TTIC 31230 Fundamentals of Deep Learning, winter 2019

CNN Problems

In these problems, as in the lecture notes, capital letter indeces are used to indicate subtensors (slices) so that, for example, $M[I,J]$ denotes a matrix while $M[i,j]$ denotes one element of the matrix, $M[i,J]$ denotes the ith row, and $M[I,j]$ denotes the jth collumn.

Throughout these problems we assume a word embedding matrix $e[W,I]$ where $e[w,I]$ is the word vector for word w. We then have that $e[w,I]^\top h[t,I]$ is the inner product of the word vector $w[w,I]$ and the hidden state vector $h[t,I]$.

We will adopt the convention, similar to true Einstein notation, that repeated capital indeces in a product of tensors are implicitly summed. We can then write the inner product $e[w,I]^\top h[t,I]$ simply as $e[w,I]h[t,I]$ without the need for the (meaningless) transpose operation.

Problem 1. Consider convolving a filter $W[\Delta x, \Delta y, i, j]$ with thresholds $B[j]$ on a "data box" $L[b,x,y,i]$ where B, X, Y, $I, J, \Delta X$, ΔY are the number of possible values for b, x, y, i, j, Δx and Δy respectively. How many floating point multiplies are required in computing the convolution on the batch (without any activation function)?

Solution:

$$BXY\ \Delta X\ \Delta Y\ IJ$$

Problem 2: Suppose that we want a video CNN producing layers of the form $L[b,x,y,t,i]$ which are the same as the layers of an image CNN but with an additional time index. Write the equation for computing $L_{\ell+1}[b,x,y,t,j]$ from the tensor $L_\ell[B,X,Y,T,I]$. Your filter should include an index Δt and handle a stride s applied to both space and time.

Solution:

$$L_{\ell+1}[b,x,y,t,j] = \sum_{\Delta x, \Delta y, \Delta t, i} W[\Delta x, \Delta y, \Delta t, i, j] L_\ell[b, sx+\Delta x, sy+\Delta y, st+\Delta t, i]$$

Problem 3. Consider a bottleneck multi-layer perceptron (MLP) with residual connections defined as follows where $h[0,J]$ is an input vector and where I is small compared to J.

$$\begin{aligned} b[\ell, I] &= \mathrm{ReLU}(W^b[I,J]h[\ell,J]) \\ h[\ell+1, J] &= h[\ell,J] + \mathrm{ReLU}(W^h[\ell,J,I]b[\ell,I]) \end{aligned}$$

(a) What is the number of multiplications done by this network as a function of the hidden layer dimension J, the bottleneck vector dimension I and the number of layers L? Under what conditions does this give fewer multiplications than the standard MLP with one matrix between layers? (For the tensor $h[L, I]$ we have that ℓ ranges from 0 to $L-1$. We use this as a standard convention for tensor indeces. The input layer has $\ell = 0$ and the final layer has $\ell = L-1$.)

Solution: The number of multiplications is 2JI(L-1). For a standard MLP (with no botleneck) the number of multiplications is $J^2(L-1)$. The bottleneck layer has fewer multiplications for $I < J/2$.

(b) We now consider introducing a multiplicative constant γ into the residual connection.

$$\begin{aligned} b[\ell, I] &= \text{ReLU}(W^b[I, J]h[\ell, J]) \\ h[\ell+1, J] &= \gamma(\ h[\ell, J] + \ \text{ReLU}(W^h[\ell, J, I]b[\ell, I])\ ) \end{aligned}$$

If the network is initialized such that each of $h[\ell, j]$ and $\text{ReLU}(W^h[\ell, j, I]b[\ell, I])$ are zero mean and unit variance, and are assummed to be independent, what value of γ gives that $h[\ell+1, j]$ has zero mean and unit variance.

Solution: $1/\sqrt{2}$

(c) The main advantage of a stack of residual connections is that there is direct additive path from the loss to each layer of the stack, including the input layer. Give a reason why the introduction of the constant $\gamma < 1$ as in part (b) might be damaging to the optimization of the lower layers of the residual stack.

Solution: When we introduce $\gamma < 1$ as in (b) the gradient update on the bottom layer is reduced by γ^{L-2}. This could harm the learning along the direct connection between the loss and the first layer of the network.

Problem 4: Images have translation invariance — a person detector must look for people at various places in the image. Translation invariance is the motivation for convolution — all places in the image are treated the same.

Images also have some degree of scale invariance — a person detector must look for people of different sizes (near the camera or far from the camera). We would like to design a deep architecture that treats all scales (sizes) the same just as CNNs treat all places the same.

Consider a batch of images $I[b, x, y, c]$ where c ranges over the three color values red, green, blue. We start by constructing an "image pyramid" $I_s[x, y, c]$. We assume that the original image $I[b, x, y, c]$ has spatial dimensions 2^k and construct images $I_s[b, x, y, c]$ with spatial dimensions 2^{k-s} for $0 \leq s \leq k$. The image pyramid $I_s[b,x,y,i]$ for $0 \leq s \leq k$ is defined by the following equations.

$$\begin{aligned} I_0[b,x,y,c] &= I[b,x,y,c] \\ I_{s+1}[b,x,y,c] &= \frac{1}{4}\left(\begin{array}{l} I_s[b,2x,2y,c] + I_s[b,2x+1,2y,c] \\ +I_s[b,2x,2y+1,c] + I_s[b,2x+1,2y+1,c] \end{array}\right) \end{aligned}$$

We want to compute a set of layers $L_{\ell,s}[b,x,y,i]$ where s is the scale and ℓ is the level of processing with $\ell + s \leq k$ and where $L_{\ell,s}[b,x,y,i]$ has spatial dimensions $2^{k-\ell-s}$ (increasing either the processing level or the scale reduces the spatial dimentions by a factor of 2). First we set

$$L_{0,s}[b,x,y,c] = I_s[b,x,y,c].$$

Give an equation for a linear threshold unit to compute $L_{\ell+1,s}[b,x,y,j]$ from $L_{\ell,s}[b,x,y,j]$ **and** $L_{\ell,s+1}[b,x,y,j]$. Use parameters $W_{\ell+1,\leftarrow}[\Delta x, \Delta y, i, j]$ for the dependence of $L_{\ell+1,s}$ on $L_{\ell,s+1}$ and parameters $W_{\ell+1,\uparrow}[\Delta x, \Delta y, i, j]$ for the dependence of $L_{\ell+1,s}$ on $L_{\ell,s}$. Use $B_{\ell+1}[j]$ for the threshold. Note that these parameters do not depend on s — they are scale invariant.

Solution:

$$L_{\ell+1,s}[b,x,y,j] = \sigma\left(\begin{array}{ll} & \sum_{\Delta x,\Delta y,i} W_{\ell+1,\leftarrow}[\Delta x,\Delta y,i,j] L_{\ell,s+1}[b,x+\Delta x,y+\Delta y,i,j] \\ + & \sum_{\Delta x,\Delta y,i} W_{\ell+1,\uparrow}[\Delta x,\Delta y,i,j]\; L_{\ell,s}\;[b,2x+\Delta x,2y+\Delta y,i,j] \\ + & B_{\ell+1}[j] \end{array}\right)$$

Note: I am not aware of this architecture in the literature. A somewhat related architecture is "Feature Pyramid Networks" arxiv 1612.03144.