Intelligence Unleashed

An argument for AI in Education

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Open Ideas at Pearson
Sharing independent insights on the big, unanswered questions in education

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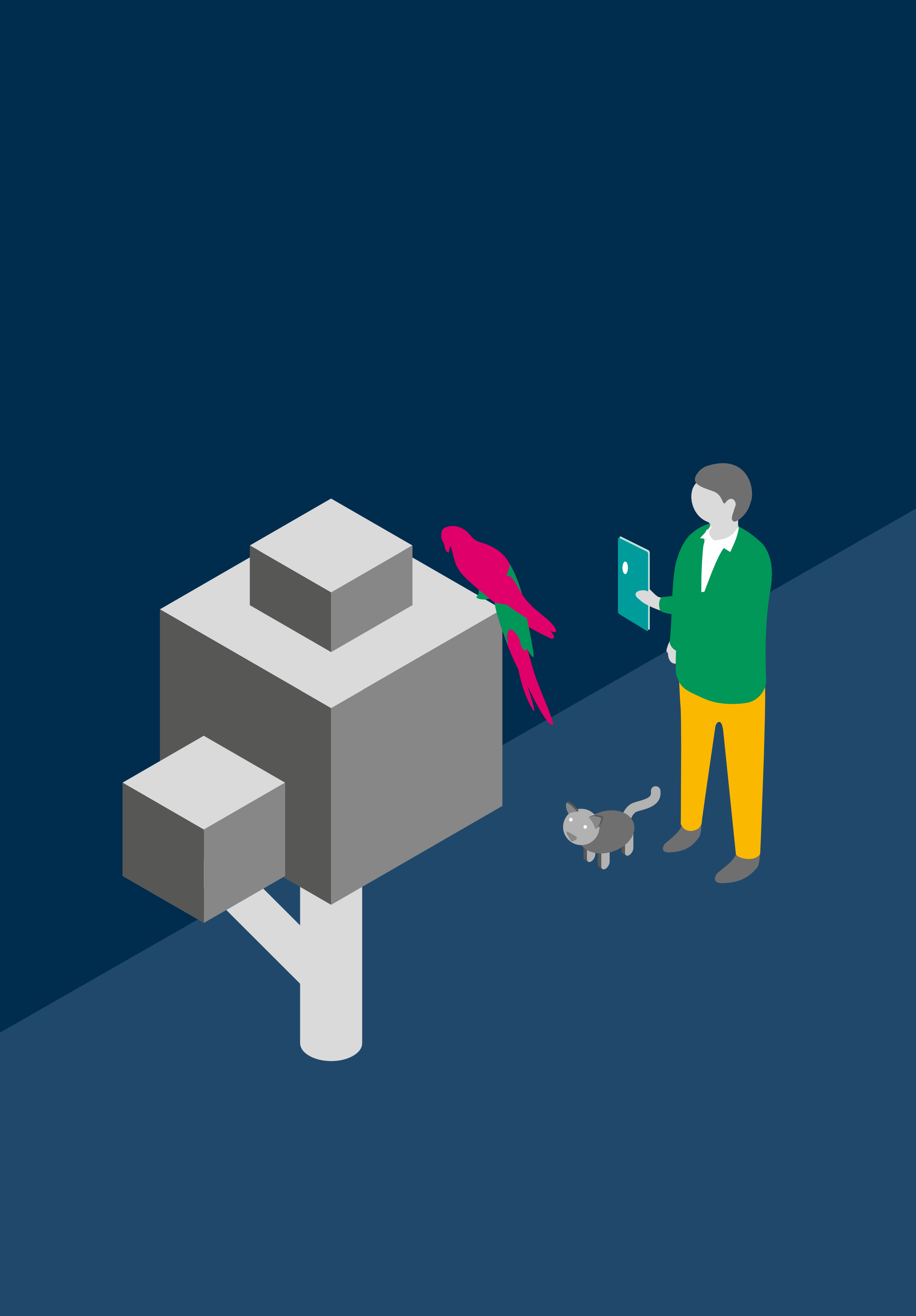

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Foreword by Sir Michael Barber

For thirty years I have attended conferences where speakers have spoken to slides comparing images of an early 20th century classroom with one from today, and have pointedly asked: 'why so little change?' The modern variant goes something like this: smart technologies have already transformed so many parts of our lives – from how we date to how we book a taxi. It would seem that there is no doubt that AI will also significantly influence what we teach and learn, as well as how we do it. And yet...

Adopting a puzzled stance as to why things have not changed more has some value. It prompts us to examine our assumptions, our habits, and our routines. It only takes us so far, though. More is needed.

What we need – what we should demand – is an explanation of why and how things could be different. First, we need to be empowered by an understanding of what artificial intelligence in education (AIEd) is, what it delivers, and how it goes about doing that.

Second, we need a clear explanation of how the field of artificial intelligence can connect to the core of teaching and learning, so that we can avoid general-purpose technologies being used in ways that do not deliver the step changes in learner outcomes we seek. For example, smart technologies that adapt to what is liked, rather than what is learnt, or that deliver more efficient administration, but not more efficient learning.

Third, we need concrete options that will allow us to make the potential of AIEd real at the system level – that is, at the scale that will allow it to support the teaching profession broadly and impact positively on the learning experience of each and every student. And fourth, we need to ask and answer some profound ethical questions – for example, about the acceptable uses that can be made of the data that AIEd collects.

In other words, what we need is a degree of specificity about AIEd that allows us to assess, invest, plan, deliver, and test. This is what this paper offers – a useful primer on AIEd and a compelling argument about what it can offer learning.

From what AI is and how AIEd-driven learning systems are built, onto its potential role in addressing the profound issue of robots and machines taking over more and more current jobs, it covers a vital range of topics with ease and elegance. It is also a good read, with entertaining references from Pac-Man and Stephen Hawking, sci-fi and ancient philosophy. And, yes, it is understandable to a non-technical reader!

To make my own case for reading this paper, let me move to a more local, anecdotal, level. Recently a member of my Pearson team talked to me about a phonics learning app he had bought for his young son. We could easily identify the affordances that the technology brought – perfect pronunciation of 42 phonics sounds, infinite patience, and a healthy spillover of engagement from the software to learning.

Yet, it was equally easy to identify ways in which some basic AIEd techniques could have made the app so much better. Content was re-presented even after it had been mastered, which led to boredom. Other content was accessible even though it was much too difficult, leading to frustration. And there were no speech recognition capabilities present to verify the learner's pronunciation, or blending of sounds.

Asking for these features is not asking for science fiction. Instead, it is asking us to incorporate findings from fields like the learning sciences into AIEd tools so that these insights are realised in cheaper, more effective ways. This paper offers a long-list of where we should look for this combination of learning insights and technology – for example, collaborative learning, meta-cognition (or knowing about one's own thinking), useful feedback, and student motivation.

Funders and founders, policy makers and philanthropists – in fact, anyone who takes seriously the urgent need to embark on the next stage of education system reform – should read and debate this paper. Only then will we (finally) make good on the promise of smarter technologies for learning (and, as a side effect, get rid of those boring slides).

Introduction

We wrote this short paper on artificial intelligence in education (AIEd) with two aims in mind. The first was to explain to a non-specialist, interested reader what AIEd is: its goals, how it is built, and how it works. After all, only by securing a certain degree of understanding can we move beyond the science-fiction imagery of AI, and the associated fears. The second aim was to set out the argument for what AIEd can offer learning, both now and in the future, with an eye towards improving learning and life outcomes for all.

Throughout, our approach has been to start with teaching and learning – and then describe how well designed and thoughtful AIEd can usefully contribute. Crucially we do not see a future in which AIEd replaces teachers. What we do see is a future in which the role of the teacher continues to evolve and is eventually transformed; one where their time is used more effectively and efficiently, and where their expertise is better deployed, leveraged, and augmented.

Although some might find the concept of AIEd alienating, the algorithms and models that comprise AIEd form the basis of an essentially human endeavour. AIEd offers the possibility of learning that is more personalised, flexible, inclusive, and engaging. It can provide teachers and learners with the tools that allow us to respond not only to what is being learnt, but also to how it is being learnt, and how the student feels. It can help learners develop the knowledge and skills that employers are seeking, and it can help teachers create more sophisticated learning environments than would otherwise be possible. For example, AIEd that can enable collaborative learning, a difficult task for one teacher to do alone, by making sure that the right group is formed for the task-at-hand, or by providing targeted support at just the right time.

We look towards a future when extraordinary AIEd tools will support teachers in meeting the needs of all learners. Drawing on the power of both human and artificial intelligence, we will lessen achievement gaps, address teacher retention and development, and equip parents to better support their children's (and their own) learning. Importantly, doing this will require much more than borrowing the language of AI – we need to go deep, harnessing the power of genuine AIEd, and then working to apply it in real-life contexts at scale.

True progress will require the development of an AIEd infrastructure. This will not, however, be a single monolithic AIEd system. Instead, it will resemble the marketplace that has developed for smartphone apps: hundreds and then thousands of individual AIEd components, developed in collaboration with educators, conformed to uniform international data standards, and shared with researchers and developers worldwide. These standards will enable system-level data collation and analysis that help us learn much more about learning itself and how to improve it.

If we are ultimately successful, AIEd will also contribute a proportionate response to the most significant social challenge that AI has already brought – the steady replacement of jobs and occupations with clever algorithms and robots. It is our view that this phenomena provides a new innovation imperative in education, which can be expressed simply: as humans live and work alongside increasingly smart machines, our education systems will need to achieve at levels that none have managed to date.

Our response, we argue, should be to take on the role of metaphorical judo masters. That is, we should harness the power and strength of AI itself. In that way we can help teachers to equip learners – whatever their age – with the knowledge and flexible skills that will allow them to unleash their human intelligence and thrive in this re-shaped workforce.

