EINSTEINVI: GENERAL AND INTEGRATED STEIN VARIATIONAL INFERENCE

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ABSTRACT

Stein variational inference is a technique for approximate Bayesian inference that has recently gained popularity because it combines the scalability of variational inference (VI) with the flexibility of non-parametric inference methods. While there has been considerable progress in developing algorithms for Stein VI, integration in existing probabilistic programming languages (PPLs) with an easy-to-use interface is currently lacking. EinSteinVI is a lightweight composable library that integrates the latest Stein VI methods with the PPL NumPyro (Phan et al., 2019). EinSteinVI provides ELBO-within-Stein to support the use of custom inference programs (guides), implementations of a wide range of kernels, non-linear scaling of the repulsion force (Wang & Liu, 2019b) and second-order gradient updates using matrix-valued kernels (Wang et al., 2019b). We illustrate EinSteinVI using toy examples and show results on par with or better than existing state-of-the-art methods for real-world problems. These include Bayesian neural networks for regression and a Stein-mixture deep Markov model, which shows EinSteinVI scales to large models with more than 500,000 parameters.

1 INTRODUCTION

Interest in Bayesian deep learning has surged due to the need for quantifying the uncertainty of predictions obtained from machine learning algorithms. The idea behind Bayesian inference is to describe observed data $\mathbf{x}$ using a model with latent variables $\mathbf{z}$. The goal is to infer a posterior distribution $p(\mathbf{z}|\mathbf{x})$ over the latent variables given a model describing the joint distribution $p(\mathbf{z}, \mathbf{x}) = p(\mathbf{x}|\mathbf{z})p(\mathbf{z})$. We obtain the posterior by following the rules of Bayesian inference:

$$p(\mathbf{z}|\mathbf{x}) = Z^{-1}p(\mathbf{x}|\mathbf{z})p(\mathbf{z})$$

where $Z = \int_{\mathbf{z}} p(\mathbf{x}|\mathbf{z})p(\mathbf{z})\mathrm{d}\mathbf{z}$ is the normalization constant. For most practical models, the normalizing constant lacks an analytic solution or requires an infeasible number of computations, complicating the Bayesian inference problem.

Variational Inference (VI) techniques (Blei et al., 2017; Hoffman et al., 2013; Ranganath et al., 2014) aim to approximate the posterior distribution. VI poses a family of distributions over the latent variables $q(\mathbf{z}) \in \mathcal{Q}$ and find

$$\arg\min_{q \in \mathcal{Q}} D(q(\mathbf{z})|p(\mathbf{z}|\mathbf{x})),$$

where D is a divergence[1] between the variational distribution q, also called the guide, and the true posterior distribution $p(\mathbf{z}|\mathbf{x})$. The Kullback-Leibler divergence is a typical choice. VI often provides good approximations that capture uncertainty and scales to millions of data points by a suitable choice of $\mathcal{Q}$ and inference method.

Stein VI is a family of VI techniques for approximate Bayesian inference based on Stein's method (see Anastasiou et al. (2021) for an overview) that is gaining popularity since it combines the scalability of traditional VI with the flexibility of non-parametric particle-based methods. Currently Stein VI methods are available in `PyMC3` (Salvatier et al., 2016) and `Edward` (Tran et al., 2016), neither of which include the advanced methods available in EinSteinVI.

[1] An asymmetric distance that might satisfy the triangle inequality.

Stein variational gradient descent (SVGD) (Liu & Wang, 2016) is a recent Stein VI technique which uses a set of particles $\{\mathbf{z}_i\}_{i=1}^N$ as the approximating distribution $q(\mathbf{z})$. As a particle-based method, SVGD is well suited for capturing correlations between latent variables. The technique preserves the scalability of traditional VI approaches while offering the flexibility and modeling scope of techniques such as Markov chain Monte Carlo (MCMC). SVGD is good at capturing multi-modality (Liu & Wang, 2016; Wang & Liu, 2019a), and has useful theoretical interpretations such as a set of particles following a gradient flow (Liu, 2017) or in terms of the properties of kernels (Liu & Wang, 2018).

Many advanced inference methods based on SVGD have been recently developed, including Stein mixtures (Nalisnick & Smyth, 2017), non-linear Stein (Wang & Liu, 2019a), factorized graphical models (Zhuo et al., 2018; Wang et al., 2018a), matrix-valued kernels (Wang et al., 2019a) and support for higher-order gradient-based optimization (Detommaso et al., 2018). These techniques have extended the power of SVGD, allowing more flexible and accurate approximations of the true posterior distribution. While algorithmic power is growing, a distinct lack of integration with a general probabilistic programming language (PPL) framework remains. Such integration would solve one of the most prominent limitations of traditional VI: its lack of flexibility in capturing rich correlations in the approximated posterior.

