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Differentially Private Markov Chain Monte Carlo

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1. Introduction

As the availability of data on private individual grows ever larger, both the potential gains from analysing the data, and the risks associated with the analysis, grow. This makes analysis techniques that can ensure the privacy of the individual whose data is analysed important. Differential privacy [DMNS06] is a formal definition attempting to capture the notion of a data analysis algorithm that preserves privacy. Markov chain Monte Carlo (MCMC) [MRR⁺53, Has70] is an algorithm that enables data analysis using Bayesian inference [GCS⁺14]. This thesis studies the combination of differential privacy and MCMC by introducing existing algorithms, developing improvements with new techniques in differential privacy, and finally comparing the algorithms on a variety of settings.

2. Background

This chapter covers the basics of differential privacy, Bayesian inference and Markov chain Monte Carlo algorithms needed in the later chapters. To keep the introduction brief, only directly needed concepts are covered, and much of the motivation behind the subjects is left out.

2.1 Differential Privacy

Differential privacy (DP) [DMNS06, DR14] is a property of an algorithm that quantifies the amount of information about private data an adversary can gain from the publication of the algorithm's output. The most commonly used definition uses two real numbers, ϵ and δ , to quantify the information gain, or, from the perspective of a data subject, the privacy loss of the algorithm. DP algorithms must necessarily[†] include randomness to mask influence of the private data, so all of the considered algorithms in this thesis are randomised. DP randomised algorithms are also called *mechanisms* in this thesis, and in the DP literature.

The most common definition is called (ϵ, δ) -approximate differential privacy (ADP) [DKM⁺06, DR14]. The case where $\delta = 0$ is called ϵ -DP or pure DP.

Definition 1. A mechanism $\mathcal{M}: \mathcal{X} \rightarrow \mathcal{U}$ is (ϵ, δ) -ADP if for all neighbouring inputs $x \in \mathcal{X}$ and $x' \in \mathcal{X}$ and all measurable sets $S \subset \mathcal{U}$

$$P(\mathcal{M}(x) \in S) \leq e^\epsilon P(\mathcal{M}(x') \in S) + \delta.$$

The neighbourhood relation in the definition is domain specific. With tabular data the most common definitions are the add/remove neighbourhood and substitute neighbourhood.

Definition 2. Two tabular datasets are said to be *add/remove neighbours* if they are equal after adding or removing at most one row to or from one of them. The datasets are said to be *in substitute neighbours* if they are equal after changing at most one row in one of them.

[†]Unless the algorithm does not actually use the private data.

The neighbourhood relation is denoted by \sim . The definitions and theorems of this section are valid for all neighbourhood relations.

There many other definitions of differential privacy that are mostly used to compute (ϵ, δ) -bounds for ADP. This thesis uses two of them: Rényi-DP (RDP) [Mir17] and zero-concentrated differential privacy (zCDP) [BS16]. Both are based on Rényi divergence [Mir17], which is a particular way of measuring the distance* between random variables.

Definition 3. For random variables with density or probability mass functions P and Q , the Rényi divergence of order $1 < \alpha < \infty$ is

$$D_\alpha(P \parallel Q) = \frac{1}{\alpha - 1} \ln E_{x \sim Q} \left(\frac{P(x)^\alpha}{Q(x)^\alpha} \right).$$

Orders $\alpha = 1$ and $\alpha = \infty$ are defined by continuity:

$$D_1(P \parallel Q) = \lim_{\alpha \rightarrow 1^-} D_\alpha(P \parallel Q),$$

$$D_\infty(P \parallel Q) = \lim_{\alpha \rightarrow \infty} D_\alpha(P \parallel Q).$$

Both Rényi-DP and zCDP can be expressed as bounds on the Rényi divergence between the outputs of a randomised algorithm with neighbouring inputs:

Definition 4. A mechanism \mathcal{M} is (α, ϵ) -Rényi DP if for all $x \sim x'$

$$D_\alpha(\mathcal{M}(x) \parallel \mathcal{M}(x')) \leq \epsilon.$$

\mathcal{M} is ρ -zCDP if for all $\alpha > 1$ and all $x \sim x'$

$$D_\alpha(\mathcal{M}(x) \parallel \mathcal{M}(x')) \leq \rho\alpha.$$

Rényi-DP and zCDP bounds can be converted to ADP bounds [Mir17, BS16]:

Theorem 1. If a mechanism \mathcal{M} is (α, ϵ) -RDP, \mathcal{M} is also $(\epsilon - \frac{\ln \delta}{\alpha - 1}, \delta)$ -ADP for any $0 < \delta < 1$. If \mathcal{M} is ρ -zCDP, \mathcal{M} is also $(\rho + \sqrt{-4\rho \ln \delta}, \delta)$ -ADP for any $0 < \delta < 1$.

A very useful property of all of these definitions is composition [DR14]: if mechanisms \mathcal{M} and \mathcal{M}' are DP, the mechanism first computing \mathcal{M} and then \mathcal{M}' , outputting both results, is also DP, although with worse bounds. More precisely:

Definition 5. Let $\mathcal{M}: \mathcal{X} \rightarrow \mathcal{U}$ and $\mathcal{M}': \mathcal{X} \times \mathcal{U} \rightarrow \mathcal{U}'$ be mechanisms. Their composition is the mechanism outputting $(\mathcal{M}(x), \mathcal{M}'(x, \mathcal{M}(x)))$ for input x .

Theorem 2. Let $\mathcal{M}: \mathcal{X} \rightarrow \mathcal{U}$ and $\mathcal{M}': \mathcal{X} \times \mathcal{U} \rightarrow \mathcal{U}'$ be mechanisms. Then

*Statistical divergences are commonly called distances, even though they typically are not metrics.

1. If \mathcal{M} is (ϵ, δ) -ADP and \mathcal{M}' is (ϵ', δ') -ADP, then their composition is $(\epsilon + \epsilon', \delta + \delta')$ -ADP [DKM⁺06]
2. If \mathcal{M} is (α, ϵ) -RDP and \mathcal{M}' is (α, ϵ') -RDP, then their composition is $(\alpha, \epsilon + \epsilon')$ -RDP [Mir17]
3. If \mathcal{M} is ρ -zCDP and \mathcal{M}' is ρ' -zCDP, then their composition is $(\rho + \rho')$ -zCDP [BS16]

All of the composition results can be extended to any number of compositions by induction. Note that any step of the composition can depend on the results of the previous steps, not only on the private data. There are also other composition theorems for ADP that trade increased δ for decreased ϵ or vice-versa, but this thesis does not apply them directly.

As any randomised algorithm that does not use private data in any way is $(0, 0)$ -ADP, 0-zCDP and $(\alpha, 0)$ -RDP with all α , Theorem 2 has the following corollary, called post-processing immunity:

Theorem 3. *Let $\mathcal{M}: \mathcal{X} \rightarrow \mathcal{U}$ be an (ϵ, δ) -ADP, (α, ϵ) -RDP or ρ -zCDP mechanism. Let $f: \mathcal{U} \rightarrow \mathcal{U}'$ be any randomised algorithm not using the private data. Then the composition of \mathcal{M} and f is (ϵ, δ) -ADP, (α, ϵ) -RDP or ρ -zCDP.*

There are many different DP mechanisms that are commonly used [DR14]. This thesis only requires one of the most commonly used ones: the Gaussian mechanism [DKM⁺06].

Definition 6. *The Gaussian mechanism with parameter σ^2 is a randomised algorithm that, with input data x and query $f: \mathcal{X} \rightarrow \mathbb{R}^d$, outputs a sample from $\mathcal{N}(f(x), \sigma^2)$, where \mathcal{N} denotes the normal distribution.*

The privacy bounds of the Gaussian mechanism require that the values of the query f do not vary too much for neighbouring inputs. This requirement is formalised as a bound on the *sensitivity* of f .

Definition 7. *The l_p -sensitivity Δ_p , with neighbourhood relation \sim , of a function $f: \mathcal{X} \rightarrow \mathbb{R}^d$ is*

$$\Delta_p f = \sup_{x \sim x'} \|f(x) - f(x')\|_p.$$

The RDP and zCDP bounds for the Gaussian mechanism are quite simple. The ADP bound is more complicated:

Theorem 4. *If $\Delta_2 f \leq \Delta$, the Gaussian mechanism for query f with noise variance σ is*

1. $(\alpha, \frac{\alpha\Delta^2}{2\sigma^2})$ -RDP [Mir17]
2. $\frac{\Delta^2}{2\sigma^2}$ -zCDP [BS16]
3. k compositions of the Gaussian mechanism, with queries f_i , where $\Delta_2 f_i \leq \Delta$ for $1 \leq i \leq k$, are $(\epsilon, \delta(\epsilon))$ -ADP [SMM19] with

$$\delta(\epsilon) = \frac{1}{2} \left(\operatorname{erfc} \left(\frac{\sigma(\epsilon - k\mu)}{\sqrt{2k}\Delta} \right) - e^\epsilon \operatorname{erfc} \left(\frac{\sigma(\epsilon + k\mu)}{\sqrt{2k}\Delta} \right) \right),$$

where $\mu = \frac{\Delta^2}{2\sigma^2}$ and erfc is the complementary error function.

Additionally, each of the above privacy bounds is tight, meaning that the Gaussian mechanism with query f is not (α, ϵ') -RDP for any $\epsilon' < \frac{\alpha\Delta^2}{2\sigma^2}$, ρ' -zCDP for any $\rho < \frac{\Delta^2}{2\sigma^2}$, and a composition of k Gaussian mechanisms with queries f_i is not $(\epsilon, \delta'(\epsilon))$ -ADP for any $\delta'(\epsilon) < \delta(\epsilon)$.

Theorem 4 implies that the value of any function with finite l_2 -sensitivity can be privately released using the Gaussian mechanism with appropriate noise variance σ^2 . Of course, the utility of the released value depends on the magnitude of σ^2 compared to the actual value. As in Definition 5, each function f_i can depend on the output of the previous functions f_j , $j < i$.

Note that while the RDP and zCDP bounds of Theorem 4 are tight, the conversion from RDP or zCDP to ADP with Theorem 1 is not tight. As a result computing ADP bounds for the Gaussian mechanism through RDP or zCDP, and converting the resulting bounds to ADP with Theorem 1 does not result in a tight bound. The difference of the two methods of computing ADP bounds on the MCMC algorithms considered in this thesis is shown in Section 6.1.

When the dataset is a table, the query f of the Gaussian mechanism is typically a sum the values of a function g for each row of the table, specifically

$$f(X) = \sum_{x \in X} g(x).$$

For the substitute neighborhood relation f ,

$$\Delta_p f = \sup_{X \sim X'} \|f(X) - f(X')\|_p = \sup_{x, x'} \|g(x) - g(x')\|_p = \Delta_p^* g,$$

where x and x' are the values of the differing row in X and X' , and Δ_p^* denotes sensitivity with the neighborhood relation that considers all values neighboring.

In case $\Delta_p^* g$ is not finite, g can still be used with the Gaussian mechanism if *clipping* is used. Clipping restricts the values of g to a maximum l_p -norm. Specifically, clipping g with the bound $b \in \mathbb{R}$ applies the function $\operatorname{clip}_b^p: \mathbb{R}^d \rightarrow \mathbb{R}^d$ where

$$\operatorname{clip}_b^p(y) = \begin{cases} \frac{y}{\|y\|_p} \min\{\|y\|_p, b\} & \text{if } y \neq 0 \\ 0 & \text{if } y = 0 \end{cases}$$

to the values of g . Then $\Delta_p^*(\text{clip}_b^p \circ g) \leq 2b$ by the triangle inequality, as $\|\text{clip}_b^p(g(x))\|_p \leq b$ for all x . As this thesis only uses the Gaussian mechanism and thus only needs to clip the l_2 -norm, the superscript p is always 2 and the notation $\text{clip}_b = \text{clip}_b^2$ is used.

2.2 Bayesian Inference and Markov Chain Monte Carlo

In Bayesian inference, the parameters θ of a statistical model are inferred from observed data using Bayes' theorem [GCS⁺14]. The result is not just a point estimate of θ , but a probability distribution describing the likelihood of different values of θ .

Bayes' theorem relates the *posterior* belief of θ , $p(\theta | X)$ to the *prior* belief $p(\theta)$ through the observed data X , and the likelihood of the data $p(X | \theta)$ as follows:

$$p(\theta | X) = \frac{p(X | \theta)p(\theta)}{\int p(X | \theta)p(\theta)d\theta}.$$

It is theoretically possible to compute $p(\theta | X)$ given any likelihood, prior and data, but the integral in the denominator is in many cases difficult to compute [GCS⁺14]. In such cases the posterior cannot be feasibly computed. However, many of the commonly used summary statistics of the posterior, such as the mean, variance and credible intervals, can be approximated from a sample of the posterior. *Markov chain Monte Carlo* (MCMC) [MRR⁺53] is a widely used method to obtain such samples.

MCMC algorithms sequentially sample values of θ with the goal of eventually having the chain of sampled values converge to a given distribution [GCS⁺14]. While this can be done in many ways, this thesis focuses on a particular MCMC algorithm: *Metropolis-Hastings* (MH) [MRR⁺53, Has70].

At each iteration i , the Metropolis-Hastings algorithm samples θ_i from a distribution π of θ by first picking a proposal θ' from a proposal distribution $q(\cdot | \theta_{i-1})$ [MRR⁺53], where θ_{i-1} is the previously sampled value*. We shorten θ_{i-1} to θ in the following. The ratio of posterior and proposal densities is calculated

$$r(\theta, \theta') = \frac{\pi(\theta') q(\theta | \theta')}{\pi(\theta) q(\theta' | \theta)},$$

and the proposal is accepted with probability $\min\{1, r\}$. If the proposal is accepted, $\theta_i = \theta'$, otherwise $\theta_i = \theta$.

It can be shown that, with a suitable proposal distribution, the chain of θ_i values converges to π [Has70]. The Gaussian distribution centered at the current value is a commonly used proposal.

*The value of θ_0 for the first iteration is given as input to the algorithm.

When MCMC is used in Bayesian inference, the distribution to approximate is

$$\pi(\theta) = p(\theta | X) = \frac{p(X | \theta)p(\theta)}{\int p(X | \theta)p(\theta)d\theta}.$$

The difficult integral $\int p(X | \theta)p(\theta)d\theta$ in the denominator cancels out when computing r , so only the likelihood and the prior are needed. For numerical stability, r is usually computed in log-space, which makes the acceptance probability $\min\{1, e^{\lambda(\theta, \theta')}\}$ where

$$\lambda(\theta, \theta') = \ln \frac{p(X | \theta')}{p(X | \theta)} + \ln \frac{p(\theta')}{p(\theta)} + \ln \frac{q(\theta | \theta')}{q(\theta' | \theta)}. \quad (2.1)$$

The dataset X is typically a table with n independent rows. The likelihood is given as $p(x_j | \theta)$ for row x_j . Independence of the rows means that

$$p(X | \theta) = \prod_{j=1}^n p(x_j | \theta),$$

which means that the log-likelihood ratio term of λ is

$$\ln \frac{p(X | \theta')}{p(X | \theta)} = \sum_{j=1}^n \ln \frac{p(x_j | \theta')}{p(x_j | \theta)}.$$

Algorithm 1 puts all of this together to summarise the MH algorithm used for Bayesian inference.

Algorithm 1: Metropolis-Hastings: number of iterations k , proposal distribution q , initial value θ_0 and dataset X as input.

```

for  $1 \leq i \leq k$  do
    denote  $\theta = \theta_{i-1}$ 
    sample  $\theta' \sim q(\cdot | \theta)$ 
     $\ln \frac{p(X|\theta')}{p(X|\theta)} = \sum_{j=1}^n (\ln p(x_j | \theta') - \ln p(x_j | \theta))$ 
     $\lambda = \ln \frac{p(X|\theta')}{p(X|\theta)} + \ln p(\theta') - \ln p(\theta) + \ln q(\theta | \theta') - \ln q(\theta' | \theta)$ 
     $\theta_i = \begin{cases} \theta' & \text{with probability } \min\{1, e^\lambda\} \\ \theta & \text{otherwise} \end{cases}$ 
end
return  $(\theta_1, \dots, \theta_k)$ 

```

3. Differentially Private MCMC

As seen in Section 2.1, an algorithm can be made differentially private by adding Gaussian noise to its output. The noise could also be added to any intermediate value calculated by the algorithm, and post processing immunity will guarantee that the same DP bounds that hold for releasing the intermediate value also hold for releasing the final result of the algorithm.

In 2019, Yildirim and Ermiş [YE19] realised that if Gaussian noise is added to the exact value of λ from Equation 2.1, the noise can be corrected for, yielding a differentially private MCMC algorithm which converges to the correct distribution. In the same year, Heikkilä et al. [HJDH19] developed another DP MCMC algorithm, called DP Barker, which uses subsampling to amplify privacy. DP Barker is based on the Barker acceptance test [Bar65] instead of the MH test, and uses an approximation of the Barker acceptance test to correct for the noise added for DP.

3.1 Differentially private MH with the penalty algorithm

In 1999, Ceperley and Dewing [CD99] developed a variant of Metropolis-Hastings called the penalty algorithm, where only a noisy approximation of λ is known. The original algorithm was developed for simulations in physics where computing λ requires computing energies of complex systems, which can only be approximated. The penalty algorithm modifies the acceptance probability to account for the noise added to λ and still converges to the correct distribution if the noise is Gaussian with known variance.

The DP penalty algorithm adds Gaussian noise to the value of λ , and uses the penalty algorithm to correct the acceptance probability so that the algorithm still converges to the correct distribution [YE19]. The corrected acceptance probability for Gaussian noise with variance σ^2 is

$$\min\{1, e^{\lambda(\theta, \theta') - \frac{1}{2}\sigma^2}\}$$

Theorem 5 gives the number of iterations DP penalty can be run for when the privacy cost is computed through zCDP, which is what Yildirim and Ermiş prove in

their paper [YE19]. A tight, but harder to use, bound can be reached by using the ADP bound of Theorem 4, without using zCDP. This is given by Theorem 6.

