TTIC 31230 Fundamentals of Deep Learning

Problems for CTC.

Problem 1. Dynamic Programing for HMMs Assume we have an input sequence $x_1, \ldots, x_T$ and a phoneme gold label $y_1, \ldots, y_T$ with $y_t \in \mathcal{P}$. This problem is simpler than CTC because the gold label has the same length as the input sequence.

In an HMM we assume a hidden state sequence $s_1, \ldots, s_T$ with $s_t \in \mathcal{S}$ where $\mathcal{S}$ is some finite sets of "hidden states". Here will assume that then some deep network has computed transition probabilities and emission probabilities.

$$P_{\text{Trans}}(s_{t+1} \mid s_t)$$

$$P_{\text{Emit}}(y_t \mid s_t)$$

We assume an initial state s_{init} and a stop state s_{stop} such that $s_1 = s_{\text{init}}$ (before emitting any phonemes). The length T is determined by when the hidden state becomes s_{stop} giving $s_{T+1} = s_{\text{stop}}$.

For a given gold sequence $y_1, \ldots, y_T$ we define a "forward tensor" as

$$F[t, s] = P(y_1, \ldots, y_{t-1} \ \wedge s_t = s)$$

We have

$$\begin{aligned} F[1, s_{\text{init}}] &= 1 \\ F[1, s] &= 0 \quad \text{for } s \neq s_{\text{init}} \end{aligned}$$

(a) Write a dynamic programming equation to compute $F[t, s]$ from $F[t-1, s']$ for various values of s'.

Solution:

$$F[t, s] = \sum_{s'} F[t-1, s'] P_{\text{Emit}}(y_{t-1}|s') P_{\text{Trans}}(s|s')$$

(b) Express $P(y_1, \ldots, y_T)$ in terms of $F[t, s]$.

Solution:

$$P(y_1, \ldots y_T) = F[T+1, s_{\text{stop}}]$$

(c) Explain why, if the forward equations are written in a framework, we do not need to also implement "backward" equations to compute

$$B[t, s] = P(y_t, \ldots, y_T \mid s_t = s).$$

Solution: Once we have expressed the loss $-\ln P(y_1, \ldots, y_T)$ in a framework we can train the model by SGD using the framework's implementation of backpropagation. Nothing more is needed.

Problem 2. CTC for image labeling

Suppose that the training data consists of pairs (I, S) where I is an image and S is a set of object types occuring in the image. For example S might be $\{\mathrm{Person}, \mathrm{Dog}, \mathrm{Car}\}$. To be concrete we can take $\mathcal{C}$ to be the set of image labels used in CIFAR 100 and take S to be a subset of $\mathcal{C}$ containing no more than five labels ($|S| \leq 5$). We want to do SGD on a model defining $P_\Phi(S \mid I)$.

We will use a latent variable $z[X, Y]$ such that for pixel coordinates (x, y) we have $z[x, y] \in \mathcal{C} \cup \{\bot\}$. For a given $z[X, Y]$ define $S(z[X, Y])$ to be the set of classes appearing in $z[X, Y]$, i.e., $S(z[X, Y]) = \{c \; \exists \; x, y \; z(x, y) = c\}$. Here the "semantic segmentation" $Z[X, Y]$ is analogous to the phoneme sequence $z[T]$ in CTC. Unlike the CTC model, the label S is a set rather than a sequence.

We assume a CNN (with convolutions of stride 1 to preserve spatial dimensions) followed by a softmax at each pixel to get a probability $P_\Phi(z[x, y] = c)$ for each pixel location (x, y) and each $c \in \mathcal{C} \cup \{\bot\}$ and where each pixel location has an independent probability distribution over classes. To simplify notation we can reshape the pixel locations into a linear sequence and replace $z[X, Y]$ by $z[T]$ with $T = X \times Y$so we have $z[0], z[1], \ldots, z[T-1]$.

Define

$$S_t = \{c \in \mathcal{C} \; \exists t' \leq t \; z[t'] = c\}$$

For $U \subseteq S$ define

$$F[U, t] = P(S_t = U)$$

Note that for $|S| \leq 5$ there are at most 32 possible values of U. Give dynamic programming equations defining $F[U, 0]$ and defining $F[U, t+1]$ in term of $F[U', t]$ for various U'.

Solution:

$F[\emptyset, 0] = 1$
For U a nonempty subset of S $F[U, 0] = 0$
For $t = 1, \ldots, T$
  For $U \subseteq S$
    $F[U, t] = P(z[t] = \bot) F[U, t-1] + \sum_{c \in U} P(z[t] = c)(F[U \backslash c, t-1] + F[U, t-1])$