This paper presents the EinSteinVI library that extends the NumPyro PPL (Bingham et al., 2019; Phan et al., 2019) with support for SVGD and its extensions mentioned above. By embedding EinSteinVI in NumPyro, the Stein VI methods can utilize the many capabilities of NumPyro. These include universal probabilistic programming (van de Meent et al., 2018), integration with deep learning using `Jax` (Frostig et al., 2018), automatically generated and custom guides, and automatic optimization. Concretely, our contributions are:

- EinSteinVI, a general library that extends NumPyro and allows SVGD to work with custom guide programs based on **E**LBO-with**in**-**Stein** (EinSteinVI) optimization (Nalisnick & Smyth, 2017). The library is compositional with NumPyro features, including support for deep learning, loss functions (ELBO, Rényi ELBO (Li & Turner, 2016), custom losses), and optimization methods, thus making it possible for EinSteinVI to grow organically with NumPyro development.
- Integration of recent developments in Stein variational inference which includes: Non-linear optimization (Wang & Liu, 2019a), a wealth of kernels (Liu & Wang, 2016; 2018; Gorham & Mackey, 2017), matrix-valued kernels (Wang et al., 2019a) supporting higher-order optimization, an (experimental) update based on Stein point MCMC (Chen et al., 2019a), and factorization based on conditional independence between elements in the model (graphical kernels) (Wang et al., 2018b).
- A series of examples demonstrate EinSteinVI and the synergy between different Stein VI techniques. The examples include a novel Stein-mixture version of the deep Markov model (SM-DMM), Bayesian neural networks for regression, and examples that explore kernels and higher-order optimization.

The paper proceeds as follows. We first present the background of SVGD in the context of our integrated implementation in Section 2. We discuss the general details of the implementation of EinSteinVI in NumPyro in Section 3. In Section 4 we present various examples using EinSteinVI, and finally, we summarize our results and discuss future work in Section 5.

1.1 Related Work

There has been a proliferation of deep probabilistic programming languages based on tensor frameworks featuring automatic differentiation and supporting various inference techniques. Pyro (Bingham et al., 2019) is a universal PPL based on PyTorch (Paszke et al., 2019). The main mode of inference in Pyro is black-box stochastic VI (SVI) (Ranganath et al., 2014) with *guides*. Guides are programs that approximate the posterior distribution by repeating the sample statements of the latent variables in the probabilistic model. They can contain deep neural networks allowing amortization of inference (Kingma & Welling, 2013; Gershman & Goodman, 2014). Pyro also supports various sampling algorithms like Hamiltonian Monte Carlo/NUTS (Duane et al., 1987; Neal, 2011; Hoffman & Gelman, 2014) and sample-adaptive MCMC (Zhu, 2019) which provide more accurate posterior

approximations and is well suited for GPU, but lack the scalability of VI techniques. NumPyro is a version of Pyro that runs on the `Jax` framework (Frostig et al., 2018), which gives access to the powerful program optimization and parallelizability provided by the `Jax` compiler. Our library, EinSteinVI, adds SVGD to NumPyro and allows approximating the optimizable parameters in the guide by a set of particles instead of a point estimate.

Other PPLs with similar functionality to EinStein are `PyMC3` (Salvatier et al., 2016) , which includes Operator Variational Inference (OVI) (Ranganath et al., 2016), amortized SVGD (Wang et al., 2016; Feng et al., 2017), and SVGD with a RBF-kernel, and `Edward` (Tran et al., 2016; 2019) which implements OVI in a repository separate from the main software.

2 Stein Variational Gradient Descent

The core idea of SVGD is to perform inference by approximating the target posterior distribution $p(\mathbf{z}|\mathbf{x})$ by an empirical distribution $q_{\mathcal{Z}}(\mathbf{z}) = N^{-1} \sum_i \delta_{\mathbf{z}_i}(\mathbf{z})$ based on a set of particles $\mathcal{Z} = \{\mathbf{z}_i\}_{i=1}^N$. Here, $\delta_{\mathbf{x}}(\mathbf{y})$ represents the Dirac delta measure, which is equal to 1 if $\mathbf{x} = \mathbf{y}$ and 0 otherwise. One could thus see the approximating distribution $q_{\mathcal{Z}}(\mathbf{z})$ as a mixture of point estimates, each represented by a particle $\mathbf{z}_i \in \mathcal{Z}$. The idea is to minimize the Kullback-Leibler divergence $D_{\mathrm{KL}}(q_{\mathcal{Z}}(\mathbf{z}) \parallel p(\mathbf{z}|\mathbf{x}))$ between the approximation and the true posterior by iteratively updating the particles using the Stein forces:

$$\mathbf{z}_i \leftarrow \mathbf{z}_i + \epsilon S_{\mathcal{Z}}(\mathbf{z}_i)$$

where ϵ is the learning rate and $S_{\mathcal{Z}}$ denotes the Stein forces.

