A Non-Asymptotic Analysis for Stein Variational Gradient Descent

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Abstract

We study the Stein Variational Gradient Descent (SVGD) algorithm, which optimises a set of particles to approximate a target probability distribution $\pi \propto e^{-V}$ on $\mathbb{R}^d$. In the population limit, SVGD performs gradient descent in the space of probability distributions on the KL divergence with respect to $\pi$, where the gradient is smoothed through a kernel integral operator. In this paper, we provide a novel finite time analysis for the SVGD algorithm. We provide a descent lemma establishing that the algorithm decreases the objective at each iteration, and rates of convergence. We also provide a convergence result of the finite particle system corresponding to the practical implementation of SVGD to its population version.

1 Introduction

The task of sampling from a target distribution is common in Bayesian inference, where the distribution of interest is the posterior distribution of the parameters. Unfortunately, the posterior distribution is generally difficult to compute due to the presence of an intractable integral. This sampling problem can be formulated from an optimization point of view (Wibisono, 2018). We assume that the target distribution $\pi$ admits a density proportional to $e^{\exp(-V)}$ with respect to Lebesgue measure over $\mathcal{X} = \mathbb{R}^d$, where $V: \mathcal{X} \to \mathbb{R}$ is referred to as the potential function. In this setting, the target distribution $\pi$ is the solution to the optimization problem defined on the set $\mathcal{P}_2(\mathcal{X})$ of probability measures $\mu$ such that $\int \|x\|^2 d\mu(x) < \infty$ by:

$$\min_{\mu \in \mathcal{P}_2(\mathcal{X})} \text{KL}(\mu | \pi),$$

where KL denotes the Kullback-Leibler divergence, and assuming $\pi \in \mathcal{P}_2(\mathcal{X})$. Many existing methods for the sampling task can be related to this optimization problem. Variants of the Langevin Monte Carlo algorithm (Durmus and Moulines, 2016; Dalalyan and Karagulyan, 2019) can be seen as time-discretized schemes of the gradient flow of the relative entropy. These methods generate a Markov chain whose law converges to $\pi$ under mild assumptions, but the rates of convergence
deteriorate quickly in high dimensions \cite{Durmus et al. (2018b)}. Variational inference methods instead restrict the search space of problem (1) to a family of parametric distributions \cite{Zhang et al. (2018); Ranganath et al. (2014)}. These methods are much more tractable in the large scale setting, since they benefit from efficient optimization methods (parallelization, stochastic optimization); however they can only return an approximation of the target distribution.

Recently, the Stein Variational Gradient Descent (SVGD) algorithm \cite{Liu and Wang (2016)} was introduced as a non-parametric alternative to variational inference methods. It uses a set of interacting particles to approximate the target distribution, and applies iteratively to these particles a form of gradient descent of the relative entropy, where the descent direction is restricted to belong to a unit ball in a Reproducing Kernel Hilbert space (RKHS) \cite{Steinwart and Christmann (2008)}. In particular, this algorithm can be seen as a discretization of the gradient flow of the relative entropy on the space of probability distributions, equipped with a distance that depends on the kernel \cite{Liu (2017); Feng et al. (2017); Liu and Zhu (2018); Detommaso et al. (2018)}, learning deep probabilistic models \cite{Wang and Liu (2016); Pu et al. (2017)}, or reinforcement learning \cite{Liu et al. (2017)}. In the limit of infinite particles, the algorithm is known to converge to the target distribution under appropriate growth assumptions on the potential \cite{Lu et al. (2019)}. Nonetheless, its non-asymptotic analysis remains incomplete: in particular, to the best of our knowledge, quantitative rates of convergence have yet to be obtained. The present paper aims at answering this question. Our first contribution is to provide in the infinite-particle regime a descent lemma showing that SVGD decreases at each iteration for a sufficiently small but constant step-size, with an analysis different from \cite{Liu (2017)}. We view this problem as an optimization problem over $\mathcal{P}_2(\mathcal{X})$ equipped with the Wasserstein distance, and use this framework and optimization techniques to obtain our results. Then, by leveraging a kernel version of the log-Sobolev inequality, called the Stein log-Sobolev inequality as proposed by \cite{Duncan et al. (2019)}, we derive rates of convergence in terms of the KL objective.

