
Momentum Accelerated Training of Kernel Machines

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Abstract

In this paper we derive a novel iterative algorithm for learning kernel machines. Our algorithm, **AxlePro**, extends the **EigenPro** family of algorithms via momentum-based acceleration. **AxlePro** can be applied to train kernel machines with arbitrary positive semidefinite kernels. We provide a convergence guarantee for the algorithm and demonstrate the speed-up of **AxlePro** over competing algorithms via numerical experiments. Furthermore, we also derive a version of **AxlePro** to train large kernel models over arbitrarily large datasets.

1 INTRODUCTION

Deep neural networks have become the dominant paradigm of modeling and data analysis for large scale problems in machine learning today. These model architectures have shown remarkable progress in our ability to extract information from complex datasets, breaking unprecedented benchmarks every so often. Certain architectures of these networks, such as wide networks [18], have been shown to behave like the more classical Kernel machines. This has sparked renewed interest into the capabilities of kernel methods and their application towards solving large scale problems in machine learning.

Newer families of kernels, so-called *neural kernels*, have also shown remarkable performance on contemporary machine learning problems, see [4, 5, 8, 16, 32] among others. Furthermore, recent work also shows that kernel machines can be re-engineered to learn task-specific features in a supervised manner [7, 25], which leads to further performance gains. Learning a kernel machine in a scalable manner thus remains an important fundamental problem in machine learning.

Formally, kernel machines are functions of the form

$$f(x) = \sum_{i=1}^n \alpha_i K(x, x_i). \quad (\text{KM})$$

where x_i are training inputs, $\alpha_i \in \mathbb{R}$ are trainable weights, and *kernel* $K : \mathbb{X} \times \mathbb{X} \rightarrow \mathbb{R}$ is a positive definite function.

We consider the training of (KM) by solving the $n \times n$ positive definite linear system of equations,

$$\text{K_solve}(K, X, Y) : \text{Find } \alpha : K(X, X)\alpha = Y, \quad (1)$$

where $K(X, X) = (K(x_i, x_j))$ is a $n \times n$ positive definite matrix of pairwise evaluations of the kernel K on training inputs, and $Y \in \mathbb{R}^n$ is the vector of all n targets. If \mathbb{H} is the RKHS corresponding to K , (KM) with weights given by $\text{K_solve}(K, X, Y)$ is the minimum \mathbb{H} -norm solution to the least squares problem,

$$\min_{f \in \mathbb{H}} \mathcal{L}(f) := \frac{1}{2} \sum_{i=1}^n (f(x_i) - y_i)^2. \quad (2)$$

Remark 1. While there are many variations, such as different loss functions and regularizers, we leave aside these generalizations for future work. However we note that solving (1) subsumes the important case of kernel ridge regression. This somewhat easier case is equivalent to choosing a modified kernel $\tilde{K}(x, z) = K(x, z) + \lambda \cdot \mathbf{1}_{\{x=z\}}$, where $\lambda > 0$ is a tunable parameter of the ridge penalty, since our framework allows arbitrary kernels, even discontinuous ones.

1.1 Main contributions

We derive a new class of algorithms, Algorithms (1-??), called **AxlePro**. These algorithms are derived to emulate momentum-accelerated preconditioned stochastic gradient descent in the RKHS, as detailed in Section 3. Our theoretical result Theorem 6 provides a guarantee on the exponential convergence of Algorithm 1. Our numerical experiments demonstrate that **AxlePro** is fast, numerically stable, and scalable. We provide a **PyTorch** implementation. We also derive a version of **AxlePro** in Section 3.5, given in Algorithm 2, that can train so-called *general kernel models* [1] (see Section 2).

Algorithm	fast precondition ^p	momentum	batching	stable [‡]	order	complexity ^c	mem [*]
PCG [15]	✗	✓	✗	✗		$n^2 \cdot \sqrt{\kappa}$	n
EigenPro [22]	✗	✗	✓	✓	1 st	$nm \cdot \kappa_m$	n
EigenPro 2 [23]	✓	✗	✓	✓	1 st	$nm \cdot \kappa_m$	$\log^4 n$
ASkotch [27]	✗	✓	✓		2 nd	$(nm + m^2)\sqrt{\kappa_m}$	m
Alt.-proj. [34]	✗	✗	✓		2 nd	$m^3 \cdot \kappa_m$	m^2
Algorithm 1 (ours)	✓	✓	✓	✓	1 st	$nm \cdot \sqrt{\kappa_m}$	$\log^4 n$

Table 1: Iterative algorithms for solving equation (1). m is the batch size. Condition number κ is the ratio of largest and smallest positive eigenvalues of $K(X, X)$, $\kappa_m, \tilde{\kappa}_m$ are modified versions of κ defined in equation (22), with $\kappa_m \leq \kappa$ depending on m in a data-dependent manner.

