The Future of Education in a Post-AI World: Lessons from the First Industrial Revolution and the Coming Transformation of STEM

Redline Rising Research Team

Abstract

The rapid proliferation of artificial intelligence (AI) is triggering a technological and epistemological shift comparable to the First Industrial Revolution. Unlike past revolutions, however, today's AI revolution directly redefines cognitive labor, automating many tasks that once required human reasoning. This paper argues that education must pivot from procedural skill toward *interpretive agency*: teaching students to use AI as a critical tool rather than as a crutch. We first trace historical parallels: nineteenth-century compulsory schooling for literate factory work was a societal response to industrialization (Davis, 2024) [1]. Today's economy similarly demands an AI-literate workforce. We propose two contrasting cognitive modes emerging: **(1) Algorithmic reliance**, in which learners uncritically accept AI outputs and favor fast, heuristic solutions (Zhai *et al*., 2024) [2] [3]; and **(2) Interpretive agency**, in which learners use AI output as a starting point but actively scrutinize its assumptions, limitations, and ethics (Walter, 2024) [4] [5]. We then examine implications for STEM teaching. Across physics, biology, chemistry, mathematics, computer science, and engineering, AI now excels at large-scale computation, pattern recognition, and optimization; hence curricula must emphasize conceptual understanding, critical thinking, creativity, and ethical judgment. For example, AI-powered physics tutors and virtual labs enhance engagement [6] but "heavy reliance on AI tools could hinder students' critical thinking abilities" [7], so physics education should stress intuition and validation of simulations. In biology, AI predicts protein structures and automates experiments [8] [9], but students must focus on experimental design, systems thinking, and bioethics. In chemistry, AI-driven retrosynthesis and virtual compound screening transform research [10] [11], implying that chemical education should focus on reaction mechanisms, safety, and green chemistry principles. In mathematics, AI easily solves routine problems, so instruction should stress theorem-proof understanding, model selection, and interpreting AI-generated results (Gabriel *et al*., 2025) [12]. In computing, AI code generators like GitHub Copilot can write code from plain English [13] [14], shifting the emphasis to writing precise specifications, analyzing algorithmic complexity, and considering software ethics. In engineering, generative-design algorithms explore vast design spaces to optimize structures [15] [16], requiring engineers to emphasize systems integration, human-centered design, and risk management. We conclude with pedagogical and policy recommendations: curricula should emphasize AI-augmented critical thinking and ethics; teachers need training in AI literacy and bias recognition [17] [18]; equity initiatives must ensure all students gain AI skills to avoid a new digital divide (UNESCO, 2024; Gonzales, 2024) [19] [20]; and accreditation standards should embed AI competencies across STEM degrees. By prioritizing human interpretive agency, education can prepare citizens to shape rather than be shaped by algorithmic change.

Introduction

The First Industrial Revolution (circa 1760–1840) transformed labor with steam power and mechanization, creating factories that required literate, disciplined workers. In response, governments enacted compulsory mass schooling so citizens could operate machines and participate in the industrial economy (Davis, 2024) [1]. Similarly, today's AI revolution is redefining knowledge work. Modern machine-learning systems can generate coherent text, predict molecular structures, and analyze massive datasets far faster than humans [21] [22]. These advances present a **critical choice for education**: do we allow learners to become passive "consumers" of AI outputs, or do we cultivate **interpretive agency**, training them to use AI with judgment and insight?

The economic impact of AI rivals that of the Industrial Revolution. For instance, Columbia Business School research finds that AI and big-data tools may be "almost as transformative to the economy as the Industrial Revolution" [23]. In finance, AI adoption has already shifted income and labor patterns similarly to historical industrial shifts [24]. The labor market increasingly demands AI collaboration skills: workers adding AI expertise can increase their earnings substantially [25]. Just as basic literacy became foundational for the industrial age, **AI literacy** – the ability to understand and responsibly use AI – is becoming a basic 21st-century competency (Milberg, 2025) [26]. Education systems must therefore evolve. This paper examines the needed pedagogical transformation by drawing historical lessons and exploring STEM disciplines one by one.

