Probabilistic Inference and Learning with Stein's Method

Lester Mackey

Microsoft Research New England

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Collaborators: Jackson Gorham, Andrew Duncan, Sebastian Vollmer, Jonathan Huggins, Wilson Chen, Alessandro Barp, Francois-Xavier Briol, Mark Girolami, Chris Oates, Murat Erdogdu, Ohad Shamir, Marina Riabiz, Jon Cockayne, Pawel Swietach, Steven Niederer, Anant Raj, Jiaxin Shi, and Chang Liu

Motivation: Large-scale Posterior Inference

Example: Bayesian logistic regression

1. Fixed feature vectors: $v_l \in \mathbb{R}^d$ for each datapoint $l = 1, \ldots, L$
2. Binary class labels: $Y_l \in \{0, 1\}$, $\mathbb{P}(Y_l = 1 \mid v_l, \beta) = \frac{1}{1+e^{-\langle \beta, v_l \rangle}}$
3. Unknown parameter vector: $\beta \sim \mathcal{N}(0, I)$

- Generative model simple to express
- Posterior distribution over unknown parameters is complex
  - Normalization constant unknown, exact integration intractable

Standard inferential approach: Use Markov chain Monte Carlo (MCMC) to (eventually) draw samples from the posterior distribution

- **Benefit:** Approximates intractable posterior expectations $\mathbb{E}_P[h(Z)] = \int_{\mathcal{X}} p(x)h(x)dx$ with asymptotically exact sample estimates $\mathbb{E}_Q[h(X)] = \frac{1}{n}\sum_{i=1}^n h(x_i)$
- **Problem:** Each new MCMC sample point x_i requires iterating over entire observed dataset: prohibitive when dataset is large!

Motivation: Large-scale Posterior Inference

Question: How do we scale Markov chain Monte Carlo (MCMC) posterior inference to massive datasets?

- **MCMC Benefit:** Approximates intractable posterior expectations $\mathbb{E}_P[h(Z)] = \int_{\mathcal{X}} p(x)h(x)dx$ with asymptotically exact sample estimates $\mathbb{E}_Q[h(X)] = \frac{1}{n}\sum_{i=1}^{n} h(x_i)$
- **Problem:** Each point x_i requires iterating over entire dataset!

Template solution: Approximate MCMC with subset posteriors

[Welling and Teh, 2011, Ahn, Korattikara, and Welling, 2012, Korattikara, Chen, and Welling, 2014]

- Approximate standard MCMC procedure in a manner that makes use of only a small subset of datapoints per sample
- Reduced computational overhead leads to faster sampling and reduced Monte Carlo variance
- Introduces asymptotic bias: target distribution is not stationary
- Hope that for fixed amount of sampling time, variance reduction will outweigh bias introduced

Motivation: Large-scale Posterior Inference

Template solution: Approximate MCMC with subset posteriors

[Welling and Teh, 2011, Ahn, Korattikara, and Welling, 2012, Korattikara, Chen, and Welling, 2014]

- Hope that for fixed amount of sampling time, variance reduction will outweigh bias introduced

Introduces new challenges

- How do we compare and evaluate samples from approximate MCMC procedures?
- How do we select samplers and their tuning parameters?
- How do we quantify the bias-variance trade-off explicitly?

Difficulty: Standard evaluation criteria like effective sample size, trace plots, and variance diagnostics assume convergence to the target distribution and do not account for asymptotic bias

This talk: Introduce new quality measures suitable for comparing the quality of approximate MCMC samples

Quality Measures for Samples

Challenge: Develop measure suitable for comparing the quality of *any* two samples approximating a common target distribution

Given

- **Continuous target distribution** P with support $\mathcal{X} = \mathbb{R}^d$ and density p
  - p known up to normalization, integration under P is intractable
- **Sample points** $x_1, \ldots, x_n \in \mathcal{X}$
  - Define **discrete distribution** Q_n with, for any function h, $\mathbb{E}_{Q_n}[h(X)] = \frac{1}{n}\sum_{i=1}^n h(x_i)$ used to approximate $\mathbb{E}_P[h(Z)]$
  - We make no assumption about the provenance of the x_i

Goal: Quantify how well $\mathbb{E}_{Q_n}$ approximates $\mathbb{E}_P$ in a manner that

I. Detects when a sample sequence is converging to the target

II. Detects when a sample sequence is not converging to the target

III. Is computationally feasible

Integral Probability Metrics

Goal: Quantify how well $\mathbb{E}_{Q_n}$ approximates $\mathbb{E}_P$

Idea: Consider an **integral probability metric (IPM)** [Müller, 1997]

$$d_{\mathcal{H}}(Q_n, P) = \sup_{h \in \mathcal{H}} |\mathbb{E}_{Q_n}[h(X)] - \mathbb{E}_P[h(Z)]|$$

- Measures maximum discrepancy between sample and target expectations over a class of real-valued test functions $\mathcal{H}$
- When $\mathcal{H}$ sufficiently large, convergence of $d_{\mathcal{H}}(Q_n, P)$ to zero implies $(Q_n)_{n \geq 1}$ converges weakly to P (Requirement II)

Problem: Integration under P intractable!

$\Rightarrow$ Most IPMs cannot be computed in practice

Idea: Only consider functions with $\mathbb{E}_P[h(Z)]$ known *a priori* to be 0

- Then IPM computation only depends on Q_n!
- How do we select this class of test functions?
- Will the resulting discrepancy measure track sample sequence convergence (Requirements I and II)?
- How do we solve the resulting optimization problem in practice?

