

Bayesian Statistics I

Lecture 7 - Monte Carlo. Gibbs sampling.

Oskar Gustafsson

Department of Statistics, Stockholm University
(Original slides: Mattias Villani)



Lecture overview

- Monte Carlo simulation
- Gibbs sampling
- Data augmentation
 - ▶ Mixture models
 - ▶ Probit regression
- Regularized regression

Monte Carlo sampling

- If $\theta^{(1)}, \dots, \theta^{(N)}$ is an **iid sequence** from $p(\theta)$, then

$$\bar{\theta} = \frac{1}{N} \sum_{t=1}^N \theta^{(t)} \rightarrow E(\theta)$$

$$\bar{g}(\theta) = \frac{1}{N} \sum_{t=1}^N g(\theta^{(t)}) \rightarrow E[g(\theta)]$$

for some function $g(\theta)$ of interest.

- $\mathbb{V}(\bar{g}(\theta)) = \frac{c}{N}$ for some constant c .
- Easy to compute **tail probabilities** $\Pr(\theta \leq c)$ by letting

$$g(\theta) = I(\theta \leq c)$$

and

$$\frac{1}{N} \sum_{t=1}^N g(\theta^{(t)}) = \frac{\# \text{ } \theta\text{-draws smaller than } c}{N}.$$

Direct sampling by the inverse CDF method

■ Let $F(x)$ be the CDF of X . **Inverse CDF method:**

- 1 Generate u from the uniform distribution on $[0, 1]$.
- 2 Compute $x = F^{-1}(u)$.

■ **Exponential distribution:**

$$u = F(x) = 1 - \exp(-\lambda x)$$

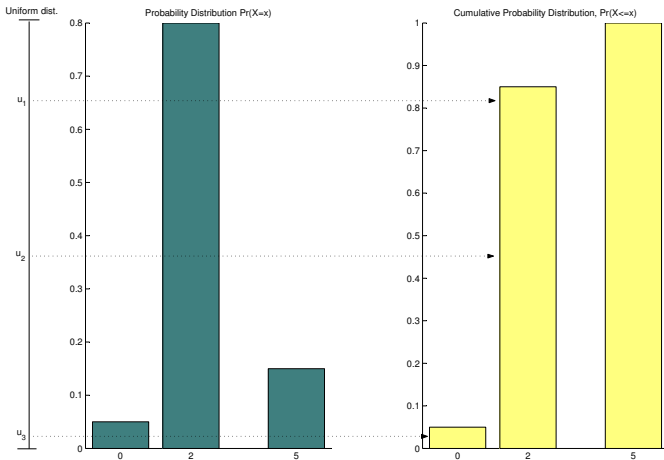
Inverting gives

$$x = -\ln(1 - u)/\lambda$$

■ So, if $u \sim U(0, 1)$ then

$$x = -\ln(1 - u)/\lambda \sim \text{Expon}(\lambda)$$

Inverse CDF method, discrete case



Gibbs sampling

- Easily implemented methods for **sampling from multivariate distributions**, $p(\theta_1, \dots, \theta_k)$
- Typically conditioned on some observed data, $p(\theta_1, \dots, \theta_k | y)$
- Requirements: Easily sampled **full conditional distributions**:
 - ▶ $p(\theta_1 | \theta_2, \theta_3, \dots, \theta_k)$
 - ▶ $p(\theta_2 | \theta_1, \theta_3, \dots, \theta_k)$
 - ▶ \vdots
 - ▶ $p(\theta_k | \theta_1, \theta_2, \dots, \theta_{k-1})$ or $p(\theta_k | \theta_1, \dots, \theta_{k-1}, y)$
- Gibbs sampling is a special case of **Metropolis-Hastings** (see Lecture 8).
- Metropolis-Hastings is a **Markov Chain Monte Carlo (MCMC)** algorithm.