This paper is organized as follows. Section 2 introduces the background needed on optimal transport, while Section 3 presents the point of view adopted to study SVGD in the infinite number of particles regime and reviews related work. Section 4 studies the continuous time dynamics of SVGD, and presents the Stein log Sobolev inequality that will be used in this paper. Our main result is presented in Section 5 where we provide a descent lemma and rates of convergence for the SVGD algorithm. The complete proofs, toy experiments and an auxiliary convergence result of the finite particle system to its population version are deferred to the appendix.

2 Preliminaries on optimal transport

Let $\mathcal{X} = \mathbb{R}^d$. We denote by $C^l(\mathcal{X})$ the space of $l$ continuously differentiable functions on $\mathcal{X}$. If $\psi : \mathcal{X} \to \mathbb{R}^p$, $p \geq 0$, is differentiable, we denote by $J \psi : \mathcal{X} \to \mathbb{R}^{p \times d}$ the Jacobian matrix of $\psi$. If $p = 1$, the gradient of $\psi$ denoted $\nabla \psi$ is seen as a column vector. Moreover, if $\nabla \psi$ is differentiable, the Jacobian of $\nabla \psi$ is the Hessian of $\psi$ denoted $H_\psi$. If $p = d$, $d\psi(\psi)$ denotes the divergence of $\psi$, i.e., the trace of the Jacobian. The Hilbert-Schmidt norm of a matrix is denoted $\| \cdot \|_{HS}$ and the operator norm denoted $\| \cdot \|_{op}$.

2.1 The Wasserstein space and the continuity equation

In this section, we recall some background from optimal transport. The reader may refer to \cite{Ambrosio et al. (2008)} for more details.