To be candid, the impetus for this paper arose from our impatience with the status quo. Despite nearly three decades of work, AIEd is in many ways still a cottage industry, and the benefits and enormous potential of the field remain mostly unrealised. Sadly, many of the best ideas in AIEd currently make it no further than the lab, or perhaps a lecture hall. AIEd is hampered by a funding system that encourages siloed research, and that shies away from dealing with the essential messiness of education contexts. We believe this needs to change.

This is our attempt at contributing to that change, through explaining, arguing, and putting forward some evocative, and perhaps provocative, views of the future. It is our hope that this paper will provide a deeper understanding of AIEd, and stimulate a much-needed debate.

Let us start by introducing AI.

What is Artificial Intelligence (AI)?

It can be difficult to define artificial intelligence (AI), even for experts. One reason is that what AI includes is constantly shifting. As Nick Bostrom, a leading AI expert from Oxford University, explains: "[a] lot of cutting edge AI has filtered into general applications, often without being called AI because once something becomes useful enough and common enough it is not labeled AI anymore."[1] Instead, it is considered a computer program, or an algorithm, or an app, but not AI.

Another reason for the difficulty in defining AI is the interdisciplinary nature of the field. Anthropologists, biologists, computer scientists, linguists, philosophers, psychologists, and neuroscientists all contribute to the field of AI, and each group brings their own perspective and terminology.

For our purposes, we define AI as computer systems that have been designed to interact with the world through capabilities (for example, visual perception and speech recognition) and intelligent behaviours (for example, assessing the available information and then taking the most sensible action to achieve a stated goal) that we would think of as essentially human.[2]

The use of AI in our day-to-day life is increasing ever more rapidly. For example, AI scientists are currently building on new approaches in machine learning, computer modelling, and probability statistics to improve financial decision making[3], and are using decision theory and neuroscience to drive the development of more effective medical diagnostics.[4] And with the recent launch of OpenAI, a non-profit artificial intelligence research company with an initial investment of $1B, we expect this acceleration to continue apace – including, we predict, in the area of AIEd.[5]

ALGORITHM
A defined list of steps for solving a problem. A computer program can be viewed as an elaborate algorithm. In AI, an algorithm is usually a small procedure that solves a recurrent problem.

MACHINE LEARNING
Computer systems that learn from data, enabling them to make increasingly better predictions.

DECISION THEORY
The mathematical study of strategies for optimal decision-making between options involving different risks or expectations of gain or loss depending on the outcome.

Will AI take over from humans?

Some in the scientific community worry that AI is a Pandora's box with dangerous consequences. As far back as 1993, the computer scientist Vernon Vinge popularised the notion of the *singularity*, the point at which an AI-powered computer or robot becomes capable of redesigning and improving itself or of designing AI more advanced than itself. Inevitably, it is argued, this will lead to AI that far exceeds human intelligence, understanding, and control, and to what Vinge describes as the end of the human era.[6] More recently, Stephen Hawking and other leading scientists including Stuart Russell, Max Tegmark, and Frank Wilczek have also warned us about the potential downsides of AI becoming too clever.[7]

This worrying idea has fed Hollywood films for decades, from *2001: A Space Odyssey* in the 60s, the *Terminator* series of the 80s, and the more recent *Transcendence* – all of which depict one version or another of a dystopian world dominated by out-of-control AI.

Before we get too worried, however, it is worth making a note about the current capabilities of artificial intelligence. Major advances in 'general AI', AI that that could successfully perform *any* intellectual task that a human being could, would be necessary for any singularity to occur. And right now, general AI does not exist.

General AI is very different from the "domain specific AI" most of us are familiar with. These domain specific AIs focus on one thing – for example, mastering chess (Deep Blue or Giraffe), or Go (Google's Deep Mind), driving a car (Google's self-driving cars), or recognising a passport photograph as a representation of a particular person. Even for leading AI advocates, the singularity appears to be due to arrive at some ever-receding future date, usually around thirty years from the time they are writing![8]

However, AI *is* getting more sophisticated, and it is already having a profound impact on our economy. In a 2013 study, the economists Frey and Osborne used AI techniques themselves to begin the task of identifying the effects of automation on the jobs market. According to their estimates about 47 percent of current US jobs are at high-risk of being carried out by machines in the next decade or two.[9] To date, it is middle-income jobs that have been most affected, reflecting the tasks that are currently most susceptible to automation.[10]

Past waves of profound changes in the economy (for example, the move from an agricultural driven economy to an industrial one) have been accommodated by changing the reach and the nature of education and learning.

The understandable guiding thought has been that if "workers have flexible skills and if the educational infrastructure expands sufficiently, [then] ... the race between technology and education will not be won by either side and prosperity will be widely shared."[11]

Whether this will hold true in the face of rapidly developing AI is contested. An historical view provides evidence that technological change has always brought with it a host of new roles that we could not have previously predicted or imagined. Others, like Martin Ford, believe that as automation takes over more and more sophisticated tasks, the number of jobs will be simply too small to sustain current employment rates.[12]

We take an optimistic stance that aligns with the historical view. We also believe that AIEd has a major role to play in helping us prepare for the new roles that the economy will create – a topic we return to later in this paper.

A brief introduction to Artificial Intelligence in Education (AIEd)

The application of artificial intelligence to education (AIEd) has been the subject of academic research for more than 30 years. The field investigates learning wherever it occurs, in traditional classrooms or in workplaces, in order to support formal education as well as lifelong learning. It brings together AI, which is itself interdisciplinary, and the learning sciences (education, psychology, neuroscience, linguistics, sociology, and anthropology) to promote the development of adaptive learning environments and other AIEd tools that are flexible, inclusive, personalised, engaging, and effective.

At the heart of AIEd is the scientific goal to *"make computationally precise and explicit forms of educational, psychological and social knowledge which are often left implicit."*[13] In other words, in addition to being the engine behind much 'smart' ed tech, AIEd is also a powerful tool to open up what is sometimes called the 'black box of learning,' giving us deeper, and more fine-grained understandings of how learning actually happens (for example, how it is influenced by the learner's socio-economic and physical context, or by technology).

These understandings may then be applied to the development of future AIEd software and, importantly, can also inform approaches to learning that do not involve technology. For example, AIEd can help us see and understand the micro-steps that learners go through in learning physics, or the common misconceptions that arise.[14] These understandings can then be used to good effect by classroom teachers.

As we have said, AI involves computer software that has been programmed to interact with the world in ways normally requiring human intelligence. This means that AI depends both on knowledge about the world, and algorithms to intelligently process that knowledge.

This knowledge about the world is represented in so called 'models'. There are three key models at the heart of AIEd: the pedagogical model, the domain model, and the learner model.

Take the example of an AIEd system that is designed to provide appropriate individualised feedback to a student. Achieving this requires that the AIEd system knows something about:

- Effective approaches to teaching (which is represented in a pedagogical model)
- The subject being learned (represented in the domain model)
- The student (represented in the learner model)

Examples of the specific knowledge that might be integrated into each of these models is displayed opposite.

ADAPTIVE LEARNING ENVIRONMENTS
A digital learning environment that adapts teaching and learning approaches and materials to the capabilities and needs of individual learners.

MODELS
These represent something from the real world in a computer system or process, to assist calculations and predictions.

AIEd models	What the model represents	Examples of specific knowledge represented in AIEd models
Pedagogical model	The knowledge and expertise of teaching	'Productive failure' (allowing students to explore a concept and make mistakes before being shown the 'right' answer)
		Feedback (questions, hints, or haptics), triggered by student actions, which is designed to help the student improve their learning
		Assessment to inform and measure learning
Domain model	Knowledge of the subject being learned (domain expertise)	How to add, subtract, or multiply two fractions
		Newton's second law (forces)
		Causes of World War I
		How to structure an argument
		Different approaches to reading a text (e.g. for sense or for detail)
Learner model	Knowledge of the learner	The student's previous achievements and difficulties
		The student's emotional state
		The student's engagement in learning (for example: time-on-task)

To delve deeper into just one of these examples, learner models are ways of representing the interactions that happen between the computer and the learner. The interactions represented in the model (such as the student's current activities, previous achievements, emotional state, and whether or not they followed feedback) can then be used by the domain and pedagogy components of an AIEd programme to infer the success of the learner (and teacher). The domain and pedagogy models also use this information to determine the next most appropriate interaction (learning materials or learning activities). Importantly, the learner's activities are continually fed back into the learner model, making the model richer and more complete, and the system 'smarter'.

HAPTICS
Any form of interaction involving touch. In the case of AIEd, this could be something like a smartphone vibration in response to a correct answer.

So, what would a piece of education technology driven by AIEd look like? *Figure 1* (shown opposite) is a simplified picture of a typical model-based adaptive tutor. It is based on the three core models as described above: the learner model (knowledge of the individual learner), the pedagogy model (knowledge of teaching), and the domain model (knowledge of the subject being learned and the relationships between the different parts of that subject matter). AIEd algorithms (implemented in the system's computer code) process that knowledge to select the most appropriate content to be delivered to the learner, according to their individual capabilities and needs.