Stein's Method

Stein's method [1972] provides a recipe for controlling convergence:

1. **Identify operator $\mathcal{T}$ and set $\mathcal{G}$** of functions $g : \mathcal{X} \to \mathbb{R}^d$ with
$$\mathbb{E}_P[(\mathcal{T}g)(Z)] = 0 \quad \text{for all} \quad g \in \mathcal{G}.$$
$\mathcal{T}$ and $\mathcal{G}$ together define the **Stein discrepancy** [Gorham and Mackey, 2015]
$$\boldsymbol{\mathcal{S}(Q_n, \mathcal{T}, \mathcal{G})} \triangleq \sup_{g \in \mathcal{G}} |\mathbb{E}_{Q_n}[(\mathcal{T}g)(X)]| = d_{\mathcal{T}\mathcal{G}}(Q_n, P),$$
an IPM-type measure with no explicit integration under P

2. **Lower bound $\mathcal{S}(Q_n, \mathcal{T}, \mathcal{G})$ by reference IPM $d_{\mathcal{H}}(Q_n, P)$**
$\Rightarrow (Q_n)_{n \geq 1}$ converges to P whenever $\mathcal{S}(Q_n, \mathcal{T}, \mathcal{G}) \to 0$ (Req. II)
   - Performed once, in advance, for large classes of distributions

3. **Upper bound $\mathcal{S}(Q_n, \mathcal{T}, \mathcal{G})$ by any means necessary** to demonstrate convergence to 0 (Requirement I)

Standard use: As analytical tool to prove convergence
Our goal: Develop Stein discrepancy into practical quality measure

Identifying a Stein Operator $\mathcal{T}$

Goal: Identify operator $\mathcal{T}$ for which $\mathbb{E}_P[(\mathcal{T}g)(Z)] = 0$ for all $g \in \mathcal{G}$

Approach: **Generator method** of Barbour [1988, 1990], Götze [1991]

- Identify a Markov process $(Z_t)_{t\geq 0}$ with stationary distribution P
- Under mild conditions, its **infinitesimal generator**

$$(\mathcal{A}u)(x) = \lim_{t\to 0} (\mathbb{E}[u(Z_t) \mid Z_0 = x] - u(x))/t$$

satisfies $\mathbb{E}_P[(\mathcal{A}u)(Z)] = 0$

Overdamped Langevin diffusion: $dZ_t = \frac{1}{2}\nabla \log p(Z_t)dt + dW_t$

- Generator: $(\mathcal{A}_P u)(x) = \frac{1}{2}\langle \nabla u(x), \nabla \log p(x)\rangle + \frac{1}{2}\langle \nabla, \nabla u(x)\rangle$
- **Stein operator:** $(\mathcal{T}_P g)(x) \triangleq \langle g(x), \nabla \log p(x)\rangle + \langle \nabla, g(x)\rangle$

  [Gorham and Mackey, 2015, Oates, Girolami, and Chopin, 2016]

  - Depends on P only through $\nabla \log p$; computable even if p cannot be normalized!
  - $\mathbb{E}_P[(\mathcal{T}_P g)(Z)] = 0$ for all $g : \mathcal{X} \to \mathbb{R}^d$ in **classical Stein set**

$$\mathcal{G}_{\|\cdot\|} = \left\{g : \sup_{x\neq y} \max\left(\|g(x)\|^*, \|\nabla g(x)\|^*, \frac{\|\nabla g(x)-\nabla g(y)\|^*}{\|x-y\|}\right) \leq 1\right\}$$

Detecting Convergence and Non-convergence

Goal: Show **classical Stein discrepancy** $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|}) \to 0$ if and only if $(Q_n)_{n\geq 1}$ converges to P

- In the univariate case ($d = 1$), known that for many targets P, $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|}) \to 0$ only if Wasserstein $d_{\mathcal{W}_{\|\cdot\|}}(Q_n, P) \to 0$
  [Stein, Diaconis, Holmes, and Reinert, 2004, Chatterjee and Shao, 2011, Chen, Goldstein, and Shao, 2011]
- Few multivariate targets have been analyzed (see [Reinert and Röllin, 2009, Chatterjee and Meckes, 2008, Meckes, 2009] for multivariate Gaussian)

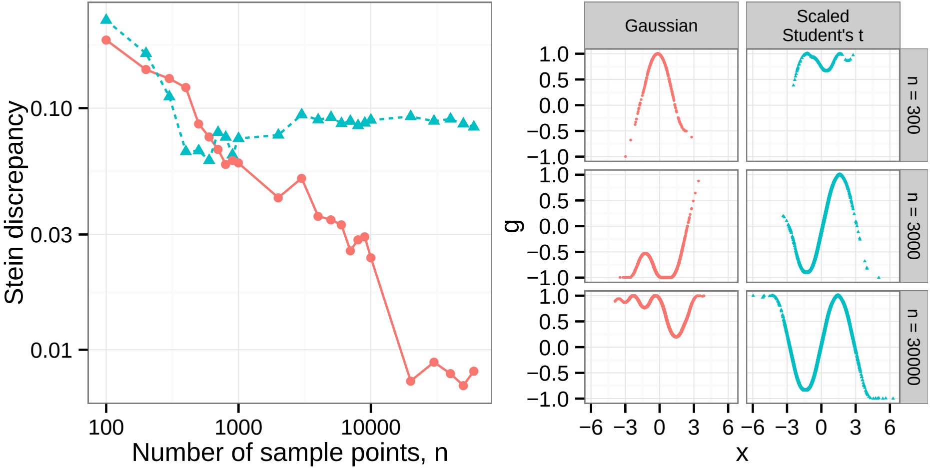
New contribution [Gorham, Duncan, Vollmer, and Mackey, 2019]

Theorem (Stein Discrepancy-Wasserstein Equivalence)

If the Langevin diffusion couples at an integrable rate and $\nabla \log p$ is Lipschitz, then $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|}) \to 0 \Leftrightarrow d_{\mathcal{W}_{\|\cdot\|}}(Q_n, P) \to 0$.

