

AMS 241: Bayesian Nonparametric Methods

Notes 2 – Dirichlet process mixture models

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Outline

- 1 Introduction
- 2 Dirichlet process mixtures: definitions and model properties
- 3 Posterior simulation methods
- 4 Applications

Motivating Dirichlet process mixtures

- Recall that the Dirichlet process (DP) is a conjugate prior for random distributions under i.i.d. sampling.
- However, posterior draws under a DP model correspond (almost surely) to discrete distributions. This is somewhat unsatisfactory if we are modeling continuous data ...
- In the spirit of kernel density estimation, one solution is to use convolutions to smooth out posterior estimates.
- In a model-based context, this leads to DP mixture models, i.e., a mixture model where the mixing distribution is unknown and assigned a DP prior (recall that this is different from a mixture of DPs, in which the parameters of the DP are random).
- Strong connection with finite mixture models.
- More generally, we might be interested in using a DP as part of a hierarchical Bayesian model to place a prior on the unknown distribution of some of its parameters (e.g., random effects models). This leads to semiparametric Bayesian models.

Mixture distributions

- Mixture models arise naturally as flexible alternatives to standard parametric families.
- Continuous mixture models (e.g., t , Beta-binomial, and Poisson-gamma models) typically achieve increased heterogeneity but are still limited to unimodality and usually symmetry.
- Finite mixture distributions provide more flexible modeling, and are now relatively easy to implement, using simulation-based model fitting (e.g., Richardson and Green, 1997; Stephens, 2000; Jasra, Holmes and Stephens, 2005).
- Rather than handling the very large number of parameters of finite mixture models with a large number of mixture components, it may be easier to work with an infinite dimensional specification by assuming a random mixing distribution, which is not restricted to a specified parametric family.

Finite mixture models

- Recall the structure of a finite mixture model with K components, for example, a mixture of $K = 2$ Gaussian densities:

$$y_i \mid w, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2 \stackrel{\text{ind.}}{\sim} wN(y_i \mid \mu_1, \sigma_1^2) + (1 - w)N(y_i \mid \mu_2, \sigma_2^2),$$

that is, observation y_i arises from a $N(\mu_1, \sigma_1^2)$ distribution with probability w or from a $N(\mu_2, \sigma_2^2)$ distribution with probability $1 - w$ (independently for each $i = 1, \dots, n$, given the parameters).

- In the Bayesian setting, we also set priors for the unknown parameters

$$(w, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2) \sim p(w, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2).$$

Finite mixture models

- The model can be rewritten in a few different ways. For example, we can introduce auxiliary random variables L_1, \dots, L_n such that $L_i = 1$ if y_i arises from the $N(\mu_1, \sigma_1^2)$ component (component 1) and $L_i = 2$ if y_i is drawn from the $N(\mu_2, \sigma_2^2)$ component (component 2). Then, the model can be written as

$$\begin{aligned}y_i \mid L_i, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2 &\stackrel{\text{ind.}}{\sim} N(y_i \mid \mu_{L_i}, \sigma_{L_i}^2) \\ P(L_i = 1 \mid w) &= w = 1 - P(L_i = 2 \mid w) \\ (w, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2) &\sim p(w, \mu_1, \mu_2, \sigma_1^2, \sigma_2^2)\end{aligned}$$

- If we marginalize over L_i , for $i = 1, \dots, n$, we recover the original mixture formulation.
- The inclusion of indicator variables is very common in finite mixture models, and it is also used extensively for DP mixtures.

Finite mixture models

- We can also write

$$wN(y_i | \mu_1, \sigma_1^2) + (1 - w)N(y_i | \mu_2, \sigma_2^2) = \int N(y_i | \mu, \sigma^2) dG(\mu, \sigma^2),$$

where

$$G(\cdot) = w\delta_{(\mu_1, \sigma_1^2)}(\cdot) + (1 - w)\delta_{(\mu_2, \sigma_2^2)}(\cdot).$$

- A similar expression can be used for a general K mixture model.
- Note that G is discrete (and random) — a natural alternative is to use a DP prior for G , resulting in a Dirichlet process mixture (DPM) model, or more general nonparametric priors for discrete distributions.
- Working with a countable mixture (rather than a finite one) provides theoretical advantages (full support) as well as practical benefits: the number of mixture components is estimated from the data based on a model that supports a countable number of components in the prior.

Definition of the Dirichlet process mixture model

- The **Dirichlet process mixture model**

$$F(\cdot | G) = \int K(\cdot | \theta) dG(\theta), \quad G \sim \text{DP}(\alpha, G_0),$$

where $K(\cdot | \theta)$ is a parametric distribution function indexed by θ .

- The Dirichlet process has been the most widely used prior for the random mixing distribution G , following the early work by Antoniak (1974), Lo (1984) and Ferguson (1983).
- Corresponding mixture density (or probability mass) function,

$$f(\cdot | G) = \int k(\cdot | \theta) dG(\theta),$$

where $k(\cdot | \theta)$ is the density (or probability mass) function of $K(\cdot | \theta)$.

- Because G is random, the c.d.f. $F(\cdot | G)$ and the density function $f(\cdot | G)$ are random (Bayesian nonparametric mixture models).

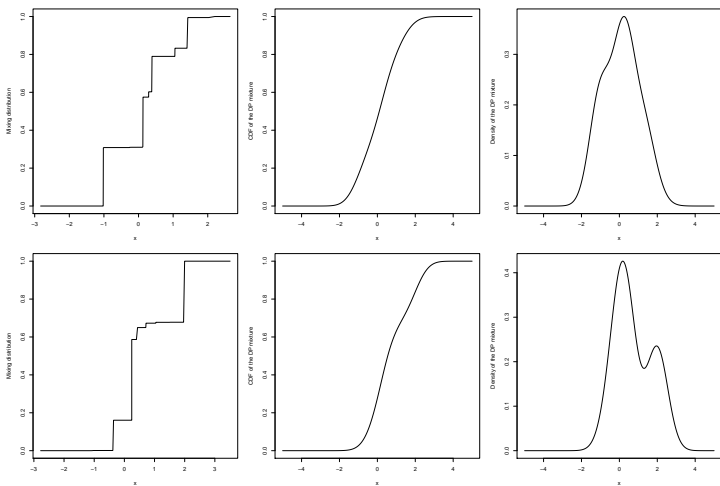


Figure 2.1: Two realizations from a $DP(\alpha = 2, G_0 = N(0, 1))$ (left column) and the associated cumulative distribution function (center column) and density function (right column) for a location DP mixture of Gaussian kernels with standard deviation 0.6.

An equivalent formulation

- In the context of DP mixtures, the (almost sure) discreteness of realizations G from the $\text{DP}(\alpha, G_0)$ prior is an asset — it allows ties in the mixing parameters, and thus makes DP mixture models appealing for many applications, including density estimation and regression.
- Using the constructive definition of the DP, $G = \sum_{\ell=1}^{\infty} \omega_{\ell} \delta_{\vartheta_{\ell}}$, the prior probability model $f(\cdot | G)$ admits an (almost sure) representation as a countable mixture of parametric densities,

$$f(\cdot | G) = \sum_{\ell=1}^{\infty} \omega_{\ell} k(\cdot | \vartheta_{\ell})$$

- *Weights:* $\omega_1 = z_1$, $\omega_{\ell} = z_{\ell} \prod_{r=1}^{\ell-1} (1 - z_r)$, $\ell \geq 2$, with z_r i.i.d. $\text{Beta}(1, \alpha)$.
- *Locations:* ϑ_{ℓ} i.i.d. G_0 (and the sequences $\{z_r : r = 1, 2, \dots\}$ and $\{\vartheta_{\ell} : \ell = 1, 2, \dots\}$ are independent).

Support of Dirichlet process mixture models

- Contrary to DP prior models, DP mixtures can model
 - discrete distributions (e.g., $K(\cdot | \theta)$ might be Poisson or binomial)
 - and continuous distributions, either univariate ($K(\cdot | \theta)$ can be, e.g., normal, gamma, or uniform) or multivariate (with $K(\cdot | \theta)$, say, multivariate normal).
- Much more than just density estimation:
 - Non-Gaussian and non-linear regression through DP mixture modeling for the joint response-covariate distribution.
 - Flexible models for ordinal categorical responses.
 - Modeling of point process intensities through density estimation.
 - Time-series and/or spatial modeling, using dependent DP priors for temporally and/or spatially dependent mixing distributions.

Support of Dirichlet process mixture models

- Several approximation or representation results for mixtures.
 - (Discrete) normal location-scale mixtures, $\sum_{j=1}^M w_j \mathbf{N}(\cdot \mid \mu_j, \sigma_j^2)$, can approximate arbitrarily well (as $M \rightarrow \infty$) any density on the real line (Ferguson, 1983; Lo, 1984).
 - The c.d.f. of the Erlang mixture, $\sum_{j=1}^J w_j \text{gamma}(t \mid j, \varphi)$, converges pointwise to any continuous c.d.f. $H(t)$ on \mathbb{R}^+ , as $J \rightarrow \infty$ and the common scale parameter $\varphi \rightarrow 0$ (set $w_j = H(j\theta) - H((j-1)\theta)$).
 - As $K \rightarrow \infty$, the Bernstein density, $\sum_{j=1}^K w_j \text{Beta}(u \mid j, K - j + 1)$, converges uniformly to any continuous density $h(u)$ (with c.d.f. H) on $(0, 1)$ (set $w_j = H(j/K) - H((j-1)/K)$).
 - For any non-increasing density $f(t)$ on the positive real line there exists a distribution function G such that f can be represented as a scale mixture of uniform densities, i.e., $f(t) = \int \theta^{-1} \mathbf{1}_{[0, \theta]}(t) dG(\theta)$ — the result yields flexible DP mixture models for symmetric unimodal densities (Brunner and Lo, 1989; Brunner, 1995) as well as general unimodal densities (Brunner, 1992; Lavine and Mockus, 1995; Kottas and Gelfand, 2001; Kottas and Krnjajić, 2009).

Support of Dirichlet process mixture models

- Results on Kullback-Leibler support for various types of DP mixture models (e.g., Wu and Ghosal, 2008).
- Consider the space of densities defined on sample space \mathcal{X} .
- For any density f_0 in that space, the Kullback-Leibler neighborhood of size $\varepsilon > 0$ is given by

$$K_\varepsilon(f_0) = \left\{ f : \int f_0(x) \log \left(\frac{f_0(x)}{f(x)} \right) dx < \varepsilon \right\}$$

- A nonparametric prior model for densities satisfies the Kullback-Leibler property if it assigns positive probability to $K_\varepsilon(f_0)$ for any density f_0 in the space of interest, and for any $\varepsilon > 0$ (e.g., Walker, Damien and Lenk, 2004).

Semiparametric Dirichlet process mixture models

- Typically, semiparametric DP mixtures are employed

$$y_i | G, \phi \stackrel{i.i.d.}{\sim} f(\cdot | G, \phi) = \int k(\cdot | \theta, \phi) dG(\theta), \quad i = 1, \dots, n,$$

$$G \sim \text{DP}(\alpha, G_0),$$

with a parametric prior $p(\phi)$ placed on ϕ (and, perhaps, hyperpriors for α and/or the parameters ψ of $G_0 \equiv G_0(\cdot | \psi)$).