Theorem 5. *Let $\epsilon > 0$, $0 < \delta < 1$, $\alpha > 0$, $\tau > 0$ and $n > 0$. Let*

$$\rho = (\sqrt{\epsilon - \ln \delta} - \sqrt{-\ln \delta})^2$$

$$c(\theta, \theta') = \sup_{x_j, x'_j} (p(x_j | \theta') - p(x_j | \theta) - (p(x'_j | \theta') - p(x'_j | \theta)))$$

$$\sigma^2(\theta, \theta') = \tau^2 n^{2\alpha} c^2(\theta, \theta')$$

Then running DP penalty for

$$k = \lfloor 2\tau^2 n^{2\alpha} \rho \rfloor$$

iterations with dataset size n , when using σ^2 as the variance of the Gaussian noise and the substitute neighborhood relation, is (ϵ, δ) -ADP.

Theorem 6. *Let $\epsilon > 0$, $\alpha > 0$, $\tau > 0$ and $n > 0$. Define c and σ^2 as in Theorem 5. The DP penalty algorithm, after running for k iterations using σ^2 as the noise variance with dataset size n , is $(\epsilon, \delta(\epsilon))$ -DP, with the substitute neighborhood relation, for*

$$\delta(\epsilon) = \frac{1}{2} \left(\operatorname{erfc} \left(\frac{\epsilon - k\mu}{2\sqrt{k\mu}} \right) - e^\epsilon \operatorname{erfc} \left(\frac{\epsilon + k\mu}{2\sqrt{k\mu}} \right) \right)$$

where $\mu = \frac{1}{2\tau^2 n^{2\alpha}}$. Furthermore, this privacy bound is tight.

Proof. DP penalty is an adaptive composition of Gaussian mechanisms that release noisy values of $\lambda(\theta, \theta')$. With the substitute neighborhood relation, the sensitivity of $\lambda(\theta, \theta')$ is $c(\theta, \theta')$. For the tight ADP bound used here, the sensitivity must be constant in each iteration. This is achieved by releasing $\frac{\lambda(\theta, \theta')}{c(\theta, \theta')}$ instead, which has sensitivity 1. $c(\theta, \theta')$ does not depend on X , so $\lambda(\theta, \theta')$ can be obtained from $\frac{\lambda(\theta, \theta')}{c(\theta, \theta')}$ by post-processing.

Adding Gaussian noise with variance σ_n^2 to $\frac{\lambda(\theta, \theta')}{c(\theta, \theta')}$ is equivalent to adding Gaussian noise with variance $\sigma_n^2 c^2(\theta, \theta')$ to $\lambda(\theta, \theta')$. Setting $\sigma_n^2 = \tau^2 n^{2\alpha}$ and plugging into the ADP bound of Theorem 4 proves the claim. \square

The τ -parameter controls the trade-off between the amount of noise and the number of iterations the algorithm is allowed to run for. From the expression for σ^2 and k in Theorem 5, the standard deviation of the noise increases linearly with τ , while the number of iterations increases quadratically.

Yildirim and Ermiş [YE19] see α as a bound on c of the form

$$c(\theta, \theta') \leq Cn^{-\alpha}$$

for almost all θ and θ' and constant $C > 0$. This bound would mean that σ would not increase with n , which Yildirim and Ermiş see as a necessary condition for the DP

penalty algorithm to perform well. They also recommend having $\alpha = \frac{1}{2}$, which is used in the experiments in Chapter 6. With clipping, this can be achieved by setting the clip bound based on n . For the experiments in Chapter 6, the parameters are optimised separately for each n that is used, so setting any clip bound can be seen as choosing a value for C .

Theorem 6 is harder to use than Theorem 5 because the number of iteration DP penalty can be run for given an (ϵ, δ) -bound cannot be computed analytically for the former. However, the maximum number of iterations can be solved for numerically. Algorithm 2 shows a simple procedure that solves the maximum number of iterations using the bisection method.

Algorithm 2: Maximise the number of iterations given ϵ, δ, τ and n . The `zcdp`-function computes the number of iterations Theorem 5 allows, and the `adp`-function computes $\delta(\epsilon)$ from Theorem 6. $\lfloor \cdot \rfloor$ is the floor function that rounds real numbers down. Note that the variables *low*, *high* and *new* are not necessarily integers, as Theorem 6 can handle a non-integer number of iterations.

```

low = zcdp( $\epsilon, \delta, \tau, n$ )
high = max{low, 1}
while adp( $\epsilon, high, \tau, n$ ) <  $\delta$  do
  | high = high · 2
end
while  $\lfloor high \rfloor - \lfloor low \rfloor > 1$  do
  | new =  $\frac{high+low}{2}$ 
  | if adp( $\epsilon, new, \tau, n$ ) >  $\delta$  then
  | | high = new
  | end
  | else
  | | low = new
  | end
end
if adp( $\epsilon, \lfloor high \rfloor, \tau, n$ ) <  $\delta$  then
  | return  $\lfloor high \rfloor$ 
end
else
  | return  $\lfloor low \rfloor$ 
end

```

Theorems 5 and 6 require a bound on sensitivity of the log-likelihood ratio. If there is a bound

$$|\ln p(x_j | \theta') - \ln p(x_j | \theta)| \leq L \|\theta - \theta'\|_2$$

for all D_j, θ and θ' then

$$c(\theta, \theta') \leq 2L\|\theta - \theta'\|_2.$$

The former bound is true in some models, such as logistic regression [YE19]. In other models it can be forced by clipping the log-likelihood ratios with the bound $b = L\|\theta - \theta'\|_2$. This will remove the guarantee of eventually converging to the correct posterior, but if L is chosen to be large enough, the clipping will not affect the acceptance decision frequently. As a tradeoff, picking a large L will increase the variance of the Gaussian noise and slow down convergence through it.

Yildirim and Ermiş [YE19] propose two potential variations to improve the performance of the penalty algorithm. The first variation, called *one component updates* (OCU) in this thesis, is only proposing changes in one dimension in a multidimensional problem. This decreases $\|\theta - \theta'\|_2$, which means that it decreases the noise variance.

The second variation is called *guided walk Metropolis Hastings* (GWMH) [YE19]. In GWMH, proposals change only one dimension, as in OCU. Additionally, a direction is associated with each dimension, and proposals are only made in the current direction of the chosen dimension. After an accepted proposal, the direction is kept the same, but after a reject it is switched. This means that the chain can move towards areas of higher probability faster because, after some initial proposals are rejected, the directions for each dimension point towards the area of high probability, so all proposals are towards it. Without GRMH, most proposals would move the chain away from the area of high probability, and would likely be rejected.

3.2 The Barker acceptance test

The DP Barker algorithm of Heikkilä et al. [HJDH19] is based on the Barker acceptance test [Bar65] instead of the Metropolis-Hastings test. Instead of using the MH acceptance probability, the Barker acceptance test samples $V_{log} \sim \text{Logistic}(0, 1)$ and accepts if

$$\lambda + V_{log} > 0.$$

If Gaussian noise with variance σ^2 is added to λ , as long as σ^2 is not too large, there exists an approximate correction distribution V_{corr} such that $\mathcal{N}(0, \sigma^2) + V_{corr}$ has approximately the same distribution as V_{log} . Because the variance of V_{log} is $\frac{\pi^2}{3}$ [HJDH19], the variance of V_{corr} must be $\frac{\pi^2}{3} - \sigma^2$ which means that there is an upper bound to the noise variance: $\sigma^2 < \frac{\pi^2}{3}$. Testing whether $\lambda + \mathcal{N}(0, \sigma^2) + V_{corr} > 0$ is approximately equivalent to testing whether $\lambda + V_{log} > 0$, which means that it is possible to derive a DP MCMC algorithm based on the Barker acceptance test if the correction distribution can be sampled from.

However, the analytical form of V_{corr} is not known [HJDH19]. Heikkilä et al. approximate the distribution with a Gaussian mixture model. This means that their algorithm only converges to an approximately correct distribution, but the approximation error can be made very small.

If the sum in λ was only computed over a subset of the data, the algorithm would take less computation to run, and would be less sensitive to changes in the data. The latter property is called *subsampling amplification* of differential privacy [WBK19]. Using the λ computed with subsampling instead of the full data λ introduces an additional error that must be corrected for to have the algorithm converge to the correct distribution.

The *central limit theorem* (CLT) states that the distribution of a sum of random variables approaches a Gaussian distribution as more random variables are summed, if some conditions on the independence and variance of the random variables are met [SPCC17]. With the CLT, it can be argued that the error from using the subsampled λ instead of the full data λ has an approximately Gaussian distribution, if the subsample is large enough [SPCC17].

The variance of the error from subsampling can be estimated by the sample variance of the individual terms in the sum in λ [SPCC17]. This allows combining the errors from subsampling and the Gaussian noise from the Gaussian mechanism to a single Gaussian noise value. The V_{corr} distribution can then be used to approximate the Barker acceptance test as above [HJDH19]. See Algorithm 3 for the DP Barker algorithm*.

Heikkilä et al. [HJDH19] do not directly bound the sensitivity of λ as is done in DP penalty, because the sample variance also depends on input data. Instead they directly bound the Rényi divergence between $\mathcal{N}(0, \sigma^2 - \sigma_b^2)$, where σ_b^2 is the batch sample variance, for two adjacent inputs. Subsampling amplification is accounted for with an amplification theorem for Rényi DP [WBK19].

Theorem 7. *If*

$$|\ln p(x_j | \theta') - \ln p(x_j | \theta)| \leq \frac{\sqrt{|B|}}{n}$$

$$\alpha < \frac{|B|}{5}, \alpha \in \mathbb{N}$$

for all $\theta, \theta' \in \Theta$, all X and $1 \leq j \leq n$, running k iterations of DP Barker with dataset size n is $(\alpha, k\epsilon(\alpha))$ -RDP for the substitute neighborhood relation, with

$$\epsilon(\alpha) = \frac{1}{\alpha - 1} \ln \left(1 + q^2 \binom{\alpha}{2} \min\{4(e^{\epsilon'(2)} - 1), 2e^{\epsilon'(2)}\} + 2 \sum_{j=3}^{\alpha} q^j \binom{\alpha}{j} e^{(j-1)\epsilon'(j)} \right)$$

*See [HJDH19] for the sampling procedure of V_{corr} .

and

$$\epsilon'(\alpha) = \frac{5}{2|B|} + \frac{1}{2(\alpha - 1)} \ln \frac{2|B|}{|B| - 5\alpha} + \frac{2\alpha}{|B| - 5\alpha}$$

where n is the number of rows in D , $|B|$ is the size of the minibatch and $q = \frac{|B|}{n}$.

The RDP bounds given by Theorem 7 can be converted to ADP bounds with Theorem 1. Algorithm 2 can be modified to compute the maximum number of iterations Theorem 7 allows by computing ϵ -bounds given δ with Theorem 7 and Theorem 1, instead of computing δ -bounds given ϵ . The variable *low* of Algorithm 2 must be initialised to 0, and the variable *high* must be initialised to a value greater than 0*.

Like DP penalty, DP Barker requires a bound on the log-likelihood ratio for one row of data. The bound can be forced through clipping if the model does not meet it, but because of the n in the denominator of the bound, it can get very tight for large values of n . As a result, clipping may be needed for almost all log-likelihood ratios, which may cause the algorithm to converge to a very different distribution from the posterior.

To alleviate the tight bound on log-likelihood sensitivity, DP Barker is best used with a tempered likelihood [HJDH19]. In tempering, the log-likelihood is multiplied by a number $T = \frac{n_0}{n} < 1$. This increases the variance of the resulting posterior and may lower modeling error in some cases [HJDH19].

Using the tempered likelihood, the log-likelihood bound becomes

$$T |\ln p(x_j | \theta') - \ln p(x_j | \theta)| \leq \frac{\sqrt{|B|}}{n},$$

which is equivalent to

$$|\ln p(x_j | \theta') - \ln p(x_j | \theta)| \leq \frac{\sqrt{|B|}}{n_0}.$$

Typically $n_0 \ll n$ for large datasets, so using a tempered likelihood requires significantly

*Choosing a value close to the maximum number of iterations speeds up the computation of the maximum number of iterations. The experiments in this thesis used the value 1024.

less clipping than a nontempered likelihood.

Algorithm 3: DP Barker: number of iterations, initial value θ_0 , proposal distribution q , noise variance σ^2 , data X as input.

```

for  $1 \leq i \leq k$  do
  denote  $\theta = \theta_{i-1}$ 
  sample  $\theta' \sim q(\cdot \mid \theta)$ 
  sample  $B \subset \{1, \dots, n\}$ 
  for  $j \in B$  do
     $r_j = \ln p(\theta' \mid x_j) - \ln p(\theta \mid x_j)$ 
  end
   $\sigma_b^2 = \text{Var}\{r_j \mid j \in B\}$ 
   $\lambda = \frac{n}{|B|} \sum_{j \in B} r_j + \ln \frac{p(\theta')}{p(\theta)} + \ln \frac{q(\theta \mid \theta')}{q(\theta' \mid \theta)}$ 
  sample  $s \sim \mathcal{N}(0, \sigma^2 - \sigma_b^2)$ 
  sample  $c \sim V_{corr}^{\sigma^2}$ 
   $\theta_i = \begin{cases} \theta' & \text{if } \lambda + s + c > 0 \\ \theta & \text{otherwise} \end{cases}$ 
end
return  $(\theta_1, \dots, \theta_k)$ 

```

Tuning the parameters of DP Barker is more restrictive than DP penalty, as the former does not have a tunable clip bound, and its noise variance has an upper bound. In addition, choosing a noise variance requires computing the V_{corr} approximation for that variance.

3.3 The Penalty Algorithm with Subsampling

In the DP Barker algorithm, the log-likelihood ratio is computed using only a subsample of the dataset to amplify privacy. Subsampling can also be used with the penalty algorithm in the same way, if the acceptance test is corrected for the error from subsampling.

As with DP Barker, the error from subsampling is approximately normally distributed by the central limit theorem. The variance of the subsampling error can be estimated from the sample variance of individual terms of the sum in the log-likelihood ratio. This means that the penalty method can be used to correct for the subsampling error.

The acceptance probability with subsampling is

$$\min\{1, e^{\lambda^*(\theta, \theta') - \frac{1}{2}(\sigma^2 + \sigma_b^2)}\},$$

where

$$\lambda^*(\theta, \theta') = \frac{nT}{|B|} \sum_{j \in B} \ln \frac{p(x_j | \theta')}{p(x_j | \theta)} + \ln \frac{p(\theta')q(\theta | \theta')}{p(\theta)q(\theta' | \theta)},$$

T is the tempering multiplier, and σ_b^2 is the sample variance of the log-likelihood ratios in batch B . Denote

$$r_j = \ln \frac{p(x_j | \theta')}{p(x_j | \theta)},$$

$$R = \sum_{x \in B} r_j.$$

Then σ_b^2 can be estimated from the sample variance of r_j :

$$\begin{aligned} \sigma_b^2 &= \text{Var} \left(\frac{nT}{|B|} \sum_{j \in B} r_j \right) = \frac{nT^2}{|B|^2} \sum_{j \in B} \text{Var}(r_j) = \frac{nT^2}{|B|} \text{Var}(r_j) \\ &\approx \frac{(nT)^2}{|B|^2} \sum_{j \in B} \left(r_j - \frac{R}{|B|} \right)^2 = \frac{(nT)^2}{|B|^2} \left(\sum_{j \in B} r_j^2 - \frac{R^2}{|B|} \right). \end{aligned}$$

Because σ_b^2 depends on the data, releasing λ privately is not enough, $\lambda - \frac{1}{2}\sigma_b^2$ must be released privately. This means that using subsampling requires adding additional noise to account for the sensitivity of $\frac{1}{2}\sigma_b^2$.

The sensitivity of $\lambda - \frac{1}{2}\sigma_b^2$ is

$$\Delta\lambda + \frac{1}{2}\Delta\sigma_b^2.$$

With the bound $r_j \leq L\|\theta - \theta'\|_2$ used in DP penalty, the bound sensitivity of λ is the same as without subsampling. The sensitivity of σ_b^2 must be bounded separately.

