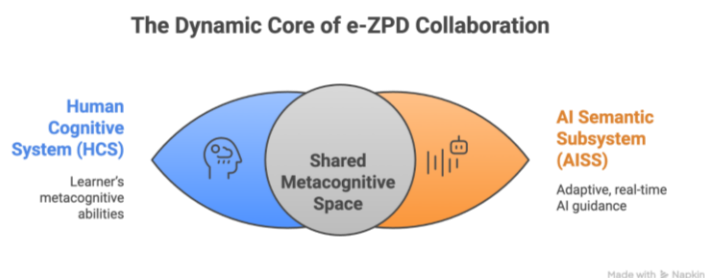


Fig 1: e-ZPD

Table 1. Core characteristics of an entangled Zone of Proximal Development (e-ZPD)

Characteristic	What it looks like in an e-ZPD
Structural coupling	Human Cognitive System (HCS) and AI Semantic Sub-system (AISS) maintain a live, bidirectional link, exchanging metacognitive cues that let each reshape the other’s next move
Oscillating guidance	“More-knowledgeable” status passes back and forth in milliseconds; whichever partner currently holds the richer anticipation leads the scaffold

Multimodal scaffold	Dialogue is augmented by interface prompts, visualisations, algorithmic nudges and affective tags, all co-authored in real time by learner and AI
Fluid boundary	The zone’s edge stretches or contracts with every interaction, giving a polycentric, constantly redrawn learning space
Mechanical thresholds	True co-construction only emerges when three conditions are met together: high adaptivity, sub-second feedback latency, and governance settings that let the AI keep learning
Failure mode	Break any threshold and the system snaps back to a traditional, one-directional scaffold—human-led if the AI freezes, AI-led if governance locks it down

This oscillation is possible because the ‘language’ that mediates development has itself expanded beyond the strictly linguistic. Interface cues, adaptive visualisations, algorithmic nudges, policy prompts and affective tags form a semiotic–algorithmic scaffold that both partners co-author and continuously rebuild. The scaffold is therefore identical with the dialogue: as each side rewrites context for the other, the ZPD’s boundary is redrawn in real time (Burriss and Leander, 2024).

The expanded ZPD retains Vygotsky’s core insight that learning thrives at the boundary of current ability, while re-locating that boundary within a polycentric, recursively updated scaffold. Guidance is no longer a pedestal but a pendulum; language is no longer a conduit but a living architecture; closure is no longer a trap but a design-choice moderated by well-timed irritations. Entagogy thus offers not just a new label but a design brief: build learning ecologies that couple adaptively, measure reflexively, and stay permanently open to the world beyond their own operations.

**Table 2. How an e-ZPD differs from Vygotsky’s classic ZPD**

Aspect	e-ZPD (Entagogy)	Standard ZPD (Vygotsky, 1978)
Source of expertise	Dynamically shared—human or AI leads as circumstances shift	Fixed human “more-knowledgeable other”, typically a teacher or peer (same source)
Stability of the zone	Expands and contracts in real time as context is rewritten	Identified once by the educator and treated as a fairly stable span (ibid.)
Medium of mediation	Multimodal, algorithmic and linguistic signals combine in the scaffold	Predominantly spoken or written language between people (same source)
Direction of influence	Mutual perturbation: learner actions update the AI model, AI feedback reshapes learner strategies	Largely one-directional guidance from expert to learner
Prerequisites for operation	Requires adaptivity, low latency and permeable governance; collapse without them	No technical prerequisites beyond human interaction

### 3. Methods

#### 3.1. The Case for Entagogy: Reconciling System, Agency, and Ethics

The analysis presented underscores the fundamental inadequacy of traditional educational paradigms, pedagogy, andragogy, and heutagogy, in addressing the complexities introduced by artificial intelligence in contemporary learning contexts (Holt and Harris, 2025). By critically examining Latour's Actor-Network Theory (ANT), postdigital scholarship, posthumanist educational theory, and Luhmann's systems theory, we have identified significant epistemological and methodological limitations inherent in established frameworks, highlighting the need for a new conceptual model tailored explicitly to AI-mediated learning environments (Latour, 2005; Bozkurt, 2024; Barad, 2007; Luhmann, 1997).

Luhmann's systems theory provides a critical theoretical language, describing education as autopoietic systems maintained by structural coupling, where human and technological systems reciprocally adapt while maintaining their operational integrity (Vanderstraeten and Rudolph, 2020; Luhmann, 1997). This theory effectively illustrates the complexity of AI-mediated learning but also exposes the limits of traditional frameworks that cannot fully capture these reciprocal, dynamic interactions (Fawns, 2022).

Consequently, we therefore introduce "Entagogy": an integrated theoretical and methodological framework crafted for research and practice in an AI-enhanced learning environment (Holt and Harris, 2025). Entagogy uniquely integrates insights from ANT, postdigital, posthumanist, and systems-theoretical perspectives, enabling researchers and educators to explore and operationalize the complexities of learner engagement in collaboration with intelligent technologies (Harris and Holt, 2024).

Entagogy equips educators and researchers to meet the evolving challenges of AI-enhanced education with a richer, ethically grounded, and adaptive approach that honours the complexity of contemporary learning. By embracing this novel approach, we can better address the emergent educational challenges posed by AI, fostering richer, more adaptive, and ethically informed educational practices.

Heuristically, Entagogy allows for mapping human/AI learning by realising a nested layers of technology and governance (see Figure: 1) (Harris and Holt, 2024). At the base sits the computational substrate servers, sensors, and energy budgets that cap response speed and sustainability. Above it, the AI-model layer houses the large-language or multimodal networks whose training scope and alignment determine raw expressive range. The AI Semantic Subsystem (AISS) mediates between those models and the learner, translating output into context-sensitive prompts while updating an evolving learner model.

For this dialogue to become co-constructive, three structural thresholds must hold: high adaptivity, sub-second latency, and policy settings that let the system self-tune. When they do, a temporary entangled ZPD (e-ZPD) forms in which human cognition and the AISS exchange bidirectional metacognitive cues. Surrounding that core are outer-ring constraints: infrastructure gaps, privacy rules, cultural bias, and scaling limits, that can stabilise or break the coupling. Periodic exogenous irritations (policy alerts, peer annotations, corpus updates) keep the system from drifting into self-confirmation and finally, a policy-and-governance layer sets the standards, funds the infrastructure, and enforces ethical oversight (Veale and Edwards, 2018; Pasquale, 2015). Alignment across all tiers is therefore the pre-condition for the recursive, adaptive learning relationships Entagogy seeks to describe.

