Lecture 3

8/31/2023

Outline

1) Review
2) Exponential families
3) Differential identities
4) MGF

Exponential Families

An <u>s-parameter exponential family</u> is a family $\mathcal{P} = \{P_\eta : \eta \in \Xi\}$ with densities p_η wrt a common measure μ on $\mathcal{X}$ [$\mathcal{X}$ not nec. in $\mathbb{R}^n$] of the form

$$p_\eta(x) = e^{\eta' T(x) - A(\eta)} h(x) \quad , \quad \text{where}$$

$T : \mathcal{X} \to \mathbb{R}^s$ <u>sufficient statistic</u>

$h : \mathcal{X} \to \mathbb{R}$ <u>carrier / base density</u>

$\eta \in \Xi \subseteq \mathbb{R}^s$ <u>natural parameter</u>

$A : \mathbb{R}^s \to \mathbb{R}$ <u>log-partition function</u> or <u>normalizing const</u>

<u>Note</u> The function $A(\cdot)$ is totally determined by h and T, since we must always have $\int_{\mathcal{X}} p_\eta \, d\mu = 1, \ \forall \eta$.

$$\Rightarrow A(\eta) = \log \left[\int_{\mathcal{X}} e^{\eta' T(x)} h(x) \, d\mu(x) \right] \leq \infty$$

The <u>natural parameter space</u> is the set of all η that give us normalizable p_η

$$\Xi_1 = \{\eta : A(\eta) < \infty\}$$

Note Ξ_1 determined by T, h, μ

We could take $\Xi \subsetneq \Xi_1$ if we wanted

$A(\eta)$ is always convex

$$\Rightarrow \Xi_1 \text{ is convex} \quad (\text{HW 1 Prob. 2})$$

<u>Example: Poisson</u>

$$X \sim \text{Pois}(\lambda) = \frac{\lambda^x e^{-\lambda}}{x!} \qquad x \in 0, 1, \ldots$$

$$p_\lambda(x) = \exp\{(\log \lambda) x - \lambda\} \frac{1}{x!}$$

$$\eta(\lambda) = \log \lambda \qquad T(x) = x$$

$$A(\lambda) = \lambda = e^\eta \qquad h(x) = \frac{1}{x!}$$

Differential Identities

Write $e^{A(\eta)} = \int e^{\eta' T(x)} h(x)\, d\mu(x)$ $\quad (*)$

We can derive lots of useful identities by differentiating $(*)$ on both sides, pulling derivative inside $\int$ [not always allowed]

Keener Thm 2.4 for $f: \mathcal{X} \to \mathbb{R}$ let

$$\Xi_f = \{\eta \in \mathbb{R}^s : \int |f| e^{\eta' T} h\, d\mu < \infty\}$$

Then $g(\eta) = \int f e^{\eta' T} h\, d\mu$ has cts partial derivatives of all orders for $\eta \in \Xi_f^\circ$, & we can get them by differentiating under the $\int$ sign.

$\Rightarrow$ on Ξ_1°, $A(\eta)$ has all partial derivatives

Differentiate once:

$$\frac{\partial}{\partial \eta_j} e^{A(\eta)} = \frac{\partial}{\partial \eta_j} \int e^{\eta' T(x)} h(x)\, d\mu(x)$$

$$\cancel{e^{A(\eta)}} \frac{\partial A}{\partial \eta_j}(\eta) = \int T_j(x)\, e^{\eta' T(x) - A(\eta)} h(x)\, d\mu(x)$$

$$\Rightarrow \frac{\partial A}{\partial \eta_j}(\eta) = \mathbb{E}_\eta[T_j(X)]$$

$$\nabla A(\eta) = \mathbb{E}_\eta[T(X)]$$

Diff twice:

$$\frac{\partial^2}{\partial \eta_j \partial \eta_k} e^{A(\eta)} = \frac{\partial^2}{\partial \eta_j \partial \eta_k} \int e^{\eta' T} h \, d\mu$$