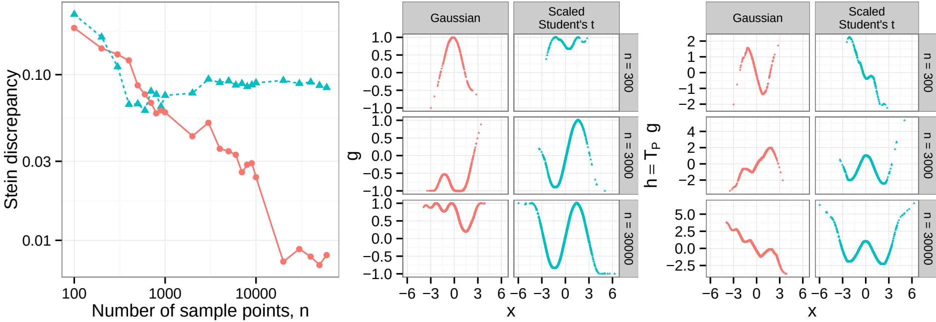
- Examples: strongly log concave P, Bayesian logistic regression or robust t regression with Gaussian priors, Gaussian mixtures
- Conditions not necessary: template for bounding $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|})$

A Simple Example



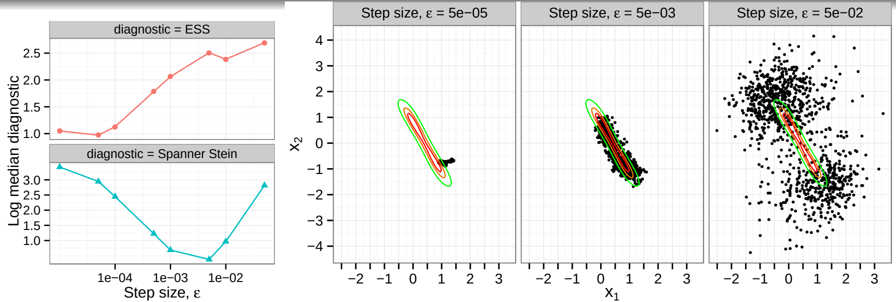
- For target $P = \mathcal{N}(0,1)$, compare i.i.d. $\mathcal{N}(0,1)$ sample sequence $Q_{1:n}$ to scaled Student's t sequence $Q'_{1:n}$ with matching variance
- Expect $\mathcal{S}(Q_{1:n}, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|,Q,G_1}) \to 0$ & $\mathcal{S}(Q'_{1:n}, \mathcal{T}_P, \mathcal{G}_{\|\cdot\|,Q,G_1}) \not\to 0$

A Simple Example



- **Middle:** Recovered optimal functions g
- **Right:** Associated test functions $h(x) \triangleq (\mathcal{T}_P g)(x)$ which best discriminate sample Q from target P

Selecting Sampler Hyperparameters



Target posterior density: $p(x) \propto \pi(x) \prod_{l=1}^{L} \pi(y_l \mid x)$

Stochastic Gradient Langevin Dynamics [Welling and Teh, 2011]

$$x_{k+1} \sim \mathcal{N}(x_k + \frac{\epsilon}{2}(\nabla \log \pi(x_k) + \frac{L}{|\mathcal{B}_k|} \sum_{l \in \mathcal{B}_k} \nabla \log \pi(y_l|x_k)), \epsilon I)$$

- Random batch $\mathcal{B}_k$ of datapoints used to draw each sample point
  - Step size ϵ too small $\Rightarrow$ slow mixing
  - Step size ϵ too large $\Rightarrow$ sampling from very different distribution
  - Standard MCMC selection criteria like **effective sample size** (ESS) and asymptotic variance do not account for this bias

ESS maximized at $\epsilon = 5 \times 10^{-2}$, Stein minimized at $\epsilon = 5 \times 10^{-3}$

Alternative Stein Sets $\mathcal{G}$

Goal: Identify a more "user-friendly" Stein set $\mathcal{G}$ than the classical

Approach: **Reproducing kernels** $k : \mathcal{X} \times \mathcal{X} \to \mathbb{R}$ [Oates, Girolami, and Chopin, 2016, Chwialkowski, Strathmann, and Gretton, 2016, Liu, Lee, and Jordan, 2016]

- A reproducing kernel k is symmetric ($k(x,y) = k(y,x)$) and positive semidefinite ($\sum_{i,l} c_i c_l k(z_i, z_l) \geq 0, \forall z_i \in \mathcal{X}, c_i \in \mathbb{R}$)
  - Gaussian: $k(x,y) = e^{-\frac{1}{2}\|x-y\|_2^2}$, IMQ: $k(x,y) = \frac{1}{(1+\|x-y\|_2^2)^{1/2}}$
- Generates a reproducing kernel Hilbert space (RKHS) $\mathcal{K}_k$
- Define the **kernel Stein set** [Gorham and Mackey, 2017]

$$\mathcal{G}_k \triangleq \{g = (g_1, \ldots, g_d) \mid \|v\|^* \leq 1 \text{ for } v_j \triangleq \|g_j\|_{\mathcal{K}_k}\}$$