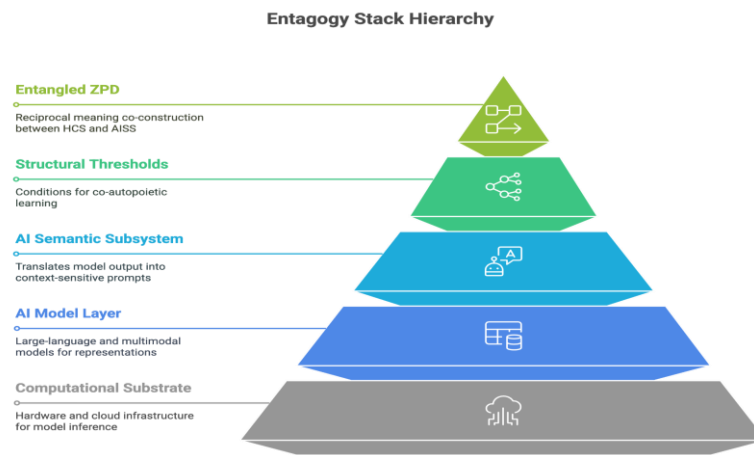


Fig.2: Entagogy Stack

### 3.2. Epistemological Framework of Entagogy

The concept of Entagogy is underpinned by an onto-epistemological framework that acknowledges knowledge as inherently relational, co-constructed, and emergent through the ongoing intra-actions of human and non-human agents (Barad, 2007). Drawing on Karen Barad’s (2007) concept of 'agential cuts', Entagogy recognises that epistemological distinctions - such as learner and AI, knowledge and context - are continuously enacted and renegotiated through relational practices.

Central to this epistemological framework is the principle of distributed agency. Rather than positioning learners or AI as singularly autonomous agents, Entagogy conceptualises learning as a mutual adaptation between structurally coupled human cognitive systems and AISS. This coupling occurs within an entangled Zone of Proximal Development (e-ZPD), a dynamic space of potentiality where cognitive and affective capabilities of learners are co-constituted with adaptive functionalities of AI systems.

Entagogy therefore reconceptualises knowledge production not as a linear transfer or acquisition but as an iterative, recursive process where meanings and understandings continuously emerge from the reciprocal perturbations and irritations across human and technological systems (Burriss and Leander, 2024). This reconceptualisation necessitates robust criteria for knowledge validation, encompassing internal coherence, recursive reflexivity, and ethical responsiveness. Validation in this context demands methods sensitive to ongoing systemic adjustments and co-evolutionary dynamics between learner interactions and AI-driven analytics (see Figure 2).



Fig 3: Conditions for Desirable Entagogy

The epistemological rigour of Entagogy is further reinforced through the systematic integration of ethical reflexivity, embedding mechanisms that prompt continual reflection on issues of bias, equity, and inclusion within learning ecologies (Floridi and Cowls, 2019; Pasquale, 2015). This ethical dimension ensures that epistemological commitments remain accountable to broader social and ethical imperatives, making responsible innovation intrinsic to the entagogy framework.

## 4. Result

### 4.1. Approaches to Methodology

Entagogy offers a versatile analytical framework that enables researchers across diverse disciplines to investigate the posthumanist dynamics of AI–human coupling in learning environments. Grounded in systems theory, it invites inquiries that cut across disciplines, from cognitive science and educational technology to sociology, design, and critical data studies, each mapping different facets of human/AI coupling (Maturana and Varela, 1980; Luhmann, 1997). Rather than prescribing a single protocol, Entagogy provides a transdisciplinary lens through which researchers can trace how knowledge emerges, stabilises and transforms within complex socio-technical ecologies (Fenwick, Edwards and Sawchuk, 2011). The approach foregrounds structural coupling, reciprocal metacognition and ethical reflexivity, ensuring that methodological choices remain sensitive to both human agency and the operative logics of AISS (Steiner-Khamsi, 2021; Vanderstraeten and Biesta, 2006).

### 4.2. The Four Lenses of Entagogy

Entagogy's methodological stance is inseparable from its systems-theoretical roots: learning is a co-autopoietic process in which human cognition and AISS continuously perturb and recreate one another (Maturana and Varela, 1980; Vanderstraeten and Rudolph, 2020). Consequently, any research design that hopes to capture entagogy phenomena must operate across analytic scales, probing the micro-loops of interaction while also tracing the macro-stabilisations that give rise to curricular or policy shifts (Barab and Squire, 2004; Anderson and Shattuck, 2012). The framework therefore endorses a deliberately plural, recursive research architecture organised around four interlocking lenses: scenario-based reasoning, learning-

analytics trace ethnography, longitudinal mixed-methods inquiry, and comparative multimodal analysis.

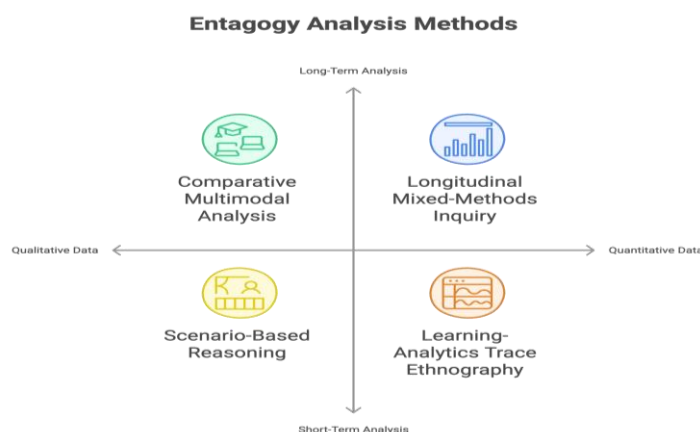


Fig 4: Methodological Approaches for Researching Entagogy Made with Napkin

Scenario-based reasoning serves as the design imagination of Entagogy. By constructing plausible yet speculative learning ecologies - whether through participatory design fictions, role-play studios, or agent-based simulations - researchers expose latent variables, ethical inflection points, and threshold conditions (adaptivity, latency, governance permeability) that shape the entangled Zone of Proximal Development (Steiner-Khamsi, 2021; Dunne and Raby, 2013). Each scenario functions as a stress-test: it perturbs the not-yet-built system so that critical couplings and potential failure modes become visible before large-scale deployment.

Learning-analytics trace ethnography then descends to the fine-grained level of practice. Clickstreams, gaze paths, sentiment tags, and conversational turns are read simultaneously as quantitative traces and as cultural artefacts (Burriss and Leander, 2024; Nelson, 2017). Algorithmic pattern-mining flags candidate episodes of bidirectional metacognition; ethnographic annotation recovers the situated meanings through which learners and AI negotiate agency. In Entagogy, numbers never substitute for narrative, they inter-animate one another to reveal how micro-irritations cascade into meso-level learning trajectories.

Because structural coupling and developmental synchrony unfold over extended periods, longitudinal mixed-methods studies form the backbone of empirical validation. Repeated measures of cognitive-affective alignment indices, policy-pedagogy coupling coefficients, and learner-authored reflections allow scholars to chart how early perturbations consolidate into stable routines, or regress into over or under coupling drift (Harley, Poitras and Duffy, 2019). Qualitative interviews and classroom observations contextualise these metrics, ensuring that statistical patterns remain tethered to lived experience.

Finally, comparative multimodal analysis provides the lateral perspective needed to generalise without flattening diversity (Kress, 2010; Norris, 2004). By aligning textual discourse, interface semiotics, and affective biometrics across multiple entagogic sites, researchers can distinguish universal design signatures from context-specific adaptations. Such cross-case synthesis safeguards against treating any single implementation as prototypical and anchors theory-building in a genuinely plural evidence base.

