BUILDING HYBRID MINDS: PEDAGOGY IN THE AGE OF LEARNING MACHINES

*Machines that learn and discover are now a critical part of science practice.
How can science education adapt to this change?*

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There is now consensus in the philosophy of science that building *explicit* models of natural phenomena is a core practice that supports scientific discovery. Following this, pedagogy based on the building of explicit models is central to the design of science learning.

However, discovery practices in contemporary science have changed — towards building *opaque* computational models, which do not provide explicit explanations. Such models dominate in the fast-developing *engineering sciences* (bioengineering, material science, systems/synthetic biology, robotics, artificial intelligence etc.), where the key objective is not developing explicit accounts, but *building*, *controlling* and *manipulating* novel synthetic artifacts, which mimic complex natural phenomena (neurons, metabolic networks, organism behavior, shape-memory etc.).

In most engineering science situations, where such synthetic artifacts are built in tandem with computational models, it is not possible to develop explicit accounts, even in principle. This is because such computational models are built as a last cognitive resort — when the non-linear interactions that are part of complex target systems are beyond both standard explicit modeling approaches and the human imagination. Opaque computational approaches (such as machine learning) are *required* to manage the overwhelming cognitive complexity in such situations.

This discovery practice has created a strange knowledge crisis, where machines built by humans discover patterns that humans cannot perceive. Machines also generate and 'meld' such patterns, to design novel solutions humans cannot imagine. Further, there is now a fast-developing 'hybrid intelligence' effort, based on interactive 'human-in-the-loop' video games, which allow two kinds of human-machine hybrids. One, such games allow crowds of novice players on the web to build novel scientific models of complex phenomena (such as protein folds, quantum computing, RNA, and neuronal networks), using their *tacit* sensory-motor capabilities, which are not available for conscious tracking and articulation. Second, in parallel, machine learning systems extract patterns from players' tacit moves, and generate novel models. Such hybrid systems create cognitive black boxes, where humans don't know what they are teaching the machine, and the machines don't know what they have learned. But they can together generate useful predictions and designs.

I will argue that the emergence of such hybrid modeling systems for discovery, and more broadly, *machines that learn and discover*, is a radical cognitive shift — similar to the emergence of tool use, language and literacy. These older cognitive shifts emerged across thousands of years, allowing learning and education systems to evolve in parallel. The ongoing shift to learning and discovery machines is occuring in internet time. To prepare students for this radical shift, science education needs to develop pedagogies that can evolve and adapt quickly, in step with fast developments in this domain.

Traditional pedagogical approaches (such as showing and telling) are not enough to adapt to this radical transition. The closest pedagogical process that appears suitable as a starting point is the *building* of prototypes, which is now promoted extensively through maker-spaces and tinkering labs. However, these building initiatives are not designed to support the building and manipulation of machine models for discovery. They are intended to kick start innovation cultures, where the building emphasis is on making of useful artifacts.

Learning to build and manipulate machines for discovery requires a new pedagogy of building. This is a very challenging and murky design problem. I will outline two directions the LSR group is pursuing to address this problem.

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