^pBy fast preconditioning we mean the preconditioner is calculated once and should be of size $o(n)$.

[‡]Stability to single precision computations, and support for ridgeless regression (KRR with $\lambda = 0^+$).

^cTotal complexities in big-Oh notation, product of per iteration complexity times number of iterations.

^{*}memory overheads due to preconditioning.

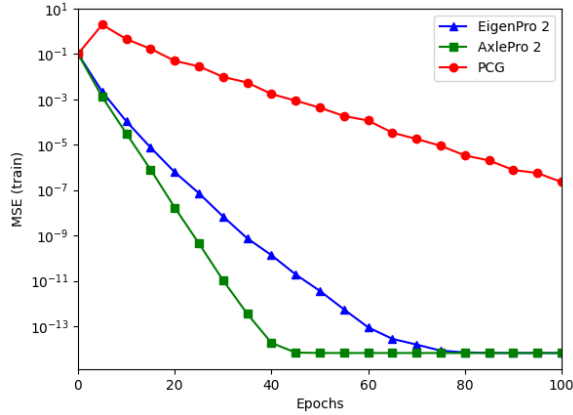


Figure 1: Comparison of iterative algorithms for the Laplace Kernel on CIFAR-10

1.2 Related work

The problem of scalable training algorithms for kernel models has been studied extensively in the past. Approaches for scalable training include: Linear system solvers for symmetric positive definite matrices. Examples of such solvers include conjugate gradient (CG) and preconditioned version PCG. See [24, 29, 35] for example. While these methods are the fastest in the asymptotic sense, they do not decrease training error monotonically, and require a large number of epochs. Hence, even though they can be implemented in a matrix-free manner, the total cost of computations is very large for machine learning applications. Furthermore CG based methods are also sensitive to quantization noise and hence are not stable to single-precision computations.

Randomized methods such as those based on random fourier features, sketching, or low-rank decompositions

Algorithm 1 AxlePro 2

- 1: **Input:** positive definite kernel K , batch size m , size of approximate preconditioner s , level of preconditioner q , learning rates $\eta_1, \eta_2 > 0$, damping factor $\gamma \in (0, 1)$.
- 2: **Output:** $f : \mathcal{X} \rightarrow \mathbb{R}$ solving (9) approximately.
- 3: **setup:** Sample $J \subset \{1, 2, \dots, n\}$ with $|J| = s$.
- 4: $(D, \Delta, \delta_{q+1}) \leftarrow$ top- q eigensystem of $K(X[J], X[J])$
- 5: $G \leftarrow D\sqrt{\Delta^{-1}(I_q - \delta_{q+1}\Delta^{-1})} \in \mathbb{R}^{s \times q}$
- 6: $\alpha \leftarrow \mathbf{0}_n$, and $\beta \leftarrow \mathbf{0}_n$.
- 7: **repeat**
- 8: Fetch batch of indices $B \subset \{1, \dots, n\}$, $|B| = m$
- 9: $v \leftarrow K(X[B], X)\beta - Y[B] \in \mathbb{R}^m$
- 10: $w \leftarrow GG^\top K(X[J], X[B])v \in \mathbb{R}^s$
- 11: $\tilde{\alpha} \leftarrow \alpha$
- 12: $\alpha \leftarrow \beta$
- 13: $\alpha[B] \leftarrow \alpha[B] - \eta_1 v$
- 14: $\alpha[J] \leftarrow \alpha[J] + \eta_1 w$
- 15: $\beta \leftarrow (1 + \gamma)\alpha - \gamma\tilde{\alpha}$
- 16: $\beta[B] \leftarrow \beta[B] + \eta_2 v$
- 17: $\beta[J] \leftarrow \beta[J] - \eta_2 w$
- 18: **until** Stopping criterion is reached
- 19: **return** $f(x) = \sum_{i=1}^n \alpha_i K(x, x_i)$

provide a way to train in a scalable manner [10, 11, 26]. See [16] and the references therein for a more recent overview on sketching and random features. However this approach is not universal, i.e., requires special structure in the kernel. Sketching based solutions have also been studied in this context [12].