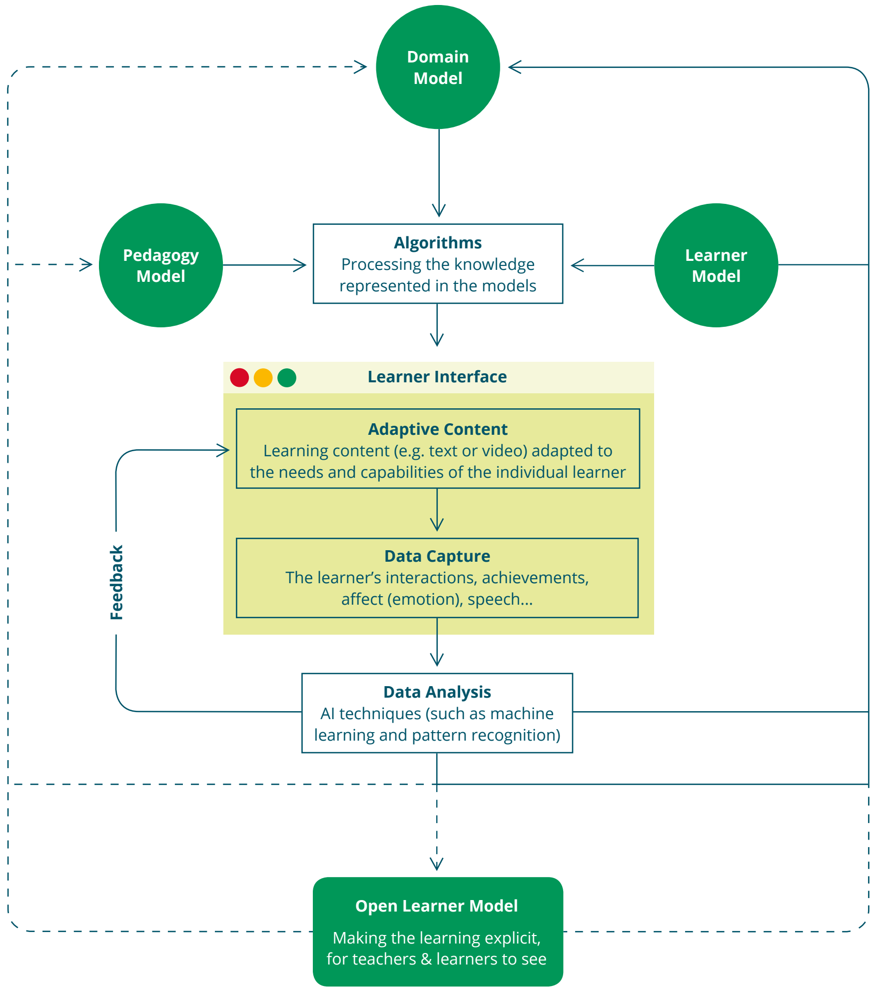
While this content (which might take the form of text, sound, activity, video, or animation) is being delivered to the learner, continuous analysis of the learner's interactions (for example, their current actions and answers, their past achievements, and their current affective state) informs the delivery of feedback (for example, hints and guidance), to help them progress through the content they are learning.

Deep analysis of the student's interactions is also used to update the learner model; more accurate estimates of the student's current state (their understanding and motivation, for example) ensures that each student's learning experience is tailored to their capabilities and needs, and effectively supports their learning.

Some systems include so-called Open Learner Models, which present the outcomes of the analysis back to the learners and teachers. These outcomes might include valuable information about the learner's achievements, their affective state, or any misconceptions that they held. This can help teachers understand their students' approach to learning, and allows them to shape future learning experiences appropriately. For the learners, Open Learner Models can help motivate them by enabling them to track their own progress, and can also encourage them to reflect on their learning.

One of the advantages of adaptive AIEd systems is that they typically gather large amounts of data, which, in a virtuous circle, can then be computed to dynamically improve the pedagogy and domain models. This process helps inform new ways to provide more efficient, personalised, and contextualised support, while also testing and refining our understanding of the processes of teaching and learning.

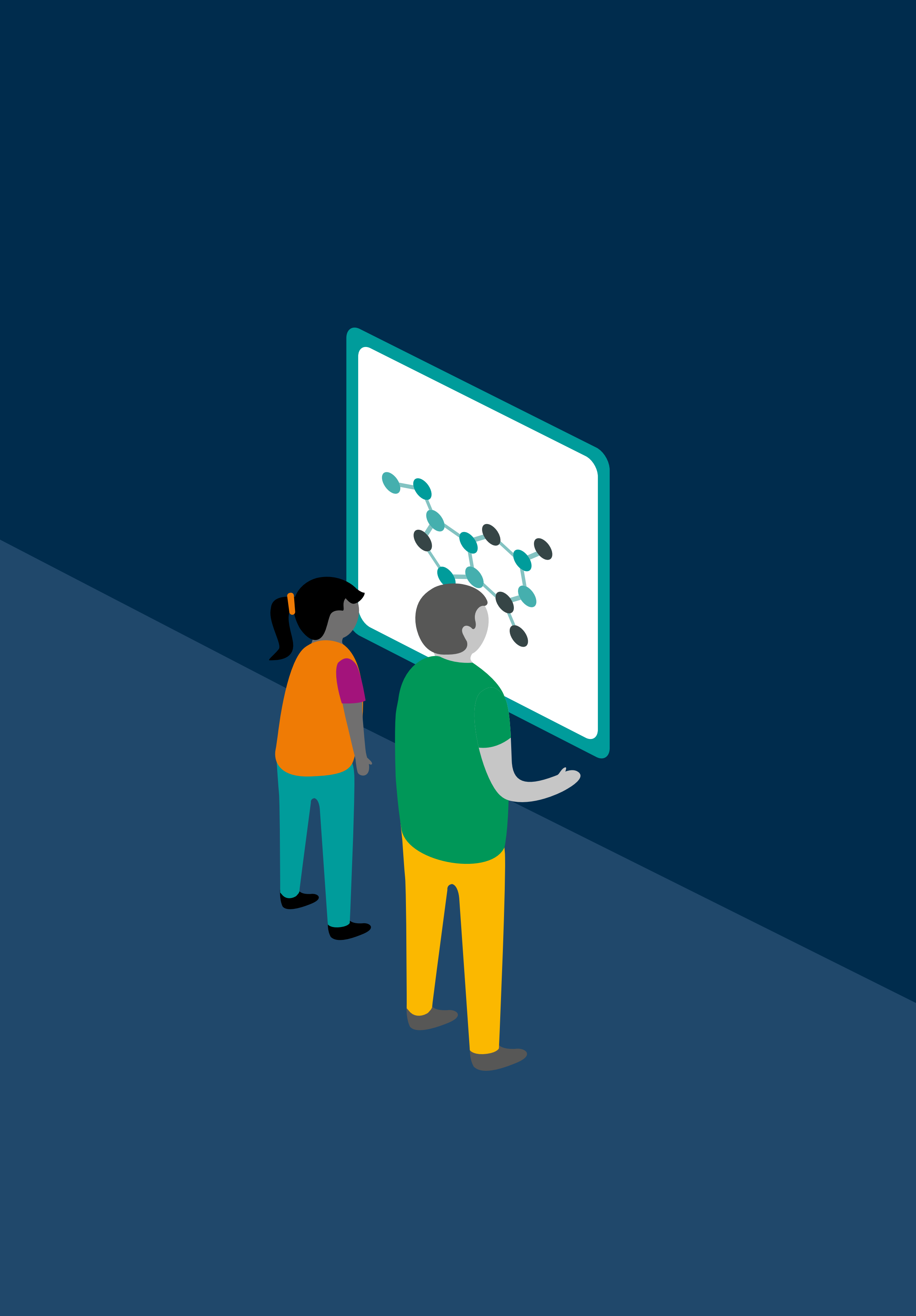
Figure 1
AIEd system showing a simplified picture of a typical model-based adaptive tutor.



In addition to the learner, pedagogical, and domain models, AIEd researchers have also developed models that represent the social, emotional, and meta-cognitive aspects of learning. This allows AIEd systems to accommodate the full range of factors that influence learning.

Taken together, this set of increasingly rich AIEd models might become the field's greatest contribution to learning.

META-COGNITIVE
Metacognition is sometimes defined simply as 'knowing about one's thinking'. It has two elements: being aware of thinking and being able to control or regulate it.



What AIEd can offer learning right now

A multitude of AIEd-driven applications are already in use in our schools and universities. Many incorporate AIEd and educational data mining (EDM) techniques to 'track' the behaviours of students – for example, collecting data on class attendance and assignment submission in order to identify (and provide support) to students at risk of abandoning their studies.

EDUCATIONAL DATA MINING
The development and use of methods to analyse and interpret the 'big data' that comes from computer-based learning systems and from school, college, or university administrative and management systems.

Other AI researchers are exploring novel user interfaces, such as natural language processing, speech and gesture recognition, eye-tracking, and other physiological sensors, which could be used to augment both AIEd and non-AIEd software.

Here, however, we focus on three categories of AIEd software applications that have been designed to support learning most directly: personal tutors for every learner, intelligent support for collaborative learning, and intelligent virtual reality.

AIEd can provide an intelligent, personal tutor for every learner

One-to-one human tutoring has long been thought to be the most effective approach to teaching and learning (since at least Aristotle's tutoring of Alexander the Great!) Unfortunately, one-to-one tutoring is untenable for all students. Not only will there never be enough human tutors; it would also never be affordable. All of this begs the question: how can we make the positive impact of one-to-one tutoring available to all learners across all subjects?

This is where Intelligent Tutoring Systems (ITS) come in. ITS use AI techniques to simulate one-to-one human tutoring, delivering learning activities best matched to a learner's cognitive needs and providing targeted and timely feedback, all without an individual teacher having to be present. Some ITS put the learner in control of their own learning in order to help students develop self-regulation skills; others use pedagogical strategies to scaffold learning so that the learner is appropriately challenged and supported.

SCAFFOLD
In the context of education, scaffolding is a teaching method that enables a student to solve a problem, carry out a task, or achieve a goal through the gradual scaling back of outside assistance.

