

# sBG-MCMC

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## 1 Introduction

In contractual settings, understanding customer attrition is crucial. Arguably, it is the duty of the manager to harness the full potential of attrition rates, given the privilege of its observation. Supplementing attrition is its counterpart, retention, commonly employed in calculating customer tenure and lifetime value. These metrics, vital for businesses, must be completely owned and understood.

Commonly, retention (the proportion of customers retained between successive periods) is assumed to be constant across a cohort. This is differentiated from what we will call the survival rate—the proportion of the total population alive in a given period. This *good-enough* approach, however, leads to a gross underestimation of tenure and value. At first glance, it may seem logical, but a more thorough examination reveals its weaknesses. A constant rate of retention requires a uniform attrition rate among a cohort’s customers, irrespective of the observation period. This, however, defies intuition. It seems implausible that a customer who has resubscribed to Netflix for the 30th time would have the same likelihood of leaving in the 31st period as a new subscriber in their first. Empirically, it is even shown retention rates increase over time.

Accordingly, some would argue that these customers are *getting better*, but this contradicts the nature of human behavior. People don’t aspire to become better consumers; they are simply guided by their own, seemingly random, desires. From our perspective, the *good customers* had always been good; identifying them, however, required observation. Customers are drawn to try new products; and, if in agreement with their preferences, they continue that relationship with the business. Such preferences remain unchanged (assuming stationarity) by the mere act of trying a product. Just as a coin landing on tails to infinity will never happen, all customers will churn, particularly if an alternative product better aligns with their preferences or current necessities.

How can we ascertain what actions our customers will take, or more aptly, how do we discern the assortment of customers we possess? Each customer, acting independently, obscures the underlying factors influencing their behavior. Yet, we endeavor to do our best. Fortunately, we have a proxy for determining customers with similar behavior patterns—the duration of our relationship.

To harness this relationship/churn data and our beliefs of customer behavior, we will employ the shifted beta-geometric (sBG) distribution (Fader and Hardie, 2007). The sBG has a hierarchical structure. On the individual level—the lowest—we model customer tenure

using the geometric distribution, particularly the shifted variant. To briefly summarize, geometric distribution aligns with our understanding of customer attrition. It is parameterized by  $\theta$  (churn propensity), which encodes the various unobservable influences impacting a customer’s decision to churn—product preferences, personality traits, occupational hazards, etc. Given we know an individual’s true  $\theta$ , we can calculate the probability of that customer surviving through period  $t$ :  $p(T > t|\theta)$ .

One level higher, the customer’s  $\theta$  is itself characterized by a beta distribution. This distribution accounts for our intuition regarding customer heterogeneity. It represents the spectrum of  $\theta$  values among our customers and is characterized by two hyperparameters,  $\alpha$  and  $\beta$ . The versatile shapes of this distribution, and the corresponding retention curves they imply, can be examined through the interactive graph [here](#)<sup>1</sup>.

A result of modeling fixed churn rates are increasing retention rates. It’s an artifact of the drop-out effect of bad customers. Accordingly, it would be ill-advised to only consider retention rates when analyzing one’s customer base. This is evident in the survival curve, which reveals that customer cohorts with high churn rates rapidly vanish, despite achieving significant retention in later stages. In contrast, cohorts with a lower churn propensity retain a substantial portion of their initial base while still attaining high retention. Typically, companies excessively inclined towards the higher-churn segment of the distribution either cease to exist or adapt, attracting more high-value customers.

## 2 Methodology

The motivation behind this analysis is straightforward. Having previously implemented the sBG employing Empirical Bayes, a compelling desire to explore a more comprehensive approach emerged. My methodology features the fully Bayesian interpretation of the model; and, to benchmark, I will include results from the Empirical Bayes method (one whose simplicity allows for implementation in Excel).

### 2.1 Bayesian Interpretations

It’s crucial to understand the implications that a Bayesian interpretation induces on a model’s architecture. Generally, we consider all unknown parameters as random variables with assigned probabilities for their possible values. Parallel with observed data, we can choose to imbue these parameters with our subjective beliefs, codified by prior distributions. This produces an updated estimate of our *belief* in model parameters—the posterior distribution. Choosing priors that are themselves parametric distributions induces a hierarchical structure (such as our sBG) complicating the posterior distribution. Commonly, the posterior has no standard form. To manage this, we will use methods such as random-walk Metropolis (RWM) and, more recently, Hamiltonian Monte Carlo (HMC). Using these tools we can more efficiently generate samples from complex posterior distributions. An alternative approach involves loosening certain strict Bayesian principles, as seen in the empirical Bayes method. For example, the joint posterior distribution for an individual can be calculated using Bayes’

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<sup>1</sup>For printed versions, the url is <https://aarondaelramsey.com/academics/statistics/sBG/#betaDist>

rule:

$$\begin{aligned}
p(\theta, \alpha, \beta|y) &= \frac{p(y|\theta, \alpha, \beta) \cdot p(\theta, \alpha, \beta)}{p(y)} \\
&= \frac{p(y|\theta, \alpha, \beta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta)}{p(y)} \\
&= \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta)}{p(y)}
\end{aligned}$$

In fact, this joint distribution is precisely what the fully Bayesian approach utilizes. Here, we also present the expanded form of the evidence— $p(y)$ .

$$p(\theta, \alpha, \beta|y) = \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta)}{\int \int \int p(y|\theta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta) d\alpha d\beta d\theta}$$

The integrals in the denominator are often intractable; and, unfortunately, given our model's structure, it is impossible to find a closed-form solution. However, the desired result,  $p(\theta, \alpha, \beta|y)$ , depends exclusively on the values of  $\theta$ ,  $\alpha$ , and  $\beta$ . Therefore, removing any terms without such dependencies ensures the estimated values remain proportional to the original distribution. Having integrated out these parameters, the posterior's bottom term, the evidence, solely concerns  $y$  and can be removed. The result is a distribution exhibiting the same qualities as the original.

$$p(\theta, \alpha, \beta|y) \propto p(y|\theta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta)$$