Consider the set $\mathcal{P}_2(\mathcal{X})$ of probability measures $\mu$ on $\mathcal{X}$ with finite second order moment. For any $\mu \in \mathcal{P}_2(\mathcal{X})$, $L^2(\mu)$ is the space of functions $f : \mathcal{X} \to \mathbb{R}$ such that $\int |f|^2 \, d\mu < \infty$. If $\mu \in \mathcal{P}_2(\mathcal{X})$, we denote by $\| \cdot \|_{L^2(\mu)}$ and $(\cdot, \cdot)_{L^2(\mu)}$ respectively the norm and the inner product of the Hilbert space $L^2(\mu)$. Given a measurable map $T : \mathcal{X} \to \mathcal{X}$ and $\mu \in \mathcal{P}_2(\mathcal{X})$, we denote by $T_\# \mu$ the pushforward measure of $\mu$ by $T$, characterized by the transfer lemma $\int \phi(T(x)) \, d\mu(x) = \int \phi(y) \, dT_\# \mu(y)$, for any measurable and bounded function $\phi$. Consider $\mu, \nu \in \mathcal{P}_2(\mathcal{X})$, the 2-norm Wasserstein distance is defined by $W_2^2(\mu, \nu) = \inf_{s \in S(\mu, \nu)} \int \|x - y\|^2 \, ds(x, y)$, where $S(\mu, \nu)$ is the set of couplings between $\mu$ and $\nu$, i.e., the set of nonnegative measures $s$ over $\mathcal{X} \times \mathcal{X}$ such that $P_\# s = \mu$ (resp. $Q_\# s = \nu$) where $P : (x, y) \mapsto x$ (resp. $Q : (x, y) \mapsto y$) denotes the projection onto the first (resp. the second) component. The Wasserstein distance is a distance over $\mathcal{P}_2(\mathcal{X})$. The metric space $(\mathcal{P}_2(\mathcal{X}), W_2)$ is called the Wasserstein space.
Let $T > 0$. Consider a weakly continuous map $\mu : (0, T) \to \mathcal{P}_2(\mathcal{X})$. The family $(\mu_t)_{t \in (0, T)}$ satisfies a continuity equation if there exists $(v_t)_{t \in (0, T)}$ such that $v_t \in L^2(\mu_t)$ and
\[
\frac{\partial \mu_t}{\partial t} + \text{div}(\mu_t v_t) = 0
\]
holds in the distributional sense. A family $(\mu_t)_{t}$ satisfying a continuity equation with $\|v_t\|_{L^2(\mu_t)}$ integrable over $(0, T)$ is said absolutely continuous. Among the possible processes $(v_t)_{t}$, one has a minimal $L^2(\mu_t)$ norm and is called the velocity field of $(\mu_t)_{t}$. In a Riemannian interpretation of the Wasserstein space (Otto, 2001), this minimality condition can be characterized by
\[
\int_0^T \langle v, H_{\mu_t}|\mu_t| \rangle d\mu_t
\]
and measure $\mu$. Consider a positive semi-definite kernel $k : \mathcal{X} \times \mathcal{X} \to \mathbb{R}$ and $\mathcal{H}_0$ its corresponding RKHS of real-valued functions on $\mathcal{X}$. The space $\mathcal{H}_0$ is a Hilbert space with inner product $\langle \cdot, \cdot \rangle_{\mathcal{H}_0}$ and norm $\| \cdot \|_{\mathcal{H}_0}$ (see Smola and Schölkopf, 1998). Moreover, $k$ satisfies the reproducing property: $\forall f \in \mathcal{H}_0$, $f(x) = \langle f, k(x, \cdot) \rangle_{\mathcal{H}_0}$. Denote by $\mathcal{H}$ the product RKHS consisting of elements $f = (f_1, \ldots, f_d)$ with $f_i \in \mathcal{H}_0$, and with a standard inner product $(f, g)_{\mathcal{H}} = \sum_{i=1}^d \langle f_i, g_i \rangle_{\mathcal{H}_0}$. Let $\mu \in \mathcal{P}_2(\mathcal{X})$; the integral operator associated to kernel $k$ and measure $\mu$ denoted by $S_\mu : L^2(\mu) \to \mathcal{H}$ is
\[
S_\mu f = \int k(x, \cdot)f(x)d\mu(x).
\]
We make the key assumption that $\int k(x, x)d\mu(x) < \infty$ for any $\mu \in \mathcal{P}_2(\mathcal{X})$; which implies that $\mathcal{H} \subset L^2(\mu)$. Consider functions $f, g \in L^2(\mu) \times \mathcal{H}$ and denote the inclusion $\iota : \mathcal{H} \to L^2(\mu)$, with $\iota^* = S_\mu$ its adjoint. Then following e.g. Steinwart and Christmann (2008), Chapter 4), we have
\[
\langle f, g \rangle_{L^2(\mu)} = \langle \iota^* f, g \rangle_{\mathcal{H}} = \langle S_\mu f, g \rangle_{\mathcal{H}}.
\]
When the kernel is integrally strictly positive definite, then $\mathcal{H}$ is dense in $L^2(\mu)$ for any probability measure $\mu$ (Sriperumbudur et al., 2011). We also define $P_\mu : L^2(\mu) \to L^2(\mu)$ the operator $P_\mu = \iota S_\mu$; notice that it differs from $S_\mu$ only in its range.
3.2 Stein Variational Gradient Descent

We can now present the Stein Variational Gradient Descent (SVGD) algorithm (Liu and Wang, 2016). The Stein Variational Gradient Descent (SVGD) algorithm is a nonparametric Bayesian inference algorithm that approximates the posterior distribution of a complex model using a set of particles. The standard gradient descent algorithm in the Wasserstein space applied to $\pi$ is not a gradient descent discretization; it rather corresponds to performing a Forward-Flow (FFl) discretization, which is biased (Wibisono, 2018, Section 2.2.2).

Remarks

Remark 1. An alternative sampling algorithm which does not imply to compute the exact gradient of the KL is the Unadjusted Langevin Algorithm (ULA). It is an implementable algorithm that computes a gradient step with $\nabla \log \pi$, and a flow step adding a Gaussian noise to the particles. However, it is not a gradient descent discretization; it rather corresponds to performing a Forward-Flow (FFl) discretization, which is biased (Wibisono, 2018, Section 2.2.2).