$$\cancel{e^{A(\eta)}} \left(\frac{\partial^2 A}{\partial \eta_j \partial \eta_k} + \underbrace{\frac{\partial A}{\partial \eta_j}}_{\mathbb{E}[T_j]} \underbrace{\frac{\partial A}{\partial \eta_k}}_{\mathbb{E}[T_k]} \right) = \underbrace{\int T_j T_k \, e^{\eta' T - A(\eta)} h \, d\mu}_{\mathbb{E}[T_j T_k]}$$

$$\frac{\partial^2 A}{\partial \eta_j \partial \eta_k}(\eta) = \mathrm{Cov}_\eta(T_j, T_k)$$

$$\nabla^2 A(\eta) = \mathrm{Var}_\eta(T(x)) \in \mathbb{R}^{s \times s}$$

Example: Poisson: $T(x) = X$, $A(\eta) = e^\eta \, (= \lambda)$

$$\mathbb{E}_\eta[X] = \frac{d}{d\eta} e^\eta = e^\eta = \lambda$$

$$\mathrm{Var}_\eta(X) = \frac{d^2}{d\eta^2} e^\eta = e^\eta = \lambda$$

NB: We would get wrong answer by differentiating wrt λ

Moment-generating function

We can get k^{th} order moments of $T(X)$ by
1) Differentiating $(*)$ k times, then
2) Dividing by $e^{A(\eta)}$

That is because $M_\eta^T(u) = e^{A(\eta+u) - A(\eta)}$
is the <u>moment-generating function</u> (<u>mgf</u>)
of $T(X)$ when $X \sim P_\eta$

$$
\begin{aligned}
M_\eta^{T(X)}(u) &= \mathbb{E}_\eta\left[e^{u'T(X)}\right] \\
&= \int e^{u'T} e^{\eta'T - A(\eta)} h \, d\mu \\
&= e^{A(\eta+u) - A(\eta)} \underbrace{\int e^{(\eta+u)'T - A(\eta+u)} h \, d\mu}_{=1}
\end{aligned}
$$

Useful for
- finding moments
- finding dist. of sums of indep. RVs

Cumulant-generating function

$K_\eta^T(u) = \log M_\eta^T(u) = A(\eta+u) - A(\eta)$ (A is sometimes called cgf)

Other Parameterizations

Sometimes it is more convenient to use a different parameterization:

$$p_\theta(x) = e^{\eta(\theta)' T(x) - B(\theta)} h(x)$$

$$B(\theta) = A(\eta(\theta))$$

Many, many examples, sometimes requires massaging to see that they are exp. fam.s:

Ex: Normal $\quad X \sim N(\mu, \sigma^2) \quad \mu \in \mathbb{R} \quad \sigma^2 > 0$

Let $\theta = (\mu, \sigma^2)$

$$p_\theta(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-(\mu - x)^2 / 2\sigma^2}$$

$$= \exp\left\{ \frac{\mu}{\sigma^2} x - \frac{1}{2\sigma^2} x^2 - \frac{\mu^2}{2\sigma^2} - \frac{1}{2}\log(2\pi\sigma^2) \right\}$$

$$\eta(\theta) = \begin{pmatrix} \mu/\sigma^2 \\ -1/2\sigma^2 \end{pmatrix} \qquad T(x) = \begin{pmatrix} x \\ x^2 \end{pmatrix} \qquad h(x) = 1$$

$$B(\theta) = \frac{\mu^2}{2\sigma^2} + \frac{1}{2}\log(2\pi\sigma^2)$$

Natural parameterization

$$p_\eta(x) = e^{\eta' \binom{x}{x^2} - A(\eta)}$$

$$A(\eta) = \frac{-\eta_1^2}{4\eta_2} + \frac{1}{2}\log\left(-\pi/\eta_2\right)$$

More examples

Binomial

$X \sim \mathrm{Binom}(n, \theta)$

$$p_\theta(x) = \theta^x (1-\theta)^{n-x} \binom{n}{x} \qquad x = 0, \ldots, n$$

$$= \left(\frac{\theta}{1-\theta}\right)^x (1-\theta)^n \binom{n}{x}$$

$$= \exp\left\{ \log\left(\frac{\theta}{1-\theta}\right) \cdot x + n \log(1-\theta) \right\} \binom{n}{x}$$

$$\eta(\theta) = \log\left(\frac{\theta}{1-\theta}\right) \qquad \text{"log odds ratio"}$$