If our interests were solely in estimating the thetas (individual churn rates) of our model, we could reduce complexity by integrating our proportional posterior over the population parameters  $\alpha$  and  $\beta$ :

$$\begin{aligned}
\int \int p(\theta, \alpha, \beta|y) d\alpha d\beta &\propto \int \int p(y|\theta) \cdot p(\theta|\alpha, \beta) \cdot p(\alpha, \beta) d\alpha d\beta \\
p(\theta|y) &\propto p(y|\theta) \cdot \int \int p(\theta|\alpha, \beta) \cdot p(\alpha, \beta) d\alpha d\beta
\end{aligned}$$

Unfortunately, we find ourselves back where we started: without a closed form solution for this integral. A common solution for such issues is the Gibbs sampler. The Gibbs sampler is an iterative algorithm relying on the model parameters' conditional distributions. This method, part the broader Markov chain Monte Carlo family, is both simple to understand and implement. Unfortunately, for our specific model, the conditional distribution of  $\alpha$  and  $\beta$  do not have a standard form, a prerequisite for the Gibbs sampler. The most popular extension addressing such concessions, Random-Walk Metropolis, uses proposed samples from known distributions in place of a conditional distribution. The Gaussian is often chosen for its symmetry. Proposed samples are then accepted or rejected according to an acceptance criterion. Another class of algorithms, another subset of MCMC, is Hamiltonian Monte Carlo. We will explore and apply both methods.

A more straightforward method is Empirical Bayes. It's facilitates statistical analysis/inference on data where the prior distribution is determined by the observed data—hence, empirical. This contrasts the traditional Bayesian approach where prior beliefs are

fixed before any data are observed. It is considered a good-enough approximation to the fully Bayesian treatment of a hierarchical model.

Rather than permitting the top-level model parameters to vary, they are instead fixed to their most likely values. Maximizing the marginal likelihood  $p(y|\alpha, \beta)$  with respect to the population-level parameters allows one to find these values. Such procedure contributes to Empirical Bayes' other name—maximum marginal likelihood. This structure greatly reduces computational complexity allowing analysis to be easily performed in Excel. With the advent of efficient and effective computational techniques, fully Bayesian approaches have mostly replaced Empirical Bayes methods; however, its ease of use, interpretability, and predictive power can neither be overstated nor overlooked.

Once found, the values of  $\alpha$  and  $\beta$  allow for the calculation of the conditional posterior distribution of  $\theta$ . The parameters  $\alpha$  and  $\beta$  are fixed points. From a Bayesian perspective, this is the same as conditioning on these parameters.

$$\begin{aligned} p(\theta|y, \alpha, \beta) &= \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta)}{p(y|\alpha, \beta)} \\ &= \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta)}{\int p(y|\theta) \cdot p(\theta|\alpha, \beta) d\theta} \end{aligned}$$

## 2.2 Data and Model

The example data consist of 1,000 customers and their corresponding churn periods, which have been censored at the 7<sup>th</sup> period. That is, it is unknown when each customer surviving through the 7<sup>th</sup> period churned. Each customer's observed churn period, denoted  $y_i$ , is assumed to follow a Geometric distribution with a corresponding parameter representing churn propensity,  $\theta_i$ . This structure implies an independent, constant retention rate for each customer. Each  $\theta_i$  is assumed to be drawn from the same Beta distribution, described by parameters,  $\alpha$  and  $\beta$ . Such structure can be represented by the following formulas:

$$\begin{aligned} y_i &\sim \text{Geom}(\theta_i) \\ \theta_i &\sim \text{Beta}(\alpha, \beta) \end{aligned}$$

A helpful analogy for internalizing this structure is to imagine each customer within a cohort (in our example the original 1000 customers acquired in the same period) reaching into a bag of coins and selecting one. The probability of this coin landing on heads is their propensity to churn ( $\theta_i$ ). The mix of coins within the bag follows a Beta distribution; and, coin selection is only done once, at the beginning of the customer relationship. At each period, the customers flip their coins, and those whose coin lands on heads, churn. These constraints again underscore the two main assumptions of the model: each period, a customer decides to leave the firm with a personal, constant probability  $\theta_i$  (stationarity) where each  $\theta_i$  was generated by a Beta distribution at the cohort inception. The Beta distribution is a convenient and intuitive choice as it exhibits conjugacy with the Geometric distribution and is bounded between 0 and 1.

In order for us to estimate these parameters, we need to incorporate the data with our model. Normally, it would involve calculating the product of likelihoods and prior distributions; however, recall that our data are right-censored at the 7th period. This structure necessitates the use of two different likelihood formulas: one based on the geometric's pdf; the other, its survival function:

$$\begin{aligned}
p(\boldsymbol{\theta}, \alpha, \beta | \mathbf{y}) &\propto p(\mathbf{y} | \boldsymbol{\theta}, \alpha, \beta) \cdot p(\boldsymbol{\theta}, \alpha, \beta) \\
&= p(\mathbf{y} | \boldsymbol{\theta}, \alpha, \beta) \cdot p(\boldsymbol{\theta} | \alpha, \beta) \cdot p(\alpha, \beta) \quad \text{where } p(\alpha, \beta) \propto 1 \\
&= \left( \prod_{i=1}^{1000} (p(y_i | \theta_i, \alpha, \beta) p(\theta_i | \alpha, \beta)) \right) \cdot p(\alpha, \beta) \\
&\propto \prod_{i=1}^{1000} (p(y_i | \theta_i) p(\theta_i | \alpha, \beta)) \\
&= \prod_{i=1}^{759} \left( \theta_i (1 - \theta_i)^{y_i - 1} \frac{\theta_i^{\alpha-1} (1 - \theta_i)^{\beta-1}}{B(\alpha, \beta)} \right) \prod_{i=760}^{1000} \left( (1 - \theta_i)^7 \frac{\theta_i^{\alpha-1} (1 - \theta_i)^{\beta-1}}{B(\alpha, \beta)} \right) \\
&= \left( \frac{1}{B(\alpha, \beta)} \right)^{1000} \left( \prod_{i=1}^{759} (\theta_i^{\alpha} (1 - \theta_i)^{\beta + y_i - 2}) \prod_{i=760}^{1000} (\theta_i^{\alpha-1} (1 - \theta_i)^{\beta+6}) \right)
\end{aligned}$$