- Yields closed-form **kernel Stein discrepancy (KSD)**

$$\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) = \|w\| \text{ for } w_j \triangleq \sqrt{\textstyle\sum_{i,i'=1}^{n} k_0^j(x_i, x_{i'})}.$$

  - Reduces to parallelizable pairwise evaluations of **Stein kernels**

$$k_0^j(x,y) \triangleq \frac{1}{p(x)p(y)} \nabla_{x_j} \nabla_{y_j} (p(x) k(x,y) p(y))$$

Detecting Non-convergence

Goal: Show $(Q_n)_{n\geq 1}$ converges to P whenever $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$

Theorem (Univariate KSD detects non-convergence [Gorham and Mackey, 2017])

Suppose $P \in \mathcal{P}$ and $k(x,y) = \Phi(x-y)$ for $\Phi \in C^2$ with a non-vanishing generalized Fourier transform. If $d = 1$, then $(Q_n)_{n\geq 1}$ converges weakly to P whenever $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$.

- $\mathcal{P}$ is the set of targets P with Lipschitz $\nabla \log p$ and distant strong log concavity ($\frac{\langle \nabla \log(p(x)/p(y)), y-x \rangle}{\|x-y\|_2^2} \geq k$ for $\|x-y\|_2 \geq r$)
  - Includes Bayesian logistic and Student's t regression with Gaussian priors, Gaussian mixtures with common covariance, ...
- Justifies use of KSD with popular Gaussian, Matérn, or inverse multiquadric kernels k **in the univariate case**

Detecting Non-convergence

Goal: Show $(Q_n)_{n\geq 1}$ converges to P whenever $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$

- In higher dimensions, KSDs based on common kernels fail to detect non-convergence, even for Gaussian targets P

Theorem (KSD fails with light kernel tails [Gorham and Mackey, 2017])

Suppose $d \geq 3$, $P = \mathcal{N}(0, I_d)$, and $\alpha \triangleq (\frac{1}{2} - \frac{1}{d})^{-1}$. If $k(x, y)$ and its derivatives decay at a $o(\|x - y\|_2^{-\alpha})$ rate as $\|x - y\|_2 \to \infty$, then $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$ for some $(Q_n)_{n\geq 1}$ not converging to P.

- Gaussian ($k(x, y) = e^{-\frac{1}{2}\|x-y\|_2^2}$) and Matérn kernels fail for $d \geq 3$
- Inverse multiquadric kernels ($k(x, y) = (1 + \|x - y\|_2^2)^{\beta}$) with $\beta < -1$ fail for $d > \frac{2\beta}{1+\beta}$
- The violating sample sequences $(Q_n)_{n\geq 1}$ are simple to construct

Problem: Kernels with light tails ignore excess mass in the tails

Detecting Non-convergence

Goal: Show $(Q_n)_{n\geq 1}$ converges to P whenever $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$

- Consider the inverse multiquadric (IMQ) kernel

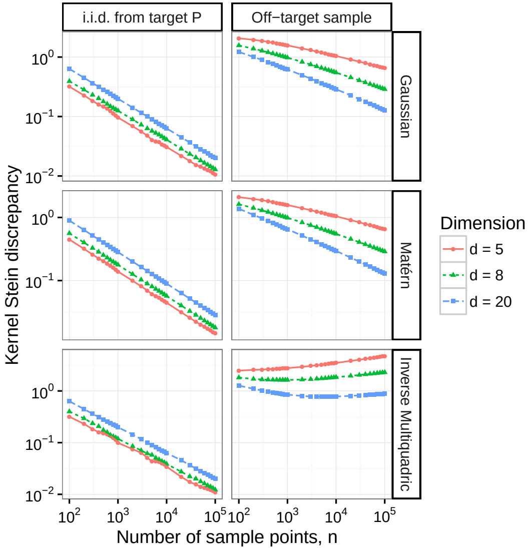
$$k(x,y) = (c^2 + \|x-y\|_2^2)^\beta \text{ for some } \beta < 0, c \in \mathbb{R}.$$

- IMQ KSD fails to detect non-convergence when $\beta < -1$
- However, IMQ KSD detects non-convergence when $\beta \in (-1, 0)$

Theorem (IMQ KSD detects non-convergence [Gorham and Mackey, 2017])

Suppose $P \in \mathcal{P}$ and $k(x,y) = (c^2 + \|x-y\|_2^2)^\beta$ for $\beta \in (-1,0)$. If $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$, then $(Q_n)_{n\geq 1}$ converges weakly to P.

The Importance of Kernel Choice



- Target $P = \mathcal{N}(0, I_d)$
- Off-target Q_n has all $\|x_i\|_2 \leq 2n^{1/d} \log n$, $\|x_i - x_j\|_2 \geq 2 \log n$
- Gaussian and Matérn KSDs driven to 0 by an off-target sequence that does not converge to P
- IMQ KSD $(\beta = -\frac{1}{2}, c = 1)$ does not have this deficiency

Detecting Convergence

Goal: Show $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$ whenever $(Q_n)_{n\geq 1}$ converges to P

Proposition (KSD detects convergence [Gorham and Mackey, 2017])

If $k \in C_b^{(2,2)}$ and $\nabla \log p$ Lipschitz and square integrable under P, then $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$ whenever the Wasserstein distance $d_{\mathcal{W}_{\|\cdot\|_2}}(Q_n, P) \to 0$.