Historical Echoes: From Steam Power to Algorithmic Power

Nineteenth-century school reforms offer a useful analogy. British policymakers, for example, passed the 1870 Elementary Education Act, mandating free schooling for children to ensure a trained workforce [1]. Education became nearly universal as governments recognized literacy and numeracy as economic necessities. Davis (2024) notes that "formal education became accessible even to the poorest people" in this era, teaching basic skills needed by factories [1]. Mandatory schooling was not altruistic: it was seen as vital for national competitiveness in an age of machines and mass production.

Today, the industries of the future likewise demand that graduates not only be able to use AI tools, but also to understand their inner workings and societal impacts. UNESCO and other organizations now emphasize that *all* students – not just computer science majors – should attain AI awareness (UNESCO, 2024) [27] [26]. UNESCO's new competency frameworks call for education systems to equip learners with the "knowledge, skills and attitudes" to engage with AI thoughtfully and ethically [27] [26]. In effect, just as nineteenth-century economies required universal literacy, twenty-first-century economies will likely require universal AI literacy. Students will need to know when AI can help, when it can mislead, and how to collaborate with these tools.

Two Future Modes of Cognition

We conceptualize two broad modes of thinking in an AI-rich age. These are **algorithmic reliance** versus **interpretive agency**.

- **Algorithmic reliance.** This mode describes learners who treat AI outputs as authoritative answers. When over-reliant, individuals tend to take the fastest available solution, favoring convenience over understanding. Research on AI dialogue systems shows that uncritical acceptance of AI recommendations can impair students' cognitive skills. For example, Zhai, Wibowo, and Li (2024) find that users who **"accept AI-generated recommendations without question"** often make more errors and lean on cognitive shortcuts [2] [3]. Over-reliance encourages heuristic thinking at the expense of deep reasoning: students may stop engaging with the material, simply clicking "accept" on the AI's answer. This raises serious concerns. If education cedes too much agency to machines, students risk losing the ability to analyze or critique information. Indeed, the literature warns that heavy dependence on AI in classrooms **"could hinder students' critical thinking abilities."** [7] AI-literate societies need to guard against this passive mode of learning.

- **Interpretive agency.** In contrast, interpretive agency describes a balanced mindset in which learners view AI as a tool – a collaborator – but remain the final arbiters of truth. Learners with interpretive agency ask probing questions about AI output: *What data was this model trained on? What biases might it have? How would I verify this result?* They might use AI to draft solutions, but then manually check the reasoning or adapt it. For instance, Walter (2024) argues that beyond merely using AI, students must gain prompt-engineering skills and critical literacy so they "can approach problems from different perspectives, analyze information critically, and develop solutions creatively" [4] [28]. The World Economic Forum likewise emphasizes that education should teach students **"the critical thinking skills to evaluate [AI] outputs"** and the **"ethical grounding to question its role in society."** [26] In short, interpretive agency means prioritizing human judgment. When students recognize both the power and limitations of AI, they become empowered to steer technology rather than be steered by it.

Educational systems should aim to foster interpretive agency. This requires not only technical training, but also epistemic reflection. For example, integrating AI in the classroom should come with curricula that highlight AI's biases and hallucinations so students learn *not* to trust blindly (Walter, 2024) [4] [18]. Instructors can model this by using AI-generated drafts as class exercises: students critique and improve them. Such practice builds the mindset that the machine's answer is provisional. Policymakers are already stressing this shift. UNESCO's AI Literacy Framework calls for teaching students to understand AI's **"potential as well as risks"** and to engage with AI in "a safe, ethical and responsible manner" [29]. In short, like the shift from rote learning to critical pedagogy in earlier educational reforms, today's shift is toward an AI-informed critical pedagogy.

The Future of STEM Education

AI is transforming STEM fields rapidly. Below we outline how each discipline is affected and how curricula should adapt. In each case, the key is to move from rote tasks (now handled by AI) to higher-order skills: conceptual understanding, creativity, and ethics.