It should be noted that I have chosen  $\alpha$  and  $\beta$  to have a flat prior for simplicity. The result is  $p(\alpha, \beta) \propto 1$ . Additionally, it's important to note that I have hard-coded  $y_i$  for the censored cell at  $t = 7$  in the second product. This is specific to this dataset, and I want to make it clear that this value doesn't change in the second product. Generally, the survival function for the geometric is  $p(T > t) = (1 - \theta_i)^t$ ; however, this may cause confusion for some users. One can reparameterize the survival function to be one more than the last observed date (8 in our case) to make implementation in Python more straightforward. Additionally, the indices of the products are also hardcoded to values specific to our dataset. To generalize the posterior, a data-agnostic formula can be given by:

$$\begin{aligned}
p(\boldsymbol{\theta}, \alpha, \beta | \mathbf{y}) &\propto \left( \frac{1}{B(\alpha, \beta)} \right)^N \left( \prod_{i=1}^{N_u} (\theta_i^{\alpha} (1 - \theta_i)^{\beta + y_i - 2}) \prod_{i=N_u+1}^N (\theta_i^{\alpha-1} (1 - \theta_i)^{\beta + y_i - 1}) \right) \\
p(\boldsymbol{\theta}, \alpha, \beta | \mathbf{y}) &\propto \left( \frac{1}{B(\alpha, \beta)} \right)^N \left( \prod_{i=1}^{N_u} (\theta_i^{\alpha} (1 - \theta_i)^{\beta + y_i - 2}) \prod_{i=N_u+1}^N (\theta_i^{\alpha-1} (1 - \theta_i)^{\beta + y_i - 2}) \right)
\end{aligned}$$

$N$  represents the total number of customers in the dataset,  $N_u$  represents the number of customers existing in the uncensored cells, and the top and bottom equations respectively represent the two interpretations of the survival function. For clarity, I will be using the former definition in all subsequent formulae.

## 2.3 Random-Walk Metropolis

We now need to sample from our joint posterior. Given its complexity, we employ the Metropolis algorithm, a Markov chain Monte Carlo method, which simplifies sampling by

conditioning on current parameter samples. In addition, it loosens the requirements of the Gibbs sampler—conditional distributions are allowed to have non-standard form.

The initial step is to determine the conditional posteriors of all our parameters. This is achieved by disregarding terms dependent on the parameters being conditioned on. Consequently, the resulting distribution is proportional to its true value. For example, the parameters  $\boldsymbol{\theta}$  have conditional posterior distributions proportional to the following equations:

$$p(\theta_i | \theta_{j \neq i}, \alpha, \beta, \mathbf{y}) \propto \begin{cases} \theta_i^\alpha (1 - \theta_i)^{\beta + y_i - 2} & \text{for } 1 \leq i < 760 \\ \theta_i^{\alpha-1} (1 - \theta_i)^{\beta+6} & \text{for } i \geq 760 \end{cases}$$

We recognize these as the functional forms of Beta distributions. We will see these again later when discussing empirical Bayes:

$$\theta_i | \theta_{j \neq i}, \alpha, \beta, \mathbf{y} \sim \begin{cases} \text{Beta}(\alpha + 1, \beta + y_i - 1) & \text{for } 1 \leq i < 760 \\ \text{Beta}(\alpha, \beta + 7) & \text{for } i \geq 760 \end{cases}$$

Similarly, by ignoring elements of the joint distribution not reliant on  $\alpha$  and  $\beta$ , a joint conditional distribution can be calculated. Unfortunately, this results in a non-standard distribution, which will require the Metropolis step of our algorithm to find samples from:

$$p(\alpha, \beta | \mathbf{y}, \boldsymbol{\theta}) \propto \prod_{i=1}^{1000} \left( \frac{\theta_i^\alpha (1 - \theta_i)^\beta}{B(\alpha, \beta)} \right)$$

In an iteration of the Metropolis algorithm, samples are drawn from each conditional distribution based on existing samples—commonly referred to as current or previous samples, depending on perspective. Each time a sample for a parameter is accepted, it becomes the current sample for that parameter, which is then used in subsequent samplings for that iteration. The follow scheme illustrates the process of sampling using this algorithm.

1. Initialize the parameters  $\boldsymbol{\theta}$ ,  $\alpha$ , and  $\beta$ , the starting points in the state space, and choose a symmetric proposal distribution  $q(x^* | x^{t-1})$  for your parameters generated by non-standard conditional distributions.
2. For each iteration  $t = 1, 2, \dots, T$ :
  - (a) Sample the parameters  $\boldsymbol{\theta}$  using
$$\theta_i | \theta_{j \neq i}, \alpha, \beta, y_i \sim \begin{cases} \text{Beta}(\alpha + 1, \beta + y_i - 1) & \text{for } 1 \leq i < 760, \\ \text{Beta}(\alpha, \beta + 7) & \text{for } i \geq 760 \end{cases}$$
  - (b) Generate a proposal  $x^*$  from the proposal distribution  $q(x^* | x^{t-1})$  for both  $\alpha$  and  $\beta$ . Where  $\sigma_\alpha$  and  $\sigma_\beta$  are tuning parameters for the algorithm. (See Appendix A.1 for information about non-symmetric proposal distributions)
    - i.  $\alpha^* \sim \text{Normal}(\alpha^{t-1}, \sigma_\alpha)$
    - ii.  $\beta^* \sim \text{Normal}(\beta^{t-1}, \sigma_\beta)$

- (c) Input the proposed values into their non-standard joint distribution and compare to the current values using a ratio  $r$ .
  - i.  $r = \frac{p(\alpha^*, \beta^* | \mathbf{y}, \boldsymbol{\theta})}{p(\alpha^{t-1}, \beta^{t-1} | \mathbf{y}, \boldsymbol{\theta})}$
- (d) We accept the proposed values with probability  $r$ . (i.e. when  $r$  is greater than  $u$  where  $u \sim \text{Uniform}(0, 1)$ )
- (e) If accepted, our current sample values are updated to the proposed values. Otherwise, the old samples remain.