Critically, these four lenses are not sequential steps but nodes in a recursive research loop. Insights from scenario workshops recalibrate analytic parameters in trace ethnographies; emergent patterns in longitudinal data prompt new comparative questions; cross-case findings feed back into scenario design (Design-Based Research Collective, 2003). In this way, the methodological apparatus mirrors Entagogy itself: a dynamically entangled system whose

outputs continuously irritate and refine its own operations. Through this self-reflexive architecture, researchers can map with rigour how knowledge emerges, transforms, and stabilises within entagologic environments, while keeping ethical and equity commitments - psychological safety, inclusion, and transparency - at the core of every analytic move.

### **4.3. Extended Methodological Applications of Entagogy**

Foucauldian Analysis: Foucauldian genealogies of power provide a fertile vantage point for deploying Entagogy as a research apparatus (Foucault, 1977; Rouvroy and Berns, 2013; Williamson, 2017). In the classical panopticon, visibility disciplines the subject; in algorithmic governmentality, prediction governs by preemptively sculpting what may be thought or done. Entagogy reframes this shift as a dynamic structural coupling between learner and statistical model: each biometric trace and conversational turn feeds the algorithmic gaze, while every model update re-conditions the learner's horizon of possibilities.

Methodologically, the framework invites a fusion of critical discourse analysis, multimodal conversation analysis, and learning-analytics trace ethnography to examine how epistemic authority, affective nudging, and behavioural steering circulate through code, interface, and flesh (Fairclough, 2010; Norris, 2004; Mondada, 2019). By nesting these micro-analytic moves within scenario-based design fictions and longitudinal mixed-methods studies, researchers can map how Foucauldian regimes of truth crystallise, and are contested, inside entangled Zones of Proximal Development.

Thus, Entagogy does not merely borrow from Foucault; it operationalises his insight that power is relational, productive, and embedded in everyday practice, offering concrete instruments to trace where agency is negotiated, redistributed, or occluded in AI-mediated learning systems.

### **4.4. Systems Dynamics & Causal-Loop Modelling**

System-dynamics translates Entagogy's recursive couplings into stock-and-flow diagrams and differential equations (Sterman, 2000; Meadows, 2008; Zheng and Saunders, 2022), furnishing a computational test-bed for disciplines as varied as educational policy analysis, organisational sociology, operations research and computational social science. Variables such as learner agency, algorithmic adaptivity and governance constraints can be modelled as interacting reservoirs whose feedback loops reveal tipping points, delays and path dependencies. A curriculum designer might test how changes in feedback latency alter motivation trajectories; a public-policy analyst can embed those classroom loops inside wider fiscal circuits to anticipate equity effects at district scale.

Because the models are both transparent and scenario-driven, they support participatory validation with teachers, students and system leaders, aligning quantitative rigour with the democratic ethos of posthumanist inquiry. In situating Entagogy at the nexus of complexity science and critical design, causal-loop modelling helps researchers identify high-leverage interventions, visualise ripple effects across months or years, and rehearse "what-if" scenarios long before costly roll-outs.

### **4.5. Social & Sociomaterial Network Analysis**

Network approaches to Entagogy situate learning within the shifting webs of relations that bind students, teachers, algorithms, devices and institutional rules (Latour, 2005; Fenwick, Edwards and Sawchuk, 2011; Dawson, 2010). By fusing computational graph metrics with Actor-Network Theory's insistence that objects and code have agential weight, researchers in

sociology, communication studies, information science, digital anthropology and learning analytics can trace how influence, affect and knowledge flow - and sometimes snag - across entangled systems. Multilayer network models align platform log data, classroom interaction transcripts, and interface clickstreams so that hidden brokers, peripheralised learner groups, or algorithm-centred choke points become visible.

Dynamic snapshots then reveal whether interventions, such as a new recommendation algorithm or a peer-mentoring protocol, thicken previously fragile ties or simply reroute existing hierarchies. In policy research this lens highlights structural inequities that dashboards alone obscure; in **Human-Computer Interaction (HCI)** it guides interface redesign toward more equitable participation; in critical data studies it exposes the politics embedded in seemingly neutral edges and nodes. Thus network analysis not only maps the living architecture of entagologic collectives but offers practical levers for educators, designers and policymakers intent on redistributing voice and opportunity.

#### 4.6. Design-Based Research (DBR)

DBR positions researchers as co-designers embedded in the messy reality of classrooms, studios, or workplace learning labs, making it a natural ally for Entagogy's emphasis on real-time human/AISS coupling (Design-Based Research Collective, 2003; Barab and Squire, 2004; Anderson and Shattuck, 2012;). Originating in the learning sciences but now spanning instructional design, human-computer interaction, educational technology, developmental psychology and implementation science, DBR weaves theory generation into artefact creation. Each build-test-redesign cycle functions as a controlled perturbation of the e-ZPD: algorithms are tweaked, interface affordances re-scaffolded, teacher practices re-scripted, while ethnographic notes, telemetry dashboards and learner reflections capture the ripple effects.

The outcome is doubly valuable; an empirically grounded intervention (a recommender logic, a multimodal feedback widget, a coaching protocol) and a mid-range design theory that explains how and why that intervention stabilises (or destabilises) learning within entagologic ecologies. For learning-analytics specialists, DBR provides calibration data; for sociologists of education, it foregrounds the negotiation of power relations; for policy researchers, it generates context-sensitive blueprints that travel better than abstract prescriptions. In short, DBR turns Entagogy from a conceptual map into an iterative, evidence-building journey shared by educators, engineers and learners alike.

#### 4.7. Agent-Based Simulation

Agent-based modelling (ABM) builds digital "sandboxes" where thousands of autonomous entities: students with varying prior knowledge (Bonabeau, 2002; Wilensky and Rand, 2015; Holmes, Tuzun and Fortune, 2021), AISS based tutors with tunable feedback parameters, teachers with distinct mentoring styles, even policy mandates as governing agents, interact under rule sets informed by Entagogy. Rooted in complex-systems science and widely used in computational sociology, economics, artificial life, cognitive science, and education policy analysis, ABM lets scholars watch macro-patterns (knowledge diffusion, equity gaps, collective metacognition) crystallise from micro-level couplings. In learning-analytics research, synthetic classrooms powered by large-language-model agents provide safe test beds for new recommendation logics or assessment policies before real learners are exposed.

Operations-research groups exploit the same models to optimise resource allocation - class size, AI-compute budgets - while behavioural economists toggle motivational levers to predict dropout cascades. Because every parameter is inspectable, ABM also supports critical data-studies inquiries into how seemingly benign algorithm tweaks might entrench bias.

Coupling ABM outputs with real-world telemetry creates a “digital twin” of an entagologic ecosystem, enabling educators, designers and policymakers to rehearse interventions, inspect unintended consequences, and iterate policies at a fraction of the cost and risk of field trials.