- Hierarchical formulation** for DP mixture models: introduce latent mixing parameter θ_i associated with y_i ,

$$y_i | \theta_i, \phi \stackrel{ind.}{\sim} k(y_i | \theta_i, \phi), \quad i = 1, \dots, n,$$

$$\theta_i | G \stackrel{i.i.d.}{\sim} G, \quad i = 1, \dots, n,$$

$$G | \alpha, \psi \sim \text{DP}(\alpha, G_0(\cdot | \psi)),$$

$$\phi, \alpha, \psi \sim p(\phi)p(\alpha)p(\psi)$$

Connection with finite mixture models

- The countable sum formulation of the DP mixture model has motivated the study of several variants and extensions.
- It also provides a link between limits of finite mixtures, with prior for the weights given by a symmetric Dirichlet distribution, and DP mixture models (e.g., Ishwaran and Zarepour, 2000).
- Consider the finite mixture model with K components:

$$\sum_{t=1}^K q_t k(y | \vartheta_t),$$

with $(q_1, \dots, q_K) \sim \text{Dir}(\alpha/K, \dots, \alpha/K)$ and $\vartheta_t \stackrel{i.i.d.}{\sim} G_0$, $t = 1, \dots, K$.

- When $K \rightarrow \infty$, this model corresponds to a DP mixture with kernel k and a $\text{DP}(\alpha, G_0)$ prior for the mixing distribution.
 - As $K \rightarrow \infty$, $\sum_{t=1}^K q_t \delta_{\vartheta_t}$ converges weakly to $\sum_{\ell=1}^{\infty} \omega_{\ell} \delta_{\vartheta_{\ell}} \sim \text{DP}(\alpha, G_0)$.

Prior specification

- Taking expectation over G with respect to its DP prior $DP(\alpha, G_0)$, we obtain:

$$E\{F(\cdot | G, \phi)\} = F(\cdot | G_0, \phi), \quad E\{f(\cdot | G, \phi)\} = f(\cdot | G_0, \phi).$$

- These expressions facilitate prior specification for the parameters ψ of $G_0(\cdot | \psi)$.
- On the other hand, recall that for the $DP(\alpha, G_0)$, α controls how *close* a realization G is to G_0 , but also the extent of discreteness of G .
- In the DP mixture model, α controls the prior distribution of the number of distinct elements n^* of the vector $\theta = (\theta_1, \dots, \theta_n)$, and hence the number of distinct components of the mixture that appear in a sample of size n (Antoniak, 1974; Escobar and West, 1995; Liu, 1996).

Prior specification

- In particular,

$$\Pr(n^* = m \mid \alpha) = c_n(m) n! \alpha^m \frac{\Gamma(\alpha)}{\Gamma(\alpha + n)}, \quad m = 1, \dots, n,$$

where the factors $c_n(m) = \Pr(n^* = m \mid \alpha = 1)$ can be computed using certain recurrence formulas (Stirling numbers) (Escobar and West, 1995).

- If α is assigned a prior $p(\alpha)$, $\Pr(n^* = m) = \int \Pr(n^* = m \mid \alpha) p(\alpha) d\alpha$.
- Moreover, for moderately large n ,

$$E(n^* \mid \alpha) = \alpha \sum_{k=1}^n \frac{1}{\alpha + k - 1} \approx \alpha \log \left(\frac{\alpha + n}{\alpha} \right)$$

which can be further averaged over the prior for α to obtain a prior estimate for $E(n^*)$.

Prior specification

- Two *limiting* special cases of the DP mixture model.
 - One distinct component, when $\alpha \rightarrow 0^+$

$$\begin{aligned}y_i | \theta, \phi &\stackrel{ind.}{\sim} k(y_i | \theta, \phi), & i = 1, \dots, n \\ \theta | \psi &\sim G_0(\cdot | \psi) \\ \phi, \psi &\sim p(\phi)p(\psi)\end{aligned}$$

- n components (one associated with each observation), when $\alpha \rightarrow \infty$

$$\begin{aligned}y_i | \theta_i, \phi &\stackrel{ind.}{\sim} k(y_i | \theta_i, \phi), & i = 1, \dots, n \\ \theta_i | \psi &\stackrel{i.i.d.}{\sim} G_0(\cdot | \psi), & i = 1, \dots, n \\ \phi, \psi &\sim p(\phi)p(\psi)\end{aligned}$$

Methods for posterior inference

- Data = $\{y_i, i = 1, \dots, n\}$ i.i.d., conditionally on G and ϕ , from $f(\cdot | G, \phi)$. (If the model includes a regression component, the data also include the covariate vectors \mathbf{x}_i , and, in such cases, ϕ , typically, includes the vector of regression coefficients).
- Interest in inference for the latent mixing parameters $\boldsymbol{\theta} = (\theta_1, \dots, \theta_n)$, for ϕ (and the hyperparameters α, ψ), for $f(y_0 | G, \phi)$, and, in general, for functionals $H(F(\cdot | G, \phi))$ of the random mixture $F(\cdot | G, \phi)$ (e.g., c.d.f. function, hazard function, mean and variance functionals, percentile functionals).
- Full and exact inference, given the data, for all these random quantities is based on the joint posterior distribution of the DP mixture model

$$p(G, \phi, \boldsymbol{\theta}, \alpha, \psi | \text{data})$$

Marginal posterior simulation methods

- Key result: representation of the joint posterior distribution

$$p(G, \phi, \boldsymbol{\theta}, \alpha, \psi \mid \text{data}) = p(G \mid \boldsymbol{\theta}, \alpha, \psi) p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$$

- $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$ is the marginal posterior for the finite-dimensional portion of the full *parameter vector* $(G, \phi, \boldsymbol{\theta}, \alpha, \psi)$.
- $G \mid \boldsymbol{\theta}, \alpha, \psi \sim \text{DP}(\tilde{\alpha}, \tilde{G}_0)$, where $\tilde{\alpha} = \alpha + n$, and

$$\tilde{G}_0(\cdot) = \frac{\alpha}{\alpha + n} G_0(\cdot \mid \psi) + \frac{1}{\alpha + n} \sum_{i=1}^n \delta_{\theta_i}(\cdot).$$

(Hence, the c.d.f., $\tilde{G}_0(t) = \frac{\alpha}{\alpha+n} G_0(t \mid \psi) + \frac{1}{\alpha+n} \sum_{i=1}^n \mathbf{1}_{[\theta_i, \infty)}(t)$).

- Sampling from the $\text{DP}(\tilde{\alpha}, \tilde{G}_0)$ is possible using one of its definitions — thus, we can obtain full posterior inference under DP mixture models if we sample from the marginal posterior $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$.

Marginal posterior simulation methods

- The marginal posterior $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$ corresponds to the marginalized version of the DP mixture model, obtained after integrating G over its DP prior (Blackwell and MacQueen, 1973),

$$y_i \mid \theta_i, \phi \stackrel{\text{ind.}}{\sim} k(y_i \mid \theta_i, \phi), \quad i = 1, \dots, n$$

$$\boldsymbol{\theta} = (\theta_1, \dots, \theta_n) \mid \alpha, \psi \sim p(\boldsymbol{\theta} \mid \alpha, \psi),$$

$$\phi, \alpha, \psi \sim p(\phi)p(\alpha)p(\psi).$$

- The induced prior distribution $p(\boldsymbol{\theta} \mid \alpha, \psi)$ for the mixing parameters θ_i can be developed by exploiting the Pólya urn characterization of the DP,

$$p(\boldsymbol{\theta} \mid \alpha, \psi) = G_0(\theta_1 \mid \psi) \prod_{i=2}^n \left\{ \frac{\alpha}{\alpha + i - 1} G_0(\theta_i \mid \psi) + \frac{1}{\alpha + i - 1} \sum_{j=1}^{i-1} \delta_{\theta_j}(\theta_i) \right\}.$$

- For increasing sample sizes, the joint prior $p(\boldsymbol{\theta} \mid \alpha, \psi)$ gets increasingly complex to work with.

Marginal posterior simulation methods

- The marginal prior $p(\theta \mid \alpha, \psi)$ can be written in an equivalent form which makes explicit the partitioning (clustering) induced by the discreteness of the DP prior (Antoniak, 1974; Lo, 1984).
- As is essentially always the case for DP mixtures, assume that G_0 is continuous (so that ties can only arise by setting θ_i equal to θ_j , $j < i$).
- Denote by $\pi = \{s_j : j = 1, \dots, n^*\}$ a generic partition of $\{1, \dots, n\}$, where: n^* is the number of cells of the partition; n_j is the number of elements in cell s_j ; $e_{j,1} < \dots < e_{j,n_j}$ are the elements of cell s_j .
- Letting \mathcal{P} denote the set of all partitions of $\{1, \dots, n\}$,

$$p(\theta \mid \alpha, \psi) = \sum_{\pi \in \mathcal{P}} p(\pi \mid \alpha) \prod_{j=1}^{n^*} G_0(\theta_{e_{j,1}} \mid \psi) \prod_{i=2}^{n_j} \delta_{\theta_{e_{j,1}}}(\theta_{e_{j,i}})$$

where $p(\pi \mid \alpha)$ is the DP induced prior probability for partition π ,

$$p(\pi \mid \alpha) = \left(\prod_{m=1}^n (\alpha + m - 1) \right)^{-1} \alpha^{n^*} \prod_{j=1}^{n^*} (n_j - 1)!$$

Marginal posterior simulation methods

- Therefore, the marginal posterior

$$p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data}) \propto p(\boldsymbol{\theta} \mid \alpha, \psi)p(\phi)p(\alpha)p(\psi) \prod_{i=1}^n k(y_i \mid \theta_i, \phi)$$

is difficult to work with — even point estimates practically impossible to compute for moderate to large sample sizes.

- Early work for posterior inference:
 - Some results for certain problems in density estimation, i.e., expressions for Bayes point estimates of $f(y_0 \mid G)$ (e.g., Lo, 1984; Brunner and Lo, 1989).
 - Approximations for special cases, e.g., for binomial DP mixtures (Berry and Christensen, 1979).
 - Monte Carlo integration algorithms to obtain point estimates for the θ_i (Ferguson, 1983; Kuo, 1986a,b).

Simulation-based model fitting

- Note that, although the joint prior $p(\boldsymbol{\theta} \mid \alpha, \psi)$ has an awkward expression for samples of realistic size n , the prior full conditionals have convenient expressions:

$$p(\theta_i \mid \{\theta_j : j \neq i\}, \alpha, \psi) = \frac{\alpha}{\alpha + n - 1} G_0(\theta_i \mid \psi) + \frac{1}{\alpha + n - 1} \sum_{j=1}^{n-1} \delta_{\theta_j}(\theta_i).$$

- Key idea** (Escobar, 1988; 1994): setup a Markov chain to explore the posterior $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$ by simulating only from posterior full conditional distributions, which arise by combining the likelihood terms with the corresponding prior full conditionals (in fact, Escobar's algorithm is essentially a Gibbs sampler developed for a specific class of models!).
- Several other Markov chain Monte Carlo (MCMC) methods that improve on the original algorithm (e.g., West et al., 1994; Escobar and West, 1995; Bush and MacEachern, 1996; Neal, 2000; Jain and Neal, 2004).