Generally it is computationally useful to work with the logarithms of our distribution. Utilizing the properties of logarithms,  $r$  can be represented as a difference of logarithms and then compared to  $\log(u)$ :

$$\begin{aligned}
 p(\alpha, \beta | \mathbf{y}, \boldsymbol{\theta}) &\propto \prod_{i=1}^{1000} \left( \frac{\theta_i^\alpha (1 - \theta_i)^\beta}{B(\alpha, \beta)} \right) \\
 &= B(\alpha, \beta)^{-1000} \cdot \prod_{i=1}^{1000} (\theta_i^\alpha (1 - \theta_i)^\beta) \\
 \log(p(\alpha, \beta | \mathbf{y}, \boldsymbol{\theta})) &\propto \log(B(\alpha, \beta)^{-1000}) + \log \left( \prod_{i=1}^{1000} \theta_i^\alpha (1 - \theta_i)^\beta \right) \\
 &= -1000 \log(B(\alpha, \beta)) + \log(\theta_1^\alpha \cdot \dots \cdot \theta_{1000}^\alpha \cdot (1 - \theta_1)^\beta \cdot \dots \cdot (1 - \theta_{1000})^\beta) \\
 &= -1000 \log(B(\alpha, \beta)) + \log(\theta_1^\alpha) + \dots + \log(\theta_{1000}^\alpha) \\
 &\quad + \log((1 - \theta_1)^\beta) + \dots + \log((1 - \theta_{1000})^\beta) \\
 &= -1000 \log(B(\alpha, \beta)) + \alpha \log(\theta_1) + \dots + \alpha \log(\theta_{1000}) \\
 &\quad + \beta \log(1 - \theta_1) + \dots + \beta \log(1 - \theta_{1000}) \\
 &= -1000 \log(B(\alpha, \beta)) + \alpha \sum_{i=1}^{1000} (\log(\theta_i)) + \beta \sum_{i=1}^{1000} (\log(1 - \theta_i)) \\
 &= \alpha \sum_{i=1}^{1000} (\log(\theta_i)) + \beta \sum_{i=1}^{1000} (\log(1 - \theta_i)) - 1000 \log(B(\alpha, \beta)) \\
 \log(r) &= \log(p(\alpha^*, \beta^* | \mathbf{y}, \boldsymbol{\theta})) - \log(p(\alpha^{t-1}, \beta^{t-1} | \mathbf{y}, \boldsymbol{\theta}))
 \end{aligned}$$

## 2.4 Hamiltonian Monte Carlo

In most cases, using RWM to generate samples from a posterior distribution is effective, yet it isn't perfect. Namely, RWM can and will propose a disproportionate number of samples outside the typical set, relative to those points' actual likelihoods. Thankfully, the acceptance criterion in RWM ensures that these deviations do not distort the characteristics of the posterior. Higher rejection, however, does decrease the algorithm's ability to effectively

explore the typical set. In multidimensional settings, the tuning parameter is set to achieve an approximate 23% acceptance rate. We see this first hand in the sBG. The algorithm struggles to diffuse through the posterior space; and, in fact, the auto-correlation is so high, roughly 800,000 samples are needed across our four chains to achieve an effective sample size of 1,000. This is neither reasonable nor practical, prompting the need to consider an alternative solution—Hamiltonian Monte Carlo.

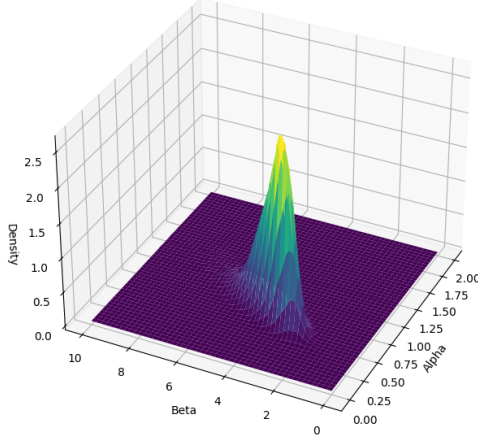
Hamiltonian Monte Carlo (HMC) is a class of algorithms which uses Hamiltonian trajectories to generate samples from a posterior distribution. One of earliest implementations, Hybrid Monte Carlo, generated samples using Hamiltonian trajectories integrated over a fixed duration ( $L * \epsilon$ ) to generate Metropolis proposals in place of a proposal distribution. While Hybrid Monte Carlo outperformed RWM, it still presented numerous inefficiencies and complications. Among those were the tuning of model parameters  $L$  (number of leapfrog steps) and  $\epsilon$  (step size), supplying gradients for trajectory calculations, and the underutilization of information contained within the trajectory’s intermediate points. Without significant HMC experience, tuning these parameters optimally is a non-trivial task. Moreover, many posterior distributions exhibit pathological behaviors with ill-set tuning parameters, especially in high-dimensional settings—an irony given such settings are one of its strengths.

In Gelman and Hoffman (2012) a new HMC variant named the No U-Turn Sampler (NUTS) was proposed. It featured automated control of tuning parameters, included information from trajectories’ intermediate points, and offered a solution for the provision of gradients required by the algorithm. The specifics of implementing NUTS will be discussed later, so for now let’s try to understand how this class of algorithms works.

### 2.4.1 Intuition

Intuition for NUTS/HMC can be more easily distilled from the construction of a physical system. Imagine a small particle—or, a ball for ease of visualization—positioned in  $\mathbb{R}^3$  on a frictionless surface. The surface’s height corresponds to our posterior distribution. Accordingly, the projection of this particle onto the  $xz$  plane represents the position in parameter space—known as the configuration in space mechanics literature. This visualization can affectionately be called Mount Likelihood.





In machine learning algorithms, the goal is to ascend/descend using a function’s gradients to guide the algorithm to some maximum or minimum. That, however, is not our goal. We want to incorporate information from the posterior’s gradients to more efficiently explore all of the typical set rather than converging to the mode of the distribution. In simple terms, we want to integrate physics into our system—hence the construction of an analogous physical system.

As it stands, our physical construction does not afford us any conveniences. Placing our ball on the constructed surface would have the ball slide (no rolling without friction) away, having never explored regions of higher density. One solution could be to imbue the ball with some momentum in the direction of higher density; however, there are two considerations. Firstly, there would need to be a determined direction in which to give the momentum. Secondly, assuming the ball were sent towards a high density region, it would not remain there for a proportional length of time. Similar to before and without one’s intervention, it would slide down the slope to disparate regions outside the typical set. As a result a stopping criterion of some sophistication would need to be applied. In either case, such interventions would introduce significant bias into the system.