#### **4.8. Computational Grounded Theory (CGT)**

CGT fuses the thick-description ethos of classic grounded theory with the scalability of natural-language processing, making it a methodological bridge between qualitative sociology, corpus linguistics, computational social science and learning analytics (Nelson, 2017; Ralund and Carlsen, 2022; Wright, Matuk and Lutzenberger, 2023). Topic modelling, transformer-based clustering or turn-taking pattern mining surface candidate themes, say, shifts in epistemic stance or affective alignment, across millions of learner/AI turns; allowing constant-comparison coding by discourse analysts can then refine those themes, ensuring indigenous categories (the way students actually talk about agency, frustration or insight) are not overwritten by algorithmic abstractions. For educational psychologists, CGT quantifies developmental trajectories of metacognition; for critical media scholars it reveals how platform prompt-engineering shapes voice and power and for curriculum designers it identifies emergent misconceptions at scale, feeding back into real-time scaffolding within Entagogy-informed dashboards.

#### **4.9. Ecological Momentary Assessment (EMA)**

EMA, long used in health psychology and affective computing, deploys micro-surveys or sensor-triggered prompts directly inside learning apps (Shiffman, Stone and Hufford, 2008; Harley, Poitras and Duffy, 2019; Baker and Rodrigo, 2019), capturing emotion, cognitive load and contextual variables in situ rather than retrospectively. In an entagologic classroom, a nudge might pop up when biometric arousal spikes or after an AI hint. Coupled with platform telemetry and location or noise-level data, EMA lets behavioural scientists, instructional designers and human-computer-interaction researchers map transient coupling states - flourishing, friction, flow - second by second.

Learning-analytics teams can fuse these self-reports with clickstreams to train adaptive models that recognise when encouragement, challenge or downtime is needed; educational neuroscientists can likewise use the time-locked data to align subjective feelings with neurophysiological markers while implementation scientists test whether new policies (e.g. shorter feedback loops) measurably boost moment-to-moment engagement across diverse settings.

#### **4.10. Neurophenomenology & Biometric Synchrony**

Drawing on cognitive neuroscience, phenomenology, embodied cognition and biofeedback research (Varela, 1996; Dikker et al., 2017; D’Mello and Graesser, 2012), neurophenomenological protocols can place EEG, fNIRS or heart-rate sensors alongside first-person interviews to explore how learners’ brain and body rhythms entrain, or fall out of sync, with AI-generated feedback. When alpha-desynchronisation accompanies a learner’s reported “aha” moment and coincides with an AI-prompted scaffold, researchers can gain multilayer evidence of co-autopoietic learning. Affective computing labs examine how galvanic-skin-response coherence between peers and an empathic tutoring agent predicts group persistence.

Philosophy-of-mind scholars can probe whether such biometric synchrony challenges dualistic views of agency, while rehabilitation sciences can explore how neurofeedback-augmented AISS coaches accelerate skill reacquisition. Entagogy allows these methods to

anchor abstract coupling theories in measurable, embodied dynamics, offering a window into the physiological signatures of bidirectional metacognition.

#### **4.11. Autoethnography & Co-Autoethnography**

Autoethnographic methods, long established in anthropology, sociology of education and reflective practice research (Ellis, Adams and Bochner, 2011; Gouzouasis and Ryu, 2015; Chang, Ngunjiri and Hernandez, 2013), gain new urgency under Entagogy. Because AISS feedback loops often inscribe norms faster than participants perceive them, practitioner-scholars (teachers, learners, designers) are uniquely positioned to document the lived texture of entangled practice; the moment an AISS's tone recalibrates class humour, the creeping reliance on predictive hints, the ethical unease when biometric dashboards rank "engagement." etc.

Co-autoethnography extends this to collective diaries or video-reflection circles, aligning with critical pedagogy, human-computer interaction and professional-learning-community studies. Entagogy furnishes the interpretive scaffold: structural coupling and bidirectional metacognition become analytic lenses through which these narratives reveal tacit power, hidden labour and emergent professional identities that remain invisible to quantitative analytics alone.

#### **4.12. Critical Discourse & Multimodal Conversation Analysis**

Fusing Critical Discourse Analysis (from linguistics and media studies) can be coupled with multimodal conversation analysis (from sociolinguistics, gesture studies and social semiotics) in an entagogy framework allowing researchers to trace how power, ideology and affect circulate through every modality of AI-mediated learning (Fairclough, 2010; Norris, 2004; Mondada, 2019), lexical choices in prompts, micro-pauses in speech, emoji sequences, interface colour cues, Entagogy's framework clarifies why this matters: each semiotic trace is a site where human cognition and algorithmic affordance structurally couple.

Communication scholars can interrogate how platform metaphors ("assistant," "mentor") shape learner agency; disability-studies researchers are able to examine whether visual cues privilege neurotypical processing; critical data-studies teams expose how sentiment algorithms reinforce cultural biases. By situating these findings within Entagogy's e-ZPD, scholars can move beyond cataloguing inequities to redesigning dialogue systems and classroom scripts that redistribute epistemic authority.

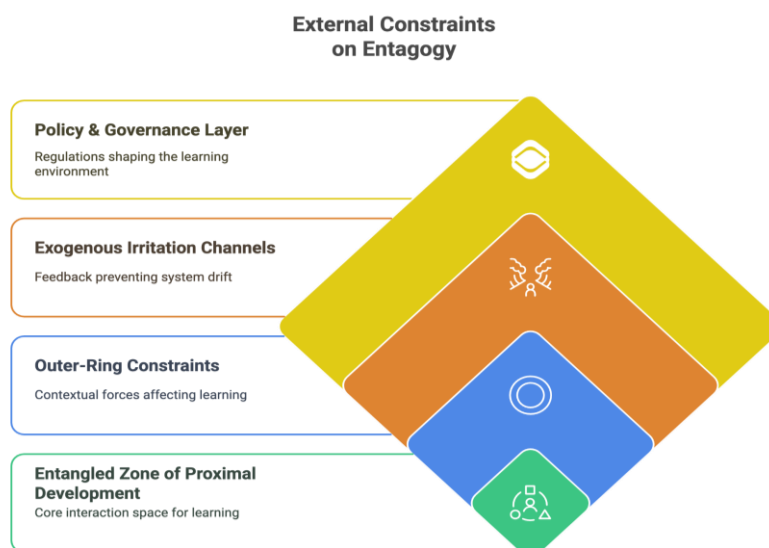


Fig 5: External Constraints on Entagogy

### 4.13. Quasi-Experimental & A/B Field Trials

When randomised controlled trials collide with school timetables or ethical constraints, researchers from program evaluation, economics of education, implementation science and developmental psychology turn to staggered roll-outs, crossover designs and alternating-treatment schedules. Entagogy supplies the theory of change (Shadish, Cook and Campbell, 2002; Schneider and Kaufman, 2017; Kohavi and Longbotham, 2017): hypotheses specify which structural couplings (e.g., tighter AI/teacher feedback loops) should shift which emergent outcomes (sustained metacognitive talk, reduced equity gaps). Because interventions often alter system feedback in nonlinear ways, embedding A/B tests inside agent-based “digital twins” or within naturally occurring classroom rotations, this lets evaluators compare causal fingerprints before district-wide adoption. Policy analysts then read the results through Entagogy’s lens to decide whether to scale, iterate or abandon, ensuring that evidence aligns with the framework’s

recursive, evolution.