The Gibbs sampling algorithm

- Choose initial values $\theta_2^{(0)}, \theta_3^{(0)}, \dots, \theta_k^{(0)}$.
- Repeat for $j = 1, \dots, N$:
 - ▶ Draw $\theta_1^{(j)}$ from $p(\theta_1 | \theta_2^{(j-1)}, \theta_3^{(j-1)}, \dots, \theta_k^{(j-1)})$
 - ▶ Draw $\theta_2^{(j)}$ from $p(\theta_2 | \theta_1^{(j)}, \theta_3^{(j-1)}, \dots, \theta_k^{(j-1)})$
 - ▶ Draw $\theta_k^{(j)}$ from $p(\theta_k | \theta_1^{(j)}, \theta_2^{(j)}, \dots, \theta_{k-1}^{(j)})$
- Return draws: $\theta^{(1)}, \dots, \theta^{(N)}$, where $\theta^{(j)} = (\theta_1^{(j)}, \dots, \theta_k^{(j)})$.

Gibbs sampling, cont.

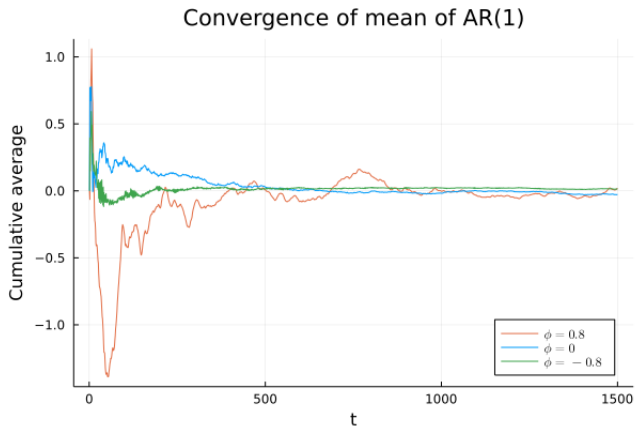
- Gibbs draws $\theta^{(1)}, \dots, \theta^{(N)}$ are **dependent**, but

$$\bar{\theta} = \frac{1}{N} \sum_{t=1}^N \theta_j^{(t)} \rightarrow E(\theta_j)$$

$$\bar{g}(\theta) = \frac{1}{N} \sum_{t=1}^N g(\theta^{(t)}) \rightarrow E[g(\theta)]$$

- $\theta^{(1)}, \dots, \theta^{(N)}$ **converges in distribution** to the target $p(\theta)$.
- $\theta_j^{(1)}, \dots, \theta_j^{(N)}$ converges to the marginal distribution of θ_j .
- **Dependent draws** \rightarrow **less efficient** than iid sampling.
- **IID samples**: $\theta^{(1)}, \dots, \theta^{(N)}$: $\text{Var}(\bar{\theta}) = \frac{\sigma^2}{N}$.
- **Autocorrelated samples**: $\text{Var}(\bar{\theta}) = \frac{\sigma^2}{N} (1 + 2 \sum_{k=1}^{\infty} \rho_k)$, where ρ_k is the autocorrelation at lag k .
- **Inefficiency factor**: $1 + 2 \sum_{k=1}^{\infty} \rho_k$.

Convergence of autocorrelated processes, Ex.



Gibbs sampling bivariate normal

■ Joint distribution

$$\begin{pmatrix} \theta_1 \\ \theta_2 \end{pmatrix} \sim N_2 \left[\begin{pmatrix} \mu_1 \\ \mu_2 \end{pmatrix}, \begin{pmatrix} 1 & \rho \\ \rho & 1 \end{pmatrix} \right]$$