3.3 Stein Fisher information

The squared RKHS norm of the gradient $S_\mu \nabla \log (\frac{\mu}{\pi})$ is defined as the Stein Fisher Information:

**Definition 1.** Let $\mu \in P_2(\mathcal{X})$. The Stein Fisher Information of $\mu$ relative to $\pi$ (Duncan et al. 2019) is defined by:

$$I_{Stein}(\mu|\pi) = \|S_\mu \nabla \log (\frac{\mu}{\pi})\|_{L^2(\pi)}^2.$$  (9)

**Remark 2.** Notice that since $P_\mu = tS_\mu$ with $t^* = S_\mu$, we can write $I_{Stein}(\mu|\pi) = (\nabla \log (\frac{\mu}{\pi}), P_\mu \nabla \log (\frac{\mu}{\pi}))_{L^2(\mu)}$. In the literature the quantity $I_{Stein}(\mu|\pi)$ is also referred to as the squared Kernel Stein Discrepancy (KSD), used in nonparametric statistical tests for goodness-of-fit (Liu et al. 2016, Chwialkowski et al. 2016, Gorham and Mackey 2017). The KSD provides a discrepancy between probability distributions, which depends on $\pi$ only through the score function $\nabla \log \pi$ that can be calculated without knowing the normalization constant of $\pi$. Whether the convergence of the KSD to zero, i.e. $I_{Stein}(\mu_n|\pi) \to 0$ when $n \to \infty$ implies the weak convergence of $\mu_n$ to $\pi$ (denoted $\mu_n \rightharpoonup \pi$) depends on the choice of the kernel relatively to the target. This question has been treated in Gorham and Mackey (2017).

Sufficient conditions include $\pi$ being distantly dissipative which is similar to strong log concavity outside a bounded domain, and the kernel having a slow decay rate (e.g. being translation invariant with a non-vanishing Fourier transform, or $k$ being the inverse multi-quadratic kernel defined by $\|x - y\|_2 = r$). This includes finite Gaussian mixtures with common covariance and all distributions strongly log-concave outside of a compact set, including Bayesian linear, logistic, and Huber regression posteriors with Gaussian priors.

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1i.e. such that $\lim_{r \to \infty} \kappa(r) > 0$ for $\kappa(r) = \inf \{-2(\nabla \log \pi(x) - \nabla \log \pi(y), x - y) / \|x - y\|_2^2; \|x - y\|_2 = r\}$. This includes finite Gaussian mixtures with common covariance and all distributions strongly log-concave outside of a compact set, including Bayesian linear, logistic, and Huber regression posteriors with Gaussian priors.
\[ k(x, y) = (c^2 + \|x - y\|^2_2^\beta)^d \] for \( c > 0 \) and \( \beta \in [-1, 0] \). In these cases, \( I_{\text{stein}}(\mu_n|\pi) \to 0 \) implies \( \mu_n \to \pi \).

In order to study the continuous time dynamics of SVGD, Duncan et al. (2019) introduced a kernel version of a log-Sobolev inequality (which usually upper bounds the KL by the Fisher divergence (Vempala and Wibisono 2019)).

**Definition 2.** We say that \( \pi \) satisfies the **Stein log-Sobolev inequality** with constant \( \lambda > 0 \) if:

\[
\text{KL}(\mu|\pi) \leq \frac{1}{2\lambda} I_{\text{stein}}(\mu|\pi).
\]