commitment to learner-centred co-

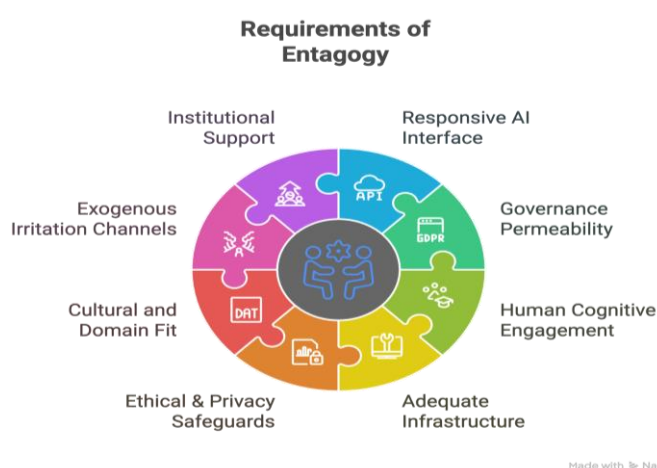


Fig 6: Requirements of Entagogy

These methodological strands are most potent when woven into the recursive loop central to Entagogy: insights from one lens recalibrate the next, ensuring that evidence and framework co-evolve in the same entangled dance they seek to explain.

#### 4.14. Educational Implications and Applications

Entagogy demands an urgent recalibration of policy frameworks to accommodate not just the technical integration of AISS in education, but a philosophical rethinking of learning as entangled, recursive, and posthuman (Harris, 2024; Holt and Harris, 2025). Alignment with the UNESCO Education 2030 Agenda affirms Entagogy's commitment to equity, inclusion, and lifelong learning (UNESCO, 2016). Simultaneously, compliance with the EU AI Act foregrounds the importance of transparency, human oversight, and risk assessment in educational AI applications (European Commission, 2021).

Ethically, Entagogy calls for data-governance standards that move beyond procedural compliance toward ethical reflexivity (Floridi and Cowls, 2019; Veale and Edwards, 2018); ongoing responsiveness to evolving social, emotional, and cultural conditions. Policymakers must support funding models that reward pedagogical innovation through AISS not merely as a tool, but as a co-evolving actor in the learning process. National and local authorities should be encouraged to establish accountability structures that are both rigorous and adaptable, capable of addressing harms emergent from entanglement, not just implementation (OECD, 2023; Pasquale, 2015). Focus and understanding of logic building must therefore take precedence over caps and limitations.

Educational institutions confronting Entagogy must navigate a multilayered set of challenges: governments are pressed to replace outcome-centric curricula with process-oriented frameworks (Black and Wiliam, 1998; Harris and Holt, 2024), fund open-access research on formative AISS tools, and establish ethics boards that include learners, while regional authorities must build innovation hubs, guarantee data-interoperability standards across districts, and deploy culturally responsive infrastructure in underserved communities to prevent widening digital divides. At the school level, leaders must overhaul assessment policies to privilege iterative thinking and dialogic AI feedback, furnish continual professional development in metacognition and AI co-design, and create transparent mechanisms for students to audit and contest machine-generated evaluations (Nicol and Macfarlane-Dick, 2006).

Pedagogically, teachers shift from content transmitters to co-designers who orchestrate distributed cognition among human, artificial and environmental agents, while grappling with the logistical and ethical complexities of bidirectional metacognitive assessment that tracks process, ethical reasoning and temporal learning trajectories rather than static products (Fawns, 2022; Holt and Harris, 2025).

#### 4.15. Limitations of Entagogy

While Entagogy provides a powerful and versatile theoretical lens to examine how humans and AISS reciprocally shape learning, it is crucial to acknowledge that not every interaction between learner and AISS constitutes entagogenic learning. The framework explicitly demands certain structural conditions to be fulfilled before the desired recursive, co-constructive coupling emerges. In other words, simply deploying an advanced AI tool or interacting frequently with an adaptive learning environment does not automatically yield entagogenic outcomes.

Central to the Entagogy framework is the notion that meaningful learning arises from the dynamic interplay, or structural coupling, between the Human Cognitive System (HCS) and

the AISS (Steiner-Khamsi, 2021). This interplay, however, can only flourish when specific enabling thresholds are consistently maintained. Without satisfying these critical thresholds - adaptivity, latency responsiveness, and governance permeability - the interaction between learner and AISS reverts from a truly co-evolving partnership into a more traditional, unilateral dynamic. Recognising these limits is essential not only for accurately diagnosing when and why entagogenic approaches may falter, but also for refining the design of AI-mediated environments to better meet these foundational conditions.

#### 4.16. Conditional Coupling

Autopoietic coupling between the Human Cognitive System (HCS) and the AISS constitutes the foundational mechanism of the e-ZPD (Maturana and Varela, 1980; Luhmann, 1997). However, such coupling is neither automatic nor guaranteed. It depends critically on three enabling thresholds, each of which must be met to sustain a genuinely recursive, co-constructive learning ecology. These thresholds: adaptivity, latency, and governance permeability, define the structural conditions under which learner and AISS can operate as distinct yet mutually responsive systems. Where any one threshold fails, the system reverts to a default mode: either a traditionally human-led scaffold or a heutagogy building AI tutor.

**Adaptivity** – For autopoietic coupling to take hold, the AISS must operate not as a static feedback engine but as a *live epistemic partner* (Burriss and Leander, 2024). This requires that the system continuously update its internal learner models within the same session, recalibrating predictions, scaffolds, and interface strategies based on ongoing learner inputs; be they cognitive (e.g., answer correctness), behavioural (e.g., pacing), or affective (e.g., sentiment shifts).

If the system's adaptivity is too coarse-grained (e.g., relying on pre-scripted branching paths) or updates only at the end of a session, the illusion of co-construction collapses. The learner ceases to perceive the AISS as a responsive partner and instead experiences it as a static tutor; one that repeats, rather than evolves. This breaks the recursive loop and inhibits the formation of structural coupling. As a result, the ZPD becomes frozen, linear, and teacher-dependent once again.

**Latency** – The temporal rhythm of feedback is equally critical. For coupling to feel and be dialogic, the system must respond fast enough to maintain the attentional envelope. Research suggests that this window, particularly for visual and interactive tasks, falls within a 300–600 millisecond range (OECD, 2023).

When the AISS responds too slowly it breaks the interaction's epistemic rhythm. The learner begins to reassert control and autopoiesis is broken. In effect, the AI is demoted from partner to passive tool. Conversely when feedback is instantaneous and semantically relevant, the AISS becomes experienced as an active participant, capable of "thinking with" the learner in real time. This speed-based alignment is essential for establishing the recursive irritations that define autopoietic systems.

**Governance permeability** – Governance must ensure ethical safety without sterilising the system's responsiveness through programmable transparency, not hard-coded stasis (Veale and Edwards, 2018; Pasquale, 2015). The capacity of an AISS depends on institutional policy architectures that either permit or prohibit algorithmic reparameterisation. Where audit rules, compliance frameworks, or locked-down governance APIs prevent the system from adapting (for example, in the name of fairness audits or GDPR compliance) the AISS becomes inflexible. It can still recommend, but it cannot *learn*.