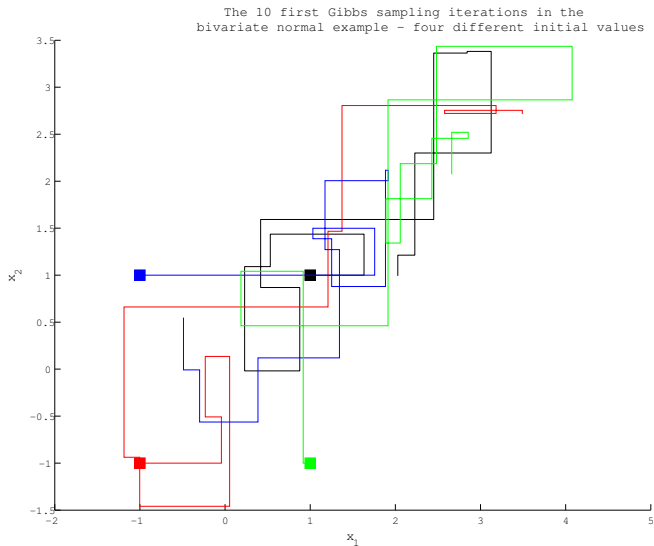
■ Ignore that we can sample directly from the bivariate normal

■ Full conditional posteriors

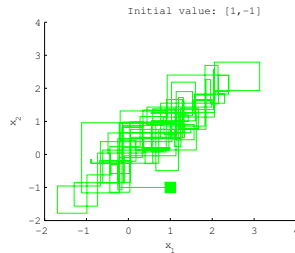
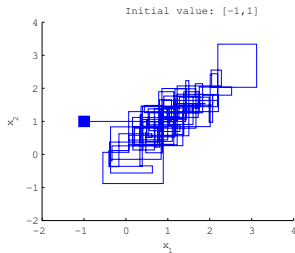
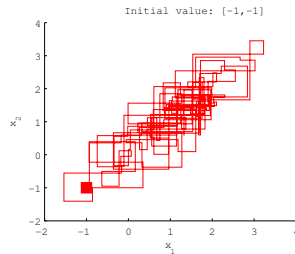
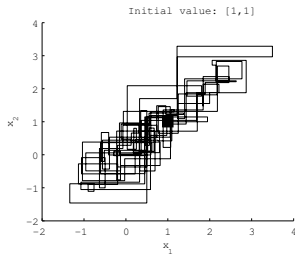
$$\theta_1 | \theta_2 \sim N[\mu_1 + \rho(\theta_2 - \mu_2), 1 - \rho^2]$$

$$\theta_2 | \theta_1 \sim N[\mu_2 + \rho(\theta_1 - \mu_1), 1 - \rho^2]$$

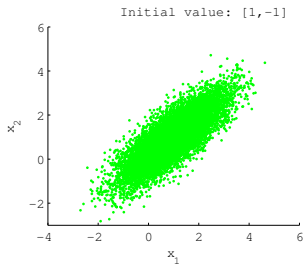
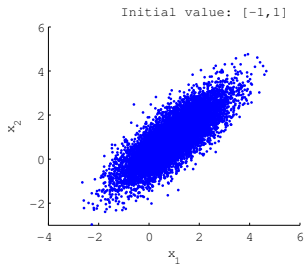
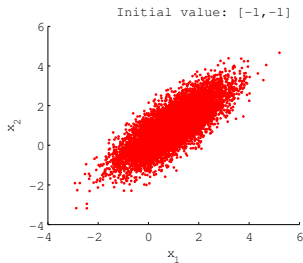
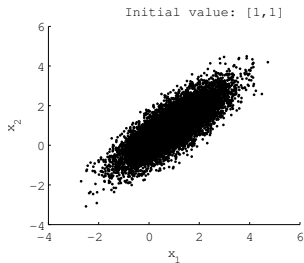
Gibbs sampling - Bivariate normal