Lemma 1. *The sensitivity of $\frac{1}{2}\sigma_b^2$, when $r_j \leq L\|\theta - \theta'\|_2$ and $b = |B|$, has upper bound*

$$\frac{1}{2}\Delta\sigma_b^2 \leq \left(\frac{nT}{b} \right)^2 \left| 1 - \frac{1}{b} \right| L^2 \|\theta - \theta'\|_2^2 + \frac{2(b-1)}{b} \left(\frac{nT}{b} \right)^2 L^2 \|\theta - \theta'\|_2^2.$$

Proof. For substitute neighboring datasets $X \sim X'$, denote the common part they have

by X^* , and the differing element by $x \in X$ and $x' \in X'$. Then

$$\begin{aligned}
\Delta\sigma_b^2 &= \sup_{D \sim D'} |\sigma_b^2(X) - \sigma_b^2(X')| \\
&= \left(\frac{nT}{b}\right)^2 \sup_{X \sim X'} \left| \sum_{x \in X} r^2(x) - \sum_{x \in X'} r^2(x) + \frac{1}{b} R^2(X') - \frac{1}{b} R^2(X) \right| \\
&= \left(\frac{nT}{b}\right)^2 \sup_{x, x', X^*} \left| r^2(x) - r^2(x') + \frac{1}{b} (R(X^*) + r(x'))^2 - \frac{1}{b} (R(X^*) + r(x))^2 \right| \\
&= \left(\frac{nT}{b}\right)^2 \sup_{x, x', X^*} \left| r^2(x) - r^2(x') + \frac{1}{b} (R^2(X^*) + 2R(X^*)r(x') + r^2(x')) \right. \\
&\quad \left. - \frac{1}{b} (R^2(X^*) + 2R(X^*)r(x) + r^2(x)) \right| \\
&= \left(\frac{nT}{b}\right)^2 \sup_{x, x', X^*} \left| \left(1 - \frac{1}{b}\right) (r^2(x) - r^2(x')) + \frac{2}{b} R(X^*) (r(x') - r(x)) \right| \\
&\leq \left(\frac{nT}{b}\right)^2 \left| 1 - \frac{1}{b} \right| \sup_{x, x'} |r^2(x) - r^2(x')| + \frac{2}{b} \left(\frac{nT}{b}\right)^2 \sup_{x, x', X^*} |R(X^*) (r(x') - r(x))| \\
&= \left(\frac{nT}{b}\right)^2 \left| 1 - \frac{1}{b} \right| \sup_{x, x'} |r^2(x) - r^2(x')| + \frac{2}{b} \left(\frac{nT}{b}\right)^2 \sup_{x, x'} |r(x') - r(x)| \sup_{X^*} |R(X^*)| \\
&\leq \left(\frac{nT}{b}\right)^2 \left| 1 - \frac{1}{b} \right| \sup_{x, x'} |r^2(x) - r^2(x')| + \frac{2}{b} \left(\frac{nT}{b}\right)^2 \sup_{x, x'} |r(x') - r(x)| (b-1) \sup_d |r(x)|.
\end{aligned}$$

Plugging the bound $\sup_x |r(x)| \leq L \|\theta - \theta'\|_2$ into the last expression proves the claim. \square

Theorem 8. Let $\epsilon > 0$, $0 \leq \delta < 1$, $\tau > 0$, $T > 0$, $L > 0$, $b > 0$, $n > 0$,

$$\begin{aligned}
\Delta_\lambda &= \frac{2nTL}{b} \|\theta - \theta'\|_2, \\
\Delta_\sigma &= \left(\frac{nT}{b}\right)^2 \left| 1 - \frac{1}{b} \right| L^2 \|\theta - \theta'\|_2^2 + \frac{2(b-1)}{b} \left(\frac{nT}{b}\right)^2 L^2 \|\theta - \theta'\|_2^2, \\
c(\theta, \theta') &= \Delta_\lambda + \Delta_\sigma, \\
\sigma^2(\theta, \theta') &= \tau c^2(\theta, \theta').
\end{aligned}$$

Then running minibatch DP penalty with subsample size b for a dataset size n for k iterations is $(\alpha, k\epsilon(\alpha))$ -RDP for the substitute neighborhood relation, with

$$\epsilon(\alpha) = \frac{1}{\alpha - 1} \ln \left(1 + q^2 \binom{\alpha}{2} \min\{4(e^{\epsilon'(2)} - 1), 2e^{\epsilon'(2)}\} + 2 \sum_{j=3}^{\alpha} q^j \binom{\alpha}{j} e^{(j-1)\epsilon'(j)} \right),$$

$$\epsilon'(\alpha) = \frac{\alpha}{2\tau},$$

and $q = \frac{b}{n}$.

Proof. By Lemma 1, $\Delta_\sigma(\theta, \theta')$ an upper bound to the sensitivity of $\frac{1}{2}\sigma_b^2$, therefore $c(\theta, \theta')$ is an upper bound to the sensitivity of $\lambda - \frac{1}{2}\sigma_b^2$.

This means that a Gaussian mechanism taking a subsample B of the data as input and uses $\sigma(\theta, \theta')$ as the noise variance is $(\alpha, \epsilon'(\alpha))$ -RDP with

$$\epsilon'(\alpha) = \frac{\alpha}{2\tau}.$$

By the subsampling amplification theorem [WBK19, Theorem 9] and the composition theorem of RDP (Theorem 2), the combination of subsampling and Gaussian mechanism is $(\alpha, k\epsilon(\alpha))$ -RDP with

$$\epsilon(\alpha) = \frac{1}{\alpha - 1} \ln \left(1 + q^2 \binom{\alpha}{2} \min\{4(e^{\epsilon'(2)} - 1), 2e^{\epsilon'(2)}\} + 2 \sum_{j=3}^{\alpha} q^j \binom{\alpha}{j} e^{(j-1)\epsilon'(j)} \right)$$

when run for k iterations for integer $\alpha \geq 2$. \square

Theorem 8 does not give tight bounds for ADP, as it is based on RDP. Computing tight ADP bounds for the minibatch penalty algorithm requires an analogue of the ADP bound of Theorem 4 for the Gaussian mechanism with subsampling. An analytical and tight ADP bound for the subsampled Gaussian mechanism is not known, but the *Fourier accountant* of Koskela et al. [KJH20] can approximate the tight bound with a very small error.

The Fourier accountant takes the subsampling ratio q and noise variance, and computes the ADP bounds of the subsampled Gaussian mechanism with sensitivity 1. For the minibatch penalty algorithm, the released value $\lambda - \frac{1}{2}\sigma_b^2$ has sensitivity $c(\theta, \theta')$, and noise variance $\tau c^2(\theta, \theta')$, but if the released value is normalised to have sensitivity 1, the noise variance becomes τ , which makes the Fourier accountant easy to apply to the minibatch penalty algorithm.

The DP Barker algorithm, like minibatch penalty, uses RDP to compute privacy bounds. Using the Fourier accountant with DP Barker may be possible, but it is not as simple as with minibatch penalty, as DP Barker does not consider releasing the sample variance σ_b^2 directly.

As with the DP penalty and DP Barker algorithms, the maximum number of iterations for minibatch DP penalty can be computed using Algorithm 2. For Theorem 8, Algorithm 2 must be modified the as it is modified for DP Barker (Section 3.2). With the Fourier accountant, the only necessary modification is computing δ with the Fourier accountant*.

The appearance of n as a multiplier of Δ_λ and n^2 as a multiplier of Δ_σ causes the noise variance to increase with n , without a corresponding decrease in ϵ' . This makes

*The Fourier accountant handles the non-integer iteration numbers used by Algorithm 2 by internally rounding them down.

subsampled DP penalty unsuitable for problems with large datasets, unless tempering is used. Like with DP Barker, using tempering $T = \frac{n_0}{n}$ cancels n out of the noise variance.

The minibatch DP penalty algorithm has the same parameters as DP penalty, with the addition of the batch size parameter. The restrictions on the noise variance of DP Barker are not present in minibatch DP penalty. In Theorem 8, the expression for σ was simplified by multiplying c^2 by only a single number τ , instead of the $\tau^2 n^{2\alpha}$ used in Theorem 5 after Yildirim and Ermis [YE19]. This makes using the Fourier accountant particularly simple, as the noise variance given to it is simply τ .

The proposed variations of the penalty algorithm, one component updates and guided walk MH, are also applicable with subsampling. The sensitivity reduction from OCU may be especially useful as the variance sensitivity contains the square of the distance between the current and proposed parameter values, so reducing the distance by updating only a single component can greatly reduce the added noise.

4. Differentially Private Hamiltonian Monte Carlo

Hamiltonian Monte Carlo (HMC[†]) [DKPR87, Nea12] is a widely used MCMC algorithm that, like Metropolis-Hastings and the penalty algorithm, was originally developed for simulations in physics and chemistry, but has since been applied to Bayesian inference.

HMC simulates the trajectory of a moving particle in a way that allows it to draw samples from a target distribution [Nea12]. With perfect simulation, an acceptance test would not be needed, but exact simulation of the moving particle is typically not possible, so a Metropolis-Hastings acceptance test is used for proposals generated by the simulation. Despite imperfections, the simulation can generate long jumps that stay in areas of high probability, giving HMC a higher acceptance rate than Metropolis-Hastings using a Gaussian distribution as the proposal, at the cost of higher computational requirements.

This chapter first introduces HMC in the non-DP setting in Section 4.1. In Section 4.2 the HMC is made differentially private using the acceptance test of the penalty algorithm and adding noise to the proposal phase appropriately.

4.1 MCMC with Hamiltonian Dynamics

The motion of a particle on a frictionless surface of varying height is governed by the initial position and velocity of the particle, and the height of the surface at different positions [Nea12]. The kinetic energy of the particle with momentum[‡] $p \in \mathbb{R}^2$ and mass $m \in \mathbb{R}$ is $\frac{p^T p}{2m}$. The potential energy of the particle at position $\theta \in \mathbb{R}^2$ is proportional to the height of the surface, given by a continuously differentiable function $U(\theta)$. The sum of potential and kinetic energies, the total energy of the system, is called the Hamiltonian H . Hamilton's equations give the equations of motion for a system with

[†]HMC originally stood for hybrid Monte Carlo, but the name Hamiltonian Monte Carlo has become more common.

[‡]Momentum is velocity times mass.

a given Hamiltonian:

$$\frac{d\theta}{dt} = \frac{\partial H}{\partial p}, \quad \frac{dp}{dt} = -\frac{\partial H}{\partial \theta}.$$

Given $H(\theta, p) = U(\theta) + \frac{p^T p}{2m}$, Hamilton's equations become

$$\begin{aligned} \frac{d\theta}{dt} &= \frac{p}{m}, \\ \frac{dp}{dt} &= -\nabla U(\theta). \end{aligned}$$

These equations define a function T_t taking an initial state (θ, p) of the particle to the state $T(\theta, p)$ after time t . Solving T_t analytically is usually not possible, but T_t can be approximately simulated by the *leapfrog method*. The leapfrog method sequentially updates an estimate (θ_i, p_i) of the state in steps L of η as follows:

$$\begin{aligned} p_{i+1/2} &= p_i - \frac{\eta}{2} \nabla U(\theta_i), \\ \theta_{i+1} &= \theta_i + \frac{\eta p_{i+1/2}}{m}, \\ p_{i+1} &= p_{i+1/2} - \frac{\eta}{2} \nabla U(\theta_{i+1}). \end{aligned}$$

The simulation starts with $\theta_0 = \theta$ and $p_0 = p$ and the result is given by $T_{L\eta}(\theta, p) \approx (\theta_L, p_L)$.

The above equations for two-dimensional θ and p generalize to any number of dimensions d [Nea12]. The physical analogue would be a particle moving on a d -dimensional hypersurface with “height” given by $U(\theta)$. The mass of the particle, m , can also be generalized to any positive definite matrix $M \in \mathbb{R}^{d \times d}$, which changes division by m to multiplication by M^{-1} . Specifically, the kinetic energy of the particle becomes $\frac{1}{2} p^T M^{-1} p$ and $\frac{d\theta}{dt} = M^{-1} p$. The generalization to a mass matrix does not have a physical analogue, but it can be useful for MCMC.

Hamiltonian dynamics have three important properties [Nea12] that make them useful as a proposal mechanism for MCMC. They are reversibility, conservation of the Hamiltonian and conservation of volume.

Reversibility means that the function T_t is injective, meaning that it has an inverse T_{-t} where $T_t(\theta_1, p_1) = (\theta_2, p_2)$ implies that $T_{-t}(\theta_2, p_2) = (\theta_1, p_1)$ [Nea12]. For the Hamiltonian of the particle moving on a surface, the inverse is obtained by $T_t(\theta_2, -p_2) = (\theta_1, -p_1)$.

Conservation of the Hamiltonian follows from Hamilton's equations and the chain rule of derivatives:

$$\frac{dH}{dt} = \frac{\partial H}{\partial \theta} \frac{d\theta}{dt} + \frac{\partial H}{\partial p} \frac{dp}{dt} = \frac{\partial H}{\partial \theta} \frac{\partial H}{\partial p} - \frac{\partial H}{\partial p} \frac{\partial H}{\partial \theta} = 0.$$

Conservation of volume in the (θ, p) -space follows from the fact that the absolute value of the Jacobian determinant of T_t is 1 and the injectivity of T_t . A somewhat lengthier proof for the Jacobian determinant of T_t is given by Neal [Nea12].

To see why having $|\det J_f| = 1$, where J_f is the Jacobian matrix of an injective continuously differentiable function f , implies f preserving volume, recall that the volume of a set A is given by

$$\int_A 1 dx.$$

The volume of the image of A under f , $f(A)$, is given by

$$\int_{f(A)} 1 dx = \int_A |\det J_f(x)| dx = \int_A 1 dx.$$

where the first equality follows from the change of variables formula.

The leapfrog method does not conserve the Hamiltonian exactly, but it preserves volumes and is reversible exactly [Nea12]. These properties are important for its use as a proposal mechanism for MCMC.

The HMC algorithm samples from the distribution of [Nea12]

$$\pi(\theta, p) \propto \exp(-H(\theta, p)).$$

With $H(\theta, p) = U(\theta) + \frac{1}{2}p^T M^{-1}p$,

$$\pi(\theta, p) \propto \exp(-U(\theta)) \exp\left(\frac{1}{2}p^T M^{-1}p\right)$$

This means that the marginal distributions of θ and p are independent, the marginal distribution of p is a d -dimensional Gaussian distribution with mean 0 and covariance M , and the marginal distribution of θ can have any continuously differentiable log-likelihood $-U$. Because of this, θ is used to represent the variables of interest, while p is a set of auxiliary variables used for the proposals.

Generating a (θ, p) -sample is done in two stages [Nea12], which are technically two separate Metropolis-Hastings proposals and acceptance tests. In the first stage, p is proposed from the Gaussian distribution with mean 0 and covariance M . Because the proposal matches the marginal distribution of p , the Metropolis-Hastings acceptance probability is 1, so the proposal is always accepted.

In the second stage, Hamiltonian dynamics for the particle on a surface are simulated with the leapfrog method, starting from the current value of θ and the proposed value of p . The end result is a proposal for both θ and p .

Recall that the MH acceptance test uses the ratio

$$r(\theta, p, \theta', p') = \frac{\pi(\theta, p) q(\theta, p \mid \theta', p')}{\pi(\theta', p') q(\theta', p' \mid \theta, p)}$$

where π is the density of the target distribution and q is the density of the proposal distribution.

For HMC, the leapfrog proposal l is deterministic, so q_l is a probability mass function where $q_l(\theta', p' \mid \theta, p) = 1$ if the leapfrog simulation proposes (θ', p') when starting from (θ, p) , and $q_l(\theta', p' \mid \theta, p) = 0$ otherwise. For the leapfrog proposals, $q_l(\theta', p' \mid \theta, p) = q_l(\theta, -p \mid \theta', -p')$. If the momentum p were negated after the leapfrog simulation, the resulting proposal l^* would have $q_{l^*}(\theta', p' \mid \theta, p) = q(\theta, p \mid \theta', p')$. Then

$$r(\theta, p, \theta', p') = \frac{\pi(\theta', p') q_{l^*}(\theta, p \mid \theta', p')}{\pi(\theta, p) q_l(\theta', p' \mid \theta, p)} = \frac{\pi(\theta', p')}{\pi(\theta, p)},$$

which means that the acceptance probability of the proposal is simply

$$\min\{1, r(\theta, p, \theta', p')\} = \min\{1, \exp(H(\theta, p) - H(\theta', p'))\}.$$

In practice, the values of p are not saved, and $H(\theta, p) = H(\theta, -p)$, so it does not matter whether l or l^* is used as the proposal.

If the simulation conserved H exactly, the acceptance probability would always be 1. Because this is usually not possible, there is always some probability of rejecting, which depends on the length of the jump taken by the leapfrog method, η , and the number of leapfrog steps, L . It might be expected that the errors from the leapfrog steps would accumulate during the simulation, but in practice the errors in different steps tend to cancel each other [Nea12], meaning that the acceptance probability mainly depends on η .

4.2 Differential Privacy with HMC

HMC only uses the model log-likelihood, and thus the data, through U . U is used in two ways. Firstly, its value is used in the acceptance test, and secondly, its gradients are used to obtain proposals. Adding appropriate amounts of noise to both accesses would make HMC differentially private, but the addition of noise may break some of the properties required for the algorithm's correctness.

The addition of noise to the log-likelihood ratios can be corrected using the penalty acceptance test, i.e. changing the acceptance probability to

$$\min\left\{\exp\left(H(\theta, p) - H(\theta', p') - \frac{1}{2}\sigma_l^2\right)\right\},$$

where σ_l^2 is the variance of the noise added to the log-likelihood ratios. This is because with $U(\theta) = -\ln p(X \mid \theta) - \ln p(\theta)$, for data X , the difference of the Hamiltonians in the acceptance probability is

$$H(\theta, p) - H(\theta', p') = \ln p(X \mid \theta') - \ln p(X \mid \theta) - \ln p(\theta) + \ln p(\theta') + \frac{1}{2}(p^T M^{-1} p - p'^T M^{-1} p').$$

As with the penalty algorithm, the sensitivity of the log-likelihood ratios must be bounded. If a bound does not exist, clipping must be used, nullifying the asymptotic converge guarantee of the algorithm. However, in Section 6.2 it is shown that clipping low numbers of gradients does not affect convergence in practice.

Releasing the gradients privately requires a trade-off. The leapfrog method remains reversible with noisy and potentially clipped gradients, as is shown in the following, but it no longer simulates the correct Hamiltonian dynamics [CFG14]. This does not affect asymptotic convergence, but it can potentially lower acceptance rates. The dynamics can be corrected by adding a friction term to the equations of motion of the simulation [CFG14], but this removes volume preservation of the simulation, which means that the acceptance probability must be corrected.

The leapfrog update equations with noisy and clipped gradients become

$$\begin{aligned} p_{i+1/2} &= p_i - \frac{\eta}{2}(g(\theta_i) + \mathcal{N}(0, \sigma_g^2)) \\ \theta_{i+1} &= \theta_i + \eta M^{-1} p_{i+1/2} \\ p_{i+1} &= p_{i+1/2} - \frac{\eta}{2}(g(\theta_{i+1}) + \mathcal{N}(0, \sigma_g^2)), \end{aligned}$$

where

$$g(\theta) = \sum_{x \in X} \text{clip}_b(\nabla \ln p(x \mid \theta)) + \ln p(\theta)$$

denotes the clipped gradients summed over the data X .