Primal space solvers such as SGD [9, 31] and its variants can be very effective, and are universal, i.e., apply for any kernel. In fact [1, 2, 22, 23] are state of the art in solving kernel machines in a fast and scalable manner. These methods derive an iteration in the

Algorithm	fast precondition ^p	momentum	batching	stable [‡]	order	FLOPS ^c /batch	mem. [*]
Cholesky [28]	✗	✓	✗	✗	2 nd	$p^2m + p^3$	p^2
FALKON [24, 29]	✗	✗	✗	✓	2 nd	$pm + p^2$	p^2
EigenPro 3 [1]	✓	✗	✓	✓	1 st	$pm + p^2$	$\log^4 n$
EigenPro 4 [2]	✓	✗	✓	✓	1 st	pm	$\log^4 n$
SketchySAGA [27]	✓	✓	✓		2 nd	$pm + p^2$	pm
Algorithm 2 (ours)	✓	✓	✓	✓	1 st	pm	$\log^4 n$

Table 2: Comparison between different iterative algorithms for solving (8). m is the batch size, typically $m \ll n$. Condition number κ is the ratio of largest to smallest positive eigenvalue, $\kappa_m, \tilde{\kappa}_m$ are modified versions of κ defined in equation (22), with $\tilde{\kappa}_m \leq \kappa_m \leq \kappa$.

^pBy fast preconditioning we mean the preconditioner must be calculated once and should be of size $o(n)$.

[‡]Stability to single precision computations.

^cnumber of flops/sample in big-Oh notation, product of per iteration complexity times number of iterations.

^{*}memory overheads due to preconditioning.

RKHS, but emulate these computations exactly in \mathbb{R}^n . Our algorithm AxlePro falls in this category.

Second order methods with acceleration have also been considered recently in [27] and [34] which inherently apply a stochastic Newton-type iteration in the RKHS. However, these methods involve recomputing a preconditioner at each step, which may become prohibitive. An in-depth comparison of the numerical performance with these methods on real-world datasets is deferred to future work.

General kernel models of the form (Gen-KM), defined formally in Section 2, has been an important way to train kernel machines on arbitrarily large datasets. This has become important since [1] showed that kernel machines need to scale the model size independent of the dataset size to improve performance, similar to what is done in practice for neural network models. Models given by (Gen-KM) are the preferred way to scale RKHS methods to large datasets with several new implementations. For example [1, 2, 24, 27] consider this problem. Our Algorithm 2 is along this direction, with a comparison given in table 2.

2 PRELIMINARIES

We consider the standard setting of supervised learning where we are provided a training dataset with n samples $\{(x_i, y_i)\}_{i=1}^n$ and want to obtain a map $x \mapsto f(x)$, where we $x_i \in \mathbb{X}$, an abstract space, and $y_i \in \mathbb{R}$.

Kernel machines such as equation (KM) arise as the solutions to empirical risk minimization problems over an RKHS corresponding to K ,

$$\min_{f \in \mathbb{H}} \mathbf{L}(x_1, y_1, f(x_1), \dots, x_n, y_n, f(x_n)) + \lambda \cdot \mathbf{R}(\|f\|_{\mathbb{H}}). \quad (3)$$

due to the Representer Theorem [19, 30]. This theorem requires the mild condition that \mathbf{R} is an increasing

function and $\lambda > 0$. The reproducing property of K , means we have,

$$\langle f, K(\cdot, x) \rangle_{\mathbb{H}} = f(x), \quad \forall f \in \mathbb{H}, \forall x \in \mathbb{X}, \quad (4)$$

where $K(\cdot, x) \in \mathbb{H}$ is the *Reisz representer* for the evaluation functional corresponding to the point x .

Notation. A detailed table of notations is in the appendix. For tuples $A = (a_i) \in \mathbb{X}^k$ and $U = (u_i) \in \mathbb{X}^\ell$, $K(A, U) \in \mathbb{R}^{k \times \ell}$ denotes the kernel matrix with entries $K(a_i, u_j)$. For any $f \in \mathbb{H}$, by $f \otimes_{\mathbb{H}} f$, we denote the rank-1 self-adjoint operator $\mathbb{H} \rightarrow \mathbb{H}$, which acts as $(f \otimes_{\mathbb{H}} f)(g) = f \langle f, g \rangle_{\mathbb{H}}$. Here, if $f = K(x, \cdot)$, then we have $(K(x, \cdot) \otimes_{\mathbb{H}} K(x, \cdot))(g) = K(\cdot, x)g(x)$, by equation (4).