The solution, at a high level, is to invert the posterior; so, instead of looking at Mount Likelihood, we observe the Ravine of Rareness. The more likely a set of parameters, the more negative the height. This ensures, at any time, the particle tends toward a local minimum. There need not be any concern of the particle sliding to distant points in space. With this addressed, we need only place a particle on the surface and it will tend towards high-density regions. To simulate its path, Hamilton’s equations need solved:

$$\frac{dq_i}{dt} = \frac{\partial H}{\partial p_i} \quad \text{and} \quad \frac{dp_i}{dt} = -\frac{\partial H}{\partial q_i}$$

where  $H(\mathbf{q}, \mathbf{p}) = U(\mathbf{q}) + \frac{1}{2}\mathbf{p}^T M^{-1}\mathbf{p}$

The daunting task of solving these equations must be achieved through numerical in-

tegration. That aside, we currently have only a naive understanding of what *physics* we are inducing on the system. By incorporating Hamiltonian dynamics, we have implicitly augmented our space with  $D$  additional parameters. For this example, there are now four total parameters—two for position ( $\mathbf{q}$ ) and two for their corresponding momenta ( $\mathbf{p}$ ). The bottom equation, known as the Hamiltonian, incorporates all four parameters in the augmented space. It is the sum of potential and kinetic energies contained within the system. The potential energy can be written as the height of the particle, which is generally given as the inverted log of the posterior. The choice of kinetic energy is somewhat up to us, though care must be taken in its choice as not all kinetic energies are useful or valid. The standard choice being the Euclidean-Gaussian kinetic energy.

To further describe the physical implications of HMC, the sole forces acting upon the particle are gravity and the reaction from the posterior’s surface—again no friction. Consequently, the total energy of the system is conserved along the path defined by these equations. From the perspective of our augmented system, these paths of constant energy define level sets of  $H$ . In our two-dimensional parameter space, a level set could be called a level curve or a contour line:

$$H^{-1}(E) = \{\mathbf{q}, \mathbf{p} \mid H(\mathbf{q}, \mathbf{p}) = E\}$$

In simpler terms, this represents the set of all inputs of the ordered pair  $(\mathbf{q}, \mathbf{p})$ —points in position-momentum phase space—that, when used to evaluate the Hamiltonian, yield a constant energy level  $E$ . The particle’s movement, confined to a particular energy level, is periodic—think of a swinging pendulum. This behavior limits its ability to thoroughly explore the posterior distribution; and, more importantly, without updating the level set the particle exists on, it will only continue to traverse the same path each time we compute its trajectory. We need a procedure to transition the particle between level sets.

Fortunately, our choice of kinetic energy is a result of constructing a probability distribution over the momenta. This allows us to transition between the energy levels easily. Each iteration, after generating a parameter sample, we can resample the momenta from a Gaussian distribution, refreshing the particle’s path. For a more in-depth exploration of these topics, Betancourt (2017) provides incredible insights and explanations for anyone interested in a more rigorous introduction to HMC.

To summarize the resultant structure, we begin by augmenting our model with auxiliary parameters representing the momentum,  $\mathbf{p}$ , of the particle in each dimension of the parameter space. We then separate the sampling process of the algorithm into two distinct steps. The first is a deterministic exploration of an energy level using Hamilton’s equations. The second is a stochastic update or resampling of our momenta, positioning the particle on a new level set to explore. Instead of diffusing inefficiently through parameter space alone, we now only diffuse through the various level sets. After each sampling of momenta, the algorithm relies on a predetermined path to make large jumps from the initial point. The efficiency of the deterministic step can be controlled by tuning the  $L$  and  $\epsilon$  parameters. Specifically, the NUTS algorithm dynamically sets  $L$  during trajectory construction. It uses a stopping criterion that halts the numerical integrator once the trajectory begins to turn around on itself—hence, the No U-Turn element of its name. Secondly, it employs a dual averaging algorithm (Nesterov, 2009) allowing for an optimal  $\epsilon$  to be calculated during the warm-up period.

### 2.4.2 Implementation

Talk about using torch for autodiff. Discuss that I took a log transformation of the parameters to help with autocorr and ensuring alpha, beta > 0. Talk about how I used and implemented an optimal metric.

Implementing HMC of any sort can be arduous. Before implementing, whether you are using bespoke code, STAN, pymc, etc. I would recommend in addition to the Betancourt and NUTS ppapers reading Neal (2011).

The code contained within this project's repository on [GitHub](#) contains my implementation. It deviates from the NUTS implementation and more closely resembles the scheme laid out by Betancourt—what is currently implemented by STAN.

## 2.5 Empirical Bayes

My coverage of Empirical Bayes will be brief. I have distilled the vital components for the purpose of comparison. Fader and Hardie (2007) offers an in-depth derivation and handling of the Empirical Bayes implementation of the sBG within Excel.

Our goal is to find point estimates of  $\alpha$  and  $\beta$  that maximize the likelihood of the data given the model. In our case, the model is the marginal likelihood function of the data— $p(y|\alpha, \beta)$ .

$$\begin{aligned} p(\theta|y, \alpha, \beta) &= \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta)}{p(y|\alpha, \beta)} \\ &= \frac{p(y|\theta) \cdot p(\theta|\alpha, \beta)}{\int p(y|\theta) \cdot p(\theta|\alpha, \beta) d\theta} \\ \int_0^1 p(Y = y|\theta) \cdot p(\theta|\alpha, \beta) d\theta &= \int_0^1 \theta(1 - \theta)^{y-1} \cdot \frac{\theta^{\alpha-1}(1 - \theta)^{\beta-1}}{B(\alpha, \beta)} d\theta \\ p(Y = y|\alpha, \beta) &= \frac{1}{B(\alpha, \beta)} \cdot \int_0^1 \theta(1 - \theta)^{\beta+y-2} d\theta \\ &= \frac{B(\alpha + 1, \beta + y - 1)}{B(\alpha, \beta)} \end{aligned}$$