The second leapfrog update equation is unchanged from the non-DP case, and remains both volume preserving and reversible by negating p . Both the first and third equations apply the function $l_p: \mathbb{R}^{2d} \rightarrow \mathbb{R}^{2d}$,

$$l_p(\theta, p) = \left(\theta, p - \frac{\eta}{2}(g(\theta) + \mathcal{N}(0, \sigma_g^2)) \right).$$

to θ and p .

The Jacobian of l_p is

$$J_{l_p}(\theta, p) = \begin{bmatrix} I_{d \times d} & 0_{d \times d} \\ J_g(\theta) & I_{d \times d} \end{bmatrix},$$

where $I_{d \times d}$ and $0_{d \times d}$ are the d -by- d identity and zero matrices, respectively. It is possible that $J_g(\theta)$ does not exist, but this can only happen in a null set*, if g is sufficiently well-behaved. The non-existence of $J_g(\theta)$ in a null set does not affect the volume preservation of l_p . As g is a sum of clipped log-likelihood gradients, it suffices to show that the log likelihood is sufficiently well-behaved. Appendix B gives very general sufficient conditions for the log-likelihood, and proves that all of the models considered in Chapter 5 meet the conditions.

*A set of zero Lebesgue measure.

Because $J_{l_p}(\theta, p)$ is triangular, $\det J_{l_p}(\theta, p) = 1$ for all θ and p , which means that l_p preserves volume. As the step updating θ also preserves volume, the entire leapfrog simulation preserves volume.

Showing that the ratio of proposal densities in $r(\theta, p, \theta', p')$ is 1 for the DP HMC leapfrog requires more thought, as the simulation is no longer deterministic.

The proof requires handling randomised functions that are neither discrete or continuous, as the steps in the DP HMC leapfrog are partially random and partially deterministic. A convenient way to handle such mixed random variables is using *generalised functions*, specifically the *Dirac delta function*. The Dirac delta function δ_x for $x \in \mathbb{R}$ is a generalized function with the property that $\delta_x(y) = 0$ if $x \neq y$ and

$$\int_{\mathbb{R}} f(y) \delta_x(y) dy = f(x).$$

Despite the name, the Dirac delta function is not a function by the usual definition.

A generalised function can be used as a density of a random variable, even if the random variable is not continuous and does not have a density in the usual sense. As with usual density function, for a generalised function f to be a density of a random variable X , it must have

$$\int_{\mathbb{R}} f(x) dx = 1.$$

The probability that the value of X is in a given set A is then

$$P(X \in A) = \int_A f(x) dx.$$

Let $l: \mathbb{R}^{2d} \rightarrow \mathbb{R}^{2d}$ be a function giving a random proposal (θ', p') for given (θ, p) . Such random functions are called *proposal functions* in the following. Because l is a random function, it has a (generalized) density $q_l(\theta', p' \mid \theta, p)$. The density of the composition of proposal functions l_1 and l_2 is given by

$$q_{l_2 \circ l_1}(\theta_3, p_3 \mid \theta_1, p_1) = \int_{\mathbb{R}^{2d}} d(\theta_2, p_2) q_{l_1}(\theta_2, p_2 \mid \theta_1, p_1) q_{l_2}(\theta_3, p_3 \mid \theta_2, p_2).$$

Now reversibility by negating p can be defined:

Definition 8. A proposal function l is reversible by negating p if

$$q_l(\theta', p' \mid \theta, p) = q_l(\theta, -p \mid \theta', -p')$$

This can be simplified by defining \bar{l} as the proposal function that has density $q_{\bar{l}}(\theta', p' \mid \theta, p) = q_l(\theta, p \mid \theta', p')$, and defining l_- as $l_-(\theta, p) = (\theta, -p)$. Definition 8 can then be written as $\bar{l} = l_- \circ l \circ l_-$. The function \bar{l} only exists if

$$\int_{\mathbb{R}^{2d}} q_l(\theta', p' \mid \theta, p) d(\theta, p) = 1$$

which is true for random functions reversibly by negating p .

Lemma 2. *Let l_1 and l_2 be proposal functions in \mathbb{R}^{2d} such that \bar{l}_1 and \bar{l}_2 exist. Then $\overline{l_2 \circ l_1} = \bar{l}_1 \circ \bar{l}_2$. For a sequence l_1, \dots, l_k of proposal functions such that \bar{l}_i exists for $1 \leq i \leq k$, $\overline{l_k \circ \dots \circ l_1} = \bar{l}_1 \circ \dots \circ \bar{l}_k$.*

Proof.

$$\begin{aligned} q_{\overline{l_2 \circ l_1}}(\theta_3, p_3 \mid \theta_1, p_1) &= q_{l_2 \circ l_1}(\theta_1, p_1 \mid \theta_3, p_3) \\ &= \int_{\mathbb{R}^{2d}} d(\theta_2, p_2) q_{l_1}(\theta_2, p_2 \mid \theta_3, p_3) q_{l_2}(\theta_1, p_1 \mid \theta_2, p_2) \\ &= \int_{\mathbb{R}^{2d}} d(\theta_2, p_2) q_{\bar{l}_1}(\theta_3, p_3 \mid \theta_2, p_2) q_{\bar{l}_2}(\theta_2, p_2 \mid \theta_1, p_1) \\ &= q_{\bar{l}_1 \circ \bar{l}_2}(\theta_3, p_3 \mid \theta_1, p_1) \end{aligned}$$

which means that $\overline{l_2 \circ l_1} = \bar{l}_1 \circ \bar{l}_2$. The claim for sequences follows by induction. \square

Theorem 9. *The leapfrog simulation with noisy and clipped gradients is reversible by negating p .*

Proof. The leapfrog simulation is a composition of proposal functions l_p and l_θ where

$$l_p(\theta, p) = \left(\theta, p - \frac{\eta}{2}(g(\theta) + \mathcal{N}(0, \sigma_g^2)) \right)$$

and

$$l_\theta(\theta, p) = (\theta + \eta M^{-1}p, p).$$

Specifically, the simulation is

$$(l_p \circ l_\theta \circ l_p) \circ \dots \circ (l_p \circ l_\theta \circ l_p)$$

with L compositions of $l_p \circ l_\theta \circ l_p$. Then

$$\begin{aligned} q_{l_p}(\theta', p' \mid \theta, p) &= \delta_{\theta'}(\theta) \cdot \mathcal{N}\left(p' \mid p - \frac{\eta}{2}g(\theta), \frac{\eta^2}{4}\sigma_g^2\right) \\ &= \delta_\theta(\theta') \cdot \mathcal{N}\left(-p \mid -p' - \frac{\eta}{2}g(\theta'), \frac{\eta^2}{4}\sigma_g^2\right) \\ &= q_{l_p}(\theta, -p \mid \theta', -p') \end{aligned}$$

where the second equality uses the fact that if $\delta_\theta(\theta') \neq 0$, $\theta = \theta'$, and

$$\begin{aligned} q_{l_\theta}(\theta, -p \mid \theta', -p') &= \delta_\theta(\theta' - \eta M^{-1}p') \cdot \delta_{-p}(-p') \\ &= \delta_{\theta'}(\theta + \eta M^{-1}p) \cdot \delta_{p'}(p) \\ &= q_{l_\theta}(\theta', p' \mid \theta, p), \end{aligned}$$

which means that both l_p and l_θ are reversible by negating p . Then the reverse of the leapfrog composition can be written as

$$\begin{aligned} \overline{(l_p \circ l_\theta \circ l_p) \circ \dots \circ (l_p \circ l_\theta \circ l_p)} &= (\bar{l}_p \circ \bar{l}_\theta \circ \bar{l}_p) \circ \dots \circ (\bar{l}_p \circ \bar{l}_\theta \circ \bar{l}_p) \\ &= l_- \circ (l_p \circ l_\theta \circ l_p) \circ \dots \circ (l_p \circ l_\theta \circ l_p) \circ l_-, \end{aligned}$$

where the first equality uses Lemma 2 and the fact that the sequence of compositions is symmetric. The second equality uses the fact that l_p and l_θ are reversible by negating p , and that l_- is its own inverse. This means that the leapfrog simulation with noisy and clipped gradients is reversible by negating p . \square

Because the leapfrog proposal l is reversible by negating p , $\bar{l} = l_- \circ l \circ l_-$. Denote $l^* = l_- \circ l$. Because $\bar{l}_- = l_-$, $\bar{l}^* = \bar{l} \circ \bar{l}_- = l_- \circ l \circ l_- \circ l_- = l^*$. As in the non-DP case, using l^* as the proposal is equivalent to using l , and when using l^* , the $r(\theta, p, \theta', p')$ simplifies

$$r(\theta, p, \theta', p') = \frac{\pi(\theta', p')}{\pi(\theta, p)} \frac{q_l(\theta, p \mid \theta', p')}{q_l(\theta', p' \mid \theta, p)} = \frac{\pi(\theta', p')}{\pi(\theta, p)} \frac{q_{l^*}(\theta, p \mid \theta', p')}{q_{l^*}(\theta', p' \mid \theta, p)} = \frac{\pi(\theta', p')}{\pi(\theta, p)}.$$

For HMC,

$$\frac{\pi(\theta', p')}{\pi(\theta, p)} = \exp(H(\theta, p) - H(\theta', p')),$$

so the acceptance probability from non-DP HMC, with the penalty correction for the noise added to the log-likelihood, is correct for DP HMC.

If the friction term that corrects the dynamics is used, the equations of motion become [CFG14]

$$\begin{aligned} \frac{d\theta}{dt} &= M^{-1}p \\ \frac{dp}{dt} &= -\nabla U(\theta) - \frac{1}{2}\sigma_g^2 M^{-1}p + \mathcal{N}(0, \sigma_g^2) \end{aligned}$$

The equation for θ is unchanged, but the equation for p has the additional term $-\frac{1}{2}\sigma_g^2 M^{-1}p$. For the leapfrog updates, l_θ does not change, and l_p changes to

$$l_p(\theta, p) = \left(\theta, p - \frac{\eta}{2}(g(\theta) + \frac{1}{2}\sigma_g^2 M^{-1}p + \mathcal{N}(0, \sigma_g^2)) \right).$$

l_p no longer preserves volumes, as the Jacobian of l_p is

$$J_{l_p}(\theta, p) = \begin{bmatrix} I_{d \times d} & 0_{d \times d} \\ J_g(\theta) & I_{d \times d} - \frac{\eta}{4}\sigma_g^2 M^{-1} \end{bmatrix}$$

which means that generally $|\det J_{l_p}(\theta, p)| \neq 1$. In addition, the proof of Theorem 9 depends on the fact that on the right side of

$$q_{l_p}(\theta', p' \mid \theta, p) = \delta_{\theta'}(\theta) \cdot \mathcal{N}\left(p' \mid p - \frac{\eta}{2}g(\theta), \frac{\eta^2}{4}\sigma_g^2\right),$$

p and p' have the same multiplier. With the friction term, this is no longer the case, as the multiplier for p changes to $(1 - \frac{\eta}{4}\sigma_g^2 M^{-1})$. This means that the acceptance test of non-DP HMC is no longer correct, so the friction term is not used in this thesis beyond this brief discussion, but finding a way to correct the acceptance test is a potential avenue for future research.

Algorithm 4: DP HMC: log likelihood clip bound b_l , gradient clip bound b_g , clipped gradient function g_{b_g} , number of iterations k , number of leapfrog steps L , leapfrog step size η , initial point θ_0 , gradient noise variance σ_g^2 , log likelihood ratio noise variance σ_l^2 , positive-definite mass matrix M and dataset X as input.

```

 $G_{1,0} = g_{b_g}(\theta_0) + \mathcal{N}(0, \sigma_g^2)$ 
for  $1 \leq i \leq k$  do
     $p_0 = \mathcal{N}_d(0, M)$ 
     $\theta_{i,0} = \theta_{i-1}$ 
    for  $1 \leq j \leq L$  do
         $p_{j-\frac{1}{2}} = p_{j-1} + \frac{1}{2}\eta G_{i,j-1}$ 
         $\theta_{i,j} = \theta_{i,j-1} + M^{-1}p_{j-\frac{1}{2}}$ 
         $G_{i,j} = g_{b_g}(\theta_{i,j}) + \mathcal{N}(0, \sigma_g^2)$ 
         $p_j = p_{j-\frac{1}{2}} + \frac{1}{2}\eta G_{i,j}$ 
    end
     $r_l = \ln \frac{p(\theta_{i,L}|x_l)}{p(\theta_{i-1}|x_l)}$ 
     $R = \sum_{l=1}^n \text{clip}_{b_l}(\| \theta_{i-1} - \theta_{i,L} \|_2)(r_l)$ 
     $\Delta H = R + \frac{1}{2}p_0^T M^{-1}p_0 - \frac{1}{2}p_L^T M^{-1}p_L + \ln \frac{p(\theta_{i,L})}{p(\theta_{i-1})} + \mathcal{N}(0, \sigma_l^2(\theta_{i-1}, \theta_{i,L}))$ 
     $u = \text{Unif}(0, 1)$ 
    if  $u < \Delta H - \frac{1}{2}\sigma_l^2(\theta_{i-1}, \theta_{i,L})$  then
         $\theta_i = \theta_{i,L}$ 
         $G_{i+1,0} = G_{i,L}$ 
    end
    else
         $\theta_i = \theta_{i-1}$ 
         $G_{i+1,0} = G_{i,0}$ 
    end
end

```

DP HMC is shown in Algorithm 4. Like the DP penalty algorithm, DP HMC is a composition of Gaussian mechanisms, and its privacy bounds can be computed through Theorems 2 and 4 for zCDP.

Theorem 10. Let $\epsilon \geq 0$, $0 \leq \delta < 1$, $\tau_g > 0$, $\tau_l > 0$, $b_g > 0$, $b_l > 0$, $n > 0$,

$$\sigma_l(\theta, \theta') = 2\tau_l \sqrt{nb_l} \|\theta - \theta'\|_2,$$

$$\begin{aligned}\sigma_g &= 2\tau_g\sqrt{n}b_g, \\ \rho &= \left(\sqrt{\epsilon - \ln \delta} - \sqrt{-\ln \delta}\right)^2, \\ \rho_l &= \frac{1}{2\tau_l^2 n}, \\ \rho_g &= \frac{1}{2\tau_g^2 n},\end{aligned}$$

Then running DP HMC for

$$k = \left\lfloor \frac{\rho - \rho_g}{\rho_l + L\rho_g} \right\rfloor$$

iterations using σ_l^2 as log-likelihood ratio noise variance, σ_g^2 as gradient noise variance, clipping log-likelihood ratios with b_l and clipping gradients by b_g , for a dataset of size n is (ϵ, δ) -ADP for the substitute neighborhood relation.

Proof. Each iteration of the outer for-loop computes the gradient L times and the log-likelihood ratio once. The gradient is also computed once before the outer for-loop. Releasing a single gradient has zCDP privacy cost of

$$\rho_g = \frac{4b_g^2}{2\sigma_g^2} = \frac{1}{2\tau_g^2 n}.$$

Releasing the log-likelihood ratio of θ and θ' has privacy cost

$$\rho_l = \frac{4b_l^2 \|\theta - \theta'\|_2^2}{2\sigma_l(\theta, \theta')^2} = \frac{1}{2\tau_l^2 n}.$$

The total zCDP budget with given (ϵ, δ) -bound is

$$\rho = \left(\sqrt{\epsilon - \ln \delta} - \sqrt{-\ln \delta}\right)^2.$$

This means that the number of iteration that the algorithm is allowed to run for is

$$k = \left\lfloor \frac{\rho - \rho_g}{\rho_l + L\rho_g} \right\rfloor \quad \square$$

zCDP based privacy accounting for ADP is loose, so the above bound could be improved by using the tight bound for the Gaussian mechanism from Theorem 4. Because DP HMC has both different sensitivities and different noise variances between the log-likelihood ratios and gradients, Theorem 4 is not directly applicable. However, the bound of Theorem 4 does generalise to differing variances between composition.

Theorem 11. Let $\epsilon \geq 0$, $0 \leq \delta < 1$, $\tau_l > 0$, $\tau_g > 0$, $b_l > 0$, $b_g > 0$, $n > 0$,

$$\sigma_l'^2 = \tau_l^2 n,$$

$$\sigma_g'^2 = \tau_g^2 n.$$

Then running DP HMC for k iterations with L leapfrog steps, using $2b_l\sigma_l'^2\|\theta - \theta'\|_2$ as the log-likelihood ratio noise variance, $2b_g\sigma_g'^2$ as the gradient noise variance and b_l and b_g as the log-likelihood and gradient clip bounds, with dataset size n , is $(\epsilon, \delta(\epsilon))$ -ADP for the substitute neighborhood relation, where

$$\delta(\epsilon) = \frac{1}{2} \left(\operatorname{erfc} \left(\frac{\epsilon - \mu}{2\sqrt{\mu}} \right) - e^\epsilon \operatorname{erfc} \left(\frac{\epsilon + \mu}{2\sqrt{\mu}} \right) \right)$$

and

$$\mu = \frac{k}{2\sigma_l'^2} + \frac{kL + 1}{2\sigma_g'^2}.$$

Proof. Sommer et al. [SMM19] prove the ADP bound of Theorem 4 with the *privacy loss distribution* (PLD) of the Gaussian mechanism. First, they show that the PLD of the Gaussian mechanism with sensitivity Δ and variance σ^2 is a Gaussian distribution $\mathcal{N}(\mu, 2\mu)$, where $\mu = \frac{\Delta^2}{2\sigma^2}$ [SMM19, Lemma 11]. Next, they show that the ADP bounds $(\epsilon, \delta(\epsilon))$ for a Gaussian PLD $\mathcal{N}(\mu, 2\mu)$ are given by [SMM19, Lemma 12]

$$\delta(\epsilon) = \frac{1}{2} \left(\operatorname{erfc} \left(\frac{\epsilon - \mu}{2\sqrt{\mu}} \right) - e^\epsilon \operatorname{erfc} \left(\frac{\epsilon + \mu}{2\sqrt{\mu}} \right) \right).$$

Finally, they show that the PLD of an adaptive composition is the convolution of the PLDs of the individual parts of the composition [SMM19, Theorem 1]. As convolution of distributions corresponds to summing random variables, the PLD of a convolution of Gaussian mechanisms with PLDs $\mathcal{N}(\mu_i, 2\mu_i)$ is simply $\mathcal{N}(\sum \mu_i, 2\sum \mu_i)$.