The functional inequality (10) is not as well known and understood as the classical log-Sobolev inequality, provided a first investigation into when this condition might hold. They show that it fails to hold if the kernel is too regular w.r.t. \( \pi \), more precisely for \( k \in \mathcal{C}^{1,1}(\mathcal{X} \times \mathcal{X}) \), and if \( \sum_{i=1}^d (|\partial_1 V(x)|^2 k(x, x) - \partial_1 V(x)(\partial_1^2 k(x, x) + \partial_2^2 k(x, x)) + \partial_1^2 \partial_2^2 k(x, x)) d\pi(x) < \infty \), where \( \partial_1 \) and \( \partial_2 \) denote first and second derivatives with respect to the first and second argument of \( k \) respectively (Duncan et al. 2019 Lemma 36). This holds for instance in the case where \( \pi \) has exponential tails and the derivatives of \( k \) and \( V \) grow at most at a polynomial rate. However, they provide interesting cases in dimension 1 where (10) holds, depending on \( k \) and \( \pi \). For instance, by choosing a non-differentiable kernel that is adapted to the tails of the target \( k(x, y) = \pi(x)^{-1/2} e^{-|x-y|^2/2} \), and if \( V''(x) + (V'(x))^2/2 \geq \lambda > 0 \) for any \( x \in \mathbb{R} \), then (10) holds with \( \lambda = \min(1, \lambda) \) (Duncan et al. 2019 Example 40). Conditions where (10) holds in higher dimensions are more challenging to establish, and are a topic of current research.

### 3.4 Related work

SVGD was originally introduced by Liu and Wang (2015), and was shown empirically to be competitive with state-of-the-art methods in Bayesian inference. Liu (2017) developed the first theoretical analysis and studied the weak convergence properties of SVGD. They showed that for any iteration, the empirical distribution of the SVGD samples (i.e., for a finite number of particles) weakly converges to the population distribution when the number of particles goes to infinity. In the infinite particle regime, they provided a descent lemma showing that the KL objective decreases at each iteration (see Remark 4). Finally, they derived the non-convex partial differential equation (PDE) that governs continuous time dynamics of SVGD, and provided a geometric intuition that interprets the continuous time dynamics of SVGD in the infinite number of particles regime. They showed that by choosing linear kernels, SVGD can exactly estimate the mean and variance of Gaussian distributions when the number of particles is greater than the dimension. They further derived high probability bounds that bound the Kernel Stein Discrepancy between the empirical distribution and the target measure when the kernel is approximated with random features. Lu et al. (2019) studied the kernel Stein geometry induced by the kernel. Liu and Wang (2018) studied the fixed point properties of the algorithm for a finite number of particles, and showed that it accurately estimates expectations under the target distribution, for a set of functions called the Stein matching set, that are determined by the Stein operator (depending on the target distribution) and the kernel. In particular, they showed that by choosing linear kernels, SVGD can exactly estimate the mean and variance of Gaussian distributions when the number of particles is greater than the dimension. They further derived high probability bounds that bound the Kernel Stein Discrepancy between the empirical distribution and the target measure when the kernel is approximated with random features. Liu and Wang (2018) studied the fixed point properties of the algorithm for a finite number of particles, and showed that it accurately estimates expectations under the target distribution, for a set of functions called the Stein matching set, that are determined by the Stein operator (depending on the target distribution) and the kernel. In particular, they showed that by choosing linear kernels, SVGD can exactly estimate the mean and variance of Gaussian distributions when the number of particles is greater than the dimension. They further derived high probability bounds that bound the Kernel Stein Discrepancy between the empirical distribution and the target measure when the kernel is approximated with random features. Liu et al. (2019) studied the continuous time dynamics of SVGD in the infinite number of particles regime. They showed that the PDE governing continuous-time, infinite sample SVGD dynamics is well-posed, and that the law of the particle system (for a finite number of particles) is a weak solution of the equation, under appropriate growth conditions on the score function \( \nabla \log \pi \), and they studied the regularity of the PDE. Finally, Duncan et al. (2019) investigated the contraction and equilibration properties of this PDE. In particular, they proposed conditions that induce exponential convergence to the equilibrium in continuous time, notably as the Stein log-Sobolev inequality, which relates the convexity of the KL objective to the Stein geometry (see Section 4). By contrast with Lu et al. (2019), Duncan et al. (2019), we develop a theoretical understanding of SVGD in discrete time, where to our knowledge rates of convergence have yet to be established.