- Covers Gaussian, Matérn, IMQ, and other common bounded kernels k

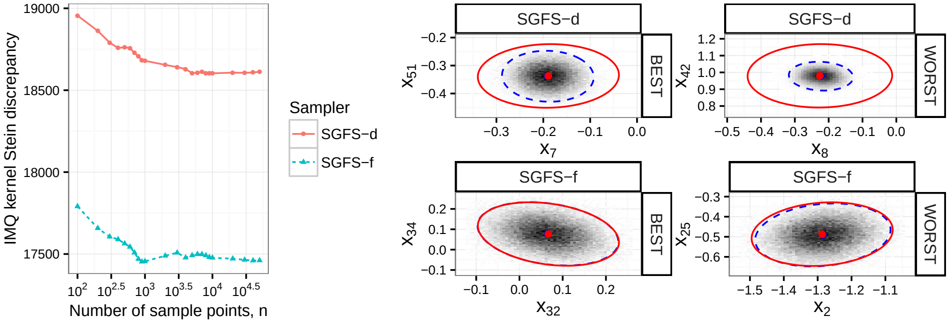
Selecting Samplers

Stochastic Gradient Fisher Scoring (SGFS)

[Ahn, Korattikara, and Welling, 2012]

- Approximate MCMC procedure designed for scalability
  - Approximates Metropolis-adjusted Langevin algorithm but does not use Metropolis-Hastings correction
  - Target P is not stationary distribution
- **Goal:** Choose between two variants
  - SGFS-f inverts a $d \times d$ matrix for each new sample point
  - SGFS-d inverts a diagonal matrix to reduce sampling time
- **MNIST handwritten digits** [Ahn, Korattikara, and Welling, 2012]
  - 10000 images, 51 features, binary label indicating whether image of a 7 or a 9
- Bayesian logistic regression posterior P

Selecting Samplers



- **Left:** IMQ KSD quality comparison for SGFS Bayesian logistic regression (no surrogate ground truth used)
- **Right:** SGFS sample points ($n = 5 \times 10^4$) with bivariate marginal means and 95% confidence ellipses (blue) that align best and worst with surrogate ground truth sample (red)
- Both suggest small speed-up of SGFS-d ($0.0017s$ per sample vs. $0.0019s$ for SGFS-f) outweighed by loss in inferential accuracy

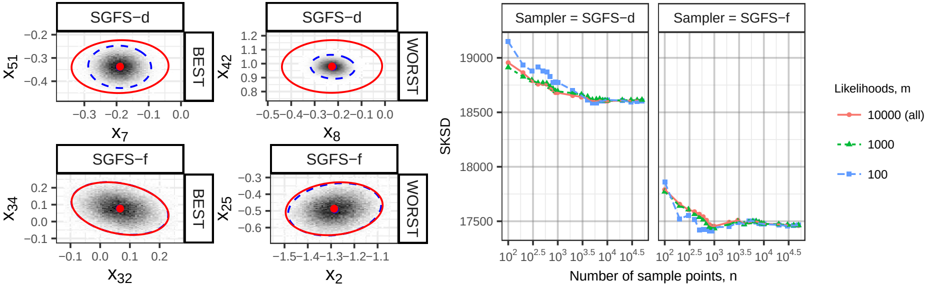
Stochastic Stein Discrepancies

Issue: What if $\nabla \log p$ is too expensive to evaluate?

- Posterior $\nabla \log p(x) = \nabla \log \pi(x) + \sum_{l=1}^{L} \nabla \log \pi(y_l \mid x)$

Solution: Stochastic Stein Discrepancies [Gorham, Raj, and Mackey, 2020]

- Replace each $\nabla \log p(x_i)$ with stochastic gradient based on random datapoint batch: $\nabla \log \pi(x_i) + \frac{L}{|\mathcal{B}_i|} \sum_{l \in \mathcal{B}_i} \nabla \log \pi(y_l|x_i)$
- Resulting stochastic Stein discrepancies inherit convergence control of standard SDs with probability 1 [Gorham, Raj, and Mackey, 2020]



Goodness-of-fit testing

- Chwialkowski, Strathmann, and Gretton [2016] used the KSD $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k)$ to test whether a sample was drawn from a target distribution P (see also Liu, Lee, and Jordan [2016])
- Test with default Gaussian kernel k experienced considerable loss of power as the dimension d increased
- We recreate their experiment with IMQ kernel $(\beta = -\frac{1}{2}, c = 1)$
  - For $n = 500$, generate sample $(x_i)_{i=1}^n$ with $x_i = z_i + u_i e_1$ $z_i \overset{\text{iid}}{\sim} \mathcal{N}(0, I_d)$ and $u_i \overset{\text{iid}}{\sim}$ Unif$[0, 1]$. Target $P = \mathcal{N}(0, I_d)$.
  - Compare with standard normality test of Baringhaus and Henze [1988]