Beta

$X \sim \mathrm{Beta}(\alpha, \beta)$

$$p_{\alpha,\beta}(x) = x^{\alpha-1} (1-x)^{\beta-1} / B(\alpha, \beta)$$

Beta function

$$= \exp\{ \alpha \log x + \beta \log(1-x) - \log B(\alpha, \beta) \} \frac{1}{x(1-x)}$$

$$\eta = \begin{pmatrix} \alpha \\ \beta \end{pmatrix} \quad T(x) = \begin{pmatrix} \log x \\ \log(1-x) \end{pmatrix} \quad h(x) = \frac{1}{x(1-x)}$$

Practically everything else on wikipedia too:

Beta, Gamma, Multinom., Dirichlet, Pareto, Wishart...

Interpretation: Exponential tilting

Can think of $p_\eta(x) = e^{\eta' T(x) - A(\eta)} h(x)$ as an <u>exponential tilt</u> of the carrier $h(x)$

1) Start with carrier $h(x)$
2) Multiply by $e^{\eta' T(x)}$
3) Re-normalize by $e^{-A(\eta)}$

$T(x) = \left(T_1(x), \ldots, T_s(x)\right)$ gives linear space of directions in which we can tilt $h(x)$

Ξ_1 = all tilts after which normalization is possible

$\Rightarrow$ Decomposition into η, T, h, A very non-unique

1) Only $\text{span}(T_1, \ldots, T_s)$ matters
2) Could absorb h into μ $\left(d\nu(x) = h \, d\mu(x)\right)$
   (wlog $h(x) \equiv 1$ if we want)
3) Can add constant to $T(x)$

Repeated Sampling

Suppose $X_1, \dots, X_n \overset{iid}{\sim} p_\eta^{(1)}(x) = e^{\eta' T(x) - A(\eta)} h(x)$

Then $X = (X_1, \dots, X_n)$ comes from a closely related family

$$p_\eta^{(n)}(x) = \prod_{i=1}^n e^{\eta' T(x_i) - A(\eta)} h(x_i)$$

$$= \exp\Big\{ \eta' \underbrace{\sum_{i=1}^n T(x_i)}_{\text{suff stat.}} - \underbrace{n A(\eta)}_{\text{log-part. fcn.}} \Big\} \underbrace{\prod_{i=1}^n h(x_i)}_{\substack{\text{carrier density} \\ (\text{wrt } \mu^n \text{ on } \mathcal{X}^n)}}$$

Important property!

This means $\sum_{i=1}^n T(X_i) \in \mathbb{R}^s$ is an effective summary of a potentially very large sample $X \in \mathcal{X}^n$

We will often analyze $T(X)$ as a proxy for the whole data set.

Distribution of $T(X)$

Suppose $X \sim p_\eta(x) = e^{\eta' T(x) - A(\eta)}$ wrt μ

(wlog $h \equiv 1$)

Then $T(X) \sim q_\eta(t) = e^{\eta' t - A(\eta)}$ wrt ν,

where ν is the measure μ "pushed forward" through $T: \mathcal{X} \to \mathbb{R}^s$

$$\nu(B) \triangleq \mu(\{x : T(x) \in B\})$$

$$\mathbb{P}_\eta(T(X) \in B) = \int 1_B(T(x)) e^{\eta' T(x) - A(\eta)} d\mu(x)$$

$$= \int 1_B(t) e^{\eta' t - A(\eta)} d\nu(t)$$

Simplest in discrete case: (drop $h \equiv 1$ assumption)

$$\mathbb{P}_\eta(T(X) = t) = \sum_{x : T(x) = t} e^{\eta' T(x) - A(\eta)} h(x) \mu(\{x\})$$

$$= e^{\eta' t - A(\eta)} \underbrace{\sum_{x : T(x) = t} h(x) \mu(\{x\})}_{\nu(\{t\})}$$