A similar process can be used to find  $p(Y > y|\alpha, \beta)$

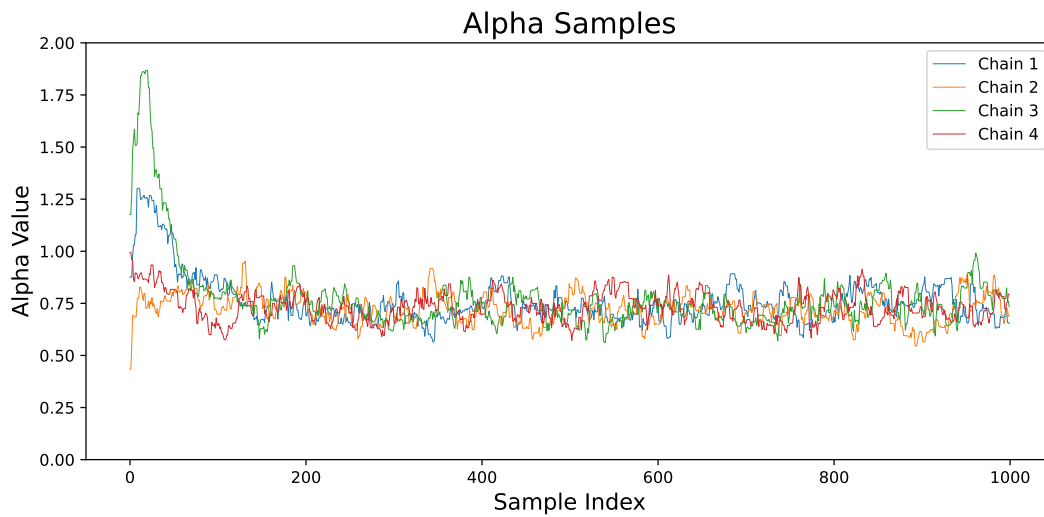
$$p(Y > y|\alpha, \beta) = \frac{B(\alpha, \beta + y)}{B(\alpha, \beta)}$$

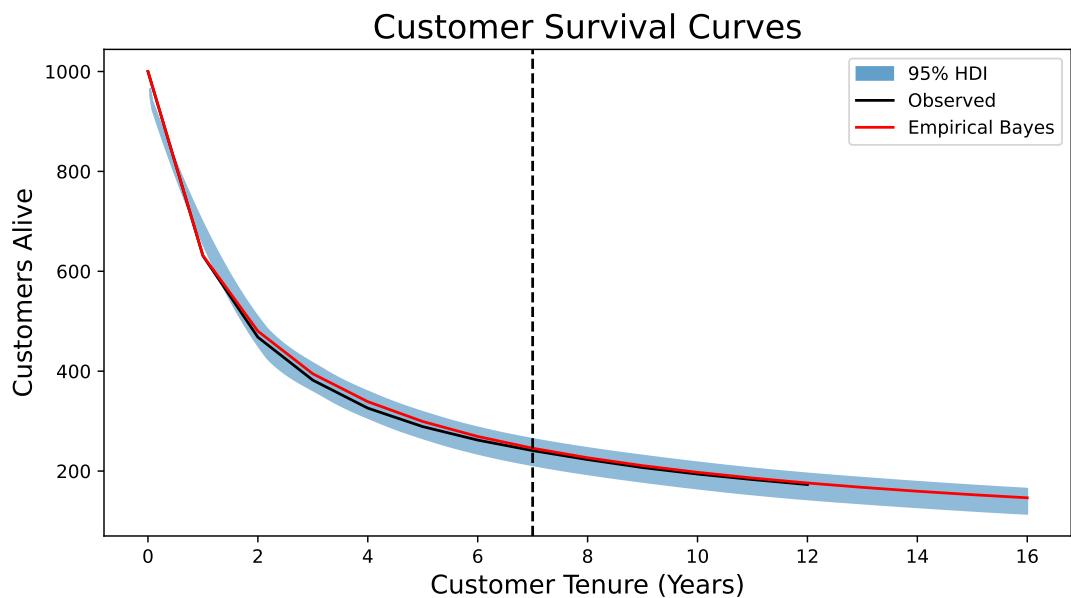
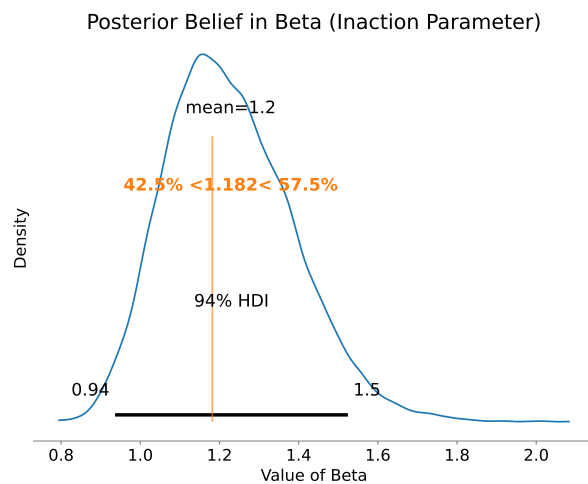
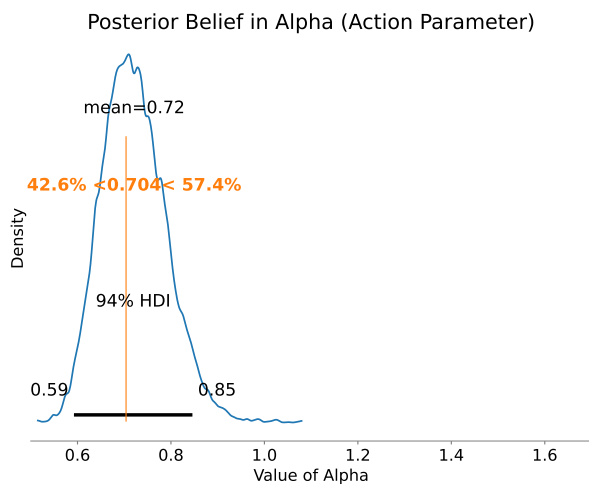
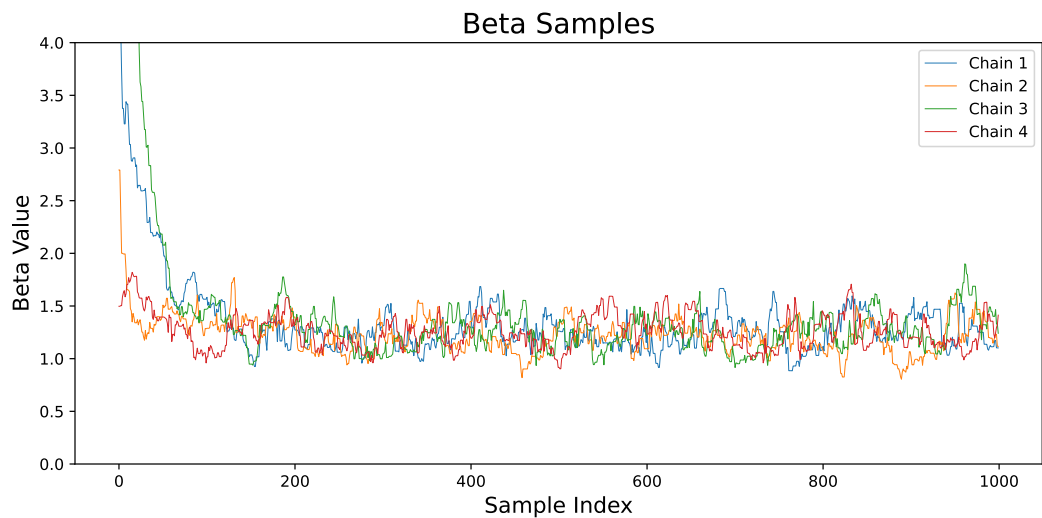
These two formulas applied to the data will give us a resultant likelihood which we can maximize using the solver in excel. Specifically, we can apply  $p(Y = y|\alpha, \beta)$  to the uncensored cells and  $p(Y > y|\alpha, \beta)$  to the censored cell. Traditionally, the likelihood is a product of these probabilities across the data. To ensure the lack of precision our computers have doesn't affect the calculations, it is common to take a log of the likelihood. This results in a sum of the log probabilities multiplied by the number of corresponding customers associated with it.