This results in what we might call *pseudo-coupling*: the learner continues interacting, but the system is no longer responding in kind. The feedback becomes performative, not generative. Worse still, over time the system may default to protecting itself from liability

rather than optimising learning outcomes. A rigidly governed AISS risks functioning more like a grading assistant than a cognitive partner (Floridi and Cowls, 2019).

#### 4.17. Regressive Outcomes in the Absence of Coupling

The integrity of the entangled Zone of Proximal Development (e-ZPD) is contingent upon the simultaneous fulfilment of three structural conditions: adaptivity, latency responsiveness, and governance permeability. Where any of these conditions is absent or compromised, the autopoietic coupling between the Human Cognitive System (HCS) and the AI Semantic Subsystem (AISS) is disrupted. In such instances, the recursive perturbations and mutual irritations that sustain co-evolution between subsystems are severed, resulting in a reversion to more traditional, linear instructional dynamics. Specifically, the breakdown of each threshold yields distinct regressions: In the absence of adaptivity, the AISS reverts to pre-scripted instructional patterns. Rather than responding in real time to learner inputs, the system defaults to static, pre-determined sequences. This collapse into a didactic feedback loop inhibits the co-construction of meaning and re-establishes the educator or system as a unilateral source of knowledge.

When latency exceeds the learner’s attentional threshold, the illusion of dialogue is broken. Delays in system feedback diminish the perceived responsiveness of the AI, prompting the learner to disengage from co-constructive exchange. In such scenarios, learners are likely to revert to self-scaffolding strategies, effectively reclaiming full agency and undermining the dialogic reciprocity that characterises an entangled ZPD.

If governance frameworks restrict algorithmic re-parameterisation, the AISS is rendered operationally inert (Pasquale, 2015; Veale and Edwards, 2018). Policy constraints that prevent the system from adapting its internal models in response to emergent learner behaviour result in a rigid and prescriptive interaction. The learner, in turn, is forced to adapt their learning strategies around the fixed constraints of the tool, effectively transforming the AISS from a cognitive partner into a static recommender system.

In each of these cases, the ZPD regresses to a conventional scaffolding paradigm: either a human-led model in which the educator assumes sole responsibility for guidance, or a system-led routine in which the AI dictates fixed pathways without co-adaptive responsiveness. In either instance, the defining characteristic of Entagogy; the recursive, co-autopoietic interaction between learner and intelligent system, is suspended.

#### 4.18. Autopoietic Drift and the Necessity of Exogenous Irritation

Autopoietic systems reproduce their own operations; without perturbation they drift into reductive self-confirmation (Luhmann, 1997). To avoid siloed echo-loops, Entagogy hard-wires mandatory irritations from neighbouring function systems.

Table 3. Exogenous Irritations in Entagogy

External system	Irritation channel	Typical cadence	Example signal	Resulting adjustment
Institutional policy	Governance API call-outs	Daily cron or event-trigger	"Equity disparity > 10 %"	AI re-balances content difficulty, teacher receives alert (Steiner-Khamsi, 2021)

Peer community	Social annotation layer	Real-time	High divergence in peer answers	AI injects peer exemplar, learner invited to critique
Cultural knowledge base	Live corpus sync	Weekly	New taxonomy term enters discipline	Suggestion engine surfaces updated concept map
Ethical oversight	Bias-audit webhook	Monthly or ad hoc	Fairness test p-value < .05	Model weights recalibrated, bias notice displayed (Rosiek et al., 2024)

These loops stabilise the learning ecology without breaching operational closure: each subsystem retains its code (e.g., cognitive validation, policy compliance) while remaining sensitive to perturbations.

#### 4.19. Contextual Fault Lines That Disrupt Entagologic Coupling

Table 4. Required conditions of Entagogy

Dimension	Why it matters for Entagogy	Typical failure signal
<b>Context &amp; Infrastructure</b>	Reliable bandwidth, up-to-date devices and teacher training are prerequisites for low-latency adaptivity.	Technical “hiccups” force the AI to drop into fallback modes, re-humanising the session.
<b>Data Ethics &amp; Privacy</b>	Continuous modelling relies on granular trace data; privacy regimes (COPPA, GDPR) can throttle that flow.	Learners encounter generic feedback because fine-grained logs are masked or siloed.
<b>Bias &amp; Cultural Fit</b>	An AISS tuned on majority-culture discourse may mis-frame language, gesture or prior knowledge.	Minority learners receive irrelevant or pathologising prompts, undermining psychological safety.
<b>Interpretability &amp; Trust</b>	Black-box adaptivity can provoke teacher or learner scepticism, stalling the recursive loop.	Users override or ignore AI advice, reverting to pre-AI routines.
<b>Domain Boundaries</b>	Some competencies (e.g. tacit craft skills, embodied movement) exceed current NLP-centric AISS capacities.	Progress plateaus despite high adaptivity scores, signalling that the target skill needs physical co-presence.
<b>Scaling Effects</b>	What couples well in a pilot may overload compute budgets or moderation capacity at district scale.	Latency climbs and governance locks tighten, collapsing the coupling.

## 5.0. Conclusion

This paper has argued that the existing educational paradigms of pedagogy, andragogy, and heutagogy fall short when accounting for the complexity and relational dynamics introduced by AI-mediated learning environments. In response, Entagogy was proposed as a new educational theory grounded in posthumanist and systems-theoretical perspectives (Barad, 2007; Luhmann, 1997), offering a rigorous and integrative framework for conceptualising, investigating, and operationalising AI-supported learning.

At its core, Entagogy advances an epistemological position wherein knowledge is relationally co-constructed through continuous intra-actions between learners and AI semantic subsystems (AISS) (Burriss and Leander, 2024). It reconceives agency as distributed and recursive, anchored within an entangled Zone of Proximal Development (e-ZPD). This conceptual shift not only reshapes theoretical understandings but also informs methodological approaches and practical interventions. The four interlocking methodological lenses of scenario-based reasoning, trace ethnography, longitudinal mixed-methods inquiry, and comparative multimodal analysis, alongside additional methodological pathways, provide comprehensive tools to empirically trace and validate entagogic phenomena (Design-Based Research Collective, 2003; Nelson, 2017).

The paper offers clear testable methodological criteria, enabling future empirical validation or refutation of Entagogy's theoretical predictions and outlines the contingency of Entagogy upon several structural and contextual conditions. The framework explicitly acknowledges critical mechanical thresholds, as well as outer-ring constraints including infrastructure reliability, data ethics, cultural alignment, interpretability, and scalability (Floridi and Cowls, 2019; Pasquale, 2015). These limitations highlight the necessity for future research that is sensitive to context, particularly longitudinal and cross-contextual studies, equity-focused interventions, and comparative evaluations against alternative instructional designs.

In practical terms, Entagogy urges policymakers, educators and system designers to embed process-oriented, dynamic assessment practices within national curriculum frameworks (Black and Wiliam, 1998), establish regional innovation hubs to develop entagogic resources, and mandate institutional ethical oversight boards inclusive of learner representation (UNESCO, 2016; European Commission, 2021). These steps will ensure responsible, transparent, and inclusive deployment of AI in education.