Because the sensitivity of the log-likelihood ratio is $2b_l\|\theta - \theta'\|_2$ and the sensitivity of the gradient is $2b_g$, both the gradient and log-likelihood ratio are divided by their sensitivities before adding noise, which normalises both to have sensitivity one. Adding noise with variance $\sigma_l^2(\theta, \theta')$ and σ_g^2 to the log-likelihood ratio and gradient respectively is equivalent to adding noise with variance $\sigma_l'^2 = \tau_l^2 n$ and $\sigma_g'^2 = \tau_g^2 n$ to the normalised log-likelihood ratio and gradient.

DP HMC releases the log-likelihood ratio k times and the gradient $kL + 1$ times. This means that the PLD of DP HMC is a Gaussian distribution $\mathcal{N}(\mu, 2\mu)$ with

$$\mu = \frac{k}{2\sigma_l'^2} + \frac{kL + 1}{2\sigma_g'^2}. \quad \square$$

The maximum number of iterations DP HMC can run for can be computed with Algorithm 2 by using Theorem 11 to compute δ , and using Theorem 10 to initialise the variable *low*.

The τ_l and b_l parameters of DP HMC are analogous to the τ and clip bound parameters of DP penalty. Additionally, DP HMC releases gradients, which requires a separate parameter τ_g to control the trade-off between noise and privacy cost of a single

iteration, and a clip bound b_g for the gradients. The number of leapfrog iterations per sample L also affects the privacy of the algorithm, as it affects the number of gradients released.

The α value from Theorem 5 for DP penalty could be included in Theorem 10, which would make Theorem 10 the special case where $\alpha = \frac{1}{2}$. Because, as argued for DP penalty in Section 3.1, having $\alpha = \frac{1}{2}$ can be guaranteed by setting the clip bound appropriately, and the clip bound can be chosen to be anything if the parameters are only used with a single value of n , Theorem 10 was simplified to not include α .

Figure 4.1 shows an example of a leapfrog trajectory of DP HMC on a circular posterior (Section 5.3). Even with noisy and clipped gradients, the trajectory is able to stay inside the thin, circular area of high probability, while moving a substantial distance on the circle.

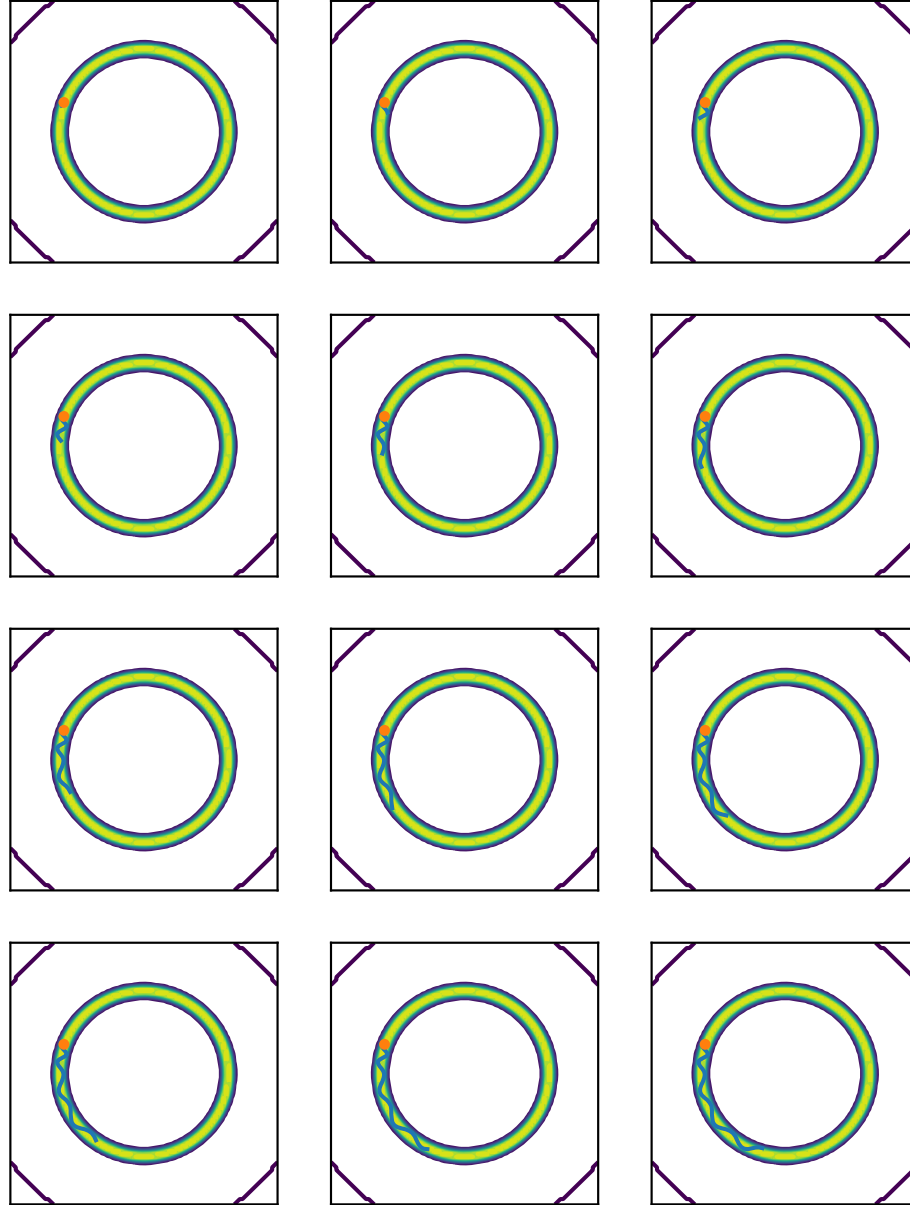


Figure 4.1: DP HMC proposal trajectory on a circular posterior (Section 5.3). The leapfrog simulation progress is shown in successive images from left to right and top to bottom. The orange point is the starting point of the leapfrog simulation and the blue line shows the progress of the leapfrog steps. The background is a contour plot of the circular posterior density.

5. Experimental Setup

To compare the performance of the DP MCMC algorithms, they were run on several models. This chapter introduces these models in Sections 5.1, 5.2 and 5.3. The practicalities, such as the hyperparameter values of the model and the initialisation of the MCMC algorithms, are considered in Section 5.4. Finally, the main performance metric used in the experiments is introduced in Section 5.5. The results of the experiments are discussed in Chapter 6.

5.1 The Gaussian Model

The simplest model used for the experiments is the Gaussian model with known covariance. The likelihood and prior for n points of d -dimensional data $X \in \mathbb{R}^{n \times d}$ and parameters $\theta \in \mathbb{R}^d$ are

$$\begin{aligned}\theta &\sim \mathcal{N}_d(\mu_0, \Sigma_0), \\ X_i &\sim \mathcal{N}_d(\theta, \Sigma),\end{aligned}$$

where X_i is a row of X , Σ is the known covariance, and μ_0 and Σ_0 are the prior hyperparameters. The posterior of this model is another d -dimensional Gaussian distribution with parameters expressible in closed form [GCS⁺14, Section 3.5], so it is easy to sample from the posterior.

5.2 The Banana Distribution

The banana distribution [TPK14] is a banana-shaped probability distribution that is a challenging target for MCMC algorithms. For this reason it has been used to test MCMC algorithms in the literature [TPK14].

Definition 9. *Let X have a d -variate Gaussian distribution with mean μ and covariance matrix Σ . Let*

$$g(x) = (x_1, x_2 - a(x_1 - m)^2 - b, x_3, \dots, x_d),$$

with $a, b, m \in \mathbb{R}$. The banana distribution with parameters μ, Σ, a, b and m is the distribution of $g(X)$. It is denoted by $\text{Ban}(\mu, \Sigma, a, b, m)$.

In the literature, the banana distribution is simply used as the target to sample from, and is not the posterior in a Bayesian inference problem [TPK14]. To test differentially private MCMC algorithms, the target distribution must be the posterior of some inference problem, as otherwise there is no data to protect with differential privacy. Theorem 12 gives a suitable inference problem for testing DP MCMC algorithms.

Theorem 12. *Let*

$$\begin{aligned}\theta &= (\theta_1, \dots, \theta_d) \sim \text{Ban}(0, \sigma_0^2 I, a, b, m), \\ X_1 &\sim \mathcal{N}(\theta_1, \sigma_1^2), \\ X_2 &\sim \mathcal{N}(\theta_2 + a(\theta_1 - m)^2 + b, \sigma_2^2), \\ X_3 &\sim \mathcal{N}(\theta_3, \sigma_3^2), \\ &\vdots \\ X_d &\sim \mathcal{N}(\theta_d, \sigma_d^2).\end{aligned}$$

Given data $x_1, \dots, x_d \in \mathbb{R}^n$ and denoting $\tau_i = \frac{1}{\sigma_i^2}$, the posterior of θ tempered with T is the banana distribution $\text{Ban}(\mu, \Sigma, a, b, m)$ with

$$\begin{aligned}\bar{x}_i &= \frac{1}{n} \sum_{j=1}^n x_{ji} \quad i \in \{1, 2\}. \\ \mu &= \left(\frac{Tn\tau_1\bar{x}_1}{Tn\tau_1 + \tau_0}, \dots, \frac{Tn\tau_d\bar{x}_d}{Tn\tau_d + \tau_0} \right), \\ \Sigma &= \text{diag} \left(\frac{1}{Tn\tau_1 + \tau_0}, \dots, \frac{1}{Tn\tau_d + \tau_0} \right).\end{aligned}$$

Proof. See Appendix A. □

The Gaussian distribution is a special case of the banana distribution, as setting $a = 0$ makes g the identity function. Similarly, setting $a = 0$ turns the Bayesian banana model into a Gaussian model.

5.3 Circle Model

Random walk MH algorithms may struggle with posteriors which are concentrated on long, but thin regions. Having a large proposal variance causes the algorithm to

frequently jump out of the region of high probability, but lowering the variance to stay in the region causes the chain to take a very long time to move around in the region. An example of such a posterior is the circular posterior described in this section.

The circle posterior is obtained from a model where the log-likelihood is

$$\ln p(r \mid x, y) = -a(x^2 + y^2 - r^2)^2$$

where $r \in \mathbb{R}$ is an observed data point, $a > 0$ is a hyperparameter, and $(x, y) \in \mathbb{R}^2$ are the parameters. The likelihood is circular in the (x, y) -plane, as it only depends on the squared distance of the point (x, y) from the origin. By choosing a flat prior, $p(x, y) = 1$ for all $(x, y) \in \mathbb{R}^2$, the posterior will be proportional to the likelihood, meaning that the posterior will also be circular.

As the prior does not integrate to 1, it is not a proper probability density, so Bayes' theorem does not guarantee that the posterior integrates to a finite value. In this case, for a single data point r and any $a > 0$,

$$\begin{aligned} \int_{\mathbb{R}^2} p(r \mid x, y) dx dy &= \int_{\mathbb{R}^2} e^{-a(x^2+y^2-r^2)^2} dx dy \\ &= \int_0^{2\pi} d\phi \int_0^\infty dt \cdot t e^{-a(t^2(\cos^2 \phi + \sin^2 \phi) - r^2)^2} \\ &= \int_0^{2\pi} d\phi \int_0^\infty dt \cdot t e^{-a(t^2 - r^2)^2} \\ &= \int_0^{2\pi} d\phi \int_0^\infty du \cdot e^{-a(u-r^2)^2} \\ &< \infty, \end{aligned}$$

as, on the second to last line, the inner integral is over an unnormalised Gaussian density, and the outer integral is over a finite interval. For multiple data points, the integral of the likelihood is

$$\int_{\mathbb{R}^2} \prod_i^n p(r_i \mid x, y) dx dy \leq \prod_i^n \left(\int_{\mathbb{R}^2} p(r_i \mid x, y)^n dx dy \right)^{\frac{1}{n}} < \infty,$$

where the first inequality is Hölder's inequality applied $n - 1$ times, and the second follows from the single data point case, as $p(r \mid x, y)^n = e^{-an(x^2+y^2-r^2)^2}$. As the likelihood integrates to a finite value, it can be considered an unnormalised density and sampled from with MCMC.

Obtaining samples from the true posterior with the circle model is not as easy as with the banana and Gaussian models, so using MMD, the metric introduced in Section 5.5 to evaluate the performance of an MCMC algorithm on the circle is nontrivial. However, as the mean of the circle is in its center, and the samples from an MCMC algorithm are likely to lie on the circle, the distance of the mean of the sample from the origin indicates how evenly the samples are distributed throughout the circle.

It remains to show that the mean of the circle is actually the origin. It turns out that this is fairly simple. For the mean of the x -coordinate

$$\begin{aligned}
E_x &= \int_{\mathbb{R}} dx \cdot x \int_{\mathbb{R}} dy p(r \mid x, y) \\
&= \int_{-\infty}^{\infty} dx \cdot x \int_{-\infty}^{\infty} dy \prod_i e^{-a(x^2+y^2-r_i^2)^2} \\
&= \int_0^{\infty} dx \cdot x \int_{-\infty}^{\infty} dy \prod_i e^{-a(x^2+y^2-r_i^2)^2} + \int_{-\infty}^0 dx \cdot x \int_{-\infty}^{\infty} dy \prod_i e^{-a(x^2+y^2-r_i^2)^2} \\
&= \int_0^{\infty} dx \cdot x \int_{-\infty}^{\infty} dy \prod_i e^{-a(x^2+y^2-r_i^2)^2} - \int_0^{\infty} dx \cdot x \int_{-\infty}^{\infty} dy \prod_i e^{-a(x^2+y^2-r_i^2)^2} \\
&= 0.
\end{aligned}$$

The mean of the y -coordinate is calculated similarly.

Unlike the banana and Gaussian models, the circle model does not give a method to generate the data points r_i from given values of x and y . The r_i values used in the experiments of Chapter 6 were sampled from a normal distribution with mean 3 and variance 1.

5.4 Practicalities of Running the MCMC Algorithms

Eight sets of model hyperparameters were used in the experiments. The hyperparameters are shown in Table 5.1 and contour plots of the 2-dimensional models are shown in Figure 5.1. All banana models had $b = m = 0$. The likelihood variance of the banana and 30-dimensional Gaussian models was $\sigma_1^2 = 20$, $\sigma_2^2 = 2.5$ and $\sigma_i^2 = 1$ for $i > 2$. The likelihood covariance for the correlated Gaussian model was

$$\begin{bmatrix} 1 & 0.999 \\ 0.999 & 1 \end{bmatrix}.$$

The true values of θ in all experiment except the circle are $\theta_2 = 3$ and $\theta_i = 0$ for $i \neq 2$.

All experiments ran 20 chains for each value of ϵ for DP MCMC experiments, or clip bound for clipping experiments, for each algorithm included. Each of the 20 chains had a different starting point, chosen from a Gaussian distribution value with standard deviation as shown in Table 5.1, but the starting points did not vary across algorithms, or values of ϵ or clip bound. The Gaussian distribution choosing the starting points was centered on the true parameter values for the banana and Gaussian experiments, and on $(0, 1)$ for the circle experiment.

The first half of the obtained samples were discarded as they may not represent the true posterior, which is standard practice with MCMC [GCS⁺14]. The latter half

was compared to a reference sample obtained from the true posterior, except in the circle experiment, where the mean of the sample was compared to the true posterior mean of $(0, 0)$.

Publicly available implementations of DP Barker^{*} and the Fourier accountant[†] were used, and the rest of the algorithms were implemented by the author. The accuracy and running time of the Fourier accountant is determined by two parameters [KJH20]. They were left at their default values. The code for running the experiments is freely available[‡].