Definition 1 (Sampling operator). For an n -tuple of inputs $X = (x_i) \in \mathbb{X}^n$, denote by $S : \mathbb{H} \rightarrow \mathbb{R}^n$ the evaluation operator which evaluates any function $f \in \mathbb{H}$, i.e.,

$$Sf = (f(x_1), \dots, f(x_n)) \in \mathbb{R}^n. \quad (5)$$

One can show that the adjoint of S , defined in equation (5), denoted $S^* : \mathbb{R}^n \rightarrow \mathbb{H}$, acts as

$$S^* \alpha = \sum_{i=1}^n K(\cdot, x_i) \alpha_i \in \mathbb{H}, \quad \forall \alpha \in \mathbb{R}^n. \quad (6)$$

We define the empirical covariance operator,

$$\mathcal{K} := \frac{1}{n} S^* S = \frac{1}{|X|} \sum_{x \in X} K(x, \cdot) \otimes_{\mathbb{H}} K(x, \cdot). \quad (7)$$

Slicing. For an n -tuple $X = (x_1, x_2, \dots, x_n)$ of size n and an s -tuple of indices $J = (j_1, j_2, \dots, j_s)$, we denote by $X[J]$ the s -tuple $(x_{j_1}, x_{j_2}, \dots, x_{j_s})$, following *python* notation. For a matrix \mathbf{A} and vector \mathbf{v} , the quantities $\mathbf{A}[J]$ and $\mathbf{v}[J]$ are the submatrix and

subvector of \mathbf{A} and \mathbf{v} respectively indexed by J . By \mathbf{H}_J we denote the $|J| \times n$ matrix formed by stacking the $|J|$ rows of identity I_n . By $S_J := \mathbf{H}_J S$ we denote the operator which maps $\mathbb{H} \rightarrow \mathbb{R}^{|J|}$ so that $S_J f = (f(x_{j_1}), f(x_{j_2}), \dots, f(x_{j_s}))$. Similarly, define $\mathcal{K}_J = \frac{1}{|J|} S_J^* S_J$.

Definition 2 (top- q eigensystem). Given a symmetric positive definite matrix $\mathbf{A} \in \mathbb{R}^{n \times n}$, for $i = 1, 2, \dots, q + 1$, let \mathbf{e}_i, λ_i be the top- $q+1$ eigenpairs of \mathbf{A} , i.e., $\mathbf{A}\mathbf{e}_i = \lambda_i \mathbf{e}_i$, with descending eigenvalues $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_{q+1} > 0$. Let $\mathbf{E} := [\mathbf{e}_1, \mathbf{e}_2, \dots, \mathbf{e}_q] \in \mathbb{R}^{n \times q}$, and $\Lambda = \text{diag}(\lambda_1, \lambda_2, \dots, \lambda_q) \in \mathbb{R}^{q \times q}$ be a diagonal matrix. We call the tuple $(\mathbf{E}, \Lambda, \lambda_{q+1})$ the top- q eigensystem of \mathbf{A} .

Spectral duality. Observe that $\mathcal{K} = \frac{1}{n} S^* S$, and $SS^* = K(X, X)$ is the kernel matrix. Let \mathbf{e} be an eigenvector of $K(X, X)$ with eigenvalue λ with unit norm, i.e. $\|\mathbf{e}\| = 1$ and $K(X, X)\mathbf{e} = \lambda \mathbf{e}$. Then, one can show using standard arguments about singular vectors of finite rank operators that, $\psi := S^* \mathbf{e} / \sqrt{\lambda}$ is an eigenfunction of \mathcal{K} with eigenvalue λ/n . Note that $\|\psi\|_{\mathbb{H}}^2 = \langle \psi, \psi \rangle_{\mathbb{H}} = \frac{1}{\lambda} \langle S^* \mathbf{e}, S^* \mathbf{e} \rangle_{\mathbb{H}} = \frac{1}{\lambda} \langle SS^* \mathbf{e}, \mathbf{e} \rangle = \langle \mathbf{e}, \mathbf{e} \rangle = 1$. The normalization $1/\sqrt{\lambda}$ used to define ψ ensures that $\|\psi\|_{\mathbb{H}} = 1$ which is necessary for how ψ gets used in the next section.