Table: Mean power of multivariate normality tests across 400 simulations

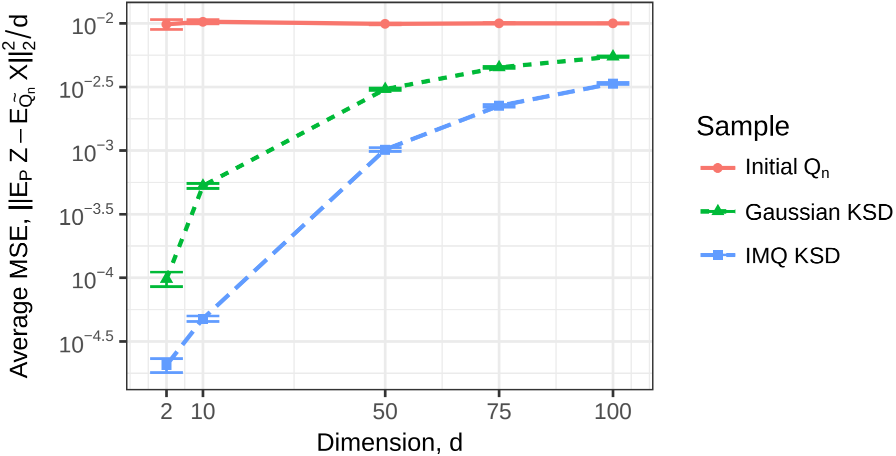
	d=2	d=5	d=10	d=15	d=20	d=25
B&H	1.0	1.0	1.0	0.91	0.57	0.26
Gaussian	1.0	1.0	0.88	0.29	0.12	0.02
IMQ	1.0	1.0	1.0	1.0	1.0	1.0

Beyond Sample Quality Comparison

Improving sample quality

- Given sample points $(x_i)_{i=1}^n$, can minimize KSD $\mathcal{S}(\tilde{Q}_n, \mathcal{T}_P, \mathcal{G}_k)$ over all weighted samples $\tilde{Q}_n = \sum_{i=1}^n q_n(x_i)\delta_{x_i}$ for q_n a probability mass function
- Liu and Lee [2016] do this with Gaussian kernel $k(x,y) = e^{-\frac{1}{h}\|x-y\|_2^2}$
  - Bandwidth h set to median of the squared Euclidean distance between pairs of sample points
- We recreate their experiment with the IMQ kernel $k(x,y) = (1 + \frac{1}{h}\|x-y\|_2^2)^{-1/2}$

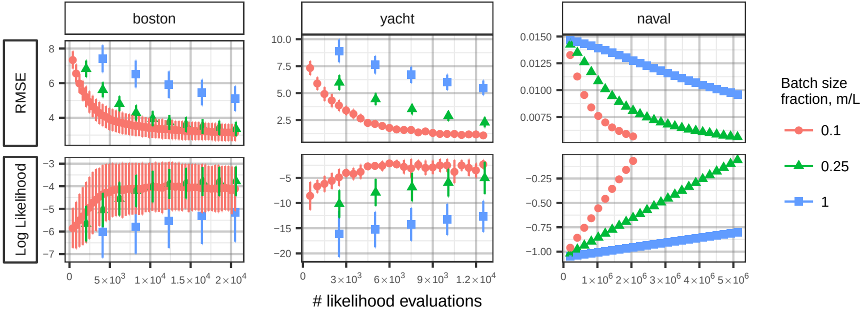
Improving Sample Quality



- MSE averaged over 500 simulations (± 2 standard errors)
- Target $P = \mathcal{N}(0, I_d)$
- Starting sample $Q_n = \frac{1}{n}\sum_{i=1}^n \delta_{x_i}$ for $x_i \overset{\text{iid}}{\sim} P$, $n = 100$.

Stein Variational Gradient Descent (SVGD) [Liu and Wang, 2016]

- Uses KSD to repeatedly update locations of n sample points:
  $x_i \leftarrow x_i + \frac{\epsilon}{n}\sum_{l=1}^{n}(k(x_l, x_i)\nabla \log p(x_l) + \nabla_{x_l} k(x_l, x_i))$
  - Approximates gradient step in KL divergence
  - Asymptotic convergence guarantees [Liu, 2017, Gorham, Raj, and Mackey, 2020]
  - Simple to implement (but each update costs n^2 time)
- **Stochastic SVGD:** uses stochastic KSD $\Rightarrow$ same guarantees with many fewer likelihood evaluations [Gorham, Raj, and Mackey, 2020]



Stein Points [Chen, Mackey, Gorham, Briol, and Oates, 2018]

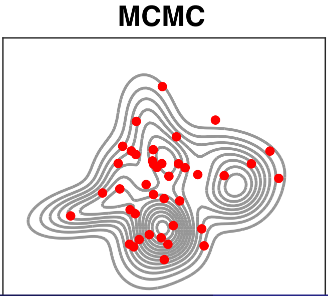
- Greedily minimizes KSD by constructing $Q_n = \frac{1}{n}\sum_{i=1}^{n} \delta_{x_i}$ with

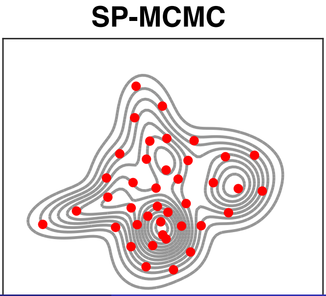
$$x_n \in \operatorname{argmin}_x \mathcal{S}(\tfrac{n-1}{n} Q_{n-1} + \tfrac{1}{n}\delta_x, \mathcal{T}_P, \mathcal{G}_k)$$
$$= \operatorname{argmin}_x \sum_{j=1}^{d} \frac{k_0^j(x,x)}{2} + \sum_{i=1}^{n-1} k_0^j(x_i, x)$$

