

computing speed have come from parallelization across cores (either in CPUs or GPUs). This is very different from the situation of the 1990s (the previous neural network era) where the hardware implementations of neural networks (which might take two years from inception to availability of a chip) could not keep up with the rapid progress and low prices of general-purpose CPUs. Building specialized hardware is thus a way to push the envelope further, at a time when new hardware designs are being developed for low-power devices such as phones, aiming for general-public applications of deep learning (e.g., with speech, computer vision or natural language).

Recent work on low-precision implementations of backprop-based neural nets (Vanhoucke *et al.*, 2011; Courbariaux *et al.*, 2015; Gupta *et al.*, 2015) suggests that between 8 and 16 bits of precision can suffice for using or training deep neural networks with back-propagation. What is clear is that more precision is required during training than at inference time, and that some forms of dynamic fixed point representation of numbers can be used to reduce how many bits are required per number. Traditional fixed point numbers are restricted to a fixed range (which corresponds to a given exponent in a floating point representation). Dynamic fixed point representations share that range among a set of numbers (such as all the weights in one layer). Using fixed point rather than floating point representations and using less bits per number reduces the hardware surface area, power requirements and computing time needed for performing multiplications, and multiplications are the most demanding of the operations needed to use or train a modern deep network with backprop.

12.2 Computer Vision

Computer vision has traditionally been one of the most active research areas for deep learning applications, because vision is a task that is effortless for humans and many animals but challenging for computers (Ballard *et al.*, 1983). Many of the most popular standard benchmark tasks for deep learning algorithms are forms of object recognition or optical character recognition.

Computer vision is a very broad field encompassing a wide variety of ways of processing images, and an amazing diversity of applications. Applications of computer vision range from reproducing human visual abilities, such as recognizing faces, to creating entirely new categories of visual abilities. As an example of the latter category, one recent computer vision application is to recognize sound waves from the vibrations they induce in objects visible in a video (Davis *et al.*, 2014). Most deep learning research on computer vision has not focused on such