^{*}<https://github.com/DPBayes/DP-MCMC-NeurIPS2019>

[†]<https://github.com/DPBayes/PLD-Accountant>

[‡]<https://github.com/oraisa/masters-thesis>

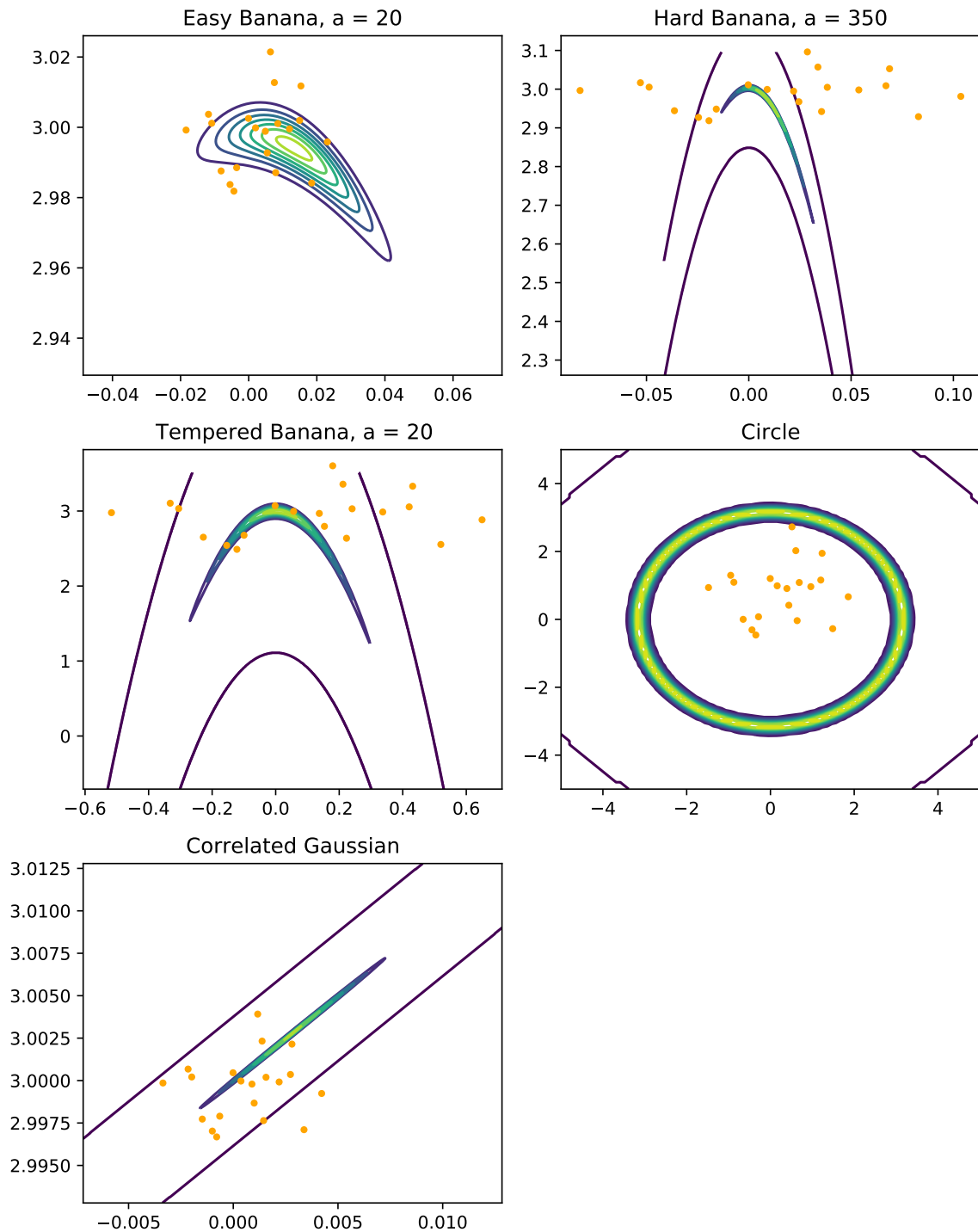


Figure 5.1: Contour plots of the posterior densities of the 2-dimensional models. The orange points are the 20 starting points for each chain.

Table 5.1: Model parameters. n_0 determines tempering by $T = \frac{n_0}{n}$. For missing n_0 , $T = 1$. Start deviation is the standard deviation of the random starting point in the DP experiments.

Name	Dim	n	n_0	Start Deviation	a	σ_0^2
Flat banana, d = 2	2	100000		0.02	20	1000
Flat banana, d = 10	10	200000		0.02	20	1000
Tempered banana, d = 2	2	100000	1000	0.15	20	1000
Tempered banana, d = 10	10	200000	1000	0.15	20	1000
High dimensional Gauss	30	200000		0.02	0	1000
Narrow banana	2	150000		0.015	350	1000
Correlated Gauss	2	200000		0.003	0	100
Circle	2	100000		0.3	1e-05	

5.5 Maximum Mean Discrepancy

The convergence of non-DP MCMC algorithms is typically assessed using \hat{R} [GCS⁺14], which measures how well multiple chains started from different points have mixed together. The utility of a sample produced by an MCMC algorithm can be evaluated using effective sample size (ESS) [GCS⁺14], which is an estimate of the size of an uncorrelated sample of the posterior with the same estimation utility as the MCMC sample.

Both \hat{R} and ESS require that the MCMC algorithm asymptotically targets the true posterior, as they cannot detect an algorithm that has converged to the wrong distribution. Because some of the DP MCMC algorithms use approximations that may cause the algorithms to not converge to the true posterior, such as clipping the log-likelihood ratios, \hat{R} and ESS are not suitable for assessing the performance of the algorithms.

Because the DP MCMC algorithms may not converge to the correct distribution, their performance should be evaluated with a metric that measures how close to the true distribution they are. A very general such metric is maximum mean discrepancy (MMD) [GBR⁺12]. MMD between distributions p and q is defined as

$$\text{MMD}(p, q) = \sup_{f \in \mathcal{F}} (E_{x \sim p} f(x) - E_{y \sim q} f(y))$$

where \mathcal{F} is some class of functions. By choosing a suitable \mathcal{F} , $\text{MMD}(p, q)$ can be estimated from a sample from p and q . The suitable classes \mathcal{F} can be characterised by a kernel function $k: P \times Q \rightarrow \mathbb{R}$, where P and Q are the supports of p and q , respectively. The Gaussian radial basis function (RBF) kernel

$$k(x, y) = \exp\left(-\frac{\|x - y\|_2^2}{2\sigma^2}\right)$$

is particularly well suited, as it has the property that $\text{MMD}(p, q) = 0$ if and only if $p = q$. After choosing a kernel, $\text{MMD}(p, q)$ may be estimated from finite samples of p and q . To evaluate MCMC algorithms, one of the samples is the output of the algorithm to be evaluated, and the other is a sample from the true posterior.

The choice of the σ parameter of k affects the way MMD evaluates different kinds of differences in p and q . For some preliminary experiments in this thesis, σ was chosen to be 1, which penalised error in the mean much more than errors in higher moments in the experiments. The σ used for the final experiments is chosen by picking 50 subsamples from both samples with replacement and setting σ to be the median between distances of points of the subsamples. This is following the procedure of Gretton et al. [GBR⁺12], with the addition of the subsampling step to handle samples of different sizes.

6. Experiments

This chapter contains the experiments performed on both non-DP and DP MCMC algorithms. Section 6.1 compares the zCDP, RDP and ADP based privacy accounting methods that are available for DP penalty, minibatch DP Penalty and DP HMC. Section 6.2 examines the effect clipping log-likelihood ratios, which is necessary for DP MCMC algorithms, but may adversely affect their convergence. Section 6.3 compares the different DP MCMC algorithms on several models.

6.1 Comparing Privacy Accounting Methods

DP penalty, minibatch DP penalty and DP HMC have two different methods to compute the number of iterations the algorithm can run for, given a privacy bound and parameters for the algorithm. These privacy accounting methods are given by Theorems 5 and 6 for DP penalty, Theorems 10 and 11 for DP HMC, and Theorem 8 and the Fourier accountant [KJH20] for minibatch DP penalty.

Figure 6.1 compares the number of iterations each of the algorithms can run for for both accounting methods and different values of ϵ in the 2-dimensional flat banana experiment. The ADP based methods of Theorems 6 and 11, as well as the Fourier accountant, significantly outperform the other accounting methods. This makes it clear that the tight bounds given by the ADP based methods should be used in favor of loose methods. The Fourier accountant is not easily applicable to DP Barker, as DP Barker does not release the sample variance directly, it may still be possible to use the Fourier accountant with DP Barker. This is an interesting question for future research, as using a better privacy accountant may significantly improve the performance of DP Barker.

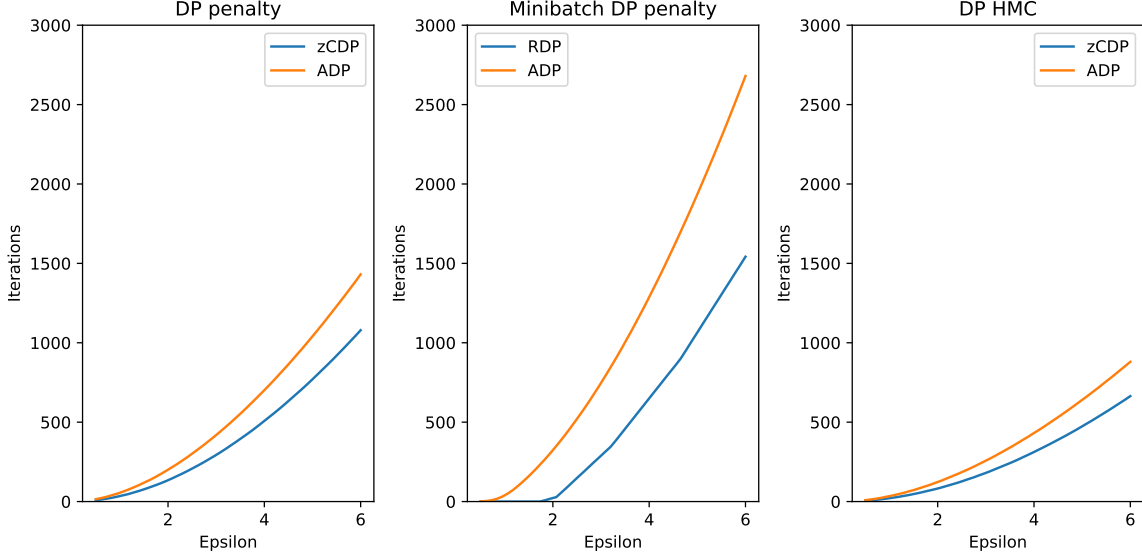


Figure 6.1: Comparing the zCDP or RDP and ADP based privacy accounting methods for the algorithms with multiple accounting methods. The left panel compares zCDP based accounting (Theorem 5) and ADP based accounting (Theorem 6) for the DP penalty algorithm. The middle panel compares the RDP accounting (Theorem 8) and the Fourier accountant. The right panel compares the zCDP (Theorem 10) and ADP (Theorem 11) based accounting. The ADP based methods significantly outperform the other methods in all cases.

6.2 The Effects of Clipping

The first experiment evaluates the effect of clipping log-likelihood ratios. Both HMC and random walk Metropolis-Hastings (RWMH)* algorithms were run on 2 and 10 dimensional banana models. DP was not used so that error from the extra noise would not affect the results.

For both 2 and 10 dimensions, 500 samples from HMC and 3000 samples from RWMH were taken and the latter half of them were compared to 2000 samples from the true posterior. The reference posterior sample was also compared to other samples from the posterior to obtain a baseline. The sample sizes and other parameters of the algorithms were tuned so that the algorithms converged without clipping.

Figure 6.2 shows the results of the clipping experiment. The top left and bottom left panels show MMD as a function of the clip bound and the fraction of log-likelihoods that was actually clipped for both HMC and RWMH in the 2-dimensional model. The effect of clipping on MMD is nonexistent for all but the lowest clip bounds. The top and bottom right panels show results for the 10-dimensional model. This time there are chains that did not converge correctly with most clip bounds, but the chains with the higher bounds converged. Based on these results, if the clip fraction is less than

*Metropolis-Hastings using the Gaussian distribution as the proposal distributions.

10%, clipping is likely undetectable without a large sample.

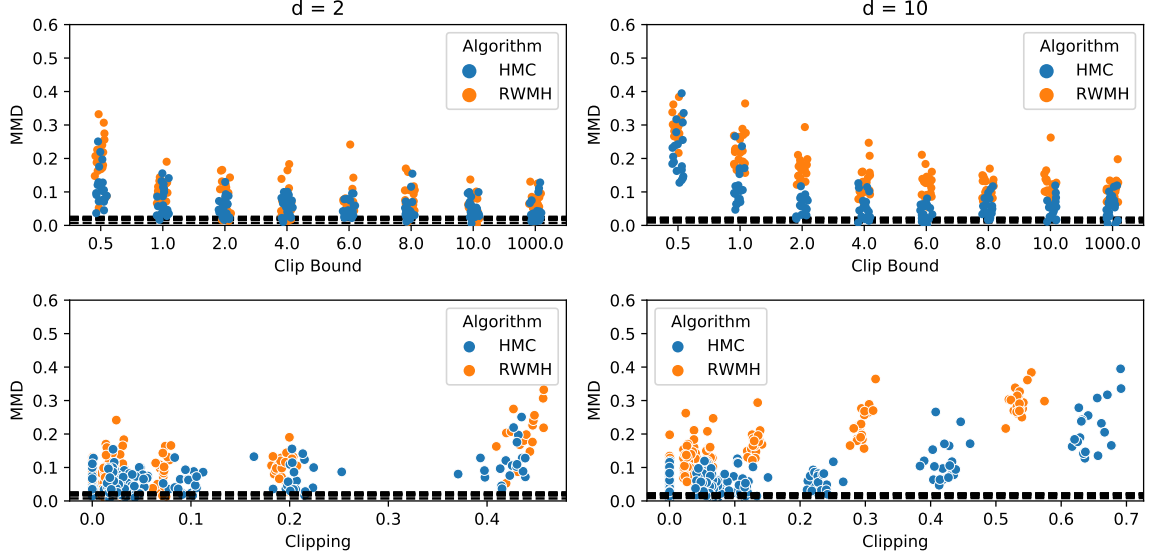


Figure 6.2: The effect of log-likelihood ratio clipping on the posterior of the banana model for random walk Metropolis-Hastings and HMC. The top row shows posterior MMD as a function of the clip bound, and the bottom row shows MMD as a function of the fraction of log-likelihoods that were clipped. The left columns used a 2-dimensional posterior while the right columns had a 10-dimensional posterior. The black lines show the MMDs of ten different samples of the true posterior compared to the reference sample. All of the lines are close to each other and appear as a single line.

6.3 Comparison of DP MCMC Algorithms

The experiments in this section compare the DP MCMC algorithms discussed in this thesis. The compared algorithms are the DP penalty algorithm with and without guided walk MH and one component updates [YE19] (Section 3.1), the DP Barker algorithm [HJDH19] (Section 3.2), the penalty algorithm with subsampling, again with and without GWMH and OCU (Section 3.3) and DP HMC (Section 4.2).

The δ for all experiments is $\frac{0.1}{n}$, and ϵ is varied. All algorithms used the best privacy accounting methods discussed in this thesis. For both variants of DP penalty and DP HMC, these are the PLD based Theorems 6 and 11. DP penalty with subsampling uses the Fourier accountant [KJH20] and DP Barker uses Theorem 7. The RDP based theorems for the minibatch algorithms are not tight for the ADP bounds that were used, so their results could be improved by using an accounting method for ADP.

The hyperparameters of the algorithms were tuned by running the algorithms with $\epsilon = 4$ and examining the results, trying to find hyperparameters that minimise MMD. Clip bounds were tuned so that less than 10% of the log-likelihood ratios were clipped, as the results of Section 6.2 show minimal effect on MMD at that point.

Figure 6.3 shows the MMD for each algorithm as a function of ϵ for the flat and tempered banana models with 2 and 10 dimensions. In the non-tempered models, the minibatch algorithms are not very useful, with the exception of DP Barker in 10 dimensions. Of the non-minibatch algorithms, with tempering HMC beats the penalty algorithms, but without tempering this is reversed.

Figure 6.4 shows MMDs for the more complicated models, the 30-dimensional Gaussian, the narrow banana and the highly correlated Gaussian. The minibatch algorithms were not included as the previous experiment indicates that they perform poorly without tempering. In the 30-dimensional Gaussian, DP penalty with OCU and GWMH beats the other two algorithms, with DP HMC narrowly beating DP penalty. In the narrow banana all algorithms are approximately equal, until $\epsilon = 4$ where DP penalty OCU+GWMH has huge variance in MMD, and in the higher values of ϵ where it performs extremely poorly. In the highly correlated Gaussian experiment, the penalty algorithms perform equally, and HMC beats both of them.

Figure 6.5 shows the fraction of log-likelihood ratios that were clipped for each ϵ and algorithm. Almost all runs had less than 10% clipping, with the exception of DP Barker, as adjusting its clip bound is not possible.

Figure 6.6 shows clipping for the harder models. Again, almost all runs have less than 10% clipping, with the exception of DP penalty OCU+GWMH on the narrow banana, where the high amount of clipping could explain the poor performance of the algorithm with larger values of ϵ .

Figure 6.7 shows the results for the circle model. The distance of the sample mean from the true mean (the origin) were used instead of MMD, as computing MMD requires a sample from the posterior, which is not trivial to obtain for the circle model. Both algorithms perform well on average, with HMC slightly beating DP penalty on $\epsilon = 0.5$. Clipping is again low for both algorithms, and HMC has a fairly large variance in clipping between different runs.

Figure 6.8 shows the fraction of clipped gradients for DP HMC. Clipping gradients does not affect the asymptotic convergence of DP HMC, but it may lower the acceptance rate and thus the performance of the algorithm. As raising the clip bound to lower gradient clipping increases the noise added to gradient, thus also lowering the acceptance rate, it is not clear what an appropriate level of gradient clipping would be. The observed levels of clipping are fairly constant across values of ϵ , but vary in the models, and in the narrow banana model, there is very large variance in clipping.