Simulation-based model fitting

- A key property for the implementation of the Gibbs sampler is the discreteness of G , which induces a clustering of the θ_i .
 - n^* : number of distinct elements (clusters) in the vector $(\theta_1, \dots, \theta_n)$.
 - $\theta_j^*, j = 1, \dots, n^*$: the distinct θ_i .
 - $\mathbf{w} = (w_1, \dots, w_n)$: vector of configuration indicators, defined by $w_i = j$ if and only if $\theta_i = \theta_j^*, i = 1, \dots, n$.
 - n_j : size of j -th cluster, i.e., $n_j = |\{i : w_i = j\}|, j = 1, \dots, n^*$.
- $(n^*, \mathbf{w}, (\theta_1^*, \dots, \theta_{n^*}^*))$ is equivalent to $(\theta_1, \dots, \theta_n)$.
- Standard Gibbs sampler to draw from $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$ (Escobar and West, 1995) is based on the following full conditionals:
 - 1 $p(\theta_i \mid \{\theta_{i'} : i' \neq i\}, \alpha, \psi, \phi, \text{data})$, for $i = 1, \dots, n$.
 - 2 $p(\phi \mid \{\theta_i : i = 1, \dots, n\}, \text{data})$.
 - 3 $p(\psi \mid \{\theta_j^* : j = 1, \dots, n^*\}, n^*, \text{data})$.
 - 4 $p(\alpha \mid n^*, \text{data})$.

(The expressions include conditioning only on the relevant variables, exploiting the conditional independence structure of the model and properties of the DP).

Simulation-based model fitting

- 1 For each $i = 1, \dots, n$, $p(\theta_i \mid \{\theta_{i'} : i' \neq i\}, \alpha, \psi, \phi, \text{data})$ is simply a mixture of n^{*-} point masses and the posterior for θ_i based on y_i ,

$$\frac{\alpha q_0}{\alpha q_0 + \sum_{j=1}^{n^{*-}} n_j^- q_j} h(\theta_i \mid \psi, \phi, y_i) + \sum_{j=1}^{n^{*-}} \frac{n_j^- q_j}{\alpha q_0 + \sum_{j=1}^{n^{*-}} n_j^- q_j} \delta_{\theta_j^{*-}}(\theta_i).$$

- $q_j = k(y_i \mid \theta_j^{*-}, \phi)$
- $q_0 = \int k(y_i \mid \theta, \phi) g_0(\theta \mid \psi) d\theta$
- $h(\theta_i \mid \psi, \phi, y_i) \propto k(y_i \mid \theta_i, \phi) g_0(\theta_i \mid \psi)$
- g_0 is the density of G_0
- The superscript “-” denotes all relevant quantities when θ_i is removed from the vector $(\theta_1, \dots, \theta_n)$, e.g., n^{*-} is the number of clusters in $\{\theta_{i'} : i' \neq i\}$.
- Updating θ_i implicitly updates w_i , $i = 1, \dots, n$; before updating θ_{i+1} , we redefine n^* , θ_j^* for $j = 1, \dots, n^*$, w_i for $i = 1, \dots, n$, and n_j , for $j = 1, \dots, n^*$.

Simulation-based model fitting

- 2 The posterior full conditional for ϕ does not involve the nonparametric part of the DP mixture model,

$$p(\phi \mid \{\theta_i : i = 1, \dots, n\}, \text{data}) \propto p(\phi) \prod_{i=1}^n k(y_i \mid \theta_i, \phi).$$

- 3 Regarding the parameters ψ of G_0 ,

$$p(\psi \mid \{\theta_j^*, j = 1, \dots, n^*\}, n^*, \text{data}) \propto p(\psi) \prod_{j=1}^{n^*} g_0(\theta_j^* \mid \psi),$$

leading, typically, to standard updates.

Simulation-based model fitting

- Although the posterior full conditional for α is not of a standard form, an augmentation method facilitates sampling if α has a gamma prior (say, with mean a_α/b_α) (Escobar and West, 1995),

$$\begin{aligned} p(\alpha \mid n^*, \text{data}) &\propto p(\alpha) \alpha^{n^*} \frac{\Gamma(\alpha)}{\Gamma(\alpha + n)} \\ &\propto p(\alpha) \alpha^{n^* - 1} (\alpha + n) \text{Beta}(\alpha + 1, n) \\ &\propto p(\alpha) \alpha^{n^* - 1} (\alpha + n) \int_0^1 \eta^\alpha (1 - \eta)^{n-1} d\eta \end{aligned}$$

- Introduce an auxiliary variable η such that

$$p(\alpha, \eta \mid n^*, \text{data}) \propto p(\alpha) \alpha^{n^* - 1} (\alpha + n) \eta^\alpha (1 - \eta)^{n-1}$$

- Extend the Gibbs sampler to draw $\eta \mid \alpha, \text{data} \sim \text{Beta}(\alpha + 1, n)$, and $\alpha \mid \eta, n^*, \text{data}$ from the two-component gamma mixture:

$$\epsilon \text{gamma}(a_\alpha + n^*, b_\alpha - \log(\eta)) + (1 - \epsilon) \text{gamma}(a_\alpha + n^* - 1, b_\alpha - \log(\eta))$$

where $\epsilon = (a_\alpha + n^* - 1) / \{n(b_\alpha - \log(\eta)) + a_\alpha + n^* - 1\}$.

Improved marginal Gibbs sampler

- (West et al., 1994; Bush and MacEachern, 1996): adds one more step where the cluster locations θ_j^* are resampled at each iteration to improve the mixing of the chain.
- At each iteration, once step (1) is completed, we obtain a specific number of clusters n^* and configuration $\mathbf{w} = (w_1, \dots, w_n)$.
- After the marginalization over G , the prior for the θ_j^* , given the partition (n^*, \mathbf{w}) , is given by $\prod_{j=1}^{n^*} g_0(\theta_j^* | \psi)$, i.e., given n^* and \mathbf{w} , the θ_j^* are i.i.d. from G_0 .
- Hence, for each $j = 1, \dots, n^*$, the posterior full conditional

$$p(\theta_j^* | \mathbf{w}, n^*, \psi, \phi, \text{data}) \propto g_0(\theta_j^* | \psi) \prod_{\{i:w_i=j\}} k(y_i | \theta_j^*, \phi).$$

Alternative computational schemes

- The Gibbs sampler can be difficult or inefficient to implement if:
 - The integral $\int k(y | \theta, \phi) g_0(\theta | \psi) d\theta$ is not available in closed form (and numerical integration is not feasible or reliable).
 - Random generation from $h(\theta | \psi, \phi, y) \propto k(y | \theta, \phi) g_0(\theta | \psi)$ is not readily available.
- For such cases, alternative MCMC algorithms have been proposed in the literature (e.g., MacEachern and Müller, 1998; Neal, 2000; Dahl, 2005; Jain and Neal, 2007).
- Extensions for data structures that include missing or censored observations are also possible (Kuo and Smith, 1992; Kuo and Mallick, 1997; Kottas, 2006).
- Alternative (to MCMC) fitting techniques have also been studied (e.g., Liu, 1996; MacEachern et al., 1999; Newton and Zhang, 1999; Naskar and Das, 2004; Blei and Jordan, 2006; Zobay, 2009; Carvalho et al., 2010).

Posterior predictive distributions

- Implementing one of the available MCMC algorithms for DP mixture models, we obtain B posterior samples

$$\{\boldsymbol{\theta}_b = (\theta_{ib} : i = 1, \dots, n), \alpha_b, \psi_b, \phi_b\}, \quad b = 1, \dots, B,$$

from $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$.

- Or, equivalently, posterior samples

$$\{n_b^*, \mathbf{w}_b, \boldsymbol{\theta}_b^* = (\theta_{jb}^* : j = 1, \dots, n_b^*), \alpha_b, \psi_b, \phi_b\}, \quad b = 1, \dots, B,$$

from $p(n^*, \mathbf{w}, \boldsymbol{\theta}^* = (\theta_j^* : j = 1, \dots, n^*), \phi, \alpha, \psi \mid \text{data})$.

- Bayesian *density estimate* is based on the posterior predictive density $p(y_0 \mid \text{data})$ corresponding to a *new* y_0 (with associated θ_0).

Posterior predictive distributions

- Using, again, the Pólya urn structure for the DP,

$$p(\theta_0 \mid n^*, \mathbf{w}, \boldsymbol{\theta}^*, \alpha, \psi) = \frac{\alpha}{\alpha + n} g_0(\theta_0 \mid \psi) + \frac{1}{\alpha + n} \sum_{j=1}^{n^*} n_j \delta_{\theta_j^*}(\theta_0).$$

- The posterior predictive density is given by

$$p(y_0 \mid \text{data}) = \int \int k(y_0 \mid \theta_0, \phi) p(\theta_0 \mid n^*, \mathbf{w}, \boldsymbol{\theta}^*, \alpha, \psi) p(n^*, \mathbf{w}, \boldsymbol{\theta}^*, \alpha, \psi, \phi \mid \text{data}) d\theta_0 d\mathbf{w} d\boldsymbol{\theta}^* d\alpha d\psi d\phi$$

- Hence, a sample $\{y_{0,b} : b = 1, \dots, B\}$ from the posterior predictive distribution can be obtained using the MCMC output, where, for each $b = 1, \dots, B$:
 - we first draw $\theta_{0,b}$ from $p(\theta_0 \mid n_b^*, \mathbf{w}_b, \boldsymbol{\theta}_b^*, \alpha_b, \psi_b)$
 - and then, draw $y_{0,b}$ from $K(\cdot \mid \theta_{0,b}, \phi_b)$.

Posterior predictive distributions

- To further highlight the mixture structure, note that we can also write

$$p(y_0 | \text{data}) = \int \left\{ \frac{\alpha}{\alpha + n} \int k(y_0 | \theta, \phi) g_0(\theta | \psi) d\theta + \frac{1}{\alpha + n} \sum_{j=1}^{n^*} n_j k(y_0 | \theta_j^*, \phi) \right\} p(n^*, \mathbf{w}, \boldsymbol{\theta}^*, \alpha, \psi, \phi | \text{data}) d\mathbf{w} d\boldsymbol{\theta}^* d\alpha d\psi d\phi$$

- The integrand above is a mixture with $n^* + 1$ components, where the last n^* components (that dominate when α is small relative to n) yield a discrete mixture (in θ) of $k(\cdot | \theta, \phi)$ with the mixture parameters defined by the distinct θ_j^* .
- The posterior predictive density for y_0 is obtained by averaging this mixture with respect to the posterior distribution of n^* , \mathbf{w} , $\boldsymbol{\theta}^*$ and all other parameters.

Inference for general functionals of the random mixture

- Note that $p(y_0 | \text{data})$ is the posterior point estimate for the density $f(y_0 | G, \phi)$ (at point y_0), i.e., $p(y_0 | \text{data}) = E(f(y_0 | G, \phi) | \text{data})$ (the Bayesian density estimate under a DP mixture model can be obtained without sampling from the posterior distribution of G).
- Analogously, we can obtain posterior moments for linear functionals $H(F(\cdot | G, \phi)) = \int H(K(\cdot | \theta, \phi))dG(\theta)$ (Gelfand and Mukhopadhyay, 1995) — for linear functionals, the functional of the mixture is the mixture of the functionals applied to the parametric kernel (e.g., density and c.d.f. functionals, mean functional).
- How about more general inference for functionals?
 - Interval estimates for $F(y_0 | G, \phi)$ for specified y_0 , and, therefore, (pointwise) uncertainty bands for $F(\cdot | G, \phi)$?
 - Inference for derived functions from $F(\cdot | G, \phi)$, e.g., cumulative hazard, $-\log(1 - F(\cdot | G, \phi))$, or hazard, $f(\cdot | G, \phi)/(1 - F(\cdot | G, \phi))$, functions?
 - Inference for non-linear functionals, e.g., for percentiles?