The Two Forces of SVGD Stein VI consists of two forces which work additively under the form $S_{\mathcal{Z}} = S^+_{\mathcal{Z}} + S^-_{\mathcal{Z}}$, where the attractive force is given by

$$S^+_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})}[k(\mathbf{z}_j, \mathbf{z}_i) \nabla_{\mathbf{z}_i} \log p(\mathbf{z}_i|\mathbf{x})]$$

and the repulsive force by

$$S^-_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})}[\nabla_{\mathbf{z}_i} k(\mathbf{z}_j, \mathbf{z}_i)].$$

Here $k : \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}$ is a kernel. The attractive force can be seen as pushing the particles towards the modes of the true posterior distribution, smoothed by some kernel. For an example of a kernel, consider the radial basis function (RBF) kernel $k(\mathbf{z}_i, \mathbf{z}_j) = \exp\left(-\frac{1}{h} \parallel \mathbf{z}_i - \mathbf{z}_j \parallel_2^2\right)$ with bandwidth parameter h, chosen as $\frac{1}{\log n}\mathrm{med}(\mathbf{z})$.

The repulsive force moves particles away from each other, ensuring that they do not collapse to the same mode. For example with the RBF kernel, the repulsive force becomes $\mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})}[-\exp\left(-\frac{1}{h} \parallel \mathbf{z}_i - \mathbf{z}_j \parallel_2^2\right) \frac{2}{h} \sum_\ell (\mathbf{z}_{i\ell} - \mathbf{z}_{j\ell})]$, which has high kernel values for particles that are close, causing them to repel.

SVGD works with unnormalized distributions p as the normalization constant becomes additive in the log-posterior $\log p(\mathbf{z}_i|\mathbf{x}) = -\log Z + \log p(\mathbf{x}|\mathbf{z}) + \log p(\mathbf{z})$ and is thus not required for the calculation of the gradient. This property is desirable as normalizing p is often computationally expensive.

Non-linear Stein In non-linear Stein (Wang & Liu, 2019a), the repulsive force can be scaled by a factor λ, resulting in $S_{\mathcal{Z}} = S^+_{\mathcal{Z}} + \lambda S^-_{\mathcal{Z}}$. This approach is useful when dealing with multi-modal distributions. It is also useful in cases where the repulsive force vanishes compared to the likelihood, which happens for large datasets ($\mathcal{X}$). Scaling the repulsive force by a constant $\lambda = c(|\mathcal{X}|)$ proportional (e.g. $c = 0.1$ or $c = 0.01$) to the size of the dataset $|\mathcal{X}|$ addresses this issue.

Matrix-valued kernels The choice of kernels can be extended to matrix-valued ones (Wang et al., 2019a), $K : \mathbb{R}^d \times \mathbb{R}^d \to \mathbb{R}^{d \times d}$, in which case the Stein forces become

$$S^+_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})}[K(\mathbf{z}_j, \mathbf{z}_i) \nabla_{\mathbf{z}_i} \log p(\mathbf{z}_i|\mathbf{x})]$$

and

$$S^-_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})}[K(\mathbf{z}_j, \mathbf{z}_i) \nabla_{\mathbf{z}_i}]$$

where the standalone del $\nabla_{\mathbf{z}_i}$ in the repulsive force represents the vector $\left(\frac{\partial}{\partial z_{i,1}}, \ldots, \frac{\partial}{\partial z_{i,d}}\right)$. This results in

$$(K(\mathbf{z}_j, \mathbf{z}_i)\nabla_{\mathbf{z}_i})_\ell = \sum_k \nabla_k K_{\ell,k}(\mathbf{z}_j, \mathbf{z}_i).$$

The advantage of matrix-valued kernels is that they allow preconditioning using the Hessian or Fisher Information matrix (second-order derivatives), which can capture local curvature and thus achieve better optima and convergence rate than standard SVGD. Furthermore, it is easy to capture graphical kernels (Wang et al., 2018a) $K = \mathrm{diag}(\{K^{(\ell)}\}_\ell)$ where the set of variables are partitioned with each their own local kernel $K^{(\ell)}$.

ELBO-within-Stein Nalisnick & Smyth (2017) showed that the Stein force for a mixture approximation of the posterior, called a Stein-mixture, can be computed as

$$\begin{aligned} S_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})} \left[k(\mathbf{z}_i, \mathbf{z}_j)\mathbb{E}_{\boldsymbol{\theta}_l \sim q(\theta|\mathbf{z}_j)} \left[p(X, \boldsymbol{\theta}_l)/q(\boldsymbol{\theta}_l|\mathbf{z}_j)\right]\right] + \\ + \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})} \left[k(\mathbf{z}_i, \mathbf{z}_j)\nabla_{\mathbf{z}_j} \log q(\mathbf{z}_j)\right] + \\ + S^-_{\mathcal{Z}}(\mathbf{z}_i), \end{aligned}$$

where we assume $\log \nabla_{\mathbf{z}_j} q(\mathbf{z}_j)$ is sufficiently small to be dropped. To evaluate $\mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})} \left[p(X, \theta)/q(\theta|\mathbf{z}_j)\right]$, Nalisnick & Smyth (2017) employ differentiable non-centered parameterizations (Kingma & Welling, 2014) and importance weighted Monte Carlo gradients (Burda et al., 2015) to obtain the black-box update,

