

et al., 2012).

At the same time that the scale and accuracy of deep networks has increased, so has the complexity of the tasks that they can solve. Goodfellow *et al.* (2014d) showed that neural networks could learn to output an entire sequence of characters transcribed from an image, rather than just identifying a single object. Previously, it was widely believed that this kind of learning required labeling of the individual elements of the sequence (Gülçehre and Bengio, 2013). Recurrent neural networks, such as the LSTM sequence model mentioned above, are now used to model relationships between *sequences* and other *sequences* rather than just fixed inputs. This sequence-to-sequence learning seems to be on the cusp of revolutionizing another application: machine translation (Sutskever *et al.*, 2014; Bahdanau *et al.*, 2015).

This trend of increasing complexity has been pushed to its logical conclusion with the introduction of neural Turing machines (Graves *et al.*, 2014a) that learn to read from memory cells and write arbitrary content to memory cells. Such neural networks can learn simple programs from examples of desired behavior. For example, they can learn to sort lists of numbers given examples of scrambled and sorted sequences. This self-programming technology is in its infancy, but in the future could in principle be applied to nearly any task.

Another crowning achievement of deep learning is its extension to the domain of **reinforcement learning**. In the context of reinforcement learning, an autonomous agent must learn to perform a task by trial and error, without any guidance from the human operator. DeepMind demonstrated that a reinforcement learning system based on deep learning is capable of learning to play Atari video games, reaching human-level performance on many tasks (Mnih *et al.*, 2015). Deep learning has also significantly improved the performance of reinforcement learning for robotics (Finn *et al.*, 2015).

Many of these applications of deep learning are highly profitable. Deep learning is now used by many top technology companies including Google, Microsoft, Facebook, IBM, Baidu, Apple, Adobe, Netflix, NVIDIA and NEC.

Advances in deep learning have also depended heavily on advances in software infrastructure. Software libraries such as Theano (Bergstra *et al.*, 2010; Bastien *et al.*, 2012), PyLearn2 (Goodfellow *et al.*, 2013c), Torch (Collobert *et al.*, 2011b), DistBelief (Dean *et al.*, 2012), Caffe (Jia, 2013), MXNet (Chen *et al.*, 2015), and TensorFlow (Abadi *et al.*, 2015) have all supported important research projects or commercial products.

Deep learning has also made contributions back to other sciences. Modern convolutional networks for object recognition provide a model of visual processing