Inference for general functionals of the random mixture

- Such inferences require the posterior distribution of G — recall,

$$p(G, \phi, \boldsymbol{\theta}, \alpha, \psi \mid \text{data}) = p(G \mid \boldsymbol{\theta}, \alpha, \psi)p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data}),$$

and

$$G \mid \boldsymbol{\theta}, \alpha, \psi \sim \text{DP} \left(\alpha + n, \tilde{G}_0(\cdot) = \frac{\alpha}{\alpha + n} G_0(\cdot \mid \psi) + \frac{1}{\alpha + n} \sum_{i=1}^n \delta_{\theta_i}(\cdot) \right).$$

- Hence, given posterior samples $(\boldsymbol{\theta}_b, \alpha_b, \psi_b, \phi_b)$, for $b = 1, \dots, B$, from the marginalized version of the DP mixture, we can draw G_b from $p(G \mid \boldsymbol{\theta}_b, \alpha_b, \psi_b)$ using:
 - The original DP definition if we only need sample paths for the c.d.f. of the mixture (and y is univariate) (e.g., Krnjajić et al., 2008).
 - More generally, the DP constructive definition with a truncation approximation (Gelfand and Kottas, 2002; Ishwaran and Zarepour, 2002).

Inference for general functionals of the random mixture

- Applying directly the DP constructive definition,

$$G_b(\cdot) = \zeta_1 \delta_{U_1}(\cdot) + \sum_{\ell=2}^{L-1} \left\{ \zeta_\ell \prod_{r=1}^{\ell-1} (1 - \zeta_r) \right\} \delta_{U_\ell}(\cdot) + \left\{ \prod_{r=1}^{L-1} (1 - \zeta_r) \right\} \delta_{U_L}(\cdot)$$

where the ζ_ℓ , $\ell = 1, \dots, L-1$, are i.i.d. $\text{Beta}(1, \alpha + n)$, and (independently) the U_ℓ , $\ell = 1, \dots, L$, are i.i.d. \tilde{G}_0 .

- A more efficient truncation approximation through an alternative representation for the conditional posterior of G (Pitman, 1996)

$$G \mid (n^*, \mathbf{w}, \boldsymbol{\theta}^*), \alpha, \psi \stackrel{\mathcal{D}}{=} q_{n^*+1} G(\cdot) + \sum_{j=1}^{n^*} q_j \delta_{\theta_j^*}(\cdot)$$

where $G \mid \alpha, \psi \sim \text{DP}(\alpha, G_0)$ and, independently of G , $(q_1, \dots, q_{n^*}, q_{n^*+1}) \mid \alpha, \mathbf{w} \sim \text{Dirichlet}(n_1, \dots, n_{n^*}, \alpha)$.

- Finally, the posterior samples G_b yield posterior samples for $\{H(F(\cdot \mid G_b, \phi_b)) : b = 1, \dots, B\}$ from any functional $H(F(\cdot \mid G, \phi))$.

Density estimation data example

- As an example, we analyze the galaxy data set: velocities (km/second) for 82 galaxies, drawn from six well-separated conic sections of the Corona Borealis region.
- The model is a location-scale DP mixture of Gaussian distributions, with a conjugate normal-inverse gamma baseline distribution:

$$f(\cdot | G) = \int N(\cdot | \mu, \sigma^2) dG(\mu, \sigma^2), \quad G \sim DP(\alpha, G_0),$$

where $G_0(\mu, \sigma^2) = N(\mu | \mu_0, \sigma^2/\kappa) \text{IGamma}(\sigma^2 | \nu, s)$.

- We consider four different prior specifications to explore the effect of increasing flexibility in the DP prior hyperparameters.
- Figure 2.2 shows posterior predictive density estimates obtained using the function `DPdensity` in the R package `DPpackage` (the code was taken from one of the examples in the help file).

Density estimation data example: Code

```

# Data      data(galaxy)
galaxy = data.frame(galaxy,speeds=galaxy$speed/1000)
attach(galaxy)
# Initial state
state = NULL
# MCMC parameters
nburn = 1000
nsave = 10000
nskip = 10
ndisplay = 100
mcmc = list(nburn=nburn,nsave=nsave,nskip=nskip,ndisplay=ndisplay)
# Example of Prior information 1
# Fixing alpha, m1, and Psi1
prior1 = list(alpha=1,m1=rep(0,1),psiinv1=diag(0.5,1),nu1=4,tau1=1,tau2=100)
# Example of Prior information 2
# Fixing alpha and m1
prior2 = list(alpha=1,m1=rep(0,1),psiinv2=solve(diag(0.5,1)),nu1=4,nu2=4,tau1=1,tau2=100)
# Example of Prior information 3
# Fixing only alpha
prior3 = list(alpha=1,m2=rep(0,1),s2=diag(100000,1),psiinv2=solve(diag(0.5,1)),nu1=4,nu2=4,tau1=1,tau2=100)
# Example of Prior information 4
# Everything is random
prior4 = list(a0=2,b0=1,m2=rep(0,1),s2=diag(100000,1),psiinv2=solve(diag(0.5,1)),nu1=4,nu2=4,tau1=1,tau2=100)
# Fit the models
fit1.1 = DPdensity(y=speeds,prior=prior1,mcmc=mcmc,state=state,status=TRUE)
fit1.2 = DPdensity(y=speeds,prior=prior2,mcmc=mcmc,state=state,status=TRUE)
fit1.3 = DPdensity(y=speeds,prior=prior3,mcmc=mcmc,state=state,status=TRUE)
fit1.4 = DPdensity(y=speeds,prior=prior4,mcmc=mcmc,state=state,status=TRUE)
# Plot the estimated density
plot(fit1.1,ask=FALSE)
plot(fit1.2,ask=FALSE)
plot(fit1.3,ask=FALSE)
plot(fit1.4,ask=FALSE)

```

Density estimation data example

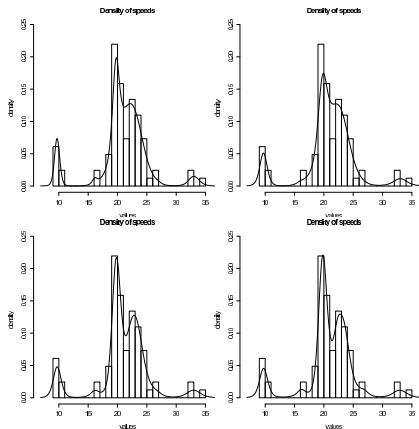


Figure 2.2: Histograms of the raw data and posterior predictive densities under four prior choices for the galaxy data. In the top left panel we set $\alpha = 1$, $\mu_0 = 0$, $s = 2$, $\nu = 4$, $\kappa \sim \text{Gam}(0.5, 50)$; the top right panel uses the same settings except $s \sim \text{IGamma}(4, 2)$; in the bottom left panel we add hyperprior $\mu_0 \sim N(0, 100000)$; and in the bottom right panel we further add hyperprior $\alpha \sim \text{Gam}(2, 2)$.

Conditional posterior simulation methods

- The main characteristic of the marginal MCMC methods is that they are based on the posterior distribution of the DP mixture model, $p(\boldsymbol{\theta}, \phi, \alpha, \psi \mid \text{data})$, resulting after marginalizing the random mixing distribution G (thus, referred to as *marginal*, or sometimes collapsed methods).
- Although posterior inference for G is possible under the collapsed sampler, it is of interest to study alternative *conditional* posterior simulation approaches that impute G as part of the MCMC algorithm.
- Most of the emphasis on conditional methods based on finite truncation approximation of G , using its stick-breaking representation — main example: Blocked Gibbs sampler (Ishwaran and Zarepour, 2000; Ishwaran and James, 2001).
- Other work based on retrospective sampling techniques (Papaspiliopoulos and Roberts, 2008), or slice sampling (Walker, 2007; Kalli et al., 2011).

Blocked Gibbs sampler

- Builds from truncation approximation to mixing distribution G given, for finite N , by

$$G_N(\cdot) = \sum_{\ell=1}^N p_{\ell} \delta_{Z_{\ell}}(\cdot).$$

- The Z_{ℓ} , $\ell = 1, \dots, N$, are i.i.d. G_0 .
- The weights arise through stick-breaking (with truncation)

$$p_1 = V_1, \quad p_{\ell} = V_{\ell} \prod_{r=1}^{\ell-1} (1 - V_r), \quad \ell = 2, \dots, N-1, \quad p_N = \prod_{r=1}^{N-1} (1 - V_r),$$

where the V_{ℓ} , $\ell = 1, \dots, N-1$, are i.i.d. $\text{beta}(1, \alpha)$.

- Choice of N follows guidelines discussed earlier
- The joint prior for $\mathbf{p} = (p_1, \dots, p_N)$, given α , corresponds to a special case of the generalized Dirichlet distribution (Connor and Mosimann, 1969),

$$f(\mathbf{p} \mid \alpha) = \alpha^{N-1} p_N^{\alpha-1} (1-p_1)^{-1} (1-(p_1+p_2))^{-1} \times \dots \times (1 - \sum_{\ell=1}^{N-2} p_{\ell})^{-1}.$$

Blocked Gibbs sampler

- Replacing G with $G_N \equiv (\mathbf{p}, \mathbf{Z})$, where $\mathbf{Z} = (Z_1, \dots, Z_N)$, in the generic DP mixture model hierarchical formulation, we have:

$$y_i \mid \theta_i, \phi \stackrel{\text{ind.}}{\sim} k(y_i \mid \theta_i, \phi), \quad i = 1, \dots, n,$$

$$\theta_i \mid \mathbf{p}, \mathbf{Z} \stackrel{\text{i.i.d.}}{\sim} G_N, \quad i = 1, \dots, n,$$

$$\mathbf{p}, \mathbf{Z} \mid \alpha, \psi \sim f(\mathbf{p} \mid \alpha) \prod_{\ell=1}^N g_0(Z_\ell \mid \psi),$$

$$\phi, \alpha, \psi \sim p(\phi)p(\alpha)p(\psi).$$

- If we marginalize over the θ_i in the first two stages of the hierarchical model, we obtain a finite mixture model for the y_i ,

$$f(\cdot \mid \mathbf{p}, \mathbf{Z}, \phi) = \sum_{\ell=1}^N p_\ell k(\cdot \mid Z_\ell, \phi)$$

(conditionally on (\mathbf{p}, \mathbf{Z}) and ϕ), which replaces the countable DP mixture, $f(\cdot \mid G, \phi) = \int k(\cdot \mid \theta, \phi) dG(\theta) = \sum_{\ell=1}^{\infty} \omega_\ell k(\cdot \mid \vartheta_\ell, \phi)$.