$$S_{\mathcal{Z}}(\mathbf{z}_i) = \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})} \left[k(z_i, z_j) \sum_{s=1}^{S} \tilde{w}_s \nabla_{z_j} \log \left(\frac{p(X, \hat{\boldsymbol{\theta}}_s)}{q(\hat{\boldsymbol{\theta}}_s|\mathbf{z}_j)}\right)\right] + S^-_{\mathcal{Z}}(\mathbf{z}_i),$$

where $\tilde{w}_s$ is an importance weight for sample $\hat{\boldsymbol{\theta}}_s = q(\mathbf{z}_j, \boldsymbol{\xi}),\ \boldsymbol{\xi} \sim p_0$ (i.e. the guide).

Note that $\sum_{s=1}^{1} \tilde{w}_s \nabla_{z_j} \log \left(p(X, \theta_s)/q(\theta_s|z_j)\right)$ is the gradient of the one sample evidence lower bound (ELBO). In EinStein we replace the weighted average over S samples by a single loss ($\mathcal{L}$). We can estimate the loss by averaging over multiple samples to reduce bias. Note this is different from Nalisnick & Smyth (2017) which estimates $\mathbb{E}_{\boldsymbol{\theta}_l \sim q(\theta|\mathbf{z}_j)} \left[p(X, \boldsymbol{\theta}_l)/q(\boldsymbol{\theta}_l|\mathbf{z}_j)\right]$ by averaging over gradients. The update thus becomes

$$z_i = z_i + \mathbb{E}_{\mathbf{z}_j \sim q_{\mathcal{Z}}(\mathbf{z})} \left[k(z_i, z_j)\nabla_{z_j}\mathcal{L}(z_j)\right] + S^-_{\mathcal{Z}}(\mathbf{z}_i) \tag{1}$$

where $\mathcal{L}$ is the ELBO.

3 Compositional Implementation using NumPyro

EinSteinVI integrates with the existing NumPyro API by adding the Stein VI interface, which closely mimicks NumPyro's SVI interface. Mimicking the SVI interface makes programs that use SVI in NumPyro trivial to convert to EinSteinVI.

Below, we discuss the key features of EinSteinVI, which include re-initializable guides, EinSteinVI's core algorithm, and the new kernel interface.

3.1 Re-initializable Guides

The Stein VI interface requires that the initialization is different for each parameter in an inference program. The reason is that different Stein particles need to be initialized to different values in order for optimization to work correctly and to avoid that all particles collapse into the posterior mode.

To support re-initializable guides, we provide the `ReinitGuide` interface, which requires implementing of a function `find_params` that accepts a list of random number generator (RNG) keys in addition to the arguments for the guide and returns a set of freshly initialized parameters for each RNG key.

The `WrappedGuide` class provides a guide written as a function. `WrappedGuide` makes a callable guide re-initializable. It works by running the provided guide multiple times and reinitializing the parameters using NumPyro's interface as follows:

- `WrappedGuide` runs the guide transforming each parameter to unconstrained space.
- It replaces the values of the parameters with values provided by a NumPyro initialization strategy, e.g., `init_to_uniform`(r), which initializes each parameter with a uniform random value in the range $[-r; r]$.
- It saves the parameter values for each particle and the required inverse transformations to constrained space to run the model correctly.

We also allow parameters without reinitialization in order to support neural network libraries like `stax` [2] that have their own initializers.

The Stein VI interface will correctly wrap the guide during initialization, so from a user perspective the syntax for guides is identical to that of the SVI api.

3.2 Stein VI in NumPyro

The integration of Stein VI into NumPyro requires handling transformations between the parameter representation of NumPyro[3] and the vectorized Stein particles that EinSteinVI operates on. For this, we rely on `Jax PyTrees`[4] which converts back and forth between Python collections and a flattened vectorized representation.

Algorithm 1 shows the core algorithm of EinSteinVI. EinSteinVI updates the standard variational model parameters $\boldsymbol{\phi}$ and guide parameters $\boldsymbol{\phi}'$ by averaging the loss over the Stein particles. For the Stein parameters, the process is more elaborate. First, we convert the set of individual parameters to a monolithic vector-encoded particle using `Jax PyTrees`. Then we compute a kernel based on the vector-encoded Stein particle; this is delegated to the kernel interface as the computation is kernel-dependent. We apply `Jax`'s `vmap` operator (Frostig et al., 2018; Phan et al., 2019) to compute the Stein forces for each particle in a vectorized manner. Note that Algorithm 1 presents how EinSteinVI works with scalar kernels and does not account for the different features presented in Section 2. Finally, we convert the monolithic Stein particle to their non-vectorized dictionary-based form and return the expected changes for standard- and Stein-parameters.