The 1970s brought some of the first AI systems to offer individualised and adaptive instruction. For example BUGGY[15], a ground-breaking system designed to teach basic addition and subtraction, used a model of the possible misconceptions that learners might exhibit in their procedural arithmetic. This 'bug library', effectively the system's domain model, was used to diagnose each error that a student made so that appropriate tutoring could be offered. Initially, it was limited by the bugs that it could recognise, those that had been included in the original code. Over time, additional misconceptions were found and added to the library.

Instead of models, many recent ITS use machine learning techniques, self-training algorithms based on large data sets, and neural networks, to enable them to make appropriate decisions about what learning content to provide to the learner. However, with this approach, it can be difficult to make the rationale for those decisions explicit.

NEURAL NETWORKS
Networks of interconnected data sets, based on a vastly simplified understanding of brain neural networks.

Modern model-based adaptive systems can be far more flexible. They enable the rationale for each decision taken by the system to be made explicit and understandable by humans (and thus potentially applicable to classroom teaching). Throughout the last decade, increasingly sophisticated learner, pedagogy, and domain models have been introduced in numerous adaptive tutors to support the individualisation of learning.

For example, the iTalk2Learn system[16], designed to help young students learn about fractions, used a learner model that included information about the learner's mathematics knowledge, their cognitive needs, their affective (emotional) state, the feedback they had received and their responses to that feedback.

Model-based adaptive tutors can include a range of AIEd tools that:

- Model learners' cognitive and affective states[17]
- Use dialogue to engage the student in Socratic learning experiences, that is learning experiences that involve enquiry and discussion, questioning and answering[18]
- Include open learner models to promote reflection and self-awareness[19]
- Adopt meta-cognitive scaffolding (for example, by providing dynamic help or using a narrative framework) to increase learner motivation and engagement[20]
- Use social simulation models – for example, to enable language learning students to engage more successfully with speakers of their target language by understanding cultural and social norms[21]

AIEd can provide intelligent support for collaborative learning

Research over decades has suggested that collaboration, whether between a pair of students undertaking a project together or a community of students participating in an online course, can foster higher learning outcomes than learning alone.[22] Collaborative learning is effective because it encourages participants to articulate and justify their thinking, to reflect on other explanations, to resolve differences through constructive dialogue, and to build shared knowledge and meaning. Collaborative learning can also enhance motivation; if students care about the group, they become more engaged with the task and achieve better learning outcomes.[23]

However, research also suggests that collaboration between learners does not happen spontaneously.[24] For example, group members might not have the social interaction skills needed to collaborate effectively. This can be especially difficult in the context of online collaborations, where participants rarely meet in person.

This is where AIEd can contribute. Several approaches have been investigated and here we focus on four: adaptive group formation, expert facilitation, virtual agents, and intelligent moderation.

Adaptive group formation

This uses AI techniques and knowledge about individual participants, most often represented in learner models, to form a group best suited for a particular collaborative task. The aim might be to design a grouping of students all at a similar cognitive level and of similar interests, or one where the participants bring different but complementary knowledge and skills.[25]

Expert facilitation

Here models of effective collaboration – known as 'collaboration patterns' – are used to provide interactive support to the collaborating students.[26] These patterns are either provided by the system authors or mined from previous collaborations. For example, AI techniques such as machine learning or Markov modelling have been used to identify effective collaborative problem-solving strategies. These can then be used to train systems to recognise when students are having trouble understanding the concepts that they are sharing with each other, or to provide targeted support of the right form at the right time.

MARKOV MODELLING
An approach used in probability theory to represent randomly changing systems.

They can also show students (and their teachers) how well an individual is contributing to group work, an historically difficult activity to parse and assess.[27]

Intelligent virtual agents

A third approach involves intelligent virtual agents that are introduced into the collaborative process.[28] These AI agents might mediate online student interaction, or simply contribute to the dialogues, by acting as:

- An expert participant (a coach or a tutor)
- A virtual peer (an artificial student at a similar cognitive level to the learner, but one who is capable of introducing novel ideas)
- Someone the participants might themselves teach – for example, the artificial student might hold deliberate misconceptions, or provide alternative points of view to stimulate productive argument or reflection[29]

Intelligent moderation

With large student numbers working in multiple collaborative groups, it can be impossible for a person to make any sense of the large volume of data that the participants are generating in their discussions.

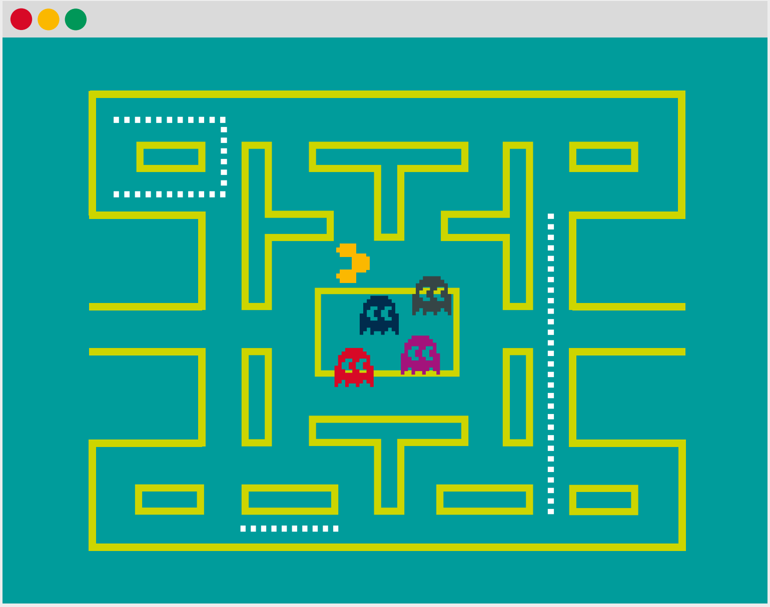
Intelligent moderation uses AI techniques such as machine learning and shallow text processing to analyse and summarise the discussions to enable a human tutor to guide the students towards fruitful collaboration. For example, the system might provide alerts to human tutors to inform them of significant events (such as students going off topic or repeating misconceptions) that may require their intervention or support.[30]

SHALLOW TEXT PROCESSING
A method of text analysis that identifies – but does not 'understand' – particular words.

Intelligent virtual reality to support learning in authentic environments

Artificial intelligence first appeared in a digital game in 1979, when the developers of Pac-Man used a technique known as state machine (transitioning between states depending on conditions) to control whether or not a ghost ran towards or away from a player. The AI in most modern digital games builds on this simple approach. As the game-based story unfolds, autonomous non-player characters (agents) take information from both the game and the player and, based on that information, use AI algorithms to determine the most appropriate actions to take.

Virtual reality for learning works in a similar way. It provides authentic immersive experiences (the subjective impression that one is participating in a realistic experience) that simulate some aspect of the real world to which the user would not otherwise have access (such as dangerous environments or somewhere geographically or historically inaccessible). Research has shown that giving opportunities for students to explore, interact with, and manipulate aspects of a simulated world, perhaps investigating 'what if' scenarios, (such as, 'what if there is a drought?'), enables them to transfer what they have learnt to the real world.[31]

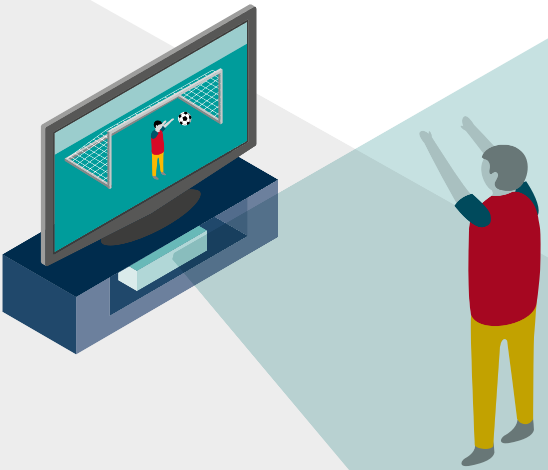


For example, a virtual submarine might allow the user to shrink to a microscopic level to investigate natural processes that occur under the surface of a rock pool, or the student might be able to explore a nuclear power plant, Ancient Rome or the outer planets.

Virtual reality becomes 'intelligent' when it is augmented with artificial intelligence. AI might be used simply to enhance the virtual world, giving it the ability to interact with and respond to the user's actions in ways that feel more natural. Or, drawing on Intelligent Tutoring Systems, AI might also be integrated to provide on-going intelligent support and guidance to ensure that the learner engages properly with the intended learning objectives without becoming confused or overwhelmed.

Virtual pedagogical agents might also be included, acting as teachers, learning facilitators, or student peers in collaborative learning 'quests'. These agents might provide alternative perspectives, ask questions, and give feedback, all based on a properly specified pedagogical model.

Many studies have demonstrated that immersion in intelligent virtual reality can enhance educational outcomes, enabling students to construct their own individual understanding of the world being explored.[32] Some have also been shown to have the potential to release what Chris Dede, a leading learning scientist, calls 'trapped intelligence' – that is, they allow low-achieving students to build their self confidence by shifting their self image from being a poor academic performer to, for example, a successful virtual scientist.[33]



In addition, intelligent synthetic characters in virtual worlds can play roles in settings that are too dangerous or unpleasant for learners. For example, FearNot is a school-based intelligent virtual environment that presents bullying incidents in the form of a virtual drama. Learners, who have been victims of bullying, play the role of an invisible friend to a character in the drama who is bullied. The learner offers the character advice about how to behave between episodes in the drama and, in so doing, explores bullying issues and effective coping strategies.[34]

Intelligent virtual reality can also be used for intelligent team training during which virtual humans are able to reason about individual events, carry out actions, and negotiate options, with the aim of guiding human trainees to make similar assessments – for example in peacekeeping scenarios.[35]

...