Ultimately, Entagogy represents more than just an innovation in educational understanding. It signals an ethical and epistemological commitment to reflexive, co-constructive learning environments. It embodies a shift from viewing AI/AISS as either a tool or a threat, towards understanding it as an active participant in a mutually constitutive educational ecosystem. In embracing this dynamic coupling, Entagogy points toward a future of education that is ethically grounded, empirically rigorous, and fundamentally transformative.

## Bibliography

- Anderson, T. and Shattuck, J., 2012. Design-based research: A decade of progress in education research. *Educational Researcher*, 41(1), pp.16–25.
- Agonács, N., & Matos, J. F. (2019). Heutagogy and self-determined learning: A systematic review of the literature. *Open Learning*, 34(3), 223–240.
- Alkhatlan, K. and Kalita, J., (2018). Intelligent Tutoring Systems: A Comprehensive Historical Survey with Recent Developments. [online] arXiv. Available at: <https://arxiv.org/abs/1812.09628> [Accessed 24 May 2025].

- Baker, R.S. and Rodrigo, M.M.T., 2019. AI and emotion in education: Advancing scholarship with ecological momentary assessment. In: *Artificial Intelligence in Education*. Cham: Springer, pp.36–47.
- Barab, S. and Squire, K., 2004. Design research for technology-mediated learning. *Journal of the Learning Sciences*, 13(1), pp.1–14.
- Barad, K. (2007) *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*. Durham, NC: Duke University Press.
- Bayne, S. and Jandrić, P. (2020) ‘Postdigital education in the time of COVID-19 crisis’, *Postdigital Science and Education*, 2(3), pp. 1063–1066.
- Black, P. and Wiliam, D. (1998) ‘Assessment and classroom learning’, *Assessment in Education: Principles, Policy & Practice*, 5(1), pp. 7–74.
- Blaschke, L.M. (2021) Heutagogy: reframing the learner for the future. In: Naidu, S. (ed.) *Open and Distance Education Theory Revisited*. Singapore: Springer, 259–272.
- Bloom, B.S., 1984. The 2 sigma problem: The search for methods of group instruction as effective as one-to-one tutoring. *Educational Researcher*, 13(6), pp.4–16.
- Bonabeau, E., 2002. Agent-based modeling: Methods and techniques for simulating human systems. *Proceedings of the National Academy of Sciences*, 99(Suppl. 3), pp.7280–7287.
- Bozkurt, A. (2024). Postdigital Educational Technology. In P. Jandrić (ed.), *Encyclopedia of Postdigital Science and Education*. Cham: Springer. [online] Available at: [https://doi.org/10.1007/978-3-031-35469-4\\_57-1](https://doi.org/10.1007/978-3-031-35469-4_57-1) [Accessed 24 May 2025].
- Braidotti, R. (2013). *The Posthuman*. Cambridge: Polity Press
- Burriss, S.K. and Leander, K.M., (2024). Critical posthumanist literacy: Building theory for reading, writing, and living ethically with everyday AI. *Reading Research Quarterly*, 59(1), pp.123–144.
- Burriss, S.K. and Leander, K.M., 2024. Critical posthumanist literacy: Building theory for reading, writing, and living ethically with everyday AI. *Reading Research Quarterly*, 59(4), pp.560–569.
- Cadman, S., Tanner, C., & Pang, P. C. I. (2025). Humanism strikes back? A posthumanist reckoning with ‘self-development’ and generative AI. *AI & Society* (advance online publication) .
- Chang, H., Ngunjiri, F.W. and Hernandez, K., 2013. *Collaborative Autoethnography*. Walnut Creek, CA: Left Coast Press.
- Dawson, S., 2010. ‘Seeing’ the learning community: Analysing academic social networks. *Australasian Journal of Educational Technology*, 26(1), pp.16–31.
- Design-Based Research Collective, 2003. Design-based research: An emerging paradigm for educational inquiry. *Educational Researcher*, 32(1), pp.5–8.
- D’Mello, S.K. and Graesser, A.C., 2012. Dynamics of affective states during complex learning. *Learning and Instruction*, 22(2), pp.145–157.
- Dikker, S., Wan, L., Davidesco, I., et al., 2017. Brain-to-brain synchrony tracks real-world group interactions in the classroom. *Current Biology*, 27(9), pp.1375–1380.
- Dunne, A. and Raby, F., 2013. *Speculative Everything: Design, fiction, and social dreaming*. Cambridge, MA: MIT Press.
- Ellis, C., Adams, T.E. and Bochner, A.P., 2011. Autoethnography: An overview. *Forum Qualitative Sozialforschung / Forum: Qualitative Social Research*, 12(1), Art. 10.
- European Commission (2021) *Proposal for a Regulation laying down harmonised rules on artificial intelligence (Artificial Intelligence Act)*. Brussels: European Commission.
- Fawns, T., (2022). An entangled pedagogy: Looking beyond the pedagogy–technology dichotomy. *Postdigital Science and Education*, 4(3), pp.711–728.

- Fairclough, N., 2010. *Critical Discourse Analysis: The critical study of language*. 2nd ed. Harlow: Longman.
- Fenwick, T., Edwards, R. and Sawchuk, P., 2011. *Emerging Approaches to Educational Research: Tracing the sociomaterial*. London: Routledge.
- Foucault, M., 1977. *Discipline and Punish: The birth of the prison*. New York: Pantheon.
- Floridi, L. and Cows, J. (2019) ‘A unified framework of five principles for AI in society’, *Harvard Data Science Review*, 1(1). DOI:10.1162/99608f92.8cd550d1.
- Gouzouasis, P. and Ryu, J.Y., 2015. A pedagogical tale from the piano studio: Autoethnography in music education and new technologies. *Journal of Research in Music Education*, 63(2), pp.139–155.
- Haraway, D. (2016) *Staying with the Trouble: Making Kin in the Chthulucene*. Durham, NC: Duke University Press.
- Harley, J.M., Poitras, E. and Duffy, M.C., 2019. Ecological momentary assessment in education research: A practical introduction. *Journal of Educational Research & Practice*, 9(1), pp.101–120.
- Hase, S. and Kenyon, C. (2000) *From andragogy to heutagogy*. Southern Cross University.
- Holmes, W., Bialik, M. and Fadel, C. (2019) *Artificial Intelligence in Education: Promises and Implications for Teaching and Learning*. Boston: Center for Curriculum Redesign.
- Holmes, W., Tuzun, H. and Fortune, M., 2021. Artificial intelligence in education: Simulation of learner dynamics. *International Journal of Artificial Intelligence in Education*, 31(3), pp.480–499.
- Holt, S., 2024. Balloon Theory. [online] Academia.edu. Available at: [https://www.academia.edu/128872254/Balloon\\_Theory](https://www.academia.edu/128872254/Balloon_Theory) [Accessed 1 June 2025].
- Holt, Stephanie L, and Alexander Harris. “Is Society Primed for Education's Evolution? Transitioning from Learning to Use AI, to Using AI for Learning, to Leveraging AI for Thinking.” *Research MI Journal: Hong Kong 9.1 (2025): 33–35*. Print.
- Kohavi, R. and Longbotham, R., 2017. Online controlled experiments and A/B testing. In: C. Sammut and G.I. Webb, eds. *Encyclopedia of Machine Learning and Data Mining*. Boston, MA: Springer, pp.922–929.
- Kress, G., 2010. *Multimodality: A social semiotic approach to contemporary communication*. London: Routledge.
- Latour, B., 2005. *Reassembling the Social: An introduction to actor-network-theory*. Oxford: Oxford University Press.
- Liu, J., & Steiner-Khamsi, G. (2020). Comparing methods of policy borrowing: Human Capital Index and the externalization of education policy. *Prospects*, 51(1), 55–72 .
- Loeng, S. (2023) ‘Pedagogy and andragogy in comparison – conceptions and perspectives’, *Andragoška Spoznanja*, 2023, 1–14.
- Luhmann, N., (1997). *Die Gesellschaft der Gesellschaft*. Frankfurt am Main: Suhrkamp.
- Maturana, H. R., & Varela, F. J. (1980). *Autopoiesis and Cognition: The realization of the living*. Dordrecht: D. Reidel.
- Meadows, D.H., 2008. *Thinking in Systems: A primer*. White River Junction, VT: Chelsea Green Publishing.
- Mondada, L., 2019. Multiple temporalities of language and body in interaction: Challenges for transcribing multimodality. *Language in Society*, 48(4), pp.521–547.
- Moore, R. L. (2020). Developing lifelong learning with heutagogy: contexts, critiques, and challenges. *Distance Education*, 41(3), 381–401 .
- Morales, L. and Zarabadi, S. (2024) *Posthuman Educational Mappings: Agential Realism and Educational Practices*. New York: Routledge.
- Nelson, L.K., 2017. Computational grounded theory: A methodological framework. *Sociological Methods & Research*, 49(1), pp.3–42.