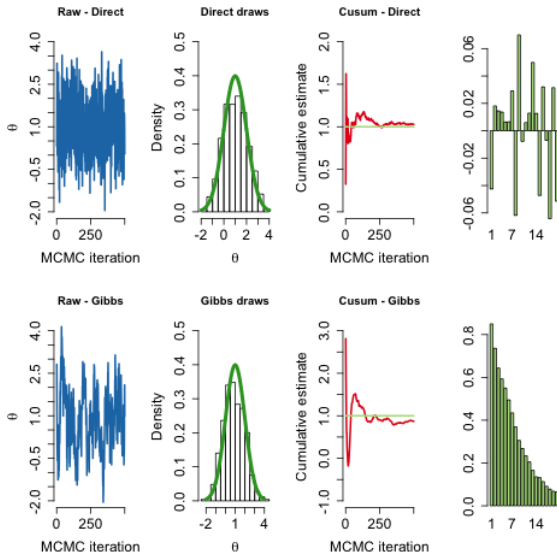
Gibbs sampling - Bivariate normal



Gibbs sampling - Bivariate normal



Direct sampling vs Gibbs sampling

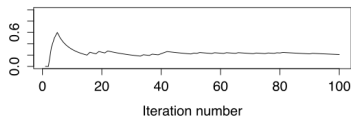


Estimating $Pr(\theta_1 > 0, \theta_2 > 0)$

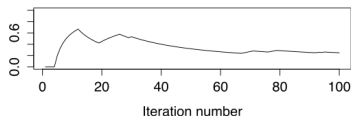
- Joint probability by counting:

$$Pr(\theta_1 > 0, \theta_2 > 0) \approx N^{-1} \sum_{i=1}^N 1(\theta_1^{(i)} > 0, \theta_2^{(i)} > 0)$$

Direct draws



Gibbs draws



Normal model with conditionally conjugate prior

■ Normal model with conditionally conjugate prior

$$\begin{aligned}\mu &\sim N(\mu_0, \tau_0^2) \\ \sigma^2 &\sim \text{Inv} - \chi^2(\nu_0, \sigma_0^2)\end{aligned}$$

■ Full conditional posteriors

$$\begin{aligned}\mu | \sigma^2, x &\sim N(\mu_n, \tau_n^2) \\ \sigma^2 | \mu, x &\sim \text{Inv} - \chi^2\left(\nu_n, \frac{\nu_0 \sigma_0^2 + \sum_{i=1}^n (x_i - \mu)^2}{n + \nu_0}\right)\end{aligned}$$

with μ_n and τ_n^2 defined the same as when σ^2 is known.

Gibbs sampling for AR processes

■ AR(p) process

$$x_t = \mu + \phi_1(x_{t-1} - \mu) + \dots + \phi_p(x_{t-p} - \mu) + \varepsilon_t, \quad \varepsilon_t \stackrel{iid}{\sim} N(0, \sigma^2).$$

■ Let $\phi = (\phi_1, \dots, \phi_p)'$.

■ Prior:

- ▶ $\mu \sim \text{Normal}$
- ▶ $\phi \sim \text{Multivariate Normal}$
- ▶ $\sigma^2 \sim \text{Scaled Inverse } \chi^2$.

■ The **posterior** can be simulated by **Gibbs sampling**¹:

- ▶ $\mu | \phi, \sigma^2, x \sim \text{Normal}$
- ▶ $\phi | \mu, \sigma^2, x \sim \text{Multivariate Normal}$
- ▶ $\sigma^2 | \mu, \phi, x \sim \text{Scaled Inverse } \chi^2$

¹Villani (2009). Steady State Priors for Vector Autoregressions. *Journal of Applied Econometrics*.

Data augmentation - Mixture distributions

■ Let $\phi(x|\mu, \sigma^2)$ denote the **PDF** of $x \sim N(\mu, \sigma^2)$.

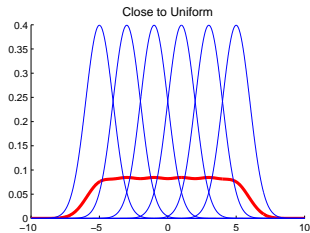
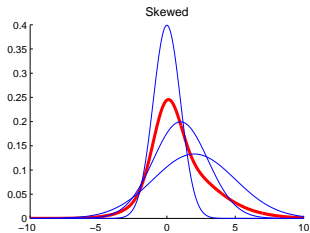
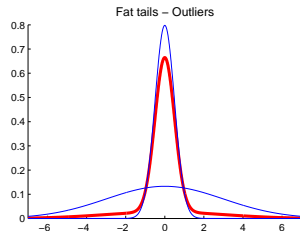
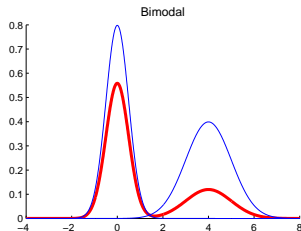
■ Two-component **mixture of normals** [MN(2)]

$$p(x) = \pi \cdot \phi(x|\mu_1, \sigma_1^2) + (1 - \pi) \cdot \phi(x|\mu_2, \sigma_2^2)$$