## 4 Continuous-time dynamics of SVGD

This section defines and describes the SVGD dynamics in continuous time. Some of the results are already stated in Liu (2017) and Duncan et al. (2019) but are necessary to understand the discrete

\[ \text{KL}(\mu|\pi) \leq 1/2\lambda \| \nabla \log \pi \|^2_{L^2(\mu)} \], which holds for instance as soon as \( V \) is \( \lambda \)-strongly convex.
The convergence of $I$ is the purpose of the inequality (10) which implies exponential convergence of the SVGD gradient flow near equilibrium. Indeed, if $\pi$ satisfies the Stein log-Sobolev inequality, the Kullback-Leibler divergence converges exponentially fast along the SVGD dynamics.

Proposition 4. Assume $\pi$ satisfies the Stein log-Sobolev inequality with $\lambda > 0$. Then

$$\text{KL}(\mu_t|\pi) \leq e^{-2\lambda t} \text{KL}(\mu_0|\pi).$$

Proof. Combining (12) and (10) yields $\frac{d\text{KL}(\mu_t|\pi)}{dt} \leq -2\lambda \text{KL}(\mu_t|\pi)$. We conclude by applying Gronwall’s lemma.

In the next section, we provide a non-asymptotic analysis for SVGD. Our first result holds without any convexity assumptions on the KL, but mainly under a smoothness assumption on $\pi$, while our second result leverages (10) to obtain rates of convergence.
5 Non-asymptotic analysis for SVGD

This section studies the SVGD dynamics in discrete time. Although one of the results echoes \[\text{Liu (2017)[Theorem 3.3]},\] we provide new convergence rates for the discrete time SVGD under mild conditions, and using different techniques: we return to this point in detail in Remark 4 below. Moreover, our proof technique is different. As in the previous section, we provide intuitive sketch of the proofs exploiting the differential calculus over the Wasserstein space. Each step of the proofs is rigorously justified in the Supplementary material.

Recall that the SVGD update is defined as (7). Let \(\mu_0 \in \mathcal{P}_2(\mathcal{X})\) and assume that it admits a density. For every \(n \geq 0\), \(\mu_n\) is the distribution of \(x_n\), where

\[
x_{n+1} = x_n - \gamma P_{\mu_n} \nabla \log \left( \frac{\mu_n}{\pi} \right) (x_n), \quad x_0 \sim \mu_0.
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\[
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\]
The first term $\psi_1(t)$ is bounded using Assumption $[A_2]$:

$$\psi_1(t) \leq M \|g\|^2_{L^2(\mu_0)} \leq MB^2I_{\text{Stein}}(\mu_n|\pi).$$

The second term $\psi_2(t)$ is the most challenging to bound as $\|Ju\|_{HS}$ cannot be controlled by $\|u\|$ for a general $u$. However, in our case, $u = -g \circ (\phi_t)^{-1}$, and $-J_{u} \circ (\phi_t)^{-1} = Jg(J\partial_x)^{-1}$. Therefore,

$$\|Ju\|_{HS} \leq \|Jg(x)\|_{HS}((\phi_t)^{-1}(x))^2 \leq \alpha^2B^2I_{\text{Stein}}(\mu_n|\pi).$$

Combining each of the quantity in the Taylor expansion gives the desired result.

Although the Hessian of $KL(\cdot|\pi)$ is not bounded over the whole tangent space, our proof relies on controlling the Hessian when restricted to $\mathcal{H}$. Since $I_{\text{Stein}}(\mu_n|\pi)$ is nonnegative, Proposition $5$ shows that the KL divergence w.r.t. $\pi$ decreases along the SVGD algorithm, i.e. the KL is a Lyapunov functional for SVGD. A first consequence of Proposition $5$ is the convergence of $I_{\text{Stein}}(\mu_n|\pi)$ to zero, similarly to the continuous time case, see Proposition $2$. Indeed, the descent lemma implies that the sequence $I_{\text{Stein}}(\mu_n|\pi)$ is summable and hence converges to zero. A second consequence of the descent lemma is the following discrete time convergence rate for the average of $I_{\text{Stein}}(\mu_n|\pi)$.