STEM Field	AI Capabilities	New Emphasis in Education
Physics	AI tutors and virtual labs solve complex problems, perform simulations, and visualize fields in real time [6]. Machine learning can analyze experimental data and even discover new physical laws.	Focus on *physical intuition* and conceptual grasp: Students should generate hypotheses, interpret simulations, and validate AI predictions. Emphasize understanding why equations work, not just computing solutions [6] [7].
Biology	AI (e.g. AlphaFold) predicts protein structures to near-experimental accuracy [8]; deep learning classifies biomedical images with high accuracy [22]; and robotic "self-driving" labs autonomously run experiments [9].	Focus on *experimental design* and *systems thinking*: Learners should design meaningful experiments, understand complex biological interactions, and evaluate AI-driven results. Ethics and bioethics become critical: students must consider data privacy and equity in genomic and medical applications.
Chemistry	AI proposes synthetic routes (retrosynthesis), predicts reaction outcomes, and screens large compound libraries [10]. Gaussian and other AI-enhanced tools can compute molecular properties instantly.	Focus on *mechanistic reasoning* and *sustainability*: Instead of hand-solving titrations, emphasize understanding reaction mechanisms and principles. Safety and green chemistry become priorities: e.g. use AI to design syntheses that minimize waste and hazard [11]. Critical thinking about environmental impact replaces rote lab work.
Mathematics	Large language models and computer-algebra systems can carry out calculus, algebra, and even proofs on demand. Routine problem-solving and computations are trivialized by AI.	Focus on *proof construction*, *model selection*, and *interpretation*: Students should learn how to formulate and check proofs, choose appropriate mathematical models, and critically analyze any AI-generated solution. As Gabriel et al. (2025) argue, education must shift from producing correct answers ("products") to developing deep understanding ("processes") of mathematical concepts [12]. Address socio-emotional aspects like math anxiety so learners remain engaged.
Computer Science	Generative AI tools (e.g., GitHub Copilot, ChatGPT) can write code from descriptions, debug, and even explain code [13] [14]. AI can auto-generate documentation and examples.	Focus on *problem decomposition* and *specification*: Teach students to write clear task specifications and prompts for AI [30] [14]. Emphasize algorithmic complexity and efficiency over syntax. Debugging and code evaluation skills become vital: students must verify and refine AI-generated code rather than write everything from scratch [14]. Also cover socio-technical ethics and data privacy issues as core topics [31].

STEM Field	AI Capabilities	New Emphasis in Education
Engineering	Generative-design algorithms explore thousands of configurations to optimize weight, strength, and cost [15]. AI-driven simulation can test designs under myriad conditions rapidly.	Focus on *systems integration* and *human-centered design*: Students should learn to integrate subsystems, consider manufacturability, and prioritize user needs. Risk assessment and safety engineering are crucial human roles. For instance, while AI may suggest an optimal shape, engineers must evaluate if it meets real-world constraints. Emphasize creative design thinking and sustainability (e.g., green materials) over repetitive calculation.

Across these fields, AI excels at computational and data-driven tasks, leaving the human role to define problems, interpret results, and consider broader implications. The above table illustrates how each STEM area can adapt: by prioritizing conceptual mastery, creativity, ethical reasoning, and other human-centric skills.

Discipline Highlights

- **Physics:** AI-driven platforms (like AI tutors or virtual labs) now enable students to experiment with electromagnetic fields or differential equations interactively [6]. As Shafiq *et al.* (2025) note, tools such as ChatGPT combined with physics simulations can **"present students with hands-on opportunities to experience interaction and thus manifest intuition about abstract concepts."** [6]. However, they caution that these tools can't replace human reasoning: "heavy reliance on AI tools could hinder students' critical thinking abilities." [7]. Accordingly, physics education should emphasize *deriving* formulas and testing when simulations break down. Instructors might give students AI-generated solutions and ask them to find and correct flaws, reinforcing experimental validation.