### 3 Results and Analysis

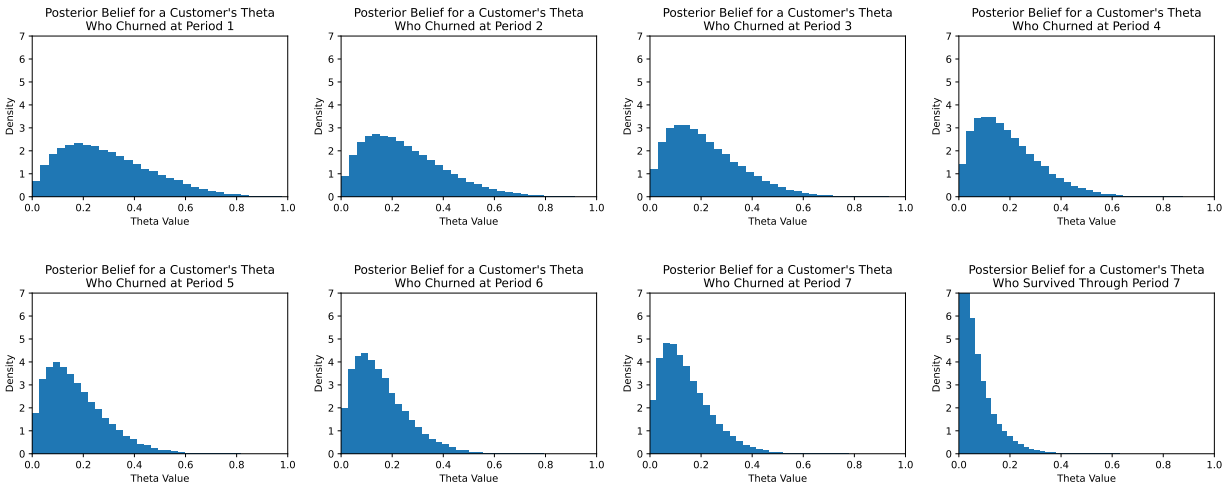
Theta posertions are cool but mostly useless for churned customers. Lets see if typing more words allows me to rectify this error.