**Corollary 6.** Let $\alpha > 1$ and $\gamma \leq \min\left(\frac{\alpha-1}{\alpha BC} \cdot \frac{2}{(\alpha+M)B^2}\right)$ and $c_\alpha = \gamma \left(1 - \gamma \frac{(\alpha^2+M)B^2}{2}\right)$. Then, the sequence $I_{\text{Stein}}(\mu_n|\pi)$ converges weakly to

$$\min_{k=1,\ldots,n} I_{\text{Stein}}(\mu_n|\pi) \leq \frac{1}{n} \sum_{k=1}^n I_{\text{Stein}}(\mu_k|\pi) \leq \frac{KL(\mu_0|\pi)}{c_\alpha n}.$$

We illustrate the validity of the rates of Corollary $6$ with simple experiments provided Section $12$. Corollary $6$ provides a $O(1/n)$ convergence rate for the arithmetic mean of the Kernel Stein Discrepancy (KSD) (which metricizes weak convergence in many cases, see section $3.3$) between the iterates $\mu_n$ and $\pi$, under assumption $[A_2]$ to assumption $[A_3]$.

It does not rely on Stein LSI nor on convexity of $V$, unlike most of the results on Langevin Monte Carlo (LMC) which assume either (standard) LSI or convexity of $V$ (Vempala and Wibisono [2019]; Durmus et al. [2019]). To guarantee convergence rates of the SVGD algorithm in terms of the KL objective, further properties are needed. We discuss the difficulty of proving rates in KL in section $10.3$.

**Remark 4.** A descent lemma was also obtained for SVGD in Liu [2017] [Theorem 3.3] under a boundedness condition of the KSD and the kernel. While we obtain similar conditions on the step size, our approach, shown in the proof sketch (and, in greater detail, the Appendix), gives clearer connections with Wasserstein gradient flows. More precisely, we prove Proposition $5$ by performing differential calculus over the Wasserstein space. We are able to replace the boundedness condition on the KSD by a simple boundedness condition of the first moment of $\mu_n$ at each iteration, which echoes analyses of some optimization algorithms like Stochastic Gradient Descent (Moulines and Bach [2011]). Our construction also brings with it a simple yet informative perspective, arising from the optimization literature, into why SVGD actually satisfies a descent lemma. In optimization, it is well known that descent lemmas can be obtained under a boundedness condition on the Hessian matrix. Here, the Hessian operator of the KL at $\mu$ is an operator on $L^2(\mu)$; and yet, this operator is not bounded (Wibisono [2018] Section 3.1.1). By restricting the Hessian operator to the RKHS however, and then using the reproducing property and our assumptions, the resulting Hessian operator is provably bounded under simple conditions on the kernel and $\pi$.

### 6 Finite number of particles regime

In this section, we investigate the deviation of the discrete distributions generated by the SVGD algorithm for a finite number of particles, to its population version. In practice, starting from $N$ i.i.d. samples $X_0 \sim \mu_0$, SVGD algorithm updates the $N$ particles as follows:

$$X_{i+1}^n = X_i^n - \gamma P_{\mu_n} \nabla \log \left(\frac{\mu_n}{\pi}\right) (X_i^n), \quad \hat{\mu}_n = \frac{1}{N} \sum_{j=1}^N \delta_{X_i^j},$$

where $\hat{\mu}_n$ denotes the empirical distribution of the interacting particles. Recall that $P_{\mu_n} \nabla \log \left(\frac{\hat{\mu}_n}{\pi}\right)$ is well defined even if $\hat{\mu}_n$ is discrete.