Taken together, these three types of applications have been used to create learning environments that are not just more personalised, but also more inclusive and engaging. For example, they can provide additional help for learners with special educational needs, motivate learners who cannot attend school, and support disadvantaged populations.[36]

AIEd applications can also be more flexible than the alternatives. Many are deployed online, meaning that they can be available on personal and portable devices within, and beyond, formal educational settings. AIEd researchers are also exploring the use of mobile devices to deliver adaptive materials for anytime, anywhere, social and collaborative learning (while still monitoring and providing intelligent support as needed).[37]

AIEd has made great progress, but has barely scratched the surface. There is exciting promise as the existing technologies develop, mature, and scale. Yet, the AIEd horizon includes much more than simply 'more of the same'. AIEd developers are getting better at recognising how to blend human and machine intelligence effectively, which means that future AIEd is poised to make significant strides in a number of critical areas.

Let's now turn our attention to this horizon.

Teachers and AIEd

We are in no doubt that teachers need to be central agents in the next phase of AIEd. In one sense this is obvious – it is teachers who will be the orchestrators of when, and how, to use these AIEd tools. In turn, the AIEd tools, and the data driven insights that these tools provide, will empower teachers to decide how best to marshal the various resources at their disposal.

More than this, though, teachers – alongside learners and parents – should be central to the design of AIEd tools, and the ways in which they are used. This participatory design methodology will ensure that the messiness of real classrooms is taken into account and that the tools deliver the support that educators need – not the support that technologists or designers think they need. Teachers who take part in these processes will gain increased technological literacy, new design skills, and a greater understanding of what AIEd systems can offer.

As mentioned earlier, we predict that the increased introduction of AI-powered tools will serve as a catalyst for the transformation of the role of the teacher. AIEd is well placed to take on some of the tasks that we currently expect teachers to do – marking and record keeping, for example.

Freedom from routine, time-consuming tasks will allow teachers to devote more of their energies to the creative and very human acts that provide the ingenuity and empathy needed to take learning to the next level.

As this transformation takes place, teachers will need to develop new skills (maybe through professional development delivered through an AIEd system). Specifically they will need:

- A sophisticated understanding of what AIEd systems can do to enable them to evaluate and make sound value judgements about new AIEd products
- To develop research skills to allow them to interpret the data provided by AIEd technologies, to ask the most useful questions of the data, and to walk students through what the data analysis is telling them (for instance, using Open Learner models)
- New teamworking and management skills as each teacher will have AI assistants in addition to their usual human teaching assistants, and they will be responsible for combining and managing these resources most effectively

Most excitingly, with the evolution of the teacher’s role will also come the evolution of the classroom, as AIEd tools allow us to realise what it is unrealistic to expect any teacher or lecturer to do alone. For example, making the positive impact of one-to-one tutoring available to every child, or realising effective collaborative learning (a difficult activity to keep on track without some form of additional support).

The next phase of AIEd

The future of AIEd is inextricably linked to the future of AI. The increasing consumerisation of AI technologies brings with it a massive increase in the number of people who are developing AI. The pace of innovation and development in general is at its fastest rate ever[38] and the current popularity of AI should mean that innovation in AIEd is a focus of attention for an increasing number of businesses.

In this section, we look to the edges of theory and practice to consider some of the advances we expect to see through the continued growth of AIEd, as well as some of the new technologies we expect to be developed. Some of these will happen sooner than others, and all can be seen as both opportunities and challenges. Having said this, we see these developments in a positive light, and have here focused on conveying the exciting potential that AIEd has to improve education for all.

AIEd will help learners gain 21st century skills

There is an increasing recognition that so-called 21st century skills are essential for current and future work environments, with many groups advancing lists (some short and others long!) of the skills people will need to fully engage in employment and society.

To take one example, the World Economic Forum have proposed 16 skills, split across three categories:[39]

Category	Helps students approach...	Related skills	
Foundational Literacies	...everyday tasks	Literacy Numeracy Scientific literacy Information communication	Technology literacy Financial literacy Cultural and civic literacy
Competencies	...complex challenges	Critical thinking and problem-solving	Communication Collaboration
Character Qualities	...changing environments	Curiosity Initiative Persistence/grit Adaptability	Leadership Social and cultural awareness

We agree with the common wisdom that skills like these are – and always have been – important, and that they should be part of any approach to lifelong learning. There are, however, at least two salient challenges that need to be addressed if we are to realise this agenda:

1. We must develop reliable and valid indicators that will allow us to track learner progress on all the skills and capabilities needed to thrive in the current century – at the level of the individual, the district, and the country. This will need to include difficult to measure characteristics such as creativity and curiosity.
2. We need a better understanding of the most effective teaching approaches and the learning contexts that allow these skills to be developed.

AIEd can help with both.

First, AIEd has the tools and techniques to conduct the fine-grained analysis that allows us to track each learner's development of skills and capabilities as they interact and learn over time. This tracking of individual learners can then be collated and interpreted as required to provide knowledge about progress at the school, district, and country level.

The increasing range of data capture devices – such as biological data, voice recognition, and eye tracking – will enable AIEd systems to provide new types of evidence for currently difficult to assess skills. For example, a practice-based learning experience that incorporates elements of problem solving or collaboration might be assessed using a combination of data sources including voice recognition (to identify who is doing and saying what in a team activity) and eye tracking (to explore which learner is focusing on which learning resources at any particular moment in time).

Second, the increasing use of AIEd systems will enable the collection of mass data about which teaching and learning practices work best. This data will enable us to track learner progress against different teaching approaches and, in turn, will allow us to develop a dynamic catalogue of the best teaching practices suited to the development of different skills and capabilities, in particular the 21st century skills, across a range of environments.

PRACTICE-BASED LEARNING
Practice-based learning is learning undertaken, typically in teams, in real-life contexts (e.g. learning undertaken by healthcare professionals in working hospitals).

Importantly, in investigating these practices, we will also be able to relate learner progress to the contexts in which learning has taken place, and then build context models into our AIEd systems. Already there are fledgling methodologies that take into account contextual elements such as the physical or virtual space, the people who are available to help, and the learning tools available such as the curriculum, technology, or books.[40]

Over time, these models will enable us to identify the best teaching approaches for different contexts. And, they will help us identify how contextual factors (such as the combinations of technology, teachers and the environment) can be adjusted to improve the efficacy of particular teaching, approaches – insights that will help students gain 21st century skills as well as other types of knowledge.

AIEd will support a Renaissance in Assessment

We echo the assertion made by Peter Hill and Michael Barber in *Preparing for a Renaissance in Assessment*, that of the three core components of learning (curriculum, learning and teaching, and assessment), it is in many ways assessment that is holding us back.[41] We also agree with the assertion that technology holds part of the solution. In the near future, we predict that AIEd will contribute to improving assessment in three key ways.

AIEd will provide just-in-time assessments to shape learning

The continued and growing use of technologies in education will allow increasing amounts of data to be collected about teachers and learners. This so called 'big data' is already being studied using learning analytics to recognise data patterns of potential educational interest. For example, analytics have been used with high levels of accuracy to predict when a student is likely to fail an assessment or 'drop-out' from an online course.

Soon the sophistication of these learning analytics will be complemented by AI techniques to provide just-in-time information about learner successes, challenges, and needs that can then be used to shape the learning experience itself. For example, AIEd will enable learning analytics to identify changes in learner confidence and motivation while learning a foreign language, say, or a tricky equation.

LEARNING ANALYTICS
Learning analytics are used to find patterns in large data sets, like those generated by online learning systems, to enable modelling and prediction.

This information can then be used to provide timely interventions to help students – which could be in the form of technology-assisted support, individual attention from a teacher, or some combination of the two.

AIEd will provide new insights into how learning is progressing

In addition to timeliness, the data gleaned from digital teaching and learning experiences will give us new insights that cannot be ascertained from existing assessments. For example, as well as identifying whether or not a learner gave the correct answer, datasets could be analysed to help teachers understand how the learner arrived at their answer. The data might also help us better understand cognitive processes such as remembering and forgetting, and the fundamental impact that these have on learning and student outcomes. AIEd analysis might also identify if and when a student is confused, bored, or frustrated, to help teachers understand and enhance a learner's emotional readiness for learning.

AIEd will help us move beyond 'stop-and-test'

As documented by Kristen DiCerbo and John Behrens in *Impacts of the Digital Ocean* on Education, the models and techniques developed by AIEd researchers over the last 25 years have resulted in an ever rising ocean of digital data on learning and teaching, telling us much about the data we need to collect in order to assess students *while they learn*.[42]

With ongoing AIEd analysis of a student's learning activities, there will be no need for the stop-and-test approach that characterises many current assessments. Instead of traditional assessments that rely upon evaluating small samples of what a student has been taught, AIEd-driven assessments will be built into meaningful learning activities, perhaps a game or a collaborative project, and will assess all of the learning (and teaching) that takes place, as it happens.[43]

AIEd will embody new insights from the learning sciences

AI and AIEd have always been interdisciplinary fields. Moving forward, AIEd will continue to leverage new insights in disciplines such as psychology and educational neuroscience to better understand the learning process, and so build more accurate models that are better able to predict – and influence – a learner's progress, motivation, and perseverance.

An example from Education Neuroscience

One example of the way that neuroscience can inform education and the design of AIEd systems can be found in the work of Paul Howard-Jones, Professor of Neuroscience and Education at the University of Bristol. His work suggests that learning can be improved when it is linked to uncertain rewards[44] – that is, situations in which a learner knows that a reward may be given upon their completion of a task, but there is no certainty that the reward will appear on every occasion. This is counter-intuitive to typical education practices where rewards are consistently related to success.