General kernel models. Consider models

$$f(x) = \sum_{i=1}^p \alpha_i K(x, z_i) \quad (\text{Gen-KM})$$

here $z_i \in \mathbb{R}^d$ are p landmarks or inducing points or model centers in the domain \mathbb{X} are better suited when training on very large datasets, i.e., when $n \geq 1$ billion samples [24]. Such models have received renewed attention [1, 2, 27]. They can be trained via

$$\min_{f \in \mathbb{H}} \sum_{i=1}^n (f(x_i) - y_i)^2 \quad \text{subject to (Gen-KM)}, \quad (8)$$

where \mathbb{H} is the reproducing kernel hilbert space (RKHS) corresponding to the kernel K .

3 ALGORITHM DERIVATION

All proofs in this section are in the Appendix.

Overview. We start by describing the derivation of EigenPro, which emulates a preconditioned SGD iteration in the RKHS [22]. We then derive AxlePro given in Algorithm 3, which extends EigenPro by applying a specific momentum acceleration inspired by the MaSS¹

¹MaSS stands for Momentum-added Stochastic Solver, and it adjusts the momentum updates in the standard Nesterov momentum update of SGD to achieve the fast rate when interpolation is possible, as is typical with overparameterized models. See [20] for a detailed discussion.

algorithm from [20]. Finally we derive the faster version AxlePro 2 in Algorithm 1, which extends EigenPro 2 [23]. Similar to EigenPro 2 our algorithm AxlePro 2 applies an approximate preconditioner in AxlePro obtained via a Nyström approximation [3].

Consider the optimization problem,

$$f^* = \arg \min_{f \in \mathbb{H}} \mathcal{L}(f) = \frac{1}{2n} \|Sf - Y\|^2. \quad (9)$$

The minimum-norm solution to the above problem is equation (KM) with $\alpha^* = \text{solve}(K, X, Y)$ from equation (1).

For $f \in \mathcal{H}$, the gradient and Hessian of \mathcal{L} at f are

$$\nabla_f \mathcal{L}(f) = \frac{1}{n} S^* (Sf - Y) \text{ and } \nabla_f^2 \mathcal{L}(f) = \frac{1}{n} S^* S = \mathcal{K}.$$

Note this is the Fréchet derivative, and belongs to the RKHS $\nabla_f \mathcal{L} \in \mathbb{H}$, and the Hessian is an operator on the RKHS $\nabla_f^2 \mathcal{L} : \mathbb{H} \rightarrow \mathbb{H}$.

Note that for a minibatch $B \subset \{1, 2, \dots, n\}$ of size $|B| = m$, the stochastic gradient is

$$\tilde{\nabla} \mathcal{L}(f) = \frac{1}{m} S_B^* (S_B f - Y[B]) = \mathcal{K}_B (f - f^*), \quad (10)$$

where we denote by $\mathcal{K}_B := \frac{1}{|B|} S_B^* S_B$.

3.1 EigenPro: Preconditioned SGD in RKHS

Our goal is to solve equation (9). If we start by initializing $f_0 \in \text{range}(S^*)$, then one can show that the iterates f_t of gradient descent

$$f_{t+1} = f_t - \eta \nabla \mathcal{L}(f_t) = f_t - \frac{\eta}{n} S^* (Sf_t - Y)$$

also lie in $\text{range}(S^*)$. Hence we can write $f_t = S^* \alpha_t$, by assuming $f_0 \in \text{range}(S^*)$.

Next, SGD in \mathbb{H} , with learning rate η_0 , can be written as

$$f_{t+1} \leftarrow f_t - \eta_0 \tilde{\nabla} \mathcal{L}(f_t). \quad (11)$$

and converges exponentially as shown in [21, Theorem 1].