Blocked Gibbs sampler

- Now, having approximated the countable DP mixture with a finite mixture, the mixing parameters θ_i can be replaced with configuration variables $\mathbf{L} = (L_1, \dots, L_n)$ — each L_i takes values in $\{1, \dots, N\}$ such that $L_i = \ell$ if and only if $\theta_i = Z_\ell$, for $i = 1, \dots, n$; $\ell = 1, \dots, N$.
- Final version of the hierarchical model:

$$y_i \mid \mathbf{Z}, L_i, \phi \stackrel{\text{i.i.d.}}{\sim} k(y_i \mid Z_{L_i}, \phi), \quad i = 1, \dots, n,$$

$$L_i \mid \mathbf{p} \stackrel{\text{i.i.d.}}{\sim} \sum_{\ell=1}^N p_\ell \delta_\ell(L_i), \quad i = 1, \dots, n,$$

$$Z_\ell \mid \psi \stackrel{\text{i.i.d.}}{\sim} \mathbf{G}_0(\cdot \mid \psi), \quad \ell = 1, \dots, N,$$

$$\mathbf{p} \mid \alpha \sim f(\mathbf{p} \mid \alpha),$$

$$\phi, \alpha, \psi \sim p(\phi)p(\alpha)p(\psi).$$

- Marginalizing over the L_i , we obtain the same finite mixture model for the y_i : $f(\cdot \mid \mathbf{p}, \mathbf{Z}, \phi) = \sum_{\ell=1}^N p_\ell k(\cdot \mid Z_\ell, \phi)$.

Posterior full conditional distributions

- ① To update Z_ℓ for $\ell = 1, \dots, N$:
 - Let n^* be the number of distinct values $\{L_j^* : j = 1, \dots, n^*\}$ of vector \mathbf{L} .
 - Then, the posterior full conditional for Z_ℓ , $\ell = 1, \dots, N$, can be expressed in general as:

$$p(Z_\ell \mid \dots, \text{data}) \propto g_0(Z_\ell \mid \psi) \prod_{j=1}^{n^*} \prod_{\{i:L_i=L_j^*\}} k(y_i \mid Z_{L_j^*}, \phi).$$

- If $\ell \notin \{L_j^* : j = 1, \dots, n^*\}$, Z_ℓ is drawn from $G_0(\cdot \mid \psi)$.
- For $\ell = L_j^*$, $j = 1, \dots, n^*$,

$$p(Z_{L_j^*} \mid \dots, \text{data}) \propto g_0(Z_{L_j^*} \mid \psi) \prod_{\{i:L_i=L_j^*\}} k(y_i \mid Z_{L_j^*}, \phi).$$

- 2 The posterior full conditional for \mathbf{p} is

$$p(\mathbf{p} \mid \dots, \text{data}) \propto f(\mathbf{p} \mid \alpha) \prod_{\ell=1}^N p_{\ell}^{M_{\ell}},$$

where $M_{\ell} = |\{i : L_i = \ell\}|$, $\ell = 1, \dots, N$.

- Results in a generalized Dirichlet distribution, which can be sampled through independent latent Beta variables.
 - $V_{\ell}^* \stackrel{\text{ind.}}{\sim} \text{beta}(1 + M_{\ell}, \alpha + \sum_{r=\ell+1}^N M_r)$ for $\ell = 1, \dots, N - 1$.
 - $p_1 = V_1^*$; $p_{\ell} = V_{\ell}^* \prod_{r=1}^{\ell-1} (1 - V_r^*)$ for $\ell = 2, \dots, N - 1$; and $p_N = 1 - \sum_{\ell=1}^{N-1} p_{\ell}$.
- 3 Updating the L_i , $i = 1, \dots, n$:

- Each L_i is drawn from the discrete distribution on $\{1, \dots, N\}$ with probabilities $\tilde{p}_{\ell i} \propto p_{\ell} k(y_i \mid Z_{\ell}, \phi)$ for $\ell = 1, \dots, N$.
- Note that the update for each L_i does not depend on the other $L_{i'}$, $i' \neq i$ — this aspect of this Gibbs sampler, along with the *block updates* for the Z_{ℓ} , are key advantages over Pólya urn based marginal MCMC methods .

- 4 The posterior full conditional for ϕ is

$$p(\phi \mid \dots, \text{data}) \propto p(\phi) \prod_{i=1}^n k(y_i \mid \theta_i, \phi).$$

- 5 The posterior full conditional for ψ is

$$p(\psi \mid \dots, \text{data}) \propto p(\psi) \prod_{j=1}^{n^*} g_0(Z_{L_j^*} \mid \psi).$$

- 6 The posterior full conditional for α is proportional to $p(\alpha)\alpha^{N-1}p_N^\alpha$, which with a $\text{Gam}(a_\alpha, b_\alpha)$ prior for α , results in a $\text{Gam}(N + a_\alpha - 1, b_\alpha - \log p_N)$ distribution. (For numerical stability, compute $\log p_N = \log \prod_{r=1}^{N-1} (1 - V_r^*) = \sum_{r=1}^{N-1} \log(1 - V_r^*)$.)

Note that the posterior samples from $p(\mathbf{Z}, \mathbf{p}, \mathbf{L}, \phi, \alpha, \psi \mid \text{data})$ yield directly the posterior for G_N , and thus, full posterior inference for any functional of the (approximate) DP mixture $f(\cdot \mid G_N, \phi) \equiv f(\cdot \mid \mathbf{p}, \mathbf{Z}, \phi)$.

Posterior predictive inference

- Posterior predictive density for *new* y_0 , with corresponding configuration variable L_0 ,

$$\begin{aligned}
 p(y_0 \mid \text{data}) &= \int k(y_0 \mid Z_{L_0}, \phi) \left(\sum_{\ell=1}^N p_\ell \delta_\ell(L_0) \right) \\
 &\quad p(\mathbf{Z}, \mathbf{p}, \mathbf{L}, \phi, \alpha, \psi \mid \text{data}) dL_0 d\mathbf{Z} d\mathbf{L} d\mathbf{p} d\phi d\alpha d\psi \\
 &= \int \left(\sum_{\ell=1}^N p_\ell k(y_0 \mid Z_\ell, \phi) \right) \\
 &\quad p(\mathbf{Z}, \mathbf{p}, \mathbf{L}, \phi, \alpha, \psi \mid \text{data}) d\mathbf{Z} d\mathbf{L} d\mathbf{p} d\phi d\alpha d\psi \\
 &= E(f(y_0 \mid \mathbf{p}, \mathbf{Z}, \phi) \mid \text{data}).
 \end{aligned}$$

- Hence, $p(y_0 \mid \text{data})$ can be estimated over a grid in y_0 by drawing samples $\{L_{0b} : b = 1, \dots, B\}$ for L_0 , based on the posterior samples for \mathbf{p} , and computing the Monte Carlo estimate

$$B^{-1} \sum_{b=1}^B k(y_0 \mid Z_{L_{0b}}, \phi_b),$$

where B is the posterior sample size.

Applications of DP mixture models: some references

Dirichlet process (DP) mixture models, and their extensions, have largely dominated applied Bayesian nonparametric work, after the technology for their simulation-based model fitting was introduced. Included below is a (small) sample of references categorized by methodological/application area.

- Density estimation, mixture deconvolution, and curve fitting (West et al., 1994; Escobar and West, 1995; Cao and West, 1996; Gasparini, 1996; Müller et al., 1996; Ishwaran and James, 2002; Do et al., 2005; Leslie et al., 2007; Lijoi et al., 2007).
- Generalized linear, and linear mixed, models (Bush and MacEachern, 1996; Kleinman and Ibrahim, 1998; Mukhopadhyay and Gelfand, 1997; Müller and Rosner, 1997; Quintana, 1998; Kyung, Gill and Casella, 2010; Hannah et al., 2011).
- Regression modeling with structured error distributions and/or regression functions (Brunner, 1995; Lavine and Mockus, 1995; Kottas and Gelfand, 2001; Dunson, 2005; Kottas and Krnjajić, 2009).

Applications of DP mixture models: some references

- Regression models for survival/reliability data (Kuo and Mallick, 1997; Gelfand and Kottas, 2003; Merrick et al., 2003; Hanson, 2006; Argiento et al., 2009; De Iorio et al., 2009).
- Models for binary and ordinal data (Basu and Mukhopadhyay, 2000; Hoff, 2005; Das and Chattopadhyay, 2004; Kottas et al., 2005; Shahbaba and Neal, 2009; DeYoreo and Kottas, 2015).
- Errors-in-variables models (Müller and Roeder, 1997); multiple comparisons problems (Gopalan and Berry, 1998); analysis of selection models (Lee and Berger, 1999).
- Meta-analysis and nonparametric ANOVA models (Mallick and Walker, 1997; Tomlinson and Escobar, 1999; Burr et al., 2003; De Iorio et al., 2004; Müller et al., 2004; Müller et al., 2005).
- Time series modeling and econometrics applications (Müller et al., 1997; Chib and Hamilton, 2002; Hirano, 2002; Hasegawa and Kozumi, 2003; Griffin and Steel, 2004).
- ROC data analysis (Erkanli et al., 2006; Hanson et al., 2008).

Semiparametric random effects models

- Linear random effects models (e.g., Laird and Ware, 1982) are a widely used class of models for repeated measurements,

$$y_i = X_i\beta + Z_ib_i + \epsilon_i, \quad i = 1, \dots, n,$$

where β is the vector of fixed effects regression parameters, b_i is the vector of random effects regression parameters, X_i and Z_i are vectors of covariates associated with the fixed and random effects respectively, and ϵ_i is the vector of observational errors.

- It is common to assume that b_i is independent from ϵ_i and that $\epsilon_i \sim N(0, \sigma^2 I)$.
- Furthermore, it is very common to assume that $b_i \sim N(0, D)$, mostly because of computational convenience.

Semiparametric random effects models

- Consider a special case, the random intercepts model

$$y_{i,j} = \mu + \theta_i + \epsilon_{i,j}, \quad \theta_i \sim N(0, \tau^2), \quad \epsilon_{i,j} \sim N(0, \sigma^2),$$

for $j = 1, \dots, m_i$ and $i = 1, \dots, l$.

- A Bayesian formulation of this model also includes priors on μ , τ^2 and σ^2 , e.g,

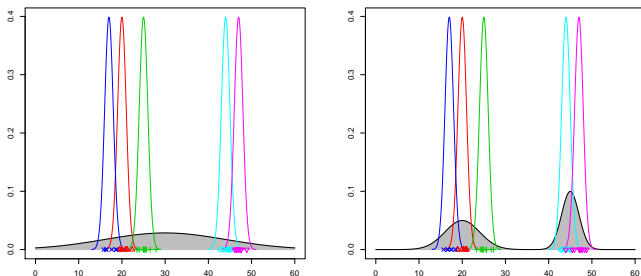
$$\mu \sim N(\mu_0, \kappa^2) \quad \sigma^2 \sim \text{IG}(a, b) \quad \tau^2 \sim \text{IG}(c, d)$$

(When selecting hyperparameters, recall that an improper prior for σ^2 would be OK, but improper priors for τ^2 are not!)

- When is the assumption of normality for the random effects distribution reasonable?

Random effects distributions

- An argument could be made that normality is, in general, an inappropriate assumption for the random effects distribution.



- Instead, you would often expect the random effects distribution to present multimodalities because of the effects of covariates that have not been included in the model.

Bayesian semiparametric random effects models

- Bayesian semiparametric random effects models have been discussed in Kleinman and Ibrahim (1998) and Kyung, Gill and Casella (2010), in addition to a number of applied papers.
- General formulation:

$$y_i \mid \beta, b_i, \sigma^2 \sim N(X_i\beta + Z_i b_i, \sigma^2 I),$$

$$b_i \mid G \sim G,$$

$$G \sim DP(\alpha, N(0, D)),$$

$$(\beta, \sigma^2, \alpha, D) \sim p(\beta, \sigma^2, \alpha, D)$$

Bayesian semiparametric random intercepts model

- For the random intercepts model discussed before:

$$y_{i,j} \mid \theta_i, \sigma^2 \sim N(\theta_i, \sigma^2), \quad j = 1, \dots, m_i, \quad i = 1, \dots, l,$$

$$\theta_i \mid G \sim G,$$

$$G \sim \text{DP}(\alpha, N(\mu, \tau^2)),$$

$$\sigma^2 \sim \text{IG}(a, b).$$

$$\mu \sim N(\mu_0, \kappa^2),$$

$$\tau^2 \sim \text{IG}(c, d).$$

- Note that, without any loss of generality, we absorbed the common intercept μ .