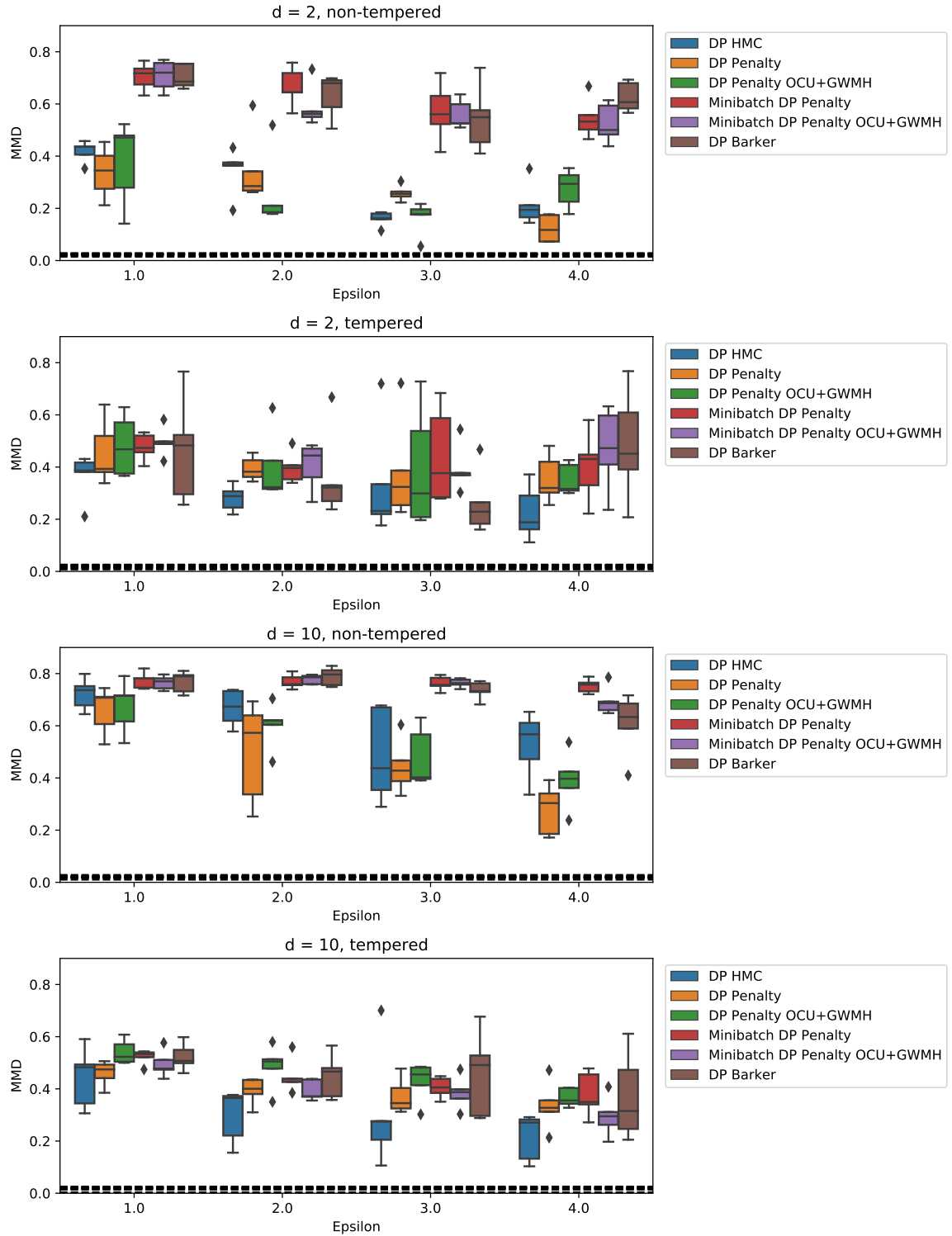


Figure 6.3: MMD as a function of ϵ for the different MCMC algorithms, on flat and tempered banana models with both a low number of dimensions (2) and a high number of dimensions (10). The black lines show the MMD of 10 different samples of the true posterior compared to the reference sample.

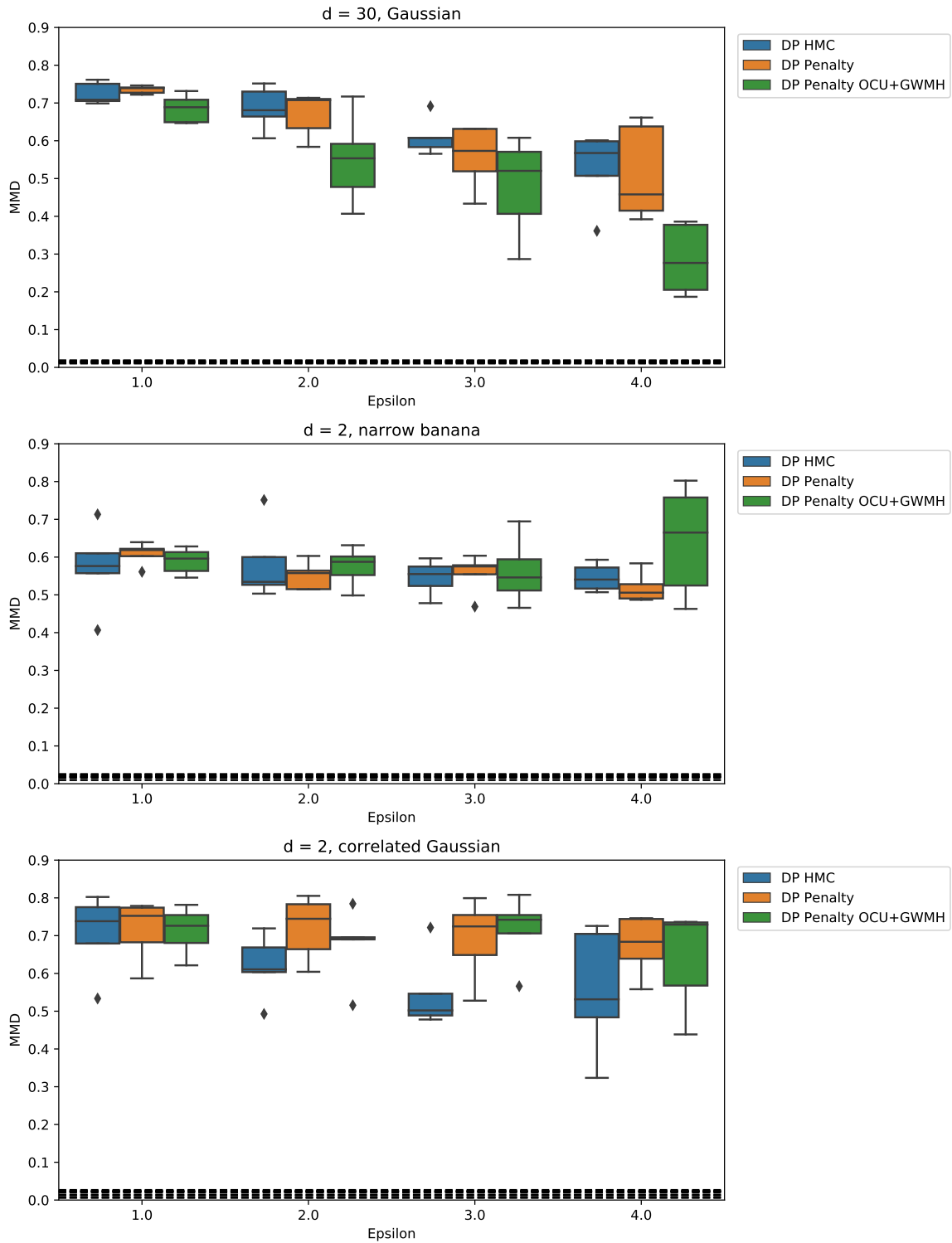


Figure 6.4: MMD for the 30-dimensional Gaussian, hard banana and highly correlated 2-dimensional Gaussian. The black lines show the MMD of 10 samples of the true posterior compared to the reference sample.

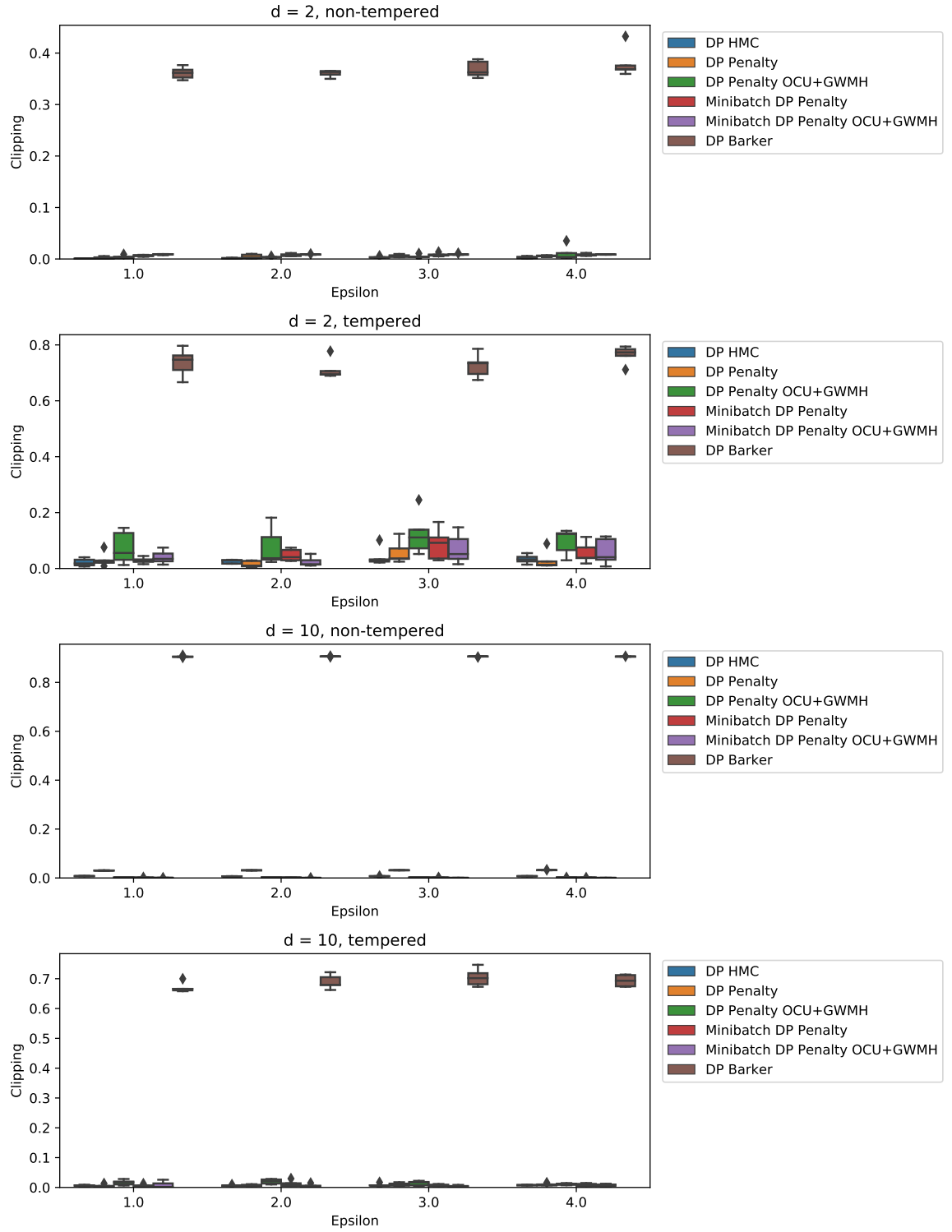


Figure 6.5: Clipping for the easy and tempered banana experiments.

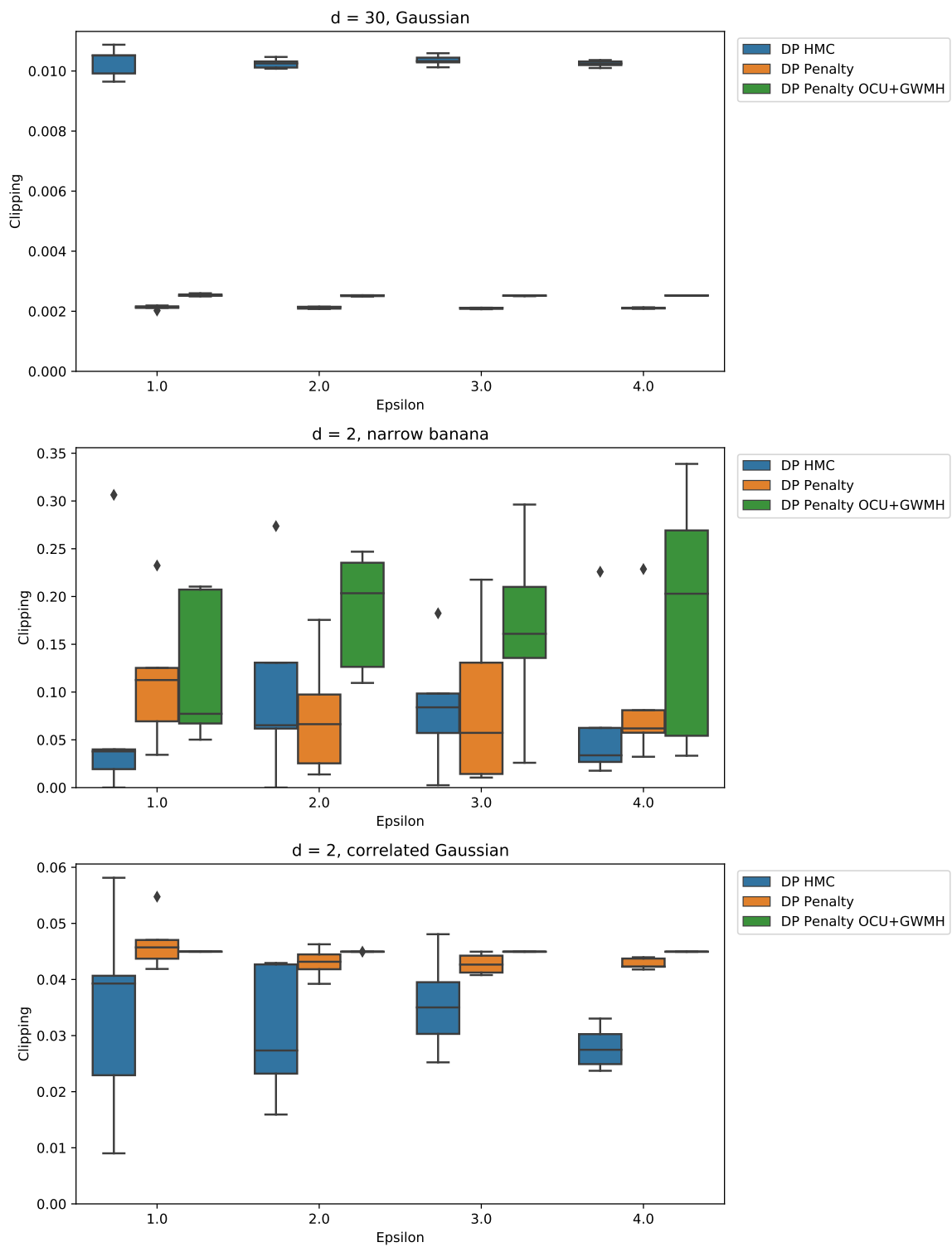


Figure 6.6: Clipping for 30-dimensional Gaussian, hard banana and highly correlated 2-dimensional Gaussian.

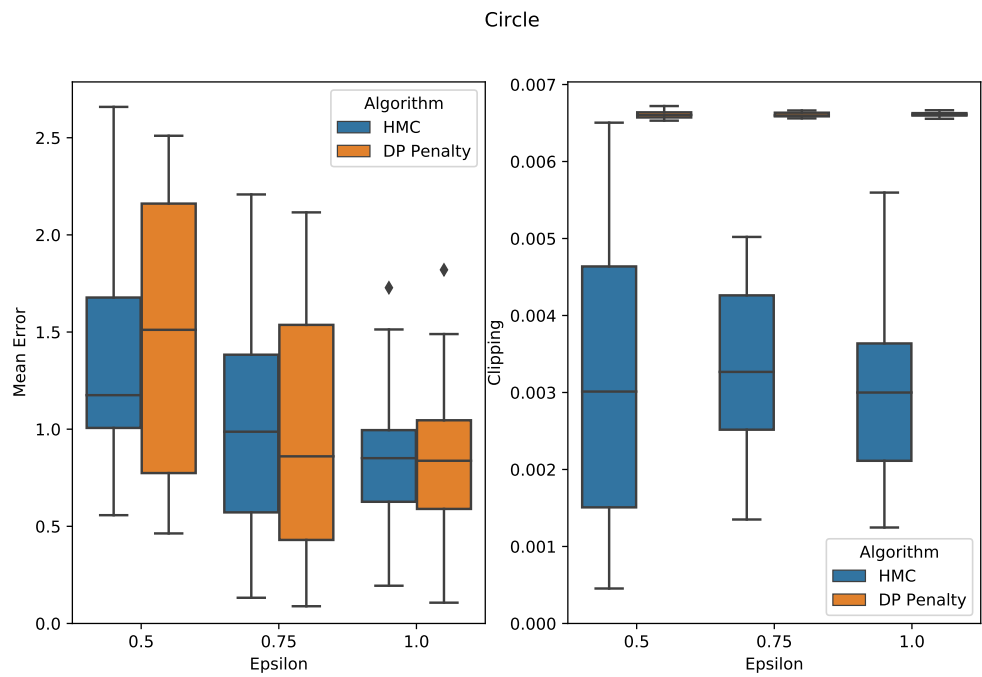


Figure 6.7: Circle mean error on the left and clipping on the right.