Input: Classical parameters $\boldsymbol{\phi}$ and $\boldsymbol{\phi}'$, Stein parameters $\{\boldsymbol{\theta}_i\}_i$, model $p_{\boldsymbol{\phi}}(\mathbf{z}, \mathbf{x})$, guide $q_{\boldsymbol{\theta},\boldsymbol{\phi}'}(\mathbf{z})$, loss $\mathcal{L}$, kernel interface KI.
Output: Parameter changes based on classical VI ($\Delta\boldsymbol{\phi}$, $\Delta\boldsymbol{\phi}'$) and Stein VI forces ($\{\Delta\boldsymbol{\theta}_i\}_i$).

```
procedure EINSTEIN(ϕ, ϕ', {θ_i}_i, p_ϕ, q_{θ,ϕ'})
    Δϕ ← E_θ[∇_ϕ L(p_ϕ, q_{θ,ϕ'})]
    Δϕ' ← E_θ[∇_ϕ' L(p_ϕ, q_{θ,ϕ'})]
    {a_i}_i ← PyTreeFlatten({θ_i}_i)
    k ← KI({a_i}_i)

    procedure EINSTEINFORCES(a_i)        ▷ Calculate forces per particle for higher-order
                                           vmap function.
        θ_i ← PYTREERESTORE(a_i)
        Δa_i ← Σ_{a_j} k(a_j, a_i) ∇_{a_i} L(p_ϕ, q_{θ_i,ϕ'}) + ∇_{a_i} k(a_j, a_i)
        return Δa_i
    end procedure

    {Δa_i}_i ← VMap({a_i}_i, EINSTEINFORCES)
    {Δθ_i}_i ← PYTREERESTORE({Δa_i}_i)
    return Δϕ, Δϕ', {Δθ_i}_i
end procedure
```

Algorithm 1: EinSteinVI

[2] `https://jax.readthedocs.io/en/latest/jax.experimental.stax.html`
[3] A dictionary mapping parameters to their values, which can be arbitrary Python type
[4] `https://jax.readthedocs.io/en/latest/pytrees.html`

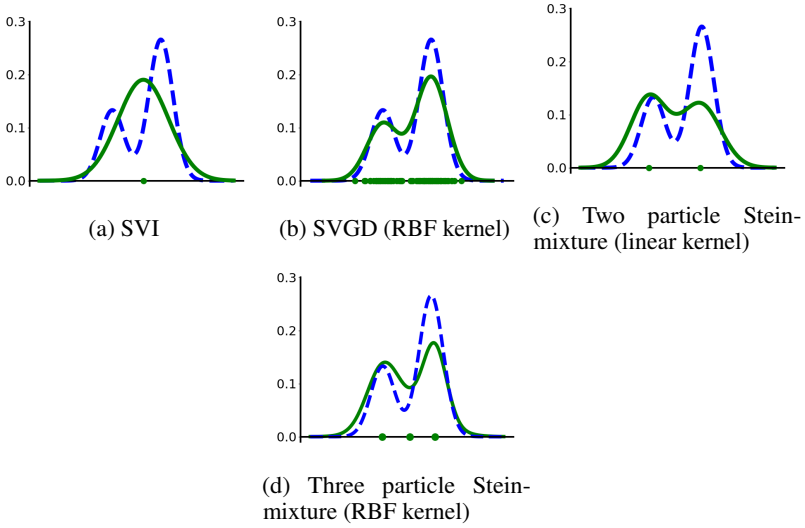
3.3 KERNEL INTERFACE

The Kernel interface is straightforward. To extend the interface users must implement the `compute` function, which accepts as input the current set of particles, the mapping between model parameters and particles, and the loss function $\mathcal{L}$ and returns a differentiable kernel k. All kernels are currently static, but the interface could be extended to stateful kernels, allowing conjugate gradients or quasi-Newton optimization. Appendix A describes the complete list of kernels in EinSteinVI. The implemented kernels are well justified for SVGD, but they do not consider information geometry and may have erratic behavior with the Stein-mixture method, as it does not use point estimates. Nalisnick & Smyth (2017) used a probability product kernels to account for this; however, these are not currently part of EinSteinVI.

4 EXAMPLES

We illustrate the features of EinSteinVI on two toy examples, namely 1D and 2D mixtures of Gaussian's. We demonstrate EinSteinVI on real-world examples where we find that EinSteinVI tends to outperform alternative methods. These examples include regression with Bayesian neural networks and deep Markov models. All experimental code, notebook tutorials and the EinSteinVI package itself are available through an Anonymized URL.