  - Sends KSD to zero at $O(\sqrt{\log(n)/n})$ rate

Stein Point MCMC [Chen, Barp, Briol, Gorham, Girolami, Mackey, and Oates, 2019]

- Suffices to optimize over iterates of a Markov chain





Future Directions

Many opportunities for future development

1. Improving scalability while maintaining convergence control
   - Subsampling of likelihood terms in $\nabla \log p$ [Gorham, Raj, and Mackey, 2020]
   - Inexpensive approximations of kernel matrix
     - Finite set Stein discrepancies [Jitkrittum, Xu, Szabó, Fukumizu, and Gretton, 2017]: low-rank kernel, linear runtime (but convergence control unclear)
     - Random feature Stein discrepancies [Huggins and Mackey, 2018]: stochastic low-rank kernel, near-linear runtime + high probability convergence control when $(Q_n)_{n\geq 1}$ moments uniformly bounded
2. Exploring the impact of Stein operator choice
   - An infinite number of operators $\mathcal{T}$ characterize P
   - How is discrepancy impacted? How do we select the best $\mathcal{T}$?
   - **Thm:** If $\nabla \log p$ bounded and $k \in C_0^{(1,1)}$, then $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$ for some $(Q_n)_{n\geq 1}$ not converging to P
   - Diffusion Stein operators $(\mathcal{T}g)(x) = \frac{1}{p(x)}\langle \nabla, p(x)a(x)g(x)\rangle$ of Gorham, Duncan, Vollmer, and Mackey [2019] may be appropriate for heavy tails

Future Directions

Many opportunities for future development

3. Addressing other inferential tasks
   - Training generative adversarial networks [Wang and Liu, 2016] and variational autoencoders [Pu, Gan, Henao, Li, Han, and Carin, 2017]

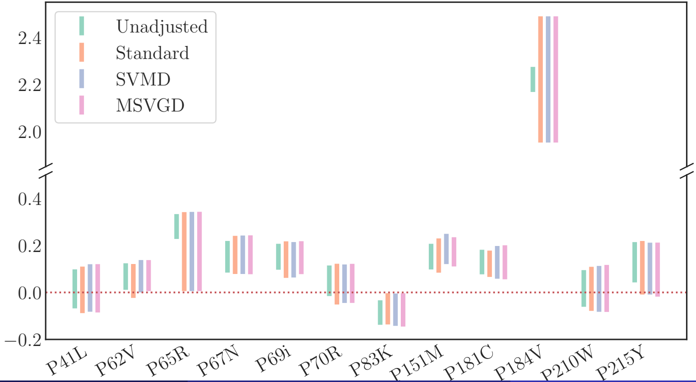
DCGAN

SteinGAN

Future Directions

Many opportunities for future development

3. Addressing other inferential tasks
   - Post-selection inference
     - Constrained targets P arise when testing significance after variable selection [Tian and Taylor, 2018]
     - Stein Variational Mirror Descent and Mirrored SVGD can derive confidence intervals for constrained P [Shi, Liu, and Mackey, 2021]



Future Directions

Many opportunities for future development

3. Addressing other inferential tasks
   - Post-selection inference
     - Stein Variational Mirror Descent and Mirrored SVGD can derive confidence intervals from constrained P [Shi, Liu, and Mackey, 2021]
   - Non-convex optimization [Erdogdu, Mackey, and Shamir, 2018]

Example (Optimization with Discretized Diffusions [Erdogdu, Mackey, and Shamir, 2018])

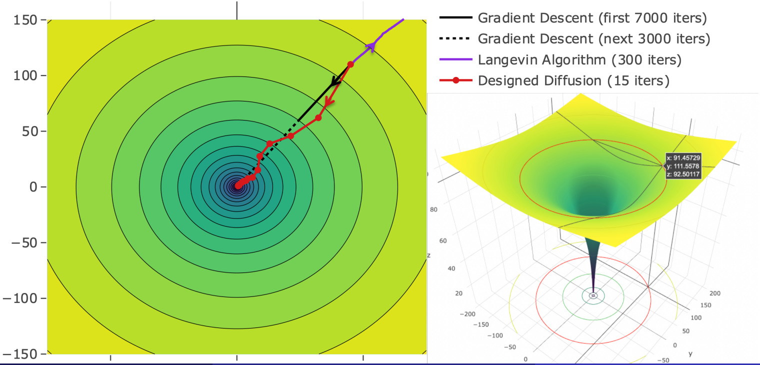
- To minimize $f(x)$, choose $a(x) \succcurlyeq cI$ with $a(x)\nabla f(x)$ Lipschitz and distantly dissipative ($\frac{\langle a(x)\nabla f(x) - a(y)\nabla f(y), x-y\rangle}{\|x-y\|_2^2} \geq k$ for $\|x-y\|_2 \geq r$)
- Approximate target sequence $p_n(x) \propto e^{-\gamma_n f(x)}$ using Markov chain $\boldsymbol{x_{n+1} \sim \mathcal{N}(x_n - \frac{\epsilon_n}{2} a(x_n)\nabla f(x_n) + \frac{\epsilon_n}{2\gamma_n}\langle \nabla, a(x_n)\rangle, \frac{\epsilon_n}{\gamma_n} a(x_n))}$
- **Thm:** $\min_{1\leq i\leq n} \mathbb{E} f(x_i) \to \min_x f(x)$ (with explicit error bounds) for appropriate ϵ_n and γ_n when $\nabla f, \nabla a$, and $a^{1/2}$ are Lipschitz