In Liu [2017], the authors show that the empirical distribution of the SVGD samples weakly converge to its population limit for any iteration. More precisely, under the assumptions that $b(x, y) = \nabla \log \pi(x)k(x, y) + \nabla_1 k(x, y)$ is jointly Lipschitz and that $\mu_0$ converges weakly to $\mu_0$ as $N \to \infty$.
(which happens by drawing $N$ i.i.d. samples of $\mu_0$), for any $n \geq 0$, they show that $\hat{\mu}_n$ converges weakly to $\mu_n$. This happens as soon as Assumption $[A_1][A_2][B_1][B_2]$ are satisfied (since the product of bounded Lipschitz functions is a Lipschitz function):

(B1) Assume that $\exists C_V$ s.t. for all $x \in X$, $\|V(x)\| \leq C_V$.

(B2) Assume that $\exists D > 0$ s.t. $k$ is continuous on $X$ and $D$-Lipschitz:

$$|k(x, x') - k(y, y')| \leq D(\|x - y\| + \|x' - y'\|) \text{ for all } x, x', y, y' \in X,$$

and $k$ is continuously differentiable on $X$ with $D$-Lipschitz gradient:

$$\|\nabla k(x, x') - \nabla k(y, y')\| \leq D(\|x - y\| + \|x' - y'\|) \text{ for all } x, x', y, y' \in X.$$

Under these assumptions, we quantify the dependency on the number of particles in the following proposition.

Proposition 7. Let $n \geq 0$ and $T > 0$. Let $\mu_n$ and $\hat{\mu}_n$ be defined by (7) and (16) respectively. Under Assumption $[A_1][A_2][B_1][B_2]$ for any $0 \leq n \leq \frac{T}{C}$:

$$\mathbb{E}[W_2^2(\mu_n, \hat{\mu}_n)] \leq \frac{1}{2} \left( \frac{1}{\sqrt{N}} \sqrt{\text{var}(\mu_0)e^{LT}} \right) (e^{2LT} - 1)$$

where $L$ is a constant depending on $k$ and $\pi$.

Proposition [7], whose proof is provided section [10, 4] uses techniques from [Jourdain et al., 2007]. It is a non-asymptotic result in the sense that it provides an explicit bound. However, it is not a bound that helps quantify the rate of minimization of the objective function, but a bound between the population distribution $\mu$ and its particle approximation $\hat{\mu}_n$. Such results are referred to as uniform in time propagation of chaos. Such results, which are subject to active research in PDE, are hard to obtain. Among the recent exceptions is [Durmus et al., 2018a] who consider the process $dx_t = -\nabla U(x_t) - \nabla W \ast \mu_t(x_t)dt$ and manage to prove such results when $U$ is strictly convex outside of a ball. However in SVGD (see [8]), the attractive force $\nabla \log \pi(x)k(x,.)$ cannot be written as the gradient of a confinement potential $U : \mathbb{R}^d \rightarrow \mathbb{R}$ in general. Hence these results do not apply, and the convergence rate for SVGD using $\hat{\mu}_n$ remains an open problem.

7 Conclusion

In this paper, we provide a non-asymptotic analysis for the SVGD algorithm. Our results build upon the connection of SVGD with gradient descent in the Wasserstein space ([Liu, 2017]). In establishing these results, we draw on perspectives and techniques used to establish convergence in optimization. Several questions remain open. Firstly, the question of deriving rates of convergence of SVGD (in the infinite particle regime) in terms of the Kullback-Leibler objective, when the potential $V$ is convex or when $\pi$ satisfies some log Sobolev inequality. Secondly, the question of deriving a unified bound for the convergence of $\hat{\mu}_n$ to $\pi$ (decreasing as the number of iterations $n$ and number of particles $N$ go to infinity). This would require to obtain a uniform in time propagation of chaos result for the SVGD particle system. Finally, another further direction would be to study SVGD dynamics when the kernel depends on the current distribution. These kind of dynamics arise in black-box variational inference and Generative Adversarial Networks ([Chu et al., 2020]) (in which case the kernel is the neural tangent kernel introduced by [Jacot et al., 2018]).

8 Broader impact

This paper aims at bringing more theoretical understanding to the Stein Variational Gradient Descent algorithm. This algorithm is widely used by machine learning practitioners but its non asymptotic properties are not as well-known as the ones of the Langevin Monte Carlo algorithm which can be considered as its competitor.
References


