TTIC 31230, Fundamentals of Deep Learning

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Variational Auto Encoders (VAEs)

Meaningful Latent Variables: Learning Phonemes and Words

A child exposed to speech sounds learns to distinguish phonemes and then words.

The phonemes and words are "latent variables" learned from listening to sounds.

We will use y for the raw input (sound waves) and z for the latent variables (phonemes).

Other Examples

z might be a parse tree, or some other semantic representation, for an observable sentence (word string) y.

z might be a segmentation of an image y.

z might be a depth map (or 3D representation) of an image y.

z might be a class label for an image y.

Here we are interested in the case where z is **latent** in the sense that we do not have training labels for z.

We want reconstructions of z from y to emerge from observations of y alone.

Latent Variables

Here we often think of z as the causal source of y.

z might be a physical scene causing image y.

z might be a word sequence causing speech sound y.

To initially simplify the discussion, we consider models $P_\Phi(z)P_\Phi(y|z)$ where all variables are discrete.

For example, z might be a parse tree and y the resulting word sequence.

Latent Variables

$$P_\Phi(y) = \sum_z P_\Phi(z)P_\Phi(y|z) = E_{z \sim P_\Phi(z)}\, P_\Phi(y|z)$$

$P_\Phi(z)$ is the prior.

$P_\Phi(z|y)$ is the posterior where y is the “evidence”.

Assumptions

We assume models $P_\Phi(z)$ and $P_\Phi(y|z)$ are both samplable and computable.

In other words, we can sample from these distributions and for any given z and y we can compute $P_\Phi(z)$ and $P_\Phi(y|z)$.

These assumptions hold for auto-regressive models (language).

However, they fail for loopy graphical models where approximations must be used.

Modeling y

We would like to use cross-entropy.

$$\Phi^* = \operatorname*{argmin}_{\Phi} \; E_{y \sim \mathrm{pop}} \; -\ln P_\Phi(y)$$

$$P_\Phi(y) = E_{z \sim P_\Phi(z)} \, P_\Phi(y|z)$$

But even when $P_\Phi(z)$ and $P_\Phi(y|z)$ are samplable and computable we cannot typically compute $P_\Phi(y)$ or $P_\Phi(z|y)$.

Modeling y

$$\Phi^* = \operatorname*{argmin}_\Phi \; E_{y \sim \mathrm{pop}} \; -\ln P_\Phi(y)$$

$$P_\Phi(y) = E_{z \sim P_\Phi(z)} \; P_\Phi(y|z)$$

VAEs side-step the intractability problem by introducing another model component — a model $\hat{P}_\Phi(z|y)$ to approximate the intractible $P_\Phi(z|y)$.

The Evidence Lower Bound (The ELBO)

$$
\begin{aligned}
\ln P_\Phi(y) &= E_{z\sim\hat{P}_\Phi(z|y)} \ln \frac{P_\Phi(y)P_\Phi(z|y)}{P_\Phi(z|y)} \\
&= E_{z\sim\hat{P}_\Phi(z|y)} \left(\ln \frac{P_\Phi(z,y)}{\hat{P}_\Phi(z|y)} + \ln \frac{\hat{P}_\Phi(z|y)}{P_\Phi(z|y)}\right) \\
&= \left(E_{z\sim\hat{P}_\Phi(z|y)} \ln \frac{P_\Phi(z,y)}{\hat{P}_\Phi(z|y)}\right) + KL(\hat{P}_\Phi(z|y), P_\Phi(z|y)) \\
&\geq E_{z\sim\hat{P}_\Phi(z|y)} \ln \frac{P_\Phi(z,y)}{\hat{P}_\Phi(z|y)} \qquad \text{The ELBO}
\end{aligned}
$$

EM is Alternating Optimization of the ELBO

Expectation Maximimization (EM) applies in the (highly special) case where the exact posterior $P_\Phi(z|y)$ is samplable and computable. EM alternates exact optimization of Ψ and Φ in:

$$\text{VAE:} \qquad \Phi^* = \operatorname*{argmin}_{\Phi} \min_{\Psi} E_{y,\; z\sim\hat{P}_\Psi(z|y)} \quad -\ln \frac{P_\Phi(z,y)}{\hat{P}_\Psi(z|y)}$$

$$\text{EM:} \qquad \Phi^{t+1} = \operatorname*{argmin}_{\Phi} \quad E_{y,\; z\sim P_{\Phi^t}(z|y)} \; -\ln P_\Phi(z,y)$$

Inference	Update
(E Step)	(M Step)
$\hat{P}_\Psi(z\|y) = P_{\Phi^t}(z\|y)$	Hold $\hat{P}_\Psi(z\|y)$ fixed

Variational Autoencoders

$$\text{ELBO:} \qquad \ln P_\Phi(y) \;\geq\; E_{z \sim \hat{P}_\Phi(z|y)} \ln \frac{P_\Phi(z,y)}{\hat{P}_\Phi(z|y)}$$

$$= \; E_{z \sim \hat{P}_\Phi(z|y)} \ln \frac{P_\Phi(z) P_\Phi(y|z)}{\hat{P}_\Phi(z|y)}$$

$$\text{VAE:} \quad -\ln P_\Phi(y) \;\leq\; E_{z \sim \hat{P}_\Phi(z|y)} \ln \frac{\hat{P}_\Phi(z|y)}{P_\Phi(z)} - \ln P_\Phi(y|z)$$

Here $\hat{P}_\Phi(z|y)$ is the encoder and $P_\Phi(y|z)$ is the decoder and the "rate term" $E_{z|y} \ln \hat{P}_\Phi(z|y)/P_\Phi(z)$ is a KL-divergence.

VAE = RDA

$$\text{VAE:} \quad \Phi^* = \operatorname*{argmin}_\Phi E_{y\sim\mathrm{Pop},\, z\sim\hat{P}_\Phi(z|y)} \;\ln\frac{\hat{P}_\Phi(z|y)}{P_\Phi(z)} - \ln P_\Phi(y|z)$$

$P_\Phi(z)$, $P_\Phi(y|z)$ and $\hat{P}_\Phi(z|y)$ are model components and we can switch the notation to $\hat{P}_\Phi(z)$ $\hat{P}_\Phi(y|z)$ and $P_\Phi(z|y)$ with no change in the model.

$$\text{RDA:} \quad \Phi^* = \operatorname*{argmin}_\Phi \; E_{y\sim\mathrm{Pop},\, z\sim P_\Phi(z|y)} \;\ln\frac{P_\Phi(z|y)}{\hat{P}_\Phi(z)} - \ln \hat{P}_\Phi(y|z)$$

In an RDA we take $P_\Phi(y,z)$ to be $\mathrm{Pop}(y)P_\Phi(z|y)$ so that the rate term is an upper bound on $I_\Phi(y,z)$.

VAE = RDA

to be continued ...

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