1D Gaussian mixture To demonstrate the two modes of VI with EinSteinVI, we consider the 1D Gaussian mixture $1/3\mathcal{N}(-2,1)+2/3\mathcal{N}(2,1)$ (see Figure 1). The Gaussian target mixture is bi-modal and well-suited for the nonparametric nature of SVGD and Stein mixtures. Figure 1 shows that both SVGD and the Stein-mixture naturally capture the bi-modality of the target distribution, compared to SVI with a simple Gaussian guide. Note the reduction in particles required to estimate the target when using Stein mixtures compared to SVGD. Also, note that the Stein-mixture overestimates the variance and slightly pertubates the locations. The error seen at the right mode for the Stein-mixture with two particles is due to the uniform weighting of the particles in SVGD (the target posterior is approximated with an empirical distribution, see Section 2), and as such is algorithmic. The Stein-mixture will therefore not be able to exactly capture the mixing components of a target mixture model with one particle per component. However, with more particles the mixture can be approximated better as demonstrated using three particles.



(a) SVI

(b) SVGD (RBF kernel)

(c) Two particle Stein-mixture (linear kernel)

(d) Three particle Stein-mixture (RBF kernel)

Figure 1: The blue dashed line is the target pdf, while the solid green line is the density of the particles. We estimate the particle density for SVGD with Gaussian kernel density estimation. We use 100 particles for SVGD, and two or three particles for the Stein-mixture. SVI uses a Gaussian guide.

Table 1: Average test RMSE and time for inference for the UCI regression benchmarks.

	Test RMSE			Time	
Dataset	**EinStein**	**PyMC3**	**Liu & Wang (2016)**	**EinStein**	**PyMC3**
Boston	2.610 ± 0.044	7.546 ± 11.182	2.990 ± 0.013	$5.758s \pm 0.048$s	1m6.396s $\pm$ 0.301s
Concrete	4.175 ± 0.025	6.255 ± 0.390	5.927 ± 0.021	5.602s $\pm$ 0.048s	1m5.845s $\pm$ 0.278s
Energy	0.321 ± 0.004	3.494 ± 1.500	1.251 ± 0.017	5.562s $\pm$ 0.053s	1m6.175s $\pm$ 0.41s
Kin8nm	0.073 ± 0.000	0.164 ± 0.040	0.115 ± 0.001	6.141s $\pm$ 0.04s	2m40.106 $\pm$ 0.298s
Naval	0.001 ± 0.000	0.029 ± 0.015	0.008 ± 0.001	6.51s $\pm$ 0.048s	3m51.05$s \pm 0.385s$
Power	3.952 ± 0.004	5.389 ± 2.219	4.215 ± 0.002	6.314s $\pm$ 0.054s	2m51.654s $\pm$ 0.566s
Protein	4.509 ± 0.006	5.921 ± 2.559	4.846 ± 0.002	9.436s $\pm$ 0.032s	11m11.9s $\pm$ 0.399s
Wine	0.599 ± 0.006	0.769 ± 0.212	0.604 ± 0.001	5.614$s \pm 0.052$s	1m7.767s $\pm$ 0.286s
Yacht	0.531 ± 0.009	8.341 ± 3.744	0.94 ± 0.03	5.519s $\pm$ 0.07s	1m4.748s $\pm$ 0.392s
Year	8.662 ± 0.002	135.316	8.895 ± 0.001	1m37.569s $\pm$ 0.07s	4h19m36s

Table 2: Time for first repetition with EinStein for UCI regression benchmarks.

Dataset	Boston	Concrete	Energy	Kin8nm	Naval	Power	Protein	Wine	Yacht	Year
Time	41.665s	41.642s	41.591s	43.592s	44.2570s	44.058s	47.87s	41.9s	41.409s	2m18.19s

Bayesian Neural Networks We compare SVGD in EinSteinVI with the implementation of SVGD by Liu & Wang (2016)[5] without model selection, and in `PyMC3` (using the Theano backend[6], Al-Rfou et al. (2016)), using Bayesian neural networks (BNN) for regression. We use an RBF-kernel in EinStein for fair comparison with Liu & Wang (2016) and `PyMC3`. Like Liu & Wang (2016) we use a BNN with one hidden layer of size fifty and `RELU` activation. We put a Gamma$(1, 0.1)$ prior on the precision of the neurons and the likelihood. For all three versions, we use 100 particles and 2000 iterations. We use a mini-batch of 1000 for Year and 100 for the rest. All measurements are repeated twenty times and obtained on a GPU[7] for EinSteinVI and `PyMC3`, except for Year with `PyMC3` which was only once. We do not report times for Liu & Wang (2016) because only the CPU version of their code could be executed without irresolvable issues.

Table 1 shows the performance in terms of the average root mean squared error (RMSE) on the test set. We find that EinSteinVI achieves significantly better RMSE than Liu & Wang (2016) and that both systems outperform SVGD in `PyMC3`. The times in Table 1 measure how long it takes to infer parameters. Table 1 excludes the first run for two reasons: i) that run will fill the GPU caches, and ii) `Jax` will trace the programs. As a result, this run is more costly than subsequent ones. The times for the first run are given in Table 2. By running EinSteinVI for more iterations, we can amortize the initial cost.