■ **Simulate** from a MN(2):

- ▶ Simulate a **membership indicator** $I \in \{1, 2\}$: $I \sim \text{Bern}(\pi)$.
- ▶ If $I = 1$, simulate x from $N(\mu_1, \sigma_1^2)$
- ▶ If $I = 2$, simulate x from $N(\mu_2, \sigma_2^2)$.

Illustration of mixture distributions



Mixture distributions, cont.

- The **likelihood** is a product of sums. **Messy** to work with.
- **Assume** that we know where each observation comes from

$$I_i = \begin{cases} 1 & \text{if } x_i \text{ came from Density 1} \\ 2 & \text{if } x_i \text{ came from Density 2} \end{cases}.$$

- Given I_1, \dots, I_n it is easy to estimate $\pi, \mu_1, \sigma_1^2, \mu_2, \sigma_2^2$ by separating the sample according to the I 's.
- But we do **not** know I_1, \dots, I_n !
- **Data augmentation**: add I_1, \dots, I_n as unknown parameters.
- **Gibbs sampling**:
 - ▶ Sample $\pi, \mu_1, \sigma_1^2, \mu_2, \sigma_2^2$ **given** I_1, \dots, I_n
 - ▶ Sample I_1, \dots, I_n **given** $\pi, \mu_1, \sigma_1^2, \mu_2, \sigma_2^2$

Gibbs sampling for mixture distributions

■ Prior: $\pi \sim \text{Beta}(\alpha_1, \alpha_2)$. Conjugate prior for (μ_j, σ_j^2) .

■ Define: $n_1 = \sum_{i=1}^n (I_i = 1)$ and $n_2 = n - n_1$.

■ **Gibbs sampling:**

▶ $\pi \mid \mathbf{I}, \mathbf{x} \sim \text{Beta}(\alpha_1 + n_1, \alpha_2 + n_2)$

▶ $\sigma_1^2 \mid \mathbf{I}, \mathbf{x} \sim \text{Inv-}\chi^2(\nu_{n_1}, \sigma_{n_1}^2)$ and $\mu_1 \mid \mathbf{I}, \sigma_1^2, \mathbf{x} \sim N\left(\mu_{n_1}, \frac{\sigma_1^2}{\kappa_{n_1}}\right)$

▶ $\sigma_2^2 \mid \mathbf{I}, \mathbf{x} \sim \text{Inv-}\chi^2(\nu_{n_2}, \sigma_{n_2}^2)$ and $\mu_2 \mid \mathbf{I}, \sigma_2^2, \mathbf{x} \sim N\left(\mu_{n_2}, \frac{\sigma_2^2}{\kappa_{n_2}}\right)$

▶ $I_i \mid \pi, \mu_1, \sigma_1^2, \mu_2, \sigma_2^2, \mathbf{x} \sim \text{Bern}(\theta_i), i = 1, \dots, n,$

$$\theta_i = \frac{(1 - \pi)\phi(x_i; \mu_2, \sigma_2^2)}{\pi\phi(x_i; \mu_1, \sigma_1^2) + (1 - \pi)\phi(x_i; \mu_2, \sigma_2^2)}.$$

Gibbs sampling for mixture distributions

■ K -component mixture of normals

$$p(x) = \sum_{k=1}^K \pi_k \phi(x; \mu_k, \sigma_k^2)$$

■ **Multi-class indicators:** $I_i = k$ if x_i comes from component k .