- **Biology:** Modern biology labs use AI for pattern recognition and prediction. For example, DeepMind's AlphaFold predicts protein 3D structures from amino acid sequences with near-experimental accuracy [8], and convolutional neural networks can detect diseases in imaging faster than clinicians [22]. Fully autonomous "self-driving" laboratories combine robotics with AI to plan and run entire experimental cycles [9]. Human learners, however, must focus on *experimental design* – deciding which experiments to run and how to interpret AI suggestions. Systems thinking is key: understanding how genes, proteins, and environmental factors interrelate (Pulipati *et al*., 2024). Ethical considerations (e.g., genetic privacy, lab automation ethics) become part of scientific literacy. For instance, when AI suggests an experiment, students should ask about data bias or unintended consequences (Cizauskas *et al*., 2025).

- **Chemistry:** In synthetic chemistry, AI tools can propose reaction pathways and screen thousands of catalysts, tasks once done by chemists manually [10]. AI can predict molecule properties or suggest greener solvents. Chemical education thus shifts away from mechanical lab work toward understanding *why* molecules behave as they do. Instructors should highlight chemical mechanisms, safety protocols, and environmental impact. A recent review emphasizes AI's role in "optimizing chemical processes to minimize environmental impact," from waste reduction to sustainable catalysts [11]. Chemistry curricula can use case studies where students must choose the greenest synthesis route, using AI suggestions as data but making the final judgment themselves.

- **Mathematics:** The routine arithmetic and algebraic manipulations that once filled textbooks are now instant for computers. Consequently, math instruction is moving toward topics AI can't easily replicate: proof writing, abstract reasoning, and interpreting results. As Gabriel *et al*. (2025) argue, educational research should shift focus from grading "products" (e.g. correct homework solutions) to understanding learning *processes*, such as overcoming math anxiety and fostering resilience [12]. AI should be used to *support* insight: for example, a student might use an AI tutor to check a proof outline, then refine it by hand. When AI gives an answer, students should be encouraged to question it. In practice, this means more open-ended projects and collaborative problem-solving where method matters as much as answer.

- **Computer Science:** Generative AI tools like GitHub Copilot can now write code from natural-language prompts [13]. An example of the impact: intro programming problems that used to be solved by students manually are now easily handled by AI, raising concerns that novices might "use new tools in ways that limit learning" [32]. Educators suggest pivoting to new learning goals. Denny *et al*. (2024) recommend tasks where students write *problem specifications* for AI, honing their ability to formulate clear requirements [30]. Students can focus on debugging, refactoring, and verifying code rather than typing every line. They also emphasize teaching algorithmic complexity and ethical issues: students should estimate an AI-generated algorithm's efficiency and reflect on data bias or privacy in software. The ultimate goal is *code literacy*: understanding what the code does and how it was generated, not just that it works [14] [31].

- **Engineering:** In design and optimization, AI-driven generative-design software (e.g. Autodesk Fusion) can automatically generate and evaluate thousands of design variants given high-level goals [15]. For example, Fusion 360 recently redesigned an auto-seat bracket to be 40% lighter and 20% stronger than the original [16]. While powerful, such tools must be used with human oversight: engineers must still define functional requirements and manufacturing constraints. Consequently, engineering programs should reinforce *systems integration* and *human-centered design*. Students should practice connecting components, validating AI suggestions against real-world constraints (like safety standards), and considering user needs. Skills in risk management become critical: for instance, after AI generates a lightweight structural design, engineers must ask if it can withstand unexpected loads. Ethical and sustainability principles (e.g., lifecycle analysis) should be integrated, since AI may optimize a design without accounting for ecological impact. In short, as AI explores possibilities, engineers focus on which possibilities make sense.

Pedagogical and Policy Implications

The above transformations imply broad shifts in education. We outline key recommendations for curricula, teaching practice, equity, and accreditation:

- **Curriculum Design:** Assessment should move away from only checking procedural accuracy. Instead, tasks should require conceptual synthesis, argumentation, and ethical reasoning. For example, instead of timed algorithm drills, math exams might ask students to critique different solution methods or connect mathematical ideas to real problems. Across STEM, projects can require students to explain or improve AI outputs. UNESCO and the World Economic Forum emphasize embedding AI literacy (including bias and ethics) across subjects [29] [26]. In practice, this means incorporating AI-related questions into existing courses and adding new modules on data ethics or algorithmic bias. For instance, a chemistry lab might include an exercise where students compare an AI-suggested synthesis plan against safety and sustainability criteria (Pulipati *et al*., 2024).