The use of uncertain rewards is much more common in the world of computer games, hence the current interest in the design of educational games that use the motivational impact of uncertain rewards to engage learners and to enhance their learning. The addition of AIEd techniques to the design of these educational games would enable, for example, the provision of uncertain rewards to be calibrated to a learner's individual reaction to a given level of uncertainty.

An example from Psychology

For several years now psychologists, most notably Carol Dweck of Stanford University, have been exploring the role of 'mindsets' in learning.[45] They make a distinction between learners who believe that intelligence does not change over time (a 'fixed mindset') and those who believe that their abilities can be developed (a 'growth mindset'). Learners with a growth mindset see challenges as things to be overcome; they persist and value effort more, which leads to them enjoying more success as learners. There is increasing evidence that a growth mindset can be taught and that changing students' mindsets can have a substantial impact on their grades and achievement test scores.[46]

There is already a role for technology when it comes to helping learners to develop a growth mindset; indeed Carol Dweck's team have developed Brainology, a piece of software to provide support and content for promoting a growth mindset.[47] The addition of AI to the technology would bring greater possibilities. For example, with AI the system could adapt to a learner's goal orientation or mindset, or scaffold learners towards a growth mindset.[48] More sophisticated learner models would be able to capture learners' mindsets, including how these change over time, and adapt teaching accordingly. This might include providing targeted feedback to teachers to enable them to support each learner to develop a growth mindset in the most effective way.

AIEd will give us lifelong learning partners

It is said that in ancient China each royal prince studied with a companion as well as a royal teacher. Perhaps the Chinese emperors knew that their children would learn more effectively with another; it is certainly the belief in much contemporary psychology.[49]

Early AIEd research in the 1980s brought this ancient story to life through the development of Learning Companion Systems. These systems provided each learner with a collaborative computer-based learning companion (or companions). It was the role of the companion to use collaboration and competition to stimulate student learning. The companion could also act as a student for the human learner to tutor, and in so doing the student learns by teaching. The computer-based teacher offered examples and guidance to human and computer student alike and determined the order and content of the topics to be tackled.[50]

The next generation of learning companions will offer huge potential for future teaching and learning. There are no technical barriers to the development of learning companions that can accompany and support individual learners throughout their studies – in and beyond school. These lifelong learning companions could be based in the cloud, accessible via a multiplicity of devices, and be operated offline as needed.

Rather than teaching all subject areas, the learning companion might call in specialist AIEd systems or humans with expertise in the particular subject area required by the learner. In addition, the companion could focus on helping learners to become better at learning through developing a growth mindset or an impressive array of 21st century skills. And because this type of system can help all learners to access learning resources that are optimal for their needs, it will be suitable for struggling learners as well as those who are high achieving.

The ethics of AI and AIEd

AI development is accelerating, permeating every aspect of our lives. The question is, are we prepared to let that happen without proper debate or control? The ethics of AI, as written about extensively by the Oxford philosopher Nick Bostrum, need especially careful attention: "responsibility, transparency, auditability, incorruptibility, predictability (...); all criteria that must be considered in an algorithm intended to replace human judgement of social functions".[51]

For example, what happens if AI 'goes wrong' (see, for example, the role of algorithms in the 2010 financial 'flash crash')?[52] Who is responsible, the end-user or the programmer? What will happen when an autonomous vehicle is involved in a traffic accident? Will it be possible to understand how it arrived at its decision so that it might be corrected to prevent future problems? Already this can be difficult if the AI uses neural networks. And are AIs open to manipulation? We are all too aware of the consequences of computer hacking; what might happen if an AI were developed or modified for criminal purposes?

For AIEd, these ethical questions are equally, if not more, acute, and questions need to be identified and addressed. For example, we know that the sharing of data is essential to the integration of AIEd systems, and that sharing of anonymised data has the potential to move the field forward by leaps and bounds by cutting back on wasteful duplicative efforts. But this type of sharing introduces a host of problems and questions, from individual privacy to proprietary intellectual property concerns. Indeed, the growing volume and diversity of data generated by AIEd systems only serves to double-down on the already existing ethical concerns about what happens to education data. What are the implications of the methods, technologies, and ideologies that underpin the generation, analysis, interpretation, and use of AIEd system data? Who owns the data, who can use it, for what purposes, and who is ultimately accountable?

Another consideration is the way in which AIEd systems aim to effect lasting behavioural change on their users. For example, a system may make recommendations, use persuasion, or offer feedback to engender personal relationships between humans and machines. Behaviour change is certainly one intervention that can be truly transformative, but it is again not without serious ethical considerations.

Other concerns have been raised with regard to learning companions. Although they are intended to support learners throughout their lives, there are fears that a companion that 'followed' you would instead result in the perpetual recording of learner failures to the detriment of future progress.

Similarly, the concept of an AIEd teaching assistant raises worries that the technology will be used as a classroom spy to record and report any perceived suboptimal performance by the teacher.

Finally, we have a new responsibility to ensure that society as a whole has sufficient AIEd literacy – that is, enough to ensure that we use these new technologies appropriately, effectively, and ethically.

AIEd and the Physical World

For some, the word 'artificial' in AIEd can give the sense that the technology is somehow removed from our real, physical lives. We have made the argument here that AIEd is at its core, a very real, very human endeavour. Moving forward, AIEd will increasingly draw on our physical environments and our physical beings – and so make these integral to the learning process.

AIEd will augment our physical landscape

Augmented reality systems (AR) will go one step beyond intelligent virtual reality systems by enabling learners and teachers to experience and interact differently with the physical world around them. AR technology can display an overlay of information about a person's environment, allowing formal classroom content to overlay the learner's physical reality. For example, the age, architecture style, or heat efficiency of the buildings around a learner could be visualised as they move around the world.

We have already seen how existing AIEd systems feature socially and culturally intelligent avatars that guide and support learners in virtual environments. The addition of AIEd to AR systems will allow for personalised, adaptive educational experiences with virtual mentors or tutors guiding students through field trips, leaving teachers to concentrate on those learners whose needs are greatest.

AIEd will connect to the Internet of Things

The network of objects or 'things' with embedded computing systems, sensors, and network connectivity are referred to collectively as the 'Internet of Things' (IoT). IoT permits any network-enabled objects to be interconnected with any other network-enabled object or machine. This opens up new possibilities for AIEd systems, for example to support learners developing motor skills that need consistent and extended practice, such as dancing, playing a musical instrument, or even learning surgical procedures.

AIEd will be attuned to how we feel and how we move

Recent research supports the idea that learning is significantly influenced by how we feel (our affect), and how we move.[53] These insights suggest that learning technologies can be improved by taking these additional inputs into account. Already, learner models are no longer limited solely to representing and recording learners' academic progress,[54] and sensors that can be worn in clothing or strapped to body parts (e.g. the Fitbit) have already been developed.

AIEd systems of the future will increasingly support the whole learner through sophisticated models that also capture data about a learner's emotional and physical state. These enriched models will further contribute to what is known about how we learn, and will provide individual teachers with real time information about their students' physical and emotional well-being as well as their cognitive development, allowing for appropriate and timely interventions in all the areas that matter to learning.

Taking it to the next level: How AIEd can help us respond to the biggest unsolved issues in education

Policy makers often call them 'wicked-issues' – social problems that are complex, connected, and seemingly resistant to intervention. Sadly, education does not lack for its fair share.

If AIEd is to attract the attention and investment that we believe it deserves, then it is only right to ask how AIEd can be realistically applied to address these unsolved issues. Here we take two big issues – achievement gaps, and teacher development, retention and shortages – and show how AIEd can provide a response.

Tackling achievement gaps

Currently, we are failing to meet the needs of all learners. The gap between those who achieve the most and those who achieve the least is a challenge that teachers, school leaders, administrators, and government officials face every day, in every country. Globally, students from poorer backgrounds perform worse than students from richer backgrounds.[55] The results of this achievement gap impacts upon a country's economy as well as the social well-being of their population.[56] The reasons behind the achievement gaps in different countries vary, but the fact remains that not all learners are achieving their potential at school.

We take it as essential that all children should have at least basic skills (reading, writing, and mathematics), and yet, across the world, we are not there. For example, in the UK, nine million working age adults have low basic skills in either literacy, numeracy, or both. To make this real, this means that these adults will struggle with simple everyday tasks such as assessing how much fuel is left in their vehicle by looking at the gauge, or understanding the instructions on over–the-counter medications.[57]

We have already shown some of the ways in which AIEd can offer a new set of tools for addressing this challenge. For example, students who need extra help can be offered one-to-one tutoring from adaptive AIEd tutors, both at school and at home, to improve their levels of success. Increased collaboration between education neuroscience and AIEd developers will provide technologies that can offer better information, and support specific learning difficulties that might be standing in the way of a child's progress. Moreover, and important to addressing the socioeconomic gap, these AIEd systems will scale broadly as the reduction in their cost makes them increasingly affordable to schools and school systems.

AIEd could also offer needed support before a learner begins formal education, perhaps even before they are born. There is strong evidence that the first five years of a child's life have a large influence on that child's educational attainment.[58] Unfortunately, we see evidence of poor school readiness for many students, particularly children from low-income families. This means they enter school at a significant disadvantage to their wealthier counterparts in areas including language, early maths and science understanding, physical well being and motor development, and social and emotional development. This can mean that a child may enter school unable to identify numbers, interact with peers, or use the bathroom on their own.[59]

Low-income parents may also have had limited education opportunities, meaning they may face serious challenges in providing at-home learning support to their children. AIEd systems can provide tailored support to parents in the same way that they can for teachers and students, improving education and outcomes for both parents and their children.