Star Distribution To illustrate the kernels included in EinSteinVI, we approximate the "star distribution", follow Wang et al. (2019b) (see Figure 2). The star distribution is constructed as a 2D Gaussian mixture,

$$p(x) = \frac{1}{K}\sum_{k=1}^{K}\mathcal{N}(x|\mu_k, \Sigma_k) \quad \mu_1 = [0, 1.5], \mu_k = U_k\mu_1 \quad \Sigma_1 = \text{diag}([1, \frac{1}{100}]), \Sigma_k = U_k\Sigma_1 U_k$$

where U_k is a rotation matrix given by

$$U_k = \begin{bmatrix} \cos(\theta) & -\sin(\theta) \\ \sin(\theta) & \cos(\theta) \end{bmatrix}, \quad (k \in [1, .., K])\theta = 2k\pi/K.$$

We use fifty particles and Adagrad with the learning rate that yields the best Maximum Mean Discrepancy (MMD) (Gretton et al., 2012) with a RBF kernel. To compute the MMD, we use 10,000 samples from the 2D gaussian mixture. Keeping these choices fixed, we vary the type of kernel, using a point mass distribution as guide.

[5] `https://github.com/dilinwang820/Stein-Variational-Gradient-Descent/blob/master/python/bayesian_nn.pyy`

[6] As far as we are aware `PyMC4`, which uses `Jax` as its backend, does not include SVGD at the time of writing.

[7] Quadro RTX 6000 with Cuda V11.4.120

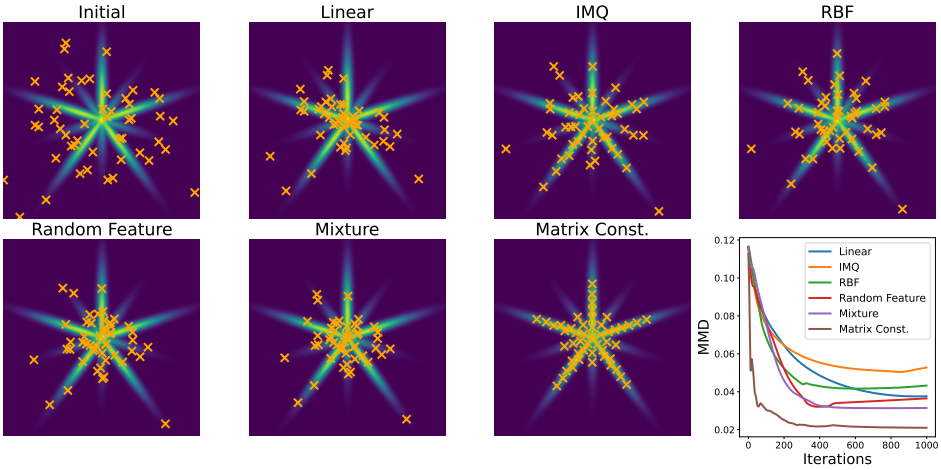


Figure 2: Particle positions for EinSteinVI with different kernels after 1000 iterations with a point mass guide, starting from particle positions given in the upper left frame labelled Initial. The MMD, bottom right frame, is evaluated using the RBF kernel.

We consider the scalar ($\mathbb{R}^d \to \mathbb{R}$) linear kernel, the inverse multiquadric (IMQ) kernel, the RBF kernel and the random feature kernel; details are given in appendix A. In addition, we use a mixture kernel, which is a uniform mixture of the linear and the random feature kernels. We also use the matrix version of the RBF kernel with a constant preconditioning, using the Hessian matrix for preconditioning. We see that including curvature information by means of the Hessian leads to faster convergence in EinSteinVI and that the matrix RBF with preconditioning yields the lowest MMD.

Stein Mixture Deep Markov Model Music generation requires a model to learn complex temporal dependencies to achieve local consistency between notes. The Stein-mixture deep Markov model (SM-DMM) is a deep Markov model that uses a mixture of Stein particles to estimate distributions over model parameters. We consider a vectorized version of the DMM (Jankowiak & Karaletsos, 2019) for the generation of polyphonic music using the JSB chorales data set.

The SM-DMM model consists of two feed-forward neural networks. The *Transition* network takes care of the conditional dependencies between subsequent latent states in the Markov chain, while the *Emitter* network produces a likelihood at each time step using the current latent state. The variational distribution is of the form $\prod_{n=1}^{N} q(z_{1:T_n}^n | f(X_{1:T_n}))$ where the parametrized feature function $f_{1:T_n}$ is a gated recurrent unit (Chung et al., 2014), with hidden dimension 400. In the JSB chorales dataset, each time step is an eighth of a note.

We run the SM-DMM using the Adam optimizer (Kingma & Ba, 2014) with a learning rate of 10^{-5}, using an RBF kernel and five Stein particles for one thousand epochs. The trained SM-DMM achieves a negative log likelihood of *6.67* on the test set, comparable to the 6.85 originally reported in Krishnan et al. (2016) and 6.82 reported in the improved version in Jankowiak & Karaletsos (2019).