Bayesian semiparametric random intercepts model

- If $\alpha \rightarrow \infty$ we recover the “traditional Gaussian random effects model with

$$y_{i,j} \mid \theta_i, \sigma^2 \sim \text{N}(\theta_i, \sigma^2), \quad j = 1, \dots, m_i, \quad i = 1, \dots, I,$$
$$\theta_i \mid \mu, \tau^2 \sim \text{N}(\mu, \tau^2).$$

- If $\alpha \rightarrow 0$ we have $\theta_1 = \theta_2 = \dots = \theta_I = \theta$ (i.e., a model without random effects). In this case

$$y_{i,j} \mid \theta, \sigma^2 \sim \text{N}(\theta, \sigma^2), \quad j = 1, \dots, m_i, \quad i = 1, \dots, I,$$
$$\theta \mid \mu_0, \tau^2 \sim \text{N}(\mu_0, \tau^2 + \kappa^2).$$

- For values of α in between, the model induces some ties among the θ_i .

Fitting linear mixed models in R

- The `DP` package includes functions to fit (generalized) linear mixed models in which the random effects distribution is assigned a DP prior.
- We illustrate with a linear mixed model (function `DP1mm`)
- Data corresponds to growth information of 20 preadolescent school-girls reported by Goldstein (1979, Table 4.3, p. 101). Four variables are included:
 - `height`: a numeric vector giving the height in cm.
 - `child`: an ordered factor giving a unique identifier for the subject in the study.
 - `age`: a numeric vector giving the age of the child in years.
 - `group`: a factor with levels 1 (short), 2 (medium), and 3 (tall) giving the mother category.
- The height of girls was measured on a yearly basis from age 6 to 10. The measurements are given at exact years of age.

Fitting linear mixed models in R

- We fit the model

$$y_{i,j} \sim \text{N}(\theta_i + x_{i,j}\beta_i, \sigma^2),$$
$$(\theta_i, \beta_i) | G \sim \text{DP}(\alpha, \text{N}(\cdot | \mu, \Sigma)),$$

where

- $y_{i,j}$ is the j -th height observation for the i -th child.
- $x_{i,j}$ is the age associated with the j -th height observation for the i -th child.
- Note that we do not use the variable `group` in the analysis (it may be used to add another layer to the hierarchy).
- Note the syntax of the function call (similar to other functions for random effects models in R).

```
DPlmm(fixed=height ~ 1, random=~ age|child,  
prior=prior, mcmc=mcmc, state=state, status=FALSE)
```

Fitting linear mixed models in R

- This R code is provided with the help file of DP1mm.

```
# School Girls Data Example
data(schoolgirls)
attach(schoolgirls)
# Prior information
prior=list(alpha=1,nu0=4.01,tau1=0.01,tau2=0.01,tinv=diag(10,2),mub=rep(0,2),Sb=diag(1000,2))
# Initial state
state = NULL
# MCMC parameters
nburn=5000
nsave=40000
nskip=20
ndisplay=1000
mcmc = list(nburn=nburn,nsave=nsave,nskip=nskip,ndisplay=ndisplay)
# Fit the model: First run
fit1=DP1mm(fixed=height ~ 1,random= ~ age|child,prior=prior,mcmc=mcmc,state=state,status=TRUE)
fit1
# Fit the model: Continuation
state=fit1$state
fit2=DP1mm(fixed=height ~ 1,random= ~ age|child,prior=prior,mcmc=mcmc,state=state,status=FALSE)
fit2
# Summary with HPD and Credibility intervals
summary(fit2)
summary(fit2,hpd=FALSE)
# Extract expected means of the random effect coefficients
DPrandom(fit2)
# Plot an specific model parameter
quartz()
plot(fit2,ask=FALSE,nfigr=1,nfigc=2,param="sigma-(Intercept)")
quartz()
plot(fit2,ask=FALSE,nfigr=1,nfigc=2,param="ncluster")
```

Fitting linear mixed models in R

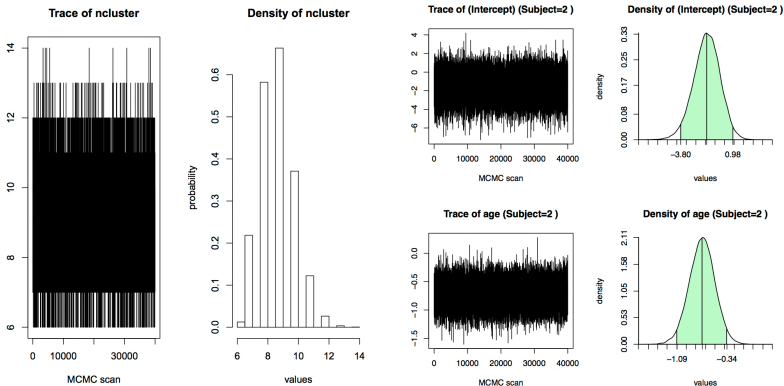


Figure 2.3. On the left, trace plot and histogram for the number of clusters generated by DP11m in the school girls example. On the right, trace and posterior density plots for the parameters of one of the individuals.

Curve fitting using Dirichlet process mixtures

- Two dominant trends in the Bayesian regression literature: seek increasingly flexible regression function models, and accompany these models with more comprehensive uncertainty quantification.
- Typically, Bayesian nonparametric modeling focuses on either the regression function or the error distribution.
- Bayesian nonparametric extension of *implied conditional regression* (West et al., 1994; Müller et al., 1996; Rodriguez et al., 2009; Müller and Quintana, 2010; Park and Dunson, 2010; Taddy & Kottas, 2009, 2010; Wade et al., 2014; DeYoreo and Kottas, 2015)
 - Flexible nonparametric mixture modeling for the joint distribution of response(s) and covariates.
 - Inference for the conditional response distribution given covariates.
- Both the response distribution and, implicitly, the regression relationship are modeled nonparametrically, thus providing a flexible framework for the general regression problem.

Curve fitting using Dirichlet process mixtures

- Focus on univariate continuous response y (though extensions for categorical and/or multivariate responses also possible).
- DP mixture model for the joint density $f(y, \mathbf{x})$ of the response y and the vector of covariates \mathbf{x} :

$$f(y, \mathbf{x}) \equiv f(y, \mathbf{x} | G) = \int k(y, \mathbf{x} | \theta) dG(\theta), \quad G \sim \text{DP}(\alpha, G_0(\psi)).$$

- For the mixture kernel $k(y, \mathbf{x} | \theta)$ use:
 - Multivariate normal for (\mathbb{R} -valued) continuous response and covariates.
 - Mixed continuous/discrete distribution to incorporate both categorical and continuous covariates.
 - Kernel component for y supported by \mathbb{R}^+ for problems in survival/reliability analysis.

Curve fitting using Dirichlet process mixtures

- Introducing latent mixing parameters $\theta = \{\theta_i : i = 1, \dots, n\}$ for each response/covariate observation (y_i, \mathbf{x}_i) , $i = 1, \dots, n$, the full posterior:

$$p(G, \theta, \alpha, \psi \mid \text{data}) = p(G \mid \theta, \alpha, \psi)p(\theta, \alpha, \psi \mid \text{data}).$$

- $p(\theta, \alpha, \psi \mid \text{data})$ is the posterior of the finite-dimensional parameter vector that results by marginalizing G over its DP prior.
 - MCMC posterior simulation to sample from this marginal posterior.
- $p(G \mid \theta, \alpha, \psi)$ is a DP with precision parameter $\alpha + n$ and mean $(\alpha + n)^{-1} \left\{ \alpha G_0(\cdot; \psi) + \sum_{j=1}^{n^*} n_j \delta_{\theta_j^*}(\cdot) \right\}$, where n^* is the number of distinct θ_i , and n_j is the size of the j -th distinct component.
 - Sample using the DP stick-breaking definition with a truncation approximation.
- Alternatively, G can be truncated from the outset resulting in a finite mixture model that can be fitted with blocked Gibbs sampling.

Curve fitting using Dirichlet process mixtures

- For any grid of values (y_0, \mathbf{x}_0) , obtain posterior samples for:
 - Joint density $f(y_0, \mathbf{x}_0 | G)$, marginal density $f(\mathbf{x}_0 | G)$, and therefore, conditional density $f(y_0 | \mathbf{x}_0, G)$.
 - Conditional expectation $E(y | \mathbf{x}_0, G)$, which, estimated over grid in \mathbf{x} , provides inference for the regression relationship.
 - Conditioning in $f(y_0 | \mathbf{x}_0, G)$ and/or $E(y | \mathbf{x}_0, G)$ may involve only a portion of vector \mathbf{x} .
 - *Inverse inferences*: inference for the conditional distribution of covariates given specified response values, $f(\mathbf{x}_0 | y_0, G)$.
- Key features of the modeling approach:
 - Model for both non-linear regression curves **and** non-standard shapes for the conditional response density.
 - Model does not rely on additive regression formulations; it can uncover interactions between covariates that might influence the regression relationship.

Data Example

- Simulated data set with a continuous response y , one continuous covariate x_c , and one binary categorical covariate x_d .
 - x_{ci} independent $N(0, 1)$.
 - $x_{di} \mid x_{ci}$ independent $\text{Ber}(\text{probit}(x_{ci}))$.
 - $y_i \mid x_{ci}, x_{di}$ ind. $N(h(x_{ci}), \sigma_{x_{di}})$, with $\sigma_0 = 0.25$, $\sigma_1 = 0.5$, and

$$h(x_c) = 0.4x_c + 0.5 \sin(2.7x_c) + 1.1(1 + x_c^2)^{-1}.$$

- Two sample sizes: $n = 200$ and $n = 2000$.
- DP mixture model with a mixed normal/Bernoulli kernel:

$$f(y, x_c, x_d \mid G) = \int N_2(y, x_c \mid \mu, \Sigma) \pi^{x_d} (1 - \pi)^{1-x_d} dG(\mu, \Sigma, \pi),$$

with

$$G \sim \text{DP}(\alpha, G_0(\mu, \Sigma, \pi) = N_2(\mu; \mathbf{m}, V) \text{IW}(\Sigma; \nu, S) \text{Beta}(\pi; a, b)).$$

Data Example

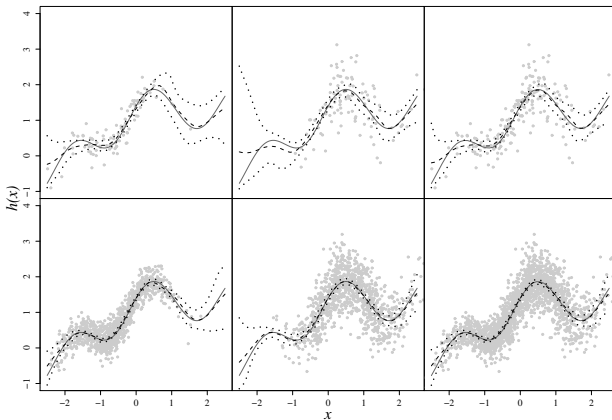


Figure 2.4. Posterior point and 90% interval estimates (dashed and dotted lines) for conditional response expectation $E(y \mid x_C, x_D = 0; G)$ (left panels), $E(y \mid x_C, x_D = 1; G)$ (middle panels), and $E(y \mid x_C; G)$ (right panels). The corresponding data is plotted in grey for the sample of size $n = 200$ (top panels) and $n = 2000$ (bottom panels). The solid line denotes the true curve.