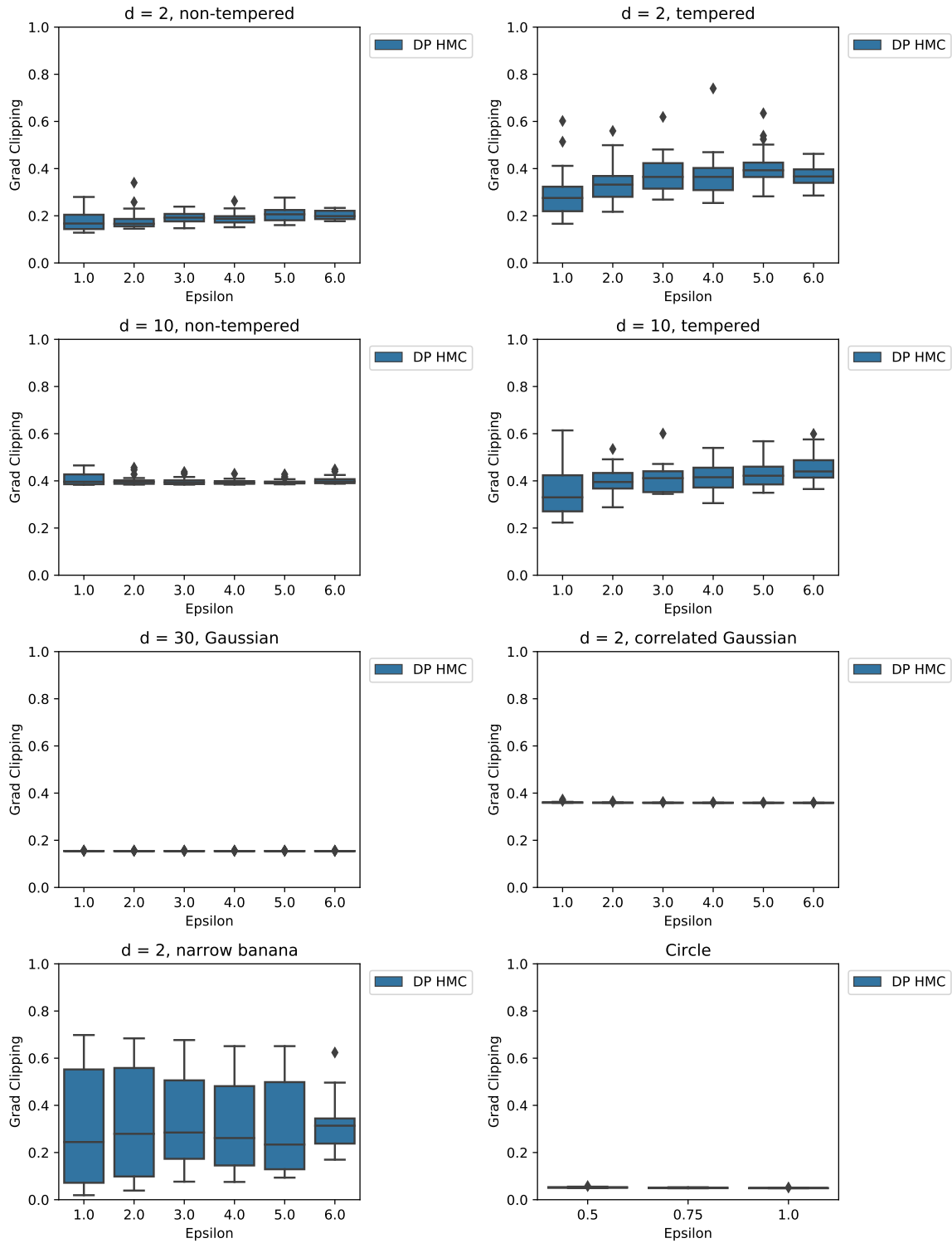


Figure 6.8: Gradient clipping for DP HMC.

7. Conclusions

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Appendix A. Proof of Theorem 12

Theorem 12. *Let*

$$\begin{aligned}
\theta &= (\theta_1, \dots, \theta_d) \sim \text{Ban}(0, \sigma_0^2 I, a, b, m) \\
X_1 &\sim \mathcal{N}(\theta_1, \sigma_1^2) \\
X_2 &\sim \mathcal{N}(\theta_2 + a(\theta_1 - m)^2 + b, \sigma_2^2) \\
X_3 &\sim \mathcal{N}(\theta_3, \sigma_3^2) \\
&\vdots \\
X_d &\sim \mathcal{N}(\theta_d, \sigma_d^2)
\end{aligned}$$

Given data $x_1, \dots, x_d \in \mathbb{R}^n$ and denoting $\tau_i = \frac{1}{\sigma_i^2}$, the posterior of θ tempered with T is the banana distribution $\text{Ban}(\mu, \Sigma, a, b, m)$ with

$$\bar{x}_i = \frac{1}{n} \sum_{j=1}^n x_{ji} \quad i \in \{1, 2\}$$

$$\mu = \left(\frac{Tn\tau_1\bar{x}_1}{Tn\tau_1 + \tau_0}, \dots, \frac{Tn\tau_d\bar{x}_d}{Tn\tau_d + \tau_0} \right),$$

$$\Sigma = \text{diag} \left(\frac{1}{Tn\tau_1 + \tau_0}, \dots, \frac{1}{Tn\tau_d + \tau_0} \right).$$

Proof. Because

$$g^{-1}(y) = (y_1, y_2 + a(y_1 - m)^2 + b, y_3, \dots, y_d)$$

and the Jacobian determinant of g^{-1} is 1, for a positive-definite Σ the banana distribution has density proportional to

$$\exp \left(-\frac{1}{2} (g^{-1}(x) - \mu)^T \Sigma^{-1} (g^{-1}(x) - \mu) \right)$$

With $\Sigma = \text{diag}(\sigma_1^2, \sigma_2^2)$ the density is proportional to

$$\exp \left(-\frac{1}{2} \left(\left(\frac{x_1 - \mu_1}{\sigma_1} \right)^2 + \left(\frac{x_2 + a(x_1 - m)^2 + b - \mu_2}{\sigma_2} \right)^2 + \sum_{i=3}^d \left(\frac{x_i - \mu_i}{\sigma_i} \right)^2 \right) \right)$$

Denote $u = \theta_2 + a(\theta_1 - m)^2 + b$. The tempered posterior of θ is

$$\begin{aligned}
p(\theta \mid X) &\propto p(X \mid \theta)^T p(\theta) \\
&= p(X_1 \mid \theta_1)^T p(X_2 \mid \theta_1, \theta_2)^T \prod_{i=3}^d p(X_i \mid \theta_i)^T p(\theta) \\
&= p(X_1 \mid \theta_1)^T p(X_2 \mid \theta_1, \theta_2)^T \prod_{i=3}^d p(X_i \mid \theta_i)^T \\
&\quad \cdot \exp \left(-\frac{1}{2} \left(\tau_0 \theta_1^2 + \tau_0 (\theta_2 + a(\theta_1 - m)^2 + b)^2 \sum_{i=3}^d \tau_0 \theta_i^2 \right) \right) \\
&= p(X_1 \mid \theta_1)^T p(X_2 \mid \theta_1, \theta_2)^T \exp \left(-\frac{1}{2} \left(\tau_0 \theta_1^2 + \tau_0 (\theta_2 + a(\theta_1 - m)^2 + b)^2 \right) \right) \\
&\quad \cdot \prod_{i=3}^d p(X_i \mid \theta_i)^T \exp \left(-\frac{1}{2} \sum_{i=3}^d \tau_0 \theta_i^2 \right)
\end{aligned}$$

Considering the upper and lower part of the last expression separately

$$\begin{aligned}
& p(X_1 \mid \theta_1)^T p(X_2 \mid \theta_1, \theta_2)^T \exp \left(-\frac{1}{2} \left(\tau_0 \theta_1^2 + \tau_0 (\theta_2 + a(\theta_1 - m)^2 + b)^2 \right) \right) \\
& \propto \left(\prod_{i=1}^n \exp \left(-\frac{(x_{i1} - \theta_1)^2 \tau_1}{2} \right) \right)^T \cdot \left(\prod_{i=1}^n \exp \left(-\frac{(x_{i2} - \theta_2 - a(\theta_1 - m)^2 - b)^2 \tau_2}{2} \right) \right)^T \\
& \cdot \exp \left(-\frac{1}{2} \left(\tau_0 \theta_1^2 + \tau_0 (\theta_2 + a(\theta_1 - m)^2 + b)^2 \right) \right) \\
& = \exp \left(-\frac{1}{2} \left(T \tau_1 \sum_{i=1}^n (x_{i1} - \theta_1)^2 + T \tau_2 \sum_{i=1}^n (x_{i2} - u)^2 + \tau_0 \theta_1^2 + \tau_0 u^2 \right) \right) \\
& = \exp \left(-\frac{1}{2} \left(T \tau_1 \sum_{i=1}^n (x_{i1} - \bar{x}_1)^2 + T \tau_1 n (\bar{x}_1 - \theta_1)^2 \right. \right. \\
& \left. \left. + T \tau_2 \sum_{i=1}^n (x_{i2} - \bar{x}_2)^2 + T \tau_2 n (\bar{x}_2 - u)^2 + \tau_0 \theta_1^2 + \tau_0 u^2 \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \left(T \tau_1 n (\bar{x}_1 - \theta_1)^2 + T \tau_2 n (\bar{x}_2 - u)^2 + \tau_0 \theta_1^2 + \tau_0 u^2 \right) \right) \\
& = \exp \left(-\frac{1}{2} \left(T \tau_1 n \bar{x}_1^2 - 2T \tau_1 n \bar{x}_1 \theta_1 + n T \tau_1 \theta_1^2 + \tau_0 \theta_1^2 \right. \right. \\
& \left. \left. + T \tau_2 n \bar{x}_2^2 - 2T \tau_2 n \bar{x}_2 u + n T \tau_2 u^2 + \tau_0 u^2 \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \left((T n \tau_1 + \tau_0) \theta_1^2 - 2T \tau_1 n \bar{x}_1 \theta_1 + (T n \tau_2 + \tau_0) u^2 - 2T \tau_2 n \bar{x}_2 u \right) \right) \\
& = \exp \left(-\frac{1}{2} \left((T n \tau_1 + \tau_0) \left(\theta_1^2 - \frac{2T \tau_1 n \bar{x}_1 \theta_1}{T n \tau_1 + \tau_0} \right) + (T n \tau_2 + \tau_0) \left(u^2 - \frac{2T \tau_2 n \bar{x}_2 u}{T n \tau_2 + \tau_0} \right) \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \left((T n \tau_1 + \tau_0) \left(\theta_1 - \frac{T \tau_1 n \bar{x}_1}{T n \tau_1 + \tau_0} \right)^2 + (T n \tau_2 + \tau_0) \left(u - \frac{T \tau_2 n \bar{x}_2}{T n \tau_2 + \tau_0} \right)^2 \right) \right)
\end{aligned}$$

and

$$\begin{aligned}
& \prod_{i=3}^d p(X_i | \theta_i)^T \cdot \exp \left(-\frac{1}{2} \sum_{i=3}^d \tau_0 \theta_i^2 \right) \\
& \propto \exp \left(-\frac{1}{2} T \sum_{j=3}^d \tau_j \sum_{i=1}^n (x_{ij} - \theta_j)^2 - \frac{1}{2} \sum_{j=3}^d \tau_0 \theta_j^2 \right) \\
& = \exp \left(-\frac{1}{2} \sum_{j=3}^d \left(T \tau_j \sum_{i=1}^n (x_{ij} - \theta_j)^2 + \tau_0 \theta_j^2 \right) \right) \\
& = \exp \left(-\frac{1}{2} \sum_{j=3}^d \left(T \tau_j \sum_{i=1}^n (x_{ij} - \bar{x}_j)^2 + T \tau_j n (\bar{x}_j - \theta_j)^2 + \tau_0 \theta_j^2 \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \sum_{j=3}^d \left(T \tau_j n (\bar{x}_j - \theta_j)^2 + \tau_0 \theta_j^2 \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \sum_{j=3}^d \left(-2T \tau_j n \bar{x}_j \theta_j + T \tau_j n \theta_j^2 + \tau_0 \theta_j^2 \right) \right) \\
& \propto \exp \left(-\frac{1}{2} \sum_{j=3}^d \left((T n \tau_j + \tau_0) \theta_j^2 - 2T n \tau_j \bar{x}_j \theta_j + \frac{(T n \tau_j \bar{x}_j)^2}{T n \tau_j + \tau_0} \right) \right) \\
& = \exp \left(-\frac{1}{2} \sum_{j=3}^d (T n \tau_j + \tau_0) \left(\theta_j - \frac{T n \tau_j \bar{x}_j}{T n \tau_j + \tau_0} \right)^2 \right)
\end{aligned}$$

Multiplying the resulting expression above gives a density proportional to the banana distribution. As $p(\theta | X)$ is proportional to the density of a banana distribution, the posterior is the banana distribution $\text{Ban}(\mu, \Sigma, a, b, m)$ with

$$\begin{aligned}
\mu &= \left(\frac{T n \tau_1 \bar{x}_1}{T n \tau_1 + \tau_0}, \dots, \frac{T n \tau_d \bar{x}_d}{T n \tau_d + \tau_0} \right), \\
\Sigma &= \text{diag} \left(\frac{1}{T n \tau_1 + \tau_0}, \dots, \frac{1}{T n \tau_d + \tau_0} \right). \quad \square
\end{aligned}$$

Appendix B. Differentiability of the clip-function

This appendix proves that functions of the form $\text{clip} \circ f$ are almost everywhere differentiable for sufficiently well-behaved f , as required by the proof of volume preservation of DP HMC leapfrog iterations (Section 4.2). Lemma 4 gives very general sufficient conditions, and Lemma 5 proves that the models considered in this thesis meet the conditions.

Lemma 3. *Let $d \geq 2$ and $g: U \rightarrow \mathbb{R}$, where U is an open subset of \mathbb{R}^d , be continuously differentiable. Let $S = \{x \in U \mid f(x) = b\}$, $b \in \mathbb{R}$. If for all $x \in S$, $\nabla f(x) \neq 0$, S is a $(d - 1)$ -dimensional hypersurface.*

Proof. See [Tu11, Section 9.2]. □

Lemma 4. *Let $f: \mathbb{R}^d \rightarrow \mathbb{R}^d$ be continuously differentiable. If the set of saddle points U of $\|f\|$ is a null set, the set $A \subset \mathbb{R}^d$ where $\text{clip}_b \circ f$ is not differentiable is a null set.*

Proof.

$$\text{clip}_b(x) = \frac{x}{\|x\|} \min\{\|x\|, b\}$$

which means that clip_b is differentiable for all $x \in \mathbb{R}^d$ with $\|x\| \neq b$. Consider $\text{clip}_b \circ f$ in a neighbourhood B of point $x_0 \in \mathbb{R}^d$. If $\|f(x)\| \leq b$ for all $x \in B$, $\text{clip}_b(f(x)) = f(x)$ in B , which is differentiable. If $\|f(x)\| \geq b$ for all $x \in B$, $\text{clip}_b(f(x)) = \frac{f(x)b}{\|f(x)\|}$ in B , which is also differentiable because $f(x) \neq 0$ when $\|f(x)\| \geq b > 0$. In both cases $\text{clip}_b \circ f$ is differentiable at x_0 . This means that for all $x_0 \in A$, $\|f(x_0)\| = b$, but every neighborhood of x_0 has points x' and x'' such that $\|f(x')\| < b$ and $\|f(x'')\| > b$. With the differentiability of f , this means that if $\nabla\|f(x_0)\| = 0$, x_0 is a saddle point of $\|f\|$.

Let $S = \{x \in \mathbb{R}^d \mid \|f(x)\| = b \text{ and } \nabla\|f(x)\| \neq 0\}$. By Lemma 3, S is a $(d - 1)$ -dimensional hypersurface, which has zero measure in d -dimensional space. Because $A \cap U^C \subset S$, $A \cap U^C$ is also a null set. Since $A = (A \cap U^C) \cup (A \cap U)$, A is a null set. □

Lemma 5. *The log-likelihoods of the Gaussian, banana and circle models meet the conditions of Lemma 4.*

Proof. For DP HMC, set $f(\theta) = \nabla \ln p(x \mid \theta)$ for some datapoint x . Denote $l(\theta) = \ln p(x \mid \theta)$. The conditions of Lemma 4 for l are met if l is twice continuously differentiable and

$$\nabla\|\nabla l(\theta)\| = \frac{2\nabla l(\theta)}{\|\nabla l(\theta)\|} J_{\nabla l}(\theta) = \frac{2\nabla l(\theta)}{\|\nabla l(\theta)\|} H_l(\theta) \neq 0$$

almost everywhere, where H_l is the Hessian matrix of l . Because $\nabla l = 0$ and $\|\nabla l\| = 0$ at only one point, having $\det H_l(x) \neq 0$ almost everywhere is sufficient.

For the Gaussian log-likelihood

$$l(\theta) = \frac{1}{2}(x - \theta)^T \Sigma^{-1}(x - \theta),$$

so

$$\nabla l(\theta) = \Sigma^{-1}(x - \theta)$$

and $H_l(\theta) = \Sigma^{-1}$.

For the banana log-likelihood, using the notation from Appendix A,

$$l(\theta) = \frac{1}{2}(g^{-1}(x) - \theta)^T \Sigma^{-1}(g^{-1}(x) - \theta),$$

so

$$\nabla l(\theta) = \Sigma^{-1}(g^{-1}(x) - \theta)$$

and $H_l(\theta) = \Sigma^{-1}$.

The circle log-likelihood is

$$l(x, y) = -a(x^2 + y^2 - r^2)^2,$$

$$\nabla l(x, y) = -4a(x^3 + xy^2 - xr^2, x^2y + y^3 - yr^2),$$

so

$$H_l(x, y) = -4a \begin{bmatrix} 3x^2 + y^2 - r^2 & 2xy \\ 2xy & 3y^2 + x^2 - r^2 \end{bmatrix}$$

and

$$\begin{aligned} \det H_l(x, y) &= -4a((3x^2 + y^2 - r^2)(3y^2 + x^2 - r^2) - 4x^2y^2) \\ &= -4a(9x^2y^2 + 3x^4 - 3x^2r^2 + 3y^4 + y^2x^2 - y^2r^2 - 3y^2r^2 - x^2r^2 + r^4 - 4x^2y^2) \\ &= -4a(6x^2y^2 + 3x^4 - 4x^2r^2 + 3y^4 - 4y^2r^2 + r^4) \\ &= -4a(6x^2y^2 + 3(x^4 + y^4) - 4r^2(x^2 + y^2) + r^4). \end{aligned}$$

$$\nabla \det H_l(x, y) = -4a(12xy^2 + 12x^3 - 8r^2x, 12yx^2 + 12y^3 - 8r^2y),$$

which is zero in the origin and on the circle

$$x^2 + y^2 = \frac{2}{3}r^2.$$

Elsewhere, Lemma 3 can be applied to $\det H_l$, which means that the set where $\det H_l(x, y) = 0$ is a 1-dimensional curve. \square