Imagine, for example, providing parents with AIEd assistants that could advise them about strategies for talking to their child, sharing songs, and enjoying books. This could enable all parents to provide the right sort of support in those all important early years. For parents who have problems with numeracy or literacy, the AIEd assistant could help boost these skills too.

To avoid what's known as the Matthew Effect[60] – the all too common situation in which learners who are already privileged gain the most from new resources, further exacerbating existing inequalities – AIEd assistants should be available for all parents, with additional support provided to those parents who need it most. This will help ensure that all parents are well informed, supported, and engaged in their child's education.

Developing teacher expertise, addressing teacher retention, and providing respite where teacher shortages are acute

Teacher expertise is key to learner attainment, but high-quality continuous teacher development has significant costs, both in terms of time and money. In the same way that AIEd systems can offer one-to-one or group tutoring to students, so it can do the same on an ongoing basis for teachers. This training can be designed to meet the specific needs of the teacher, be completed wherever and whenever they like, and can be used to access a community of like-minded professionals who give advice and guidance.

AIEd could also help teachers find and share the best teaching resources. Imagine, for example, navigating a popular tool like TES[61] or Teachers Pay Teachers[62] with your own AIEd assistant who knows the resources you have found useful in the past, the details of your students, and the teaching schemes and curricula used in your institution. Your AIEd assistant could accurately predict the resources that would work best for you and your students as well as uploading the resources you have created and successfully used.

Intelligent support for teachers could also help address the issue of teacher retention where we see many skilled professionals leaving the profession due to 'burnout'.[63] Now that a cloud-based intelligent assistant for every teacher is a realistic possibility, we can provide support to reduce teacher stress and workload. The teacher's AIEd assistant will be available through any and all of the teacher's devices so that it can be deployed as needed wherever the teacher is working.

Outside the classroom, the assistant could greatly reduce the amount of teacher time needed for grading. Inside the classroom, the teacher could give the assistant the task of offering one-to-one tutoring to a group of children who are struggling to understand fractions. The assistant would maintain a learner model for each student and would use this to identify suitable teaching materials. This would free up the teacher to turn their attention to an individual student, or work with a group on a different topic.

In many parts of the world acute teacher shortages present enormous challenges. For example, 33 countries do not currently, and will not have, enough teachers to provide every child with a primary education by 2030. In fact, the world will need to recruit 25.8 million schoolteachers to achieve this goal.[64]

Although the most effective implementations of AIEd will deploy it alongside the expertise and empathy that is peculiarly human, in some instances this simply will not be possible, at least in the short-term. This means we will need to rely on technology to make available high-quality learning experiences to places where this is currently lacking.

One illustrative example is the work of Sugatra Mitra, who famously provided children in an Indian slum with free access to a computer placed in a wall between his office and the public space. He christened this experiment the ‘Hole in the Wall’, the goal of which was to understand if children could form effective self-organised learning groups, in this case around learning how to use a computer.

This work then led to his creation of School in the Cloud, “a creative online space where children from all over the world can gather to answer ‘big questions’, share knowledge and benefit from help and guidance from online educators.”[65]

Now, imagine if we could add AIEd to technologies like these. For example, AIEd could provide the intelligent support to aid learners in their collaboration, it could provide Open Learner Models to help volunteer online educators understand the right support that a given learner might need, or it could intelligently pair the most appropriate volunteer with the right student.

This is not to disguise the urgent need to make high-quality educator expertise available to all. Far from it. However, where there is none, there is a moral urgency to act and we would be remiss to not leverage AIEd.

Bringing it all together: The continuing race between education and technology[66]

We do not lack for predictions of how the existing mix of jobs in the economy will be upended by the steady rise of the robots, and ever smarter algorithms deployed on ever bigger data-sets. However, the implications of this for learning has received relatively little sustained and serious attention.

This is not surprising given that the debate, to date, is understandably being led by economists rather than educators. It also reflects gaps in existing quantitative research which focus largely on job categories, rather than skills, and on the roles likely to be automated, rather than those likely to be created.

Throughout this paper we have set out the AIEd pieces that could – with further development and smart real-world testing – offer a proportionate response to the new innovation imperative in education. Simply stated the imperative is this: as humans live and work alongside increasingly smart machines, our education systems will need to achieve at levels that none have managed to date.

In our minds, this imperative trumps even the significant impacts of globalisation, and brings existing issues in education, such as achievement gaps, into ever sharper relief.

To summarise the argument so far we thought it would be useful to do two things. First, map the catalogue of AIEd tools that can help us address this enormous challenge by supporting the next phase of education system reform. And, second, set out the ways in which AIEd can be deployed to help us understand how successfully we are realising this reform agenda.

If you like, just as learners need timely and actionable feedback, so too do our education systems as they prepare learners for the future economy.

Before we go on to this, however, it is important to remind ourselves that the 'purposes' of education are wider than getting a job. For example, a list would include discovering your passions, experiencing the flow and satisfaction of good work, and being a moral person with the capacity and will to affect positive change in your family, community, country, and the world.

Having said this, getting a good job is consistent with the list above. Indeed, it is one of the central reasons why governments invest in education.

The table opposite shows our mapping of the tools of AIEd against the likely requirements of the jobs market in 15 years' time.

Using AIEd to effect education system reform

In 15 years time…	The implication for learning…	How AIEd can help…
Many of the new jobs created will be much more cognitively demanding than those currently available	Students will need to learn as efficiently and effectively as possible	Give every learner their own personal tutor, in every subject
		Provide every teacher with their own AI teaching assistant
		AIEd to deliver timely, smarter, teacher professional development
		AIEd tools that help every parent support their child's learning
	We will need to seriously attend to the non-cognitive factors that influence learning – grit, tenacity and perseverance; affect; 'mindset'	AIEd tools that embody new insights from neuroscience or psychology
		Making available new insights into how learning is going for an individual and the factors that make it more likely to occur
		In light of that, providing the right support, at the right time, to keep learning on track
	Students will need to achieve higher-order skills – e.g. problem solving – alongside 'knowing what'	Intelligent Virtual Reality to allow learners to be supported to learn in authentic environments – and to transfer that learning back to the real world
Social skills will be where humans continue to excel	Students need to be effective collaborative problem solvers and makers, able to build on others' ideas and extend and sensitively critique an argument	Intelligent support for collaborative learning
	The ability to get on with others, to empathise and create a human connection, will continue to be valued	AIEd techniques to help us understand better how to deliver a wider variety of attributes, and how well a learner is acquiring them
We will need to re-skill large parts of the current workforce – in essence, creating a learning society	We will need new ways of equipping adult learners with new skills – more frequently, quickly, and effectively	AIEd tools that support learners to become effective, self-regulated learners for lifelong learning
		Lifelong learning companions to advise, recommend, and track learning
		More flexible learning environments, allowing learners to learn at a time and a place that works best for them

We will need to do all this without a significant uplift in the current investment we make in learning. With the steady application of Moore's law, alongside wise investment, there is every reason to believe that the cost of AIEd applications will diminish overtime, allowing this potential to be realised at a price that is affordable within current spending parameters.

MOORE'S LAW
A computing term, established by Gordon Moore around 1970, which states that processor speeds, or overall processing power for computers, will double every two years.

Using AIEd to measure education system reform

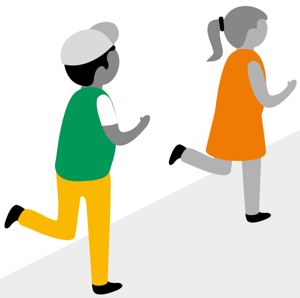
Once we put the tools of AIEd in place as described above, we will have new and powerful ways to measure system-level achievement. Through the implementation of sensible common data standards and data sharing requirements, AIEd will be able to provide analysis about teaching and learning at every level, whether that is a particular subject, class, college, district, or country. This will mean that evidence about country performance will be available from AIEd analysis, calling into question the need for international testing such as PISA and TIMMS, at least in their current form.[67]

With this information available, system leaders and strategists will need to develop fresh skills to probe the data and establish the potential causes of any underperformance, and the most likely solutions. For example, AIEd could produce the school level data analysis that will indicate in real-time when a school is experiencing problems. A team of experts could then be called in to determine how these problems can be quickly resolved.

Education systems will need to be nimble to take advantage of the rich real-time systems level analysis that will be continuously available. Synergistically, it may be AIEd systems that provide the scaffolding to enable leaders and policy makers to develop these new skills and abilities.

...

The view we have sketched out, that AIEd will play a critical role in the next phase of education system reform, will not happen by chance. This takes us to the final section of this paper: the practical things that need to be done now for the intelligence of AIEd to be unleashed.