Posterior Beliefs of Churn Propensity for Regular Customers of Similar Behavior

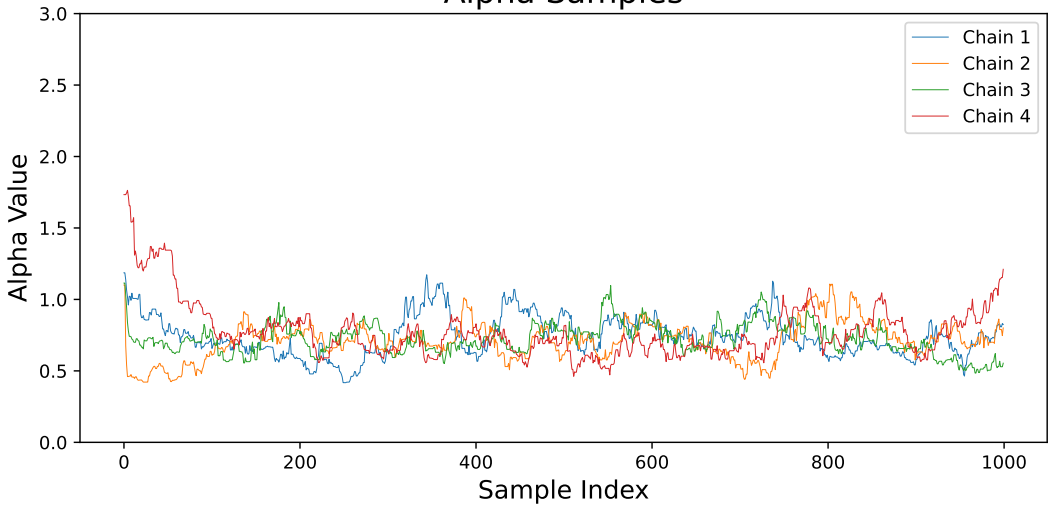




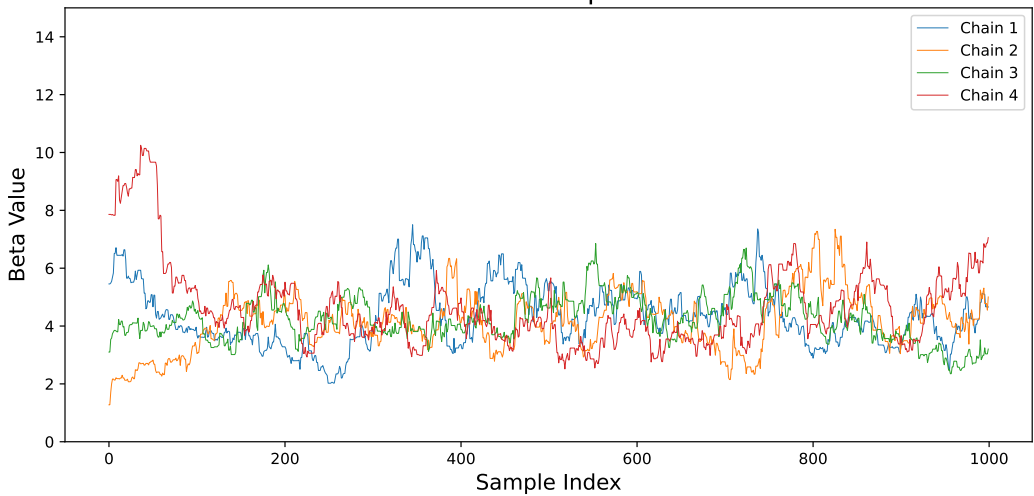
Posterior Beliefs of Churn Propensity for Regular Customers of Similar Behavior

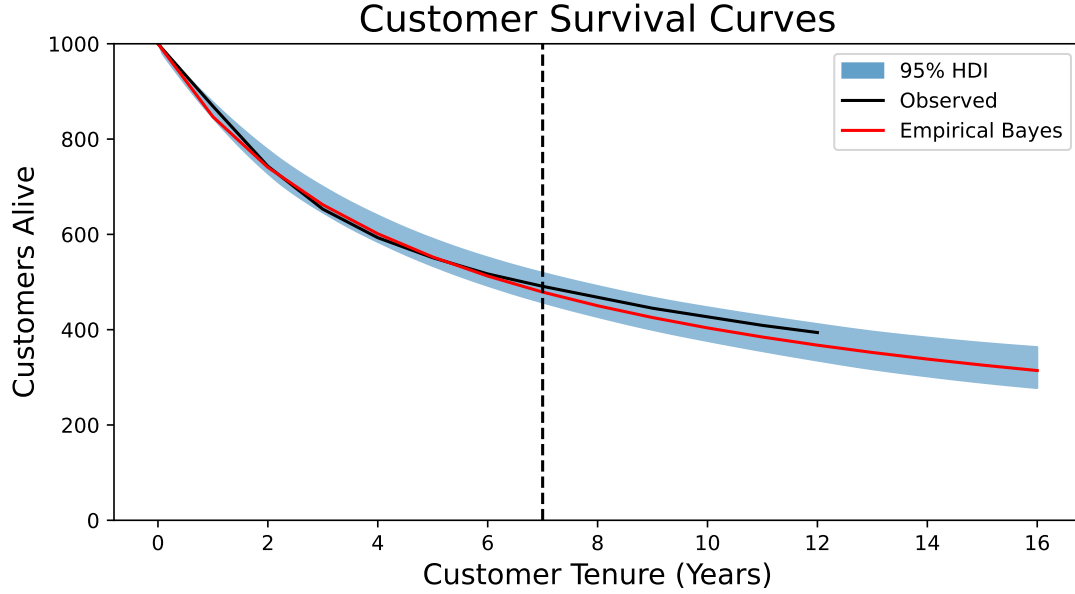
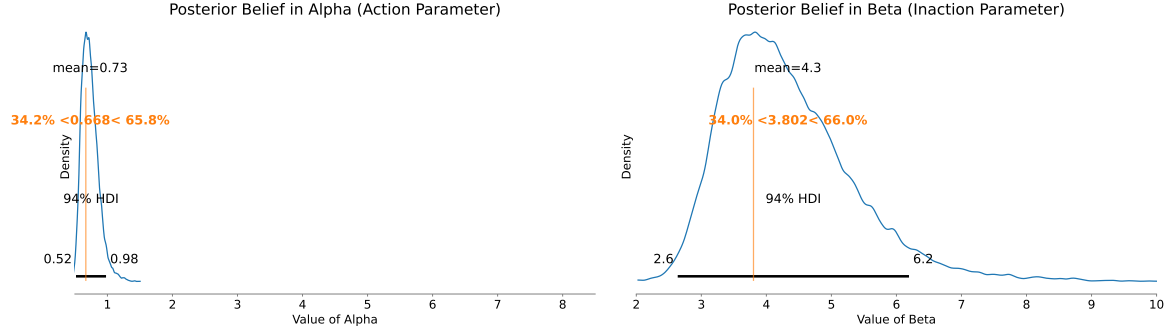


Alpha Samples



Beta Samples





## 4 Conclusion and Considerations

I want to eventually implement a generalized version of the stopping criterion as well as a riemannian-gaussian version of the model.

**Empirical Bayes**

$$p(\theta|y) = \frac{p(y|\theta) \cdot p(\theta)}{p(y)}$$

$$= \frac{p(y|\theta) \cdot p(\theta)}{\int (p(y|\theta)p(\theta))d\theta}$$

**Fully Bayesian (Our Approach)**

$$p(\theta|y) = \frac{p(y|\theta) \cdot \int \int p(\theta|\alpha, \beta)p(\alpha, \beta) d\alpha d\beta}{p(y)}$$

$$= \frac{p(y|\theta) \cdot \int \int p(\theta|\alpha, \beta)p(\alpha, \beta) d\alpha d\beta}{\int \int \int p(y|\theta)p(\theta|\alpha, \beta)p(\alpha, \beta) d\alpha d\beta d\theta}$$

## A Appendix

There are many techniques and variants of MCMC methods. As we have seen, HMC can be especially useful when dealing with problematic posteriors; however, there are still times when additional techniques must be utilized. This appendix holds the few that I have

implemented for this specific use case. It is not an exhaustive list, or even necessary, but those on similar paths to mine will find them well-suited for their needs.

### **A.1 Metropolis-Hastings Ratio**

### **A.2 Log of Log-Normal Distribution**

### **A.3 Re-parameterization**

### **A.4 Mass Matrix/Metric**