- **Teacher Role:** Instructors become guides in the age of AI. They must model critical engagement with technology, not simply provide answers. This demands extensive professional development. Walter (2024) highlights that **educator training in AI technologies is crucial**, including skills like prompt engineering and recognizing AI bias [17] [18]. Ongoing support and communities of practice can help teachers stay current with AI tools. For example, teachers might learn to use an AI tutor in class, then debrief on its mistakes. Education programs should build teachers' confidence so they can facilitate interpretive agency: helping students debug AI outputs, pose good follow-up questions, and understand the limits of automation. UNESCO similarly stresses that effective AI integration requires preparing educators, not just students (UNESCO, 2024) [29].

- **Equity and Access:** Universal access to AI tools is essential to avoid a new digital divide. The rapid diffusion of AI risks widening inequalities: Gonzales (2024) notes an emerging **"AI divide"** where marginalized communities have less exposure to AI and its benefits [19] [20]. Educational equity demands that all students — regardless of background — learn AI skills. Policies should fund AI resources (software, hardware) in under-resourced schools and develop culturally responsive AI curricula. Moreover, fostering interpretive agency is itself an equity issue: we must teach critical AI skills explicitly, so that disadvantaged students don't fall into blind reliance. Initiatives like UNESCO's AI Literacy Framework call for inclusive, locally adapted AI education programs for vulnerable groups [19] [20]. Policymakers should support community-led AI workshops, multilingual AI literacy materials, and partnerships with tech organizations to reach underserved learners.

- **Accreditation and Standards:** Educational accreditation bodies must update competencies to include AI literacy and ethics. Already, frameworks are emerging: the EU's Digital Education Action Plan and AI Act require digital and AI competencies for students and teachers [33]. Accreditation criteria for STEM degrees should mandate coverage of AI-relevant topics (data analysis, algorithmic bias, etc.). For example, the World Economic Forum's AI Literacy Framework outlines domains such as **"Engaging with AI, Creating with AI, Managing AI's actions, and Designing AI solutions"** across disciplines [34]. Universities and schools should integrate these concepts into learning outcomes. Licensing and professional societies (e.g. engineering boards) might require continuing education in AI ethics. In short, quality standards must recognize AI as an integral part of STEM literacy.

These policy measures align with the broader goal of **strengthening human interpretation in education**. Curricula and standards should reward students for showing understanding, not just correct answers, and for ethical judgment alongside technical skill. For instance, an engineering accreditation could count student projects that address AI-driven design problems ethically. By building interpretive agency into our educational policies, we help ensure society develops leaders who can thoughtfully govern AI.

Conclusion

AI is automating much of the rote problem-solving that once defined STEM expertise. To keep pace, education must elevate the human dimension of learning: critical thinking, creativity, and ethical judgment.

In an AI-powered future, humans should be **architects of knowledge**, guiding questions and values, while AI serves as a sophisticated assistant. This requires a paradigm shift mirroring that of the industrial age: we are moving from teaching *what* to think (now easily done by machines) to teaching *how* to think. Research consensus underscores this transition: Walter (2024) identifies **AI literacy, prompt engineering, and critical thinking** as the three core skills for future education [35], and the World Economic Forum emphasizes that learners need the "human skills that AI can't replicate" – empathy, judgment, and collaboration [36].

By redesigning STEM curricula to focus on interpretive agency, training teachers accordingly, and ensuring equitable access to AI education, we can turn the AI revolution into an opportunity. The goal is clear: produce graduates who harness AI's power **creatively and responsibly**. As Davis (2024) reflects on the past revolution, compulsory schooling ultimately helped societies adapt to new machines [1]. Today, a similarly bold educational vision is needed – one that teaches not just how to use AI, but how to oversee it. In doing so, we can help humanity remain in the driver's seat of technological progress rather than in the back seat.

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