5 Summary

EinSteinVI provides the latest techniques for Stein VI as an extension to Numpyro. Our results indicate that the library is substantially faster and more expressive than other available libraries for Stein VI. EinSteinVI provides a familiar and efficient interface for practitioners working with the Pyro/NumPyro PPL and provides a unified code base to researchers for benchmarking new developments in Stein VI.

Possible further extensions include (a) supporting updates inspired by Stein Points (Chen et al., 2018; 2019b), (b) extending the kernel interface with probability product kernels (Jebara et al., 2004) to account for information geometry when using Stein-mixtures, (c) adding full support for NumPyro's automatic enumeration features (Obermeyer et al., 2019) when guides are used, and (d) stateful matrix

kernels for conjugate gradient or quasi-Newton optimization. Stein Points updates could handle cases where initialization of particles is sub-optimal by initializing from a Stein point MCMC chain and interleave MCMC updates to get better mode hopping properties.

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A APPENDIX

Kernel	Definition	Detail	Type	Reference
Radial Basis Function (RBF)	$\exp(\frac{1}{h} \parallel \mathbf{x}-\mathbf{y} \parallel_2^2)$		scalar	Liu & Wang (2016)
	$\exp(\frac{1}{h}(\mathbf{x}-\mathbf{y}))$		vector	Pyro[8]
Inverse Multi-Quadratic (IMQ)	$(c^2 + \parallel \mathbf{x}-\mathbf{y} \parallel_2^2)^{\beta}$	$\beta \in (-1, 0)$ and $c > 0$	scalar	Gorham & Mackey (2017)
Random Feature Expansion	$\mathbb{E}_{\mathbf{w}}[\phi(\mathbf{x}, \mathbf{w})\phi(\mathbf{y}, \mathbf{w})]$	$\phi(\mathbf{x}, \mathbf{w}) = \sqrt{2}\cos(\frac{1}{h}\mathbf{w}_1^\top \mathbf{x} + \mathrm{w}_0)$ where $\mathrm{w}_0 \sim \mathrm{Unif}(0, 2\pi)$ and $\mathbf{w}_1 \sim \mathcal{N}(0, 1)$	scalar	Liu & Wang (2018)
Linear	$\mathbf{x}^\top \mathbf{y} + 1$		scalar	Liu & Wang (2018)
Mixture	$\sum_i w_i k_i(\mathbf{x}, \mathbf{y})$	$\{k_i\}_i$ individual kernels, weights w_i	scalar, vector, matrix	Liu & Wang (2018)
Scalar-based Matrix	$k(\mathbf{x}, \mathbf{y})\boldsymbol{I}$	k scalar-valued kernel	matrix	Wang et al. (2019a)
Vector-based Matrix	$\mathrm{diag}(k(\mathbf{x}, \mathbf{y}))$	k vector-valued kernel	matrix	Wang et al. (2019a)
Graphical	$\mathrm{diag}(\{K^{(\ell)}(\mathbf{x}, \mathbf{y})\}_\ell)$	$\{K^{(\ell)}\}_\ell$ matrix-valued kernels, each for a unique partition of latent variables	matrix	Wang et al. (2019a)
Constant Pre-conditioned	$\boldsymbol{Q}^{-\frac{1}{2}} K(\boldsymbol{Q}^{\frac{1}{2}}\mathbf{x}, \boldsymbol{Q}^{\frac{1}{2}}\mathbf{y})\boldsymbol{Q}^{-\frac{1}{2}}$	K is an inner matrix-valued kernel and $\boldsymbol{Q}$ is a preconditioning matrix like the Hessian $-\nabla^2_{\bar{\mathbf{z}}} \log p(\bar{\mathbf{z}}\|\mathbf{x})$ or Fischer information $-\mathbb{E}_{\mathbf{z}\sim q_{\mathcal{Z}}(\mathbf{z})}[\nabla^2_{\mathbf{z}} \log p(\mathbf{z}\|\mathbf{x})]$ matrices	matrix	Wang et al. (2019a)
Anchor Point Precondi-tioned	$\sum_{\ell=1}^m K_{\boldsymbol{Q}_\ell}(\mathbf{x}, \mathbf{y}) w_\ell(\mathbf{x}) w_\ell(\mathbf{y})$	$\{\mathbf{a}_\ell\}_{\ell=1}^m$ is a set of anchor points, $\boldsymbol{Q}_\ell = \boldsymbol{Q}(\mathbf{a}_\ell)$ is a preconditioning matrix for each anchor point, $K_{\boldsymbol{Q}_\ell}$ is an inner kernel conditioned using $\boldsymbol{Q}_\ell$, and $w_\ell(\mathbf{x}) = \mathrm{softmax}_\ell(\{\mathcal{N}(\mathbf{x}\|\mathbf{a}_{\ell'}, \boldsymbol{Q}_{\ell'}^{-1})\}_{\ell'})$	matrix	Wang et al. (2019a)