Quantile regression

- In regression settings, the covariates may have effect not only on the location of the response distribution but also on its shape.
- Model-based nonparametric approach to quantile regression.
 - Model joint density $f(y, \mathbf{x})$ of the response y and the M -variate vector of (continuous) covariates \mathbf{x} with a DP mixture of normals:

$$f(y, \mathbf{x}; G) = \int N_{M+1}(y, \mathbf{x}; \mu, \Sigma) dG(\mu, \Sigma), \quad G \sim \text{DP}(\alpha, G_0),$$

with $G_0(\mu, \Sigma) = N_{M+1}(\mu; \mathbf{m}, V) \text{IW}(\Sigma; \nu, S)$.

- For any grid of values (y_0, \mathbf{x}_0) , obtain posterior samples for:
 - Conditional density $f(y_0 | \mathbf{x}_0; G)$ and conditional cdf $F(y_0 | \mathbf{x}_0; G)$.
 - Conditional quantile regression $q_p(\mathbf{x}_0; G)$, for any $0 < p < 1$.
- Key features of the DP mixture modeling framework:
 - Enables simultaneous inference for more than one quantile regression.
 - Allows flexible response distributions **and** non-linear quantile regression relationships.

Data Example

- *Moral hazard* data on the relationship between shareholder concentration and several indices for managerial moral hazard in the form of expenditure with scope for private benefit (Yafeh & Yoshua, 2003).
 - Data set includes a variety of variables describing 185 Japanese industrial chemical firms listed on the Tokyo stock exchange.
 - Response y : index *MH5*, consisting of general sales and administrative expenses deflated by sales.
 - Four-dimensional covariate vector \mathbf{x} : *Leverage* (ratio of debt to total assets); $\log(\text{Assets})$; *Age* of the firm; and *TOPTEN* (the percent of ownership held by the ten largest shareholders).

Curve fitting using Dirichlet process mixtures

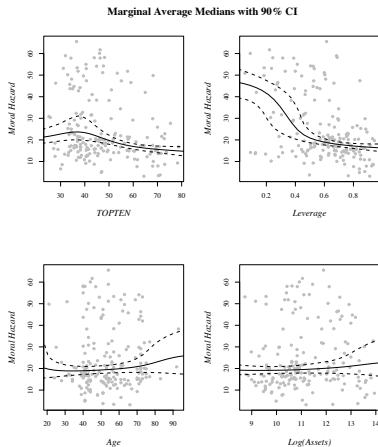


Figure 2.5. Posterior mean and 90% interval estimates for median regression for *MH5* conditional on each individual covariate. Data scatterplots are shown in grey.

Curve fitting using Dirichlet process mixtures

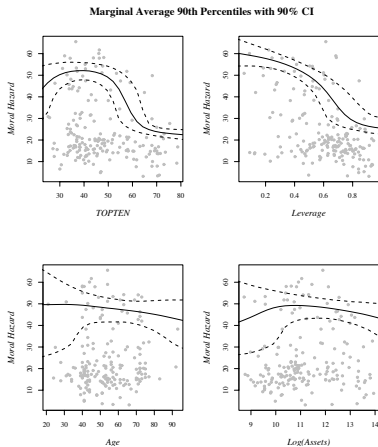


Figure 2.6. Posterior mean and 90% interval estimates for 90th percentile regression for *MH5* conditional on each individual covariate.

Data scatterplots are shown in grey.

Curve fitting using Dirichlet process mixtures

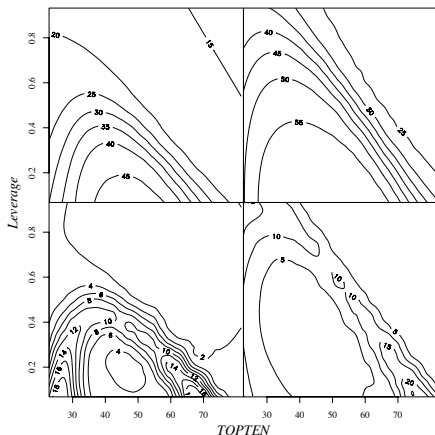


Figure 2.7. Posterior estimates of median surfaces (left column) and 90th percentile surfaces (right column) for *MH5* conditional on *Leverage* and *TOPTEN*. The posterior mean is shown on the top row and the posterior interquartile range on the bottom.

Curve fitting using Dirichlet process mixtures

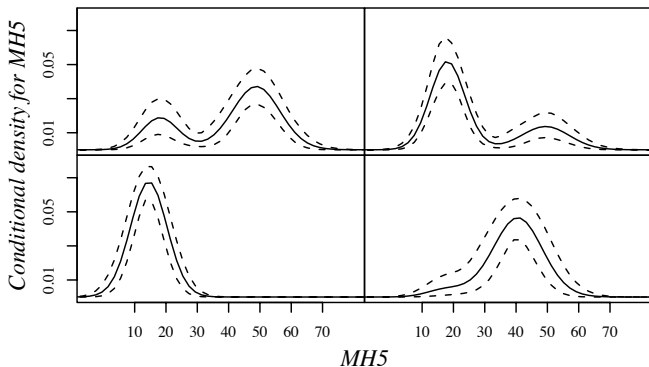


Figure 2.8. Posterior mean and 90% interval estimates for response densities $f(y | \mathbf{x}_0; G)$ conditional on four combinations of values \mathbf{x}_0 for the covariate vector $(TOPTEN, Leverage, Age, \log(Assets))$

Modeling for multivariate ordinal data

- Values of k ordinal categorical variables V_1, \dots, V_k recorded for n subjects:
 - $C_j \geq 2$: number of categories for the j -th variable, $j = 1, \dots, k$.
 - $n_{\ell_1 \dots \ell_k}$: number of observations such that

$$\mathbf{V} = (V_1, \dots, V_k) = (\ell_1, \dots, \ell_k).$$

- $p_{\ell_1 \dots \ell_k} = \Pr(V_1 = \ell_1, \dots, V_k = \ell_k)$ is the classification probability for the (ℓ_1, \dots, ℓ_k) cell.
- The data can be summarized in a k -dimensional contingency table with $C = \prod_{j=1}^k C_j$ cells, with frequencies $\{n_{\ell_1 \dots \ell_k}\}$ constrained by $\sum_{\ell_1 \dots \ell_k} n_{\ell_1 \dots \ell_k} = n$.

Modeling for multivariate ordinal data

- A possible modeling strategy (alternative to log-linear models) involves the introduction of k continuous latent variables $\mathbf{Z} = (Z_1, \dots, Z_k)$ whose joint distribution yields the classification probabilities for the table cells, i.e.,

$$p_{\ell_1 \dots \ell_k} = \Pr \left(\bigcap_{j=1}^k \{ \gamma_{j, \ell_j - 1} < Z_j \leq \gamma_{j, \ell_j} \} \right)$$

for cutoff points $-\infty = \gamma_{j,0} < \gamma_{j,1} < \dots < \gamma_{j,c_j-1} < \gamma_{j,c_j} = \infty$, for each $j = 1, \dots, k$ (e.g., Johnson & Albert, 1999).

- Common distributional assumption: $\mathbf{Z} \sim N_k(\mathbf{0}, \mathbf{S})$ (probit model).
 - Coefficients ρ_{st} , $s \neq t$: *polychoric correlation coefficients* (traditionally used in the social sciences as a measure of association).
 - $\rho_{st} = \text{Corr}(Z_s, Z_t) = 0$, $s \neq t$, implies independence of the corresponding categorical variables.

Modeling for multivariate ordinal data

- Richer modeling and inference based on normal DP mixtures for the latent variables \mathbf{Z}_i associated with data vectors \mathbf{V}_i , $i = 1, \dots, n$.
- Model $\mathbf{Z}_i | G$ i.i.d. f , with $f(\cdot; G) = \int N_k(\cdot; \mathbf{m}, \mathbf{S}) dG(\mathbf{m}, \mathbf{S})$, where

$$G | \alpha, \lambda, \boldsymbol{\Sigma}, \mathbf{D} \sim \text{DP}(\alpha, G_0(\mathbf{m}, \mathbf{S}) = N_k(\mathbf{m} | \lambda, \boldsymbol{\Sigma}) \text{IW}_k(\mathbf{S} | \nu, \mathbf{D}))$$

- Advantages of the DP mixture modeling approach:
 - Can accommodate essentially any pattern in k -dimensional contingency tables.
 - Allows local dependence structure to vary across the contingency table.
 - Implementation does not require random cutoffs (so the complex updating mechanisms for cutoffs are not needed).

Modeling for multivariate ordinal data: Data Example

- A Data Set on *Interrater Agreement*: data on the extent of scleral extension (extent to which a tumor has invaded the sclera or “white of the eye”) as coded by two raters for each of $n = 885$ eyes .
- The coding scheme uses five categories: 1 for “none or innermost layers”; 2 for “within sclera, but does not extend to scleral surface”; 3 for “extends to scleral surface”; 4 for “extrascleral extension without transection”; and 5 for “extrascleral extension with presumed residual tumor in the orbit” .
- Results under the DP mixture model (and, for comparison, using also a probit model).
- The (0.25, 0.5, 0.75) posterior percentiles for n^* are (6, 7, 8) – in fact, $\Pr(n^* \geq 4 \mid \text{data}) = 1$.

Modeling for multivariate ordinal data: Data Example

For the interrater agreement data, observed cell relative frequencies (in bold) and posterior summaries for table cell probabilities (posterior mean and 95% central posterior intervals). Rows correspond to rater A and columns to rater B.