■ Gibbs sampling

- ▶ $(\pi_1, \dots, \pi_K) \mid \mathbf{I}, \mathbf{x} \sim \text{Dirichlet}(\alpha_1 + n_1, \alpha_2 + n_2, \dots, \alpha_K + n_K)$
- ▶ $\sigma_k^2 \mid \mathbf{I}, \mathbf{x} \sim \text{Inv-}\chi^2$ and $\mu_k \mid \mathbf{I}, \sigma_k^2, \mathbf{x} \sim \text{Normal}$, for $k = 1, \dots, K$,
- ▶ $I_i \mid \pi, \mu, \sigma^2, \mathbf{x} \sim \text{Multinomial}(\theta_{i1}, \dots, \theta_{iK})$, for $i = 1, \dots, n$,

$$\theta_{ij} = \frac{\pi_j \phi(x_i; \mu_j, \sigma_j^2)}{\sum_{r=1}^K \pi_r \phi(x_i; \mu_r, \sigma_r^2)}.$$

■ Gibbs sampling is very powerful for **missing data** problems.

■ **Semi-supervised learning.**

Data augmentation - Probit regression

■ Probit regression:

$$\Pr(y_i = 1 \mid x_i) = \Phi(x_i^T \beta)$$

■ Random utility formulation:

$$\begin{aligned} u_i &\sim N(x_i^T \beta, 1) \\ y_i &= \begin{cases} 1 & \text{if } u_i > 0 \\ 0 & \text{if } u_i \leq 0 \end{cases} \end{aligned}$$

- Check: $\Pr(y_i = 1 \mid x_i) = \Pr(u_i > 0) = 1 - \Pr(u_i \leq 0) = 1 - \Pr(u_i - x_i^T \beta < -x_i^T \beta) = 1 - \Phi(-x_i^T \beta) = \Phi(x_i^T \beta)$.
- Given $u = (u_1, \dots, u_n)$, β can be analyzed by linear regression.
- u is **not observed**. Gibbs sampling to the rescue!²

²Albert and Chib (1993). Bayesian Analysis of Binary and Polychotomous Response Data. *JASA*.

Gibbs sampling for the Probit regression

- Simulate from **joint posterior** $p(u, \beta|y)$ by iterating between
 - ▶ $p(\beta|u, y)$ is multivariate normal (linear regression)
 - ▶ $p(u_i|\beta, y)$, $i = 1, \dots, n$.
- The **full conditional** posterior distribution of u_i

$$\begin{aligned} p(u_i|\beta, y) &\propto p(y_i|\beta, u_i)p(u_i|\beta) \\ &= \begin{cases} N(u_i|x_i'\beta, 1) & \text{truncated to } u_i \in (-\infty, 0] \text{ if } y_i = 0 \\ N(u_i|x_i'\beta, 1) & \text{truncated to } u_i \in (0, \infty) \text{ if } y_i = 1 \end{cases} \end{aligned}$$

- Histogram of β -draws approximates the marginal posterior of β

$$p(\beta|y) = \int p(u, \beta|y) du$$

Gibbs sampling for Regularized regression

- Recap: The joint posterior of β , σ^2 and λ is

$$\beta|\sigma^2, \lambda, \mathbf{y}, \mathbf{X} \sim N(\mu_n, \Omega_n^{-1})$$

$$\sigma^2|\lambda, \mathbf{y}, \mathbf{X} \sim \text{Inv-}\chi^2(\nu_n, \sigma_n^2)$$

$$p(\lambda|\mathbf{y}, \mathbf{X}) \propto \sqrt{\frac{|\Omega_0|}{|\mathbf{X}'\mathbf{X} + \Omega_0|}} \left(\frac{\nu_n \sigma_n^2}{2}\right)^{-\nu_n/2} \cdot p(\lambda)$$

- This is the **conditional-marginal decomposition**

$$p(\beta, \sigma^2, \lambda|\mathbf{y}, \mathbf{X}) = p(\beta|\sigma^2, \lambda, \mathbf{y}, \mathbf{X})p(\sigma^2|\lambda, \mathbf{y}, \mathbf{X})p(\lambda|\mathbf{y}, \mathbf{X})$$

- **Gibbs sampling** can instead be used:

- ▶ Sample $\beta|\sigma^2, \lambda, \mathbf{y}, \mathbf{X}$ from Normal
- ▶ Sample $\sigma^2|\beta, \lambda, \mathbf{y}, \mathbf{X}$ from $\text{Inv-}\chi^2$
- ▶ Sample $\lambda|\beta, \sigma^2, \mathbf{y}, \mathbf{X}$ from Gamma

- λ is **easy** to simulate **conditional on** β and σ^2 .