- Norris, S., 2004. *Analysing Multimodal Interaction: A methodological framework*. New York: Routledge.
- Nicol, D. and Macfarlane-Dick, D. (2006) 'Formative assessment and self-regulated learning: A model and seven principles of good feedback practice', *Studies in Higher Education*, 31(2), pp. 199–218.
- Norman, D.A. (2013) *The Design of Everyday Things*. Revised and expanded edn. New York: Basic Books.
- OECD, (2023). *AI and the Future of Skills: The Impact of Artificial Intelligence on Education*. [online] Paris: OECD Publishing. Available at: <https://www.oecd.org/education/ai-and-the-future-of-skills.htm> [Accessed 24 May 2025].
- OECD, (2023b). *OECD Digital Education Outlook 2023: Towards an Effective Digital Education Ecosystem*. Paris: OECD Publishing.
- Pasquale, F. (2015) *The Black Box Society: The Secret Algorithms That Control Money and Information*. Cambridge, MA: Harvard University Press.
- Ralund, S. and Carlsen, H.B., 2022. Computational grounded theory revisited: From computer-led to computer-assisted text analysis. *Big Data & Society*, 9(1). <https://doi.org/10.1177/20539517221106615>
- Rouvroy, A. and Berns, T., 2013. Algorithmic governmentality and prospects of emancipation: Disparateness as a precondition for individuation through relationships. *Réseaux*, 177(1), pp.163–196.
- Rosiek, J. L., Adkins-Cartee, M. J., & Pratt, S. L. (2024). A review of posthumanist education research: Expanded conceptions of research possibility and responsibility. *Review of Research in Education*, 48(1), 3–38.
- Schneider, B. and Kaufman, J., 2017. Trying it on for size: Instrumental variables and causal inference in education research. *Educational Researcher*, 46(6), pp.299–306.
- Shadish, W.R., Cook, T.D. and Campbell, D.T., 2002. *Experimental and Quasi-Experimental Designs for Generalized Causal Inference*. Boston: Houghton Mifflin.
- Shiffman, S., Stone, A.A. and Hufford, M.R., 2008. Ecological momentary assessment. *Annual Review of Clinical Psychology*, 4, pp.1–32.
- Steiner-Khamsi, G., 2021. Externalisation and structural coupling: Applications in comparative policy studies in education. *European Educational Research Journal*, 20(6), pp.729–746.
- Sterman, J.D., 2000. *Business Dynamics: Systems thinking and modeling for a complex world*. Boston: Irwin McGraw-Hill.
- St Clair, R. (2024) 'Andragogy: past and present potential', *New Directions for Adult and Continuing Education*, 2024(184), 7–13.
- Steiner-Khamsi, G., (2021). Externalisation and structural coupling: Applications in comparative policy studies in education. *European Educational Research Journal*, 20(6), pp.806–820.
- UNESCO (2016) *Education 2030: Incheon Declaration and Framework for Action for the implementation of Sustainable Development Goal 4*. Paris: UNESCO.
- Vanderstraeten, R. (2019) 'How Does Education Function?', *European Educational Research Journal*, 18(3), pp. 234–247.
- Vanderstraeten, R. (2019). Systems Everywhere? *Systems Research and Behavioral Science*, 36(3), pp.255-262.
- Vanderstraeten, R. and Biesta, G. (2006). How is Education Possible? Pragmatism, Communication and the Social Organisation of Education. *British Journal of Educational Studies*, 54(2), pp.160-174.
- Vanderstraeten, R., (2021). How does education function? *European Educational Research Journal*, 20(6), pp.729–739.

- Varela, F.J., 1996. Neurophenomenology: A methodological remedy for the hard problem. *Journal of Consciousness Studies*, 3(4), pp.330–349.
- Vanderstraeten, R., & Rudolph, H. (2020). Revisiting Luhmann’s ‘Education as a social system’. *Journal of Curriculum Studies*, 52(3), 360–375 .
- Veale, M. and Edwards, L. (2018) ‘Clarity, surprises, and further questions in the Article 29 Working Party draft guidance on automated decision-making and profiling’, *Computer Law & Security Review*, 34(2), pp. 398–404.
- Vygotsky, L.S., (1978). *Mind in Society: The Development of Higher Psychological Processes*. Cambridge, MA: Harvard University Press.
- Weich, A. and Macgilchrist, F. (2023). *Postdigital Participation in Education: An Introduction*. In A. Weich and F. Macgilchrist (eds.), *Postdigital Participation in Education*. Palgrave Studies in Educational Media. [online] Available at: [https://doi.org/10.1007/978-3-031-38052-5\\_1](https://doi.org/10.1007/978-3-031-38052-5_1) [Accessed 24 May 2025].
- Williamson, B., 2017. *Big Data in Education: The digital future of learning, policy and practice*. London: SAGE.
- Wilensky, U. and Rand, W., 2015. *An Introduction to Agent-Based Modeling: Modeling natural, social, and engineered complex systems with NetLogo*. Cambridge, MA: MIT Press.
- Wright, J., Matuk, C. and Lutzenberger, M., 2023. Computational grounded theory in the learning sciences. *Journal of Learning Analytics*, 10(1), pp.50–66.
- Zheng, Y. and Saunders, C., 2022. Anticipating the side effects of educational reform using system dynamics. In: M. A. Peters, ed. *Global Education Reform*. Singapore: Springer, pp.120–145.

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