Future Directions

Many opportunities for future development

3. Addressing other inferential tasks
    - Post-selection inference
        - Stein Variational Mirror Descent and Mirrored SVGD can derive confidence intervals from constrained P [Shi, Liu, and Mackey, 2021]
    - Non-convex optimization [Erdogdu, Mackey, and Shamir, 2018]

$$\min_x f(x) = 5\log(1+\tfrac{1}{2}\|x\|_2^2),\ a(x) = (1+\tfrac{1}{2}\|x\|_2^2)I,\ a(x)\nabla f(x) = 5x$$



Future Directions

Many opportunities for future development

1. Improving scalability while maintaining convergence control
   - Subsampling of likelihood terms in $\nabla \log p$ [Gorham, Raj, and Mackey, 2020]
   - Inexpensive approximations of kernel matrix
     - Finite set Stein discrepancies [Jitkrittum, Xu, Szabó, Fukumizu, and Gretton, 2017]
     - Random feature Stein discrepancies [Huggins and Mackey, 2018]
2. Exploring the impact of Stein operator choice
   - An infinite number of operators $\mathcal{T}$ characterize P
   - How is discrepancy impacted? How do we select the best $\mathcal{T}$?
   - Diffusion Stein operators $(\mathcal{T}g)(x) = \frac{1}{p(x)}\langle \nabla, p(x)m(x)g(x)\rangle$ of Gorham, Duncan, Vollmer, and Mackey [2019] may be appropriate for heavy tails
3. Addressing other inferential tasks
   - Post-selection inference [Shi, Liu, and Mackey, 2021]
   - Non-convex optimization [Erdogdu, Mackey, and Shamir, 2018]
   - Parameter estimation [Barp, Briol, Duncan, Girolami, and Mackey, 2019]
   - MCMC thinning [Riabiz, Chen, Cockayne, Swietach, Niederer, Mackey, and Oates, 2020]
   - Control variates [Assaraf and Caffarel, 1999, Mira, Solgi, and Imparato, 2013, Oates, Girolami, and Chopin, 2016]

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Selecting Sampler Hyperparameters

Setup [Welling and Teh, 2011]

- Consider the posterior distribution P induced by L datapoints y_l drawn i.i.d. from a Gaussian mixture likelihood
$$Y_l | X \overset{\text{iid}}{\sim} \tfrac{1}{2}\mathcal{N}(X_1, 2) + \tfrac{1}{2}\mathcal{N}(X_1 + X_2, 2)$$
under Gaussian priors on the parameters $X \in \mathbb{R}^2$
$$X_1 \sim \mathcal{N}(0, 10) \perp\!\!\!\perp X_2 \sim \mathcal{N}(0, 1)$$
  - Draw $m = 100$ datapoints y_l with parameters $(x_1, x_2) = (0, 1)$
  - Induces posterior with second mode at $(x_1, x_2) = (1, -1)$
- For range of parameters ϵ, run approximate slice sampling for 148000 datapoint likelihood evaluations and store resulting posterior sample Q_n
- Use minimum IMQ KSD ($\beta = -\frac{1}{2}, c = 1$) to select appropriate ϵ
  - Compare with standard MCMC parameter selection criterion, effective sample size (ESS), a measure of Markov chain autocorrelation
  - Compute median of diagnostic over 50 random sequences

Selecting Samplers

Setup

- **MNIST handwritten digits** [Ahn, Korattikara, and Welling, 2012]
  - 10000 images, 51 features, binary label indicating whether image of a 7 or a 9
- Bayesian logistic regression posterior P
  - L independent observations $(y_l, v_l) \in \{1, -1\} \times \mathbb{R}^d$ with

$$\mathbb{P}(Y_l = 1 | v_l, X) = 1/(1 + \exp(-\langle v_l, X \rangle))$$

  - Flat improper prior on the parameters $X \in \mathbb{R}^d$
- Use IMQ KSD ($\beta = -\frac{1}{2}, c = 1$) to compare SGFS-f to SGFS-d drawing 10^5 sample points and discarding first half as burn-in
- For external support, compare bivariate marginal means and 95% confidence ellipses with surrogate ground truth Hamiltonian Monte chain with 10^5 sample points [Ahn, Korattikara, and Welling, 2012]

The Importance of Tightness

Goal: Show $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$ only if Q_n converges to P

- A sequence $(Q_n)_{n\geq 1}$ is **uniformly tight** if for every $\epsilon > 0$, there is a finite number $R(\epsilon)$ such that $\sup_n Q_n(\|X\|_2 > R(\epsilon)) \leq \epsilon$
  - Intuitively, no mass in the sequence escapes to infinity

Theorem (KSD detects tight non-convergence [Gorham and Mackey, 2017])

Suppose that $P \in \mathcal{P}$ and $k(x, y) = \Phi(x - y)$ for $\Phi \in C^2$ with a non-vanishing generalized Fourier transform. If $(Q_n)_{n\geq 1}$ is uniformly tight and $\mathcal{S}(Q_n, \mathcal{T}_P, \mathcal{G}_k) \to 0$, then $(Q_n)_{n\geq 1}$ converges weakly to P.

- Good news, but, ideally, KSD would detect non-tight sequences automatically...