Gibbs sampling for Regularized regression

- Assume a Gamma prior for λ (same as $\lambda^{-1} \sim \text{Inv} - \chi^2$)

$$\lambda \sim \text{Gamma} \left(\frac{\eta_0}{2}, \frac{\eta_0}{2\lambda_0} \right).$$

- $\mathbb{E}(\lambda) = \frac{\eta_0/2}{\eta_0/(2\lambda_0)} = \lambda_0$ and $\mathbb{V}(\lambda) = \frac{\eta_0/2}{(\eta_0/(2\lambda_0))^2} = \frac{1}{2\eta_0\lambda_0^2}$.

- Using Bayes' theorem twice:

$$\begin{aligned} p(\lambda|\beta, \sigma^2, \mathbf{y}) &\propto p(\mathbf{y}|\beta, \sigma^2, \lambda) p(\lambda|\beta, \sigma^2) \\ &\propto p(\beta|\sigma^2, \lambda) p(\lambda|\sigma^2) \\ &\propto p(\beta|\sigma^2, \lambda) p(\lambda) \end{aligned}$$

- Note:

- ▶ likelihood $p(\mathbf{y}|\beta, \sigma^2, \lambda)$ does not depend on λ .
- ▶ prior $p(\lambda|\sigma^2)$ is assumed to not depend on σ^2 .

Gibbs sampling for Regularized regression

- Full conditional posterior

$$\begin{aligned} p(\lambda | \beta, \sigma^2, \mathbf{y}) &\propto p(\beta | \sigma^2, \lambda) p(\lambda) \\ &\propto \prod_{i=1}^m \frac{1}{\sqrt{2\pi\sigma^2/\lambda}} \exp\left(-\frac{\beta_i^2}{2\sigma^2/\lambda}\right) \cdot \lambda^{\eta_0/2-1} \exp\left(-\lambda \frac{\eta_0}{2\lambda_0}\right) \\ &\propto \lambda^{m/2} \exp\left(-\frac{\lambda}{2\sigma^2} \sum_{i=1}^m \beta_i^2\right) \cdot \lambda^{\eta_0/2-1} \exp\left(-\lambda \frac{\eta_0}{2\lambda_0}\right) \\ &\propto \lambda^{(m+\eta_0)/2-1} \exp\left(-\lambda \left(\frac{\sigma^{-2} \sum_{i=1}^m \beta_i^2 + \eta_0/\lambda_0}{2}\right)\right) \end{aligned}$$

- This shows that

$$\lambda | \beta, \sigma^2, \mathbf{y} \sim \text{Gamma}\left(\frac{m + \eta_0}{2}, \frac{\sigma^{-2} \sum_{i=1}^m \beta_i^2 + \eta_0/\lambda_0}{2}\right).$$

- $\mathbb{E}(\lambda | \beta, \sigma^2, \mathbf{y}) = \frac{m + \eta_0}{\sigma^{-2} \sum_{i=1}^m \beta_i^2 + \eta_0/\lambda_0}$, so λ is learned from variability of the β_i . Large m helps!

Improving the efficiency of the Gibbs sampler

- **Efficient blocking.** Correlated parameters should ideally be included in the same updating block.
- **Reparametrization.** Convergence can improve dramatically in alternative parametrizations.
- **Data augmentation.**
 - ▶ Augment with latent variables to make **full conditional posteriors more easily sampled** (Probit, Mixture models).
 - ▶ But typically **increases the autocorrelation** between draws.