.3288 .3264 (.2940, .3586)	.0836 .0872 (.0696, .1062)	.0011 .0013 (.0002, .0041)	.0011 .0020 (.0003, .0055)	.0011 .0008 (.0, .0033)
.2102 .2136 (.1867, .2404)	.2893 .2817 (.2524, .3112)	.0079 0.0080 (.0033, .0146)	.0079 .0070 (.0022, .0143)	.0034 .0030 (.0006, .0074)
.0023 .0021 (.0004, .0059)	.0045 .0060 (.0021, .0118)	.0 .0016 (.0004, .0037)	.0023 .0023 (.0004, .0059)	.0 .0009 (.0, .0030)
.0034 .0043 (.0012, .0094)	.0113 .0101 (.0041, .0185)	.0011 .0023 (.0004, .0058)	.0158 .0142 (.0069, .0238)	.0023 .0027 (.0006, .0066)
.0011 .0013 (.0001, .0044)	.0079 .0071 (.0026, .0140)	.0011 .0020 (.0003, .0054)	.0090 .0084 (.0033, .0159)	.0034 .0039 (.0011, .0090)

Modeling for multivariate ordinal data: Data Example

- Posterior predictive distributions $p(\mathbf{Z}_0 \mid \text{data})$ (see Figure 2.9) – DP mixture version is based on the posterior predictive distribution for corresponding mixing parameter $(\mathbf{m}_0, \mathbf{S}_0)$.
- Inference for the association between the ordinal variables:
 - For example, Figure 2.9 shows posteriors for ρ_0 , the correlation coefficient implied in \mathbf{S}_0 .
 - The probit model underestimates the association of the ordinal variables (as measured by ρ_0), since it fails to recognize clusters that are suggested by the data (which are revealed by the DP model).
- Figure 2.10 shows inferences for log-odds ratios,

$$\psi_{ij} = \log p_{i,j} + \log p_{i+1,j+1} - \log p_{i,j+1} - \log p_{i+1,j}.$$

- Utility of mixture modeling for this data example – One of the clusters dominates the others, but identifying the other three is important; one of them corresponds to agreement for large values in the coding scheme; the other two indicate regions of the table where the two raters tend to agree less strongly

Modeling for multivariate ordinal data: Data Example

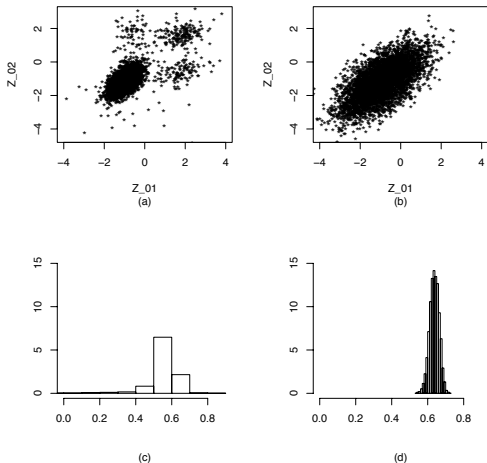


Figure 2.9. For the interrater agreement data, draws from $p(\mathbf{Z}_0 \mid \text{data})$ and $p(\rho_0 \mid \text{data})$ under the DP mixture model (panels (a) and (c), respectively) and the probit model (panels (b) and (d), respectively).

Modeling for multivariate ordinal data: Data Example

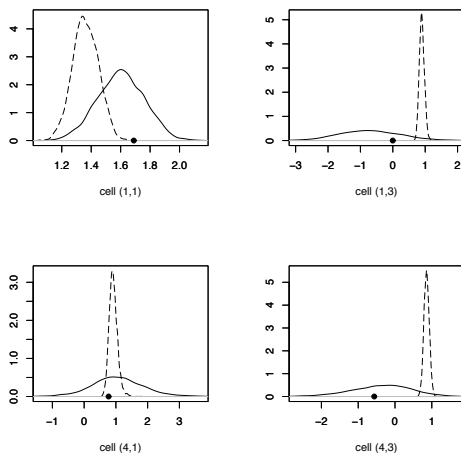


Figure 2.10. For the interrater agreement data, posteriors for four log-odds ratios under the DP mixture model (solid lines) and the probit model (dashed lines). The circles denote the corresponding empirical log-odds ratios.

Nonparametric inference for Poisson processes

- Point processes are stochastic process models for events that occur separated in time or space.
- Applications of point process modeling in traffic engineering, software reliability, neurophysiology, weather modeling, forestry, ...
- Poisson processes, along with their extensions (Poisson cluster processes, marked Poisson processes, etc.), play an important role in the theory and applications of point processes. (e.g., Kingman, 1993; Guttorp, 1995; Moller & Waagepetersen, 2004).
- Bayesian nonparametric work based on gamma processes, weighted gamma processes, and Lévy processes (e.g., Lo & Weng, 1989; Kuo & Ghosh, 1997; Wolpert & Ickstadt, 1998; Gutiérrez-Peña & Nieto-Barajas, 2003; Ishwaran & James, 2004).

Definition of Poisson processes on the real line

- For a point process over time, let $N(t)$ be the number of event occurrences in the time interval $(0, t]$.
- The point process $\mathcal{N} = \{N(t) : t \geq 0\}$ is a non-homogeneous Poisson process (NHPP) if:
 - For any $t > s \geq 0$, $N(t) - N(s)$ follows a Poisson distribution with mean $\Lambda(t) - \Lambda(s)$.
 - \mathcal{N} has independent increments, i.e., for any $0 \leq t_1 < t_2 \leq t_3 < t_4$, $N(t_2) - N(t_1)$ and $N(t_4) - N(t_3)$ are independent random variables.
- Λ is the mean measure (or cumulative intensity function) of the NHPP.
- For any $t \in R^+$, $\Lambda(t) = \int_0^t \lambda(u)du$, where λ is the NHPP intensity function – λ is a non-negative and locally integrable function (i.e., $\int_B \lambda(u)du < \infty$, for all bounded $B \subset R^+$).
- So, from a modeling perspective, the main functional of interest for a NHPP is its intensity function.

Nonparametric inference for Poisson processes

- Consider a NHPP observed over the time interval $(0, T]$ with events that occur at times $0 < t_1 < t_2 < \dots < t_n \leq T$.
- The likelihood for the NHPP intensity function λ is proportional to

$$\exp \left\{ - \int_0^T \lambda(u) du \right\} \prod_{i=1}^n \lambda(t_i).$$

- **Key observation:** $f(t) = \lambda(t)/\gamma$, where $\gamma = \int_0^T \lambda(u) du$, is a density function on $(0, T)$.
- Hence, (f, γ) provides an equivalent representation for λ , and so a nonparametric prior model for f , with a parametric prior for γ , will induce a semiparametric prior for λ — in fact, since γ only scales λ , it is f that determines the shape of the intensity function λ .

Nonparametric inference for Poisson processes

- **Beta DP mixture model** for f :

$$f(t) \equiv f(t; G) = \int \text{beta}(t; \mu, \tau) dG(\mu, \tau), \quad G \sim \text{DP}(\alpha, G_0)$$

where $\text{beta}(t; \mu, \tau)$ is the Beta density on $(0, T)$ with mean $\mu \in (0, T)$ and scale $\tau > 0$, and $G_0(\mu, \tau) = \text{Uni}(\mu; 0, T) \text{IG}(\tau; c, \beta)$ with random scale parameter β

- Flexible density shapes through mixing of Betas (e.g., Diaconis & Ylvisaker, 1985) – Beta mixture model avoids edge effects (the main drawback of a normal DP mixture model in this setting).
- Full Bayesian model:

$$e^{-\gamma} \gamma^n \left\{ \prod_{i=1}^n \int \text{beta}(t_i; \mu_i, \tau_i) dG(\mu_i, \tau_i) \right\} p(\gamma) \text{DP}(G \mid \alpha, G_0(\beta)) p(\alpha) p(\beta)$$

- Reference prior for γ , $p(\gamma) \propto \gamma^{-1}$.

Nonparametric inference for Poisson processes

- Letting $\theta = \{(\mu_i, \tau_i) : i = 1, \dots, n\}$, we have

$$p(\gamma, G, \theta, \alpha, \beta | \text{data}) = p(\gamma | \text{data})p(G | \theta, \alpha, \beta)p(\theta, \alpha, \beta | \text{data})$$

where:

- $p(\gamma | \text{data})$ is a gamma($n, 1$) distribution.
 - MCMC is used to sample from $p(\theta, \alpha, \beta | \text{data})$.
 - $p(G | \theta, \alpha, \beta)$ is a DP with updated parameters – can be sampled using the DP constructive definition.
- Full posterior inference for λ, Λ , and any other NHPP functional.
- Extensions to inference for spatial NHPP intensities, using DP mixtures with bivariate Beta kernels (Kottas & Sansó, 2007).

Data Illustrations

- Example for temporal NHPPs: data on the times of 191 explosions in mines, leading to coal-mining disasters with 10 or more men killed, over a time period of 40,550 days, from 15 March 1851 to 22 March 1962.
- Prior specification for $DP(\alpha, G_0(\mu, \tau \mid \beta) = \text{Uni}(\mu \mid 0, T)\text{IG}(\tau \mid 2, \beta))$.
 - $\text{Gam}(a_\alpha, b_\alpha)$ prior for α – recall the role of α in controlling the number n^* of distinct components in the DP mixture model.
 - Exponential prior for β – its mean can be specified using a prior guess at the range, R , of the event times t_i (e.g., $R = T$ is a natural default choice).
- Inference for the NHPP intensity under three prior choices: priors for β and α based on $R = T$, $E(n^*) \approx 7$; $R = T$, $E(n^*) \approx 15$; and $R = 1.5T$, $E(n^*) \approx 7$.
- Examples for spatial NHPPs: two forestry data sets.

Data Illustrations

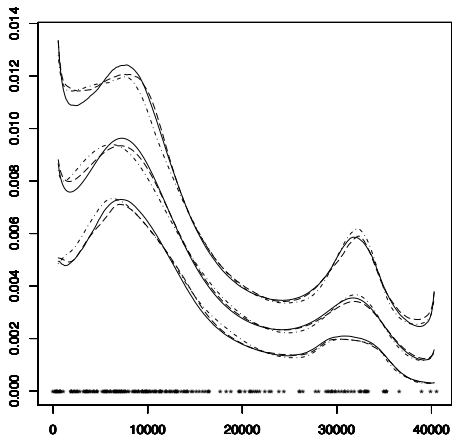


Figure 2.11. Coal-mining disasters data. Posterior point and 95% interval estimates for the intensity function under three prior settings.

The observed times of the 191 explosions in mines are plotted on the horizontal axis.

Data Illustrations

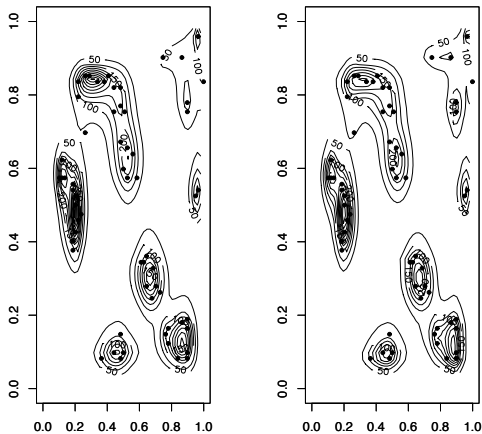


Figure 2.12. Redwood seedlings data. Contour plots of posterior mean intensity estimates under two different priors for α . The dots indicate the locations of the redwood seedlings.

Data Illustrations

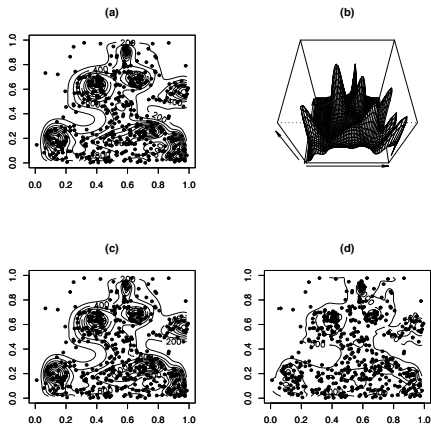


Figure 2.13. Maples data. Panels (a) and (b) include the posterior mean intensity estimate (contour and perspective plot, respectively). Panels (c) and (d) show contour plots for the posterior median and interquartile range intensity estimates, respectively. The dots denote the locations of the maple trees.

Nonparametric modeling for NHPPs: Further work

- Applications to neuronal data analysis (Kottas and Behseta, 2010; Kottas et al., 2012).
- Inference for marked Poisson processes (Taddy & Kottas, 2012).
- Dynamic modeling for spatial NHPPs (Taddy, 2010).
- Risk assessment of extremes from spatially dependent environmental time series (Kottas et al., 2012) and from correlated financial markets (Rodriguez et al., 2014).
- Dynamic modeling for time-varying seasonal intensities, with an application to predicting hurricane damage (Xiao et al., 2014).