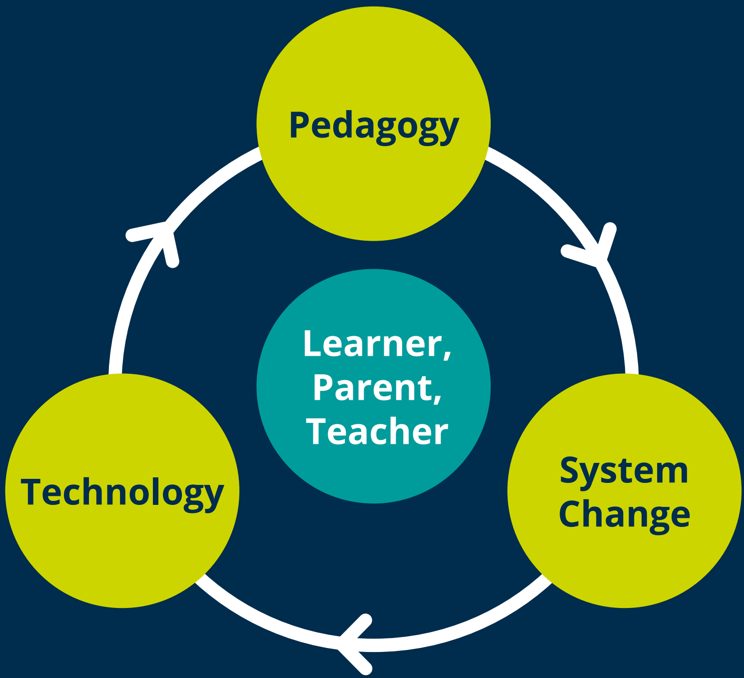


Recommendations to help us Unleash Intelligence

In Alive in the Swamp[68], Michael Fullan and Katelyn Donnelly describe three powerful forces that must be combined if we are to deliver on the promise of technology to catapult learning dramatically forward. One is pedagogy, or the science of how we teach and learn; the second is technology itself, which we have said a great deal about already; and the final component is system change, or our understanding of how to deliver change so that it has a positive impact on each and every learner.

The future ability of AIEd to tackle real-life challenges in education depends on how we attend to each of these three dimensions – that is: (i) we need intelligent technologies that embody what we know about great teaching and learning in (ii) enticing consumer grade products, which (iii) are then used effectively in real-life settings that combine the best of human and machine.

How does AIEd currently fare against these dimensions? And, more importantly, what needs to be done to unleash the full intelligence of AIEd?



Pedagogy

AIEd research has, to date, mainly tackled the low-hanging fruit of education – for example, learning in highly structured domains such as introductory mathematics or physics, or applying AI techniques on highly structured datasets such as university administration systems.

These gains are essential but they are not enough. If we are to bring about a step-change in the breadth and quality of learning for all learners, if we are to tackle the persistent and unsolved challenges of learning in the 21st century, funders and researchers need to go deeper and wider.

In short, AIEd needs to begin with the pedagogy and be more ambitious!

Recommendations

- Do not get seduced by the technology, start with the learning.
- Focus existing AIEd funding on the areas that are likely to deliver the step-changes in learning that will make a real difference.
- Move beyond the disjointed, un-prioritised and siloed approaches that characterise the current AIEd funding landscape.
- Scope out a series of ambitious challenge prizes that begin with insights from the learning sciences and educational practice (see overleaf).

Technology

AIEd is currently something of a cottage industry – research and development takes place in small pockets and at modest scale, mostly by researchers with limited funding and without commercial partnerships. The result is that many of the applications that are developed never move beyond the prototype stage, at which point much of what has been learnt is lost.

The solution is not to funnel money into the development of a single monolithic AIEd system that tackles every subject, and every possible learning scenario.

Instead, success will lie in the development of a multitude of individual AIEd components that specialise in a particular expertise: for example, a subject area or a specific learner need.

To realise this means putting in place the structures, incentives, and funding that will allow an ecosystem of innovation and collaboration to be created around AIEd.

Recommendations

- Develop the infrastructure that enables iterative innovation, and less re-invention, in AIEd (for example, APIs, shared data standards, and shared learner models).
- Create smart demand for AIEd technologies. For example, governments and philanthropists could guarantee a market for AIEd solutions that have been shown to work in real life settings. This would unlock needed collaborations between AIEd researchers and commercial entities.
- Found a DARPA for education that will accelerate the transition of AIEd tools from the lab into real-world use (see overleaf).

Learning from the approach that jump-started driverless cars

In 2004, the authors Levy and Murnane famously wrote that "executing a left turn against oncoming traffic involves so many factors that it is hard to imagine discovering the set of rules that can replicate a driver's behavior".[69]

In the same year, the US Defense Advanced Research Projects Agency (DARPA) offered $1M for the team that developed a self-driving car that could navigate a 142-mile route. For this first prize, no team was successful.

However, just one year later (when the prize money was doubled) five vehicles completed the course. The winning team was led by Stanford University's Sebastian Thrun, who went on to lead Google's autonomous vehicles team and, when there, began 'hoovering up' the best engineers from the DARPA challenges.

Similarly, we believe there would be value in a suite of well-funded, global challenge prizes that pose complex learning problems, and then reward those who provide the most exciting and effective AIEd solutions.

It's not difficult to create a list of grand challenges that could form the basis for such an approach – for example, gaps in student achievement, 21st century skills or even preparing students for jobs that do not yet exist.

Although the XPrize Foundation are currently running two 'Grand Challenges' in learning – a $7M competition to help adult learners who struggle with literacy, and a $15M competition to empower children to take control of their own learning – neither are specifically encouraging the development of AIEd based solutions. In short, there is a big gap to be filled.

Moreover, sensible challenge prizes in this area should be as much about consciousness-raising and movement building as they are about the resulting solutions. After all, there is still a lot of work to be done to convey the usefulness of AIEd to parents, policy-makers, educators, and learners.

Just such an approach has been taken by the UK innovation agency Nesta, who created huge media interest around their £10M Longitude Prize which (as a result of a public vote) was eventually focused on the urgent problem of global antibiotic resistance.

Learning from DARPA

In the US Defense Advanced Research Projects Agency (DARPA) model the best talents in diverse fields conduct basic research in order to solve real-world problems that are both ambitious and relevant. The goals are clear, but how you get there is not yet known.

Creating similar centres of independent interdisciplinary expertise in AIEd, funded long term and focused on delivering real-world capabilities, would allow us to cross the chasm of basic to applied research, and provide the long-term funding and ambition that is needed.

A fundamental goal for these agencies should be creating the technical infrastructure that allows for the development of an ecosystem of AIEd innovation. This could include standards for interoperability that enable researchers and developers to share and build upon each others' work.

They should also look at developing capabilities that can be re-applied in multiple AIEd applications. For instance, at the moment each and every AIEd application has to develop its own learner model, which can take up to a year of effort. Developing a learner model that can be called on by separate applications would head-off duplicated effort and allow the creation of bigger data sets.

These, in turn, would enable deep learning techniques to extend and refine the learner model so that it is useful for an increasing number of learner types and contexts.

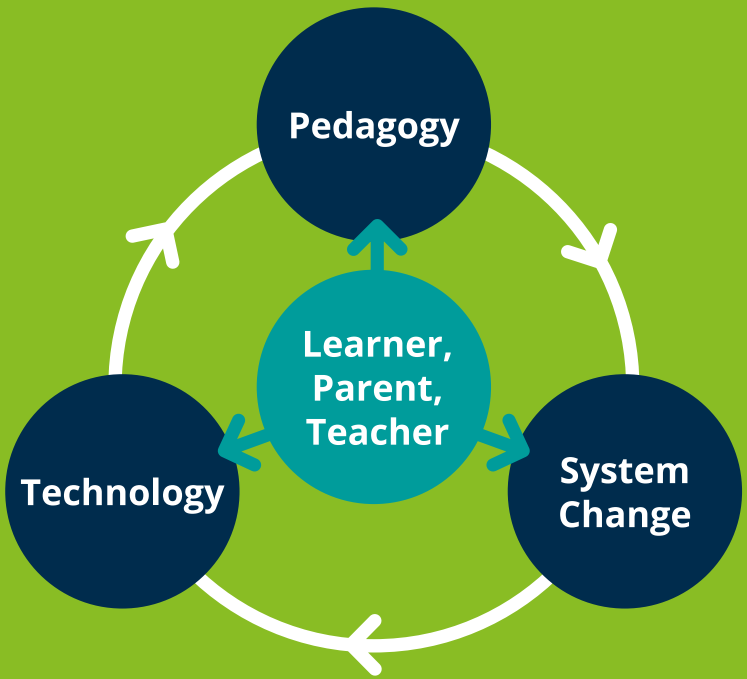
On a related note, it is striking that some of the most 'successful' uses of AIEd have been developed by the US military. For example, America's Army is an intelligent virtual learning environment which uses an AI-driven, first-person shooter, digital-game format to allow young people to experience virtual soldiering. It has been used successfully since 2002 both for recruiting and as a pedagogically-robust and immersive training tool.

Similarly, DARPA have developed a digital tutor to allow navy IT workers to develop the skills to solve complex IT problems. It has been reported to be more effective than traditional classroom learning.[70]

Imagine what we might see if we were to put the same effort into improving our schools, universities, and community colleges with properly researched and comprehensively evaluated AIEd.

System change

AIEd will have to function in blended learning spaces where digital technologies and traditional classroom activities complement each other. Realising this means addressing the 'messiness' of real classrooms, universities, or workplace-learning environments, and involving teachers and learners in the co-design of AIEd so that our diagram instead looks like this:



However, too little attention has been given to designing and describing how AIEd concretely fits within the lived experience of real learners and educators.

There has been even less attention given to providing the right professional support to allow educators to realise these re-designed models of learning.

We also need much better evidence of what works in AIEd when it is implemented in real classrooms, and universities – after all, how can we ask AIEd to tackle the big problems in education, or system owners to take AIEd seriously, if we do not also provide the means to allow us to establish whether the proposed solutions work?

Recommendations

- Involve teachers, students, and parents to ensure that future AIEd systems meet their needs (a participatory design process that will lead to better AIEd products, to teachers more knowledgeable about the processes of learning, and to more successful learners).
- Take the next step to iterate and intelligently evaluate AIEd applications in real world contexts.
- Develop data standards that prioritise both the sharing of data and the ethics underlying data use.

…

We do not underestimate the new-thinking, inevitable wrong-turns, and effort required to realise these recommendations. However, if we are to properly unleash the intelligence of AIEd, we must do things differently - via new collaborations, sensible funding, and (always) a keen eye on the pedagogy. The potential prize is too great to act otherwise.

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