A (very) brief introduction to graphical models

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Outline

The logic of generative modeling

Say we have a set of variables $\mathrm{x} = (x_1, x_2, ..., x_n)$ which might have some statistical dependence

The variable x might be an amino acid sequence, gene expression data, microscopy image, etc.

- Often we are handed a batch of empirical samples $\{\mathrm{x}_i\}_{i=1}^{N}$
- We want to know the generating distribution $p(\mathrm{x})$

In supervised generative learning, we try to explicity learn the joint distribution $p(\mathrm{x}) = \prod_{i=1}^{N-1} p(x_i|x_{i+1:N})p(x_N)$, which is generally more difficult than discriminative learning.

Primary types of graphical models

Perks of generative modeling

- Fitting complete multivariate distributions $p(\mathrm{x})$ goes beyond correlation-based or clustering approaches
- Correlations cannot discover partial correlation in the context of other neighbors
- Fitting $p(\mathrm{x})$ permits sampling based inference

Why generative modeling is difficult

When describing a distribution over multiple variables, we may not know the proper normalization Z. That is,

$$p(\mathrm{x}) = \frac{1}{Z}\tilde{p}(\mathrm{x})$$

This very important situation arises in several contexts:

1. In Bayesian inference where $p(x_1|x_2) = p(x_2|x_1)p(x_1)/p(x_2)$ is intractable due to $Z = p(x_2) = \int p(x_2|x_1)p(x_1)dx_1$. This integral can be very difficult or impossible to compute.

2. In models from statistical physics, e.g. the Ising model, we only know $\tilde{p}(\mathrm{x}) = e^{-H(\mathrm{x})}$ where $H(\mathrm{x})$ is the Hamiltonian

In image processing, graphical models are a standard technique for:

- Image denoising
- Image interpolation (resolution enhancement)
- Semantic image segmentation

In biology, graphical models are used widely in omics i.e.

- Genomics
- Transcriptomics
- Proteomics

Bayesian image reconstruction

Say a fluorophore emits photons at a rate λ_n. This is the best we can do according to QM

For a CMOS array with quantum efficiency $\gamma\ [e^-/p]$ we have

$$I_n = \gamma g_n P_n(\lambda_n) + G_n(\mu_n; \sigma_n^2) + \beta$$

where $\mu_n\ [\mathrm{ADU}]$ is the detector offset and $g_n\ [\mathrm{ADU}/e^-]$ is the gain.

All we know is λ_n, so both the true signal I_n and the detected signal $\hat{I}_n$ are stochastic processes.

$$P_\lambda(I_n, \hat{I}_n) = \frac{1}{Z}\frac{\exp\left(-\lambda_n\right)\lambda_n^p}{p!}\exp\left(-\frac{(D - g_n p - \mu_n)^2}{\sigma_n^2}\right)$$

Bayesian image reconstruction

Marginalizing over p gives the noise model as a function of the rate λ_n

$$P_\lambda(I_n) = \frac{1}{Z}\sum_p \frac{\exp\left(-\lambda_n\right)\lambda_n^p}{p!}\exp\left(-\frac{(D - g_n p - \mu_n)^2}{\sigma_n^2}\right)$$

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