Proposition 1. *The following update equations*

$$\mathbf{v}_t \leftarrow K(X[B], X) \alpha_t - Y[B] \quad (12a)$$

$$\alpha_{t+1} \leftarrow \alpha_t - \eta_0 \mathbf{H}_B^\top \mathbf{v}_t. \quad (12b)$$

emulate one step of updates in equation (11) via the relation $f_t = S^ \alpha_t$.*

Remark 2. To avoid carrying around $\frac{1}{|B|}$ in all expressions, we henceforth absorb $\frac{1}{|B|}$ in the learning rate η , which anyway has a non-trivial dependence on batch size $|B|$ for the optimal setting.

3.2 MaSS in RKHS

The MaSS updates in \mathbb{H} , following the update rule from [20] yields

$$f_{t+1} \leftarrow g_t - \eta_1 \tilde{\nabla}_f \mathbf{L}(g_t), \quad (13a)$$

$$g_{t+1} \leftarrow (1 + \gamma)f_{t+1} - \gamma f_t + \eta_2 \tilde{\nabla}_f \mathbf{L}(g_t), \quad (13b)$$

where $\eta_1, \eta_2 > 0$ are learning rates and $\gamma \in (0, 1)$ is a damping factor.

Remark 3. Note that for $\gamma = 0$, this is equivalent to SGD with learning rate $\eta_0 = \eta_1 - \eta_2$.

This iteration converges exponentially fast as shown in [20, Theorem 2].

Now, suppose $f_t, g_t \in \text{range}(S^*)$, then f_{t+1} and g_{t+1} are still in $\text{range}(S^*)$, when $\tilde{\nabla}_f \mathbf{L}(f_t) \in \text{range}(S_B^*)$.

Proposition 2. *The following update equations*

$$\mathbf{v}_t \leftarrow K(X[B], X)\beta_t - Y[B] \quad (14a)$$

$$\alpha_{t+1} \leftarrow \beta_t - \eta_1 \mathbf{H}_B^\top \mathbf{v}_t, \quad (14b)$$

$$\beta_{t+1} \leftarrow (1 + \gamma)\alpha_{t+1} - \gamma\alpha_t + \eta_2 \mathbf{H}_B^\top \mathbf{v}_t, \quad (14c)$$

emulate one step of updates in equation (13) via the relation $f_t := S^ \alpha_t$ and $g_t := S^* \beta_t$.*

The proof is similar to that of Proposition 1.

3.3 AxlePro: Preconditioned MaSS in RKHS

A key challenge in the convergence rate of iterative methods is that the condition numbers of kernel matrices $K(X, X)$ are very high. Consequently, the iterative algorithms take a large number of iterations to converge, typically κ or $\sqrt{\kappa}$ where κ is the condition number of $K(X, X)$. Several strategies for preconditioning have been studied in the literature [13, 14]. We use the following spectral preconditioner because it is easiest to approximate elegantly, as shown in [3].

Recall that ψ_i are eigenvectors of \mathcal{K} . The spectral preconditioner $\mathcal{P} : \mathbb{H} \rightarrow \mathbb{H}$ is given by,

$$\mathcal{P} := \mathcal{I} - \sum_{i=1}^q \left(1 - \frac{\lambda_{q+1}}{\lambda_i}\right) \psi_i \otimes_{\mathbb{H}} \psi_i. \quad (15)$$

Note that $\mathcal{P}f = f - \sum_{i=1}^q \left(1 - \frac{\lambda_{q+1}}{\lambda_i}\right) \langle f, \psi_i \rangle_{\mathbb{H}} \psi_i$. This choice of preconditioner is motivated by the fact that the largest eigenvalue of \mathcal{K} is λ_1/n , whereas the largest eigenvalue of $\mathcal{P}\mathcal{K}$ is λ_{q+1}/n , which governs the convergence rate. Furthermore, their smallest eigenvalues are the same, λ_n . Note that here we have used the fact that $\|\psi_i\|_{\mathbb{H}} = 1$.

Suppose we precondition the gradients before making any updates. Then the preconditioned MaSS update

equations in \mathbb{H} become

$$f_{t+1} \leftarrow g_t - \eta_1 \mathcal{P} \tilde{\nabla}_f \mathbf{L}(g_t), \quad (16a)$$

$$g_{t+1} \leftarrow (1 + \gamma)f_{t+1} - \gamma f_t + \eta_2 \mathcal{P} \tilde{\nabla}_f \mathbf{L}(g_t). \quad (16b)$$

Define $\mathbf{F} = \mathbf{E} \sqrt{I_q - \lambda_{q+1} \Lambda^{-1}} \in \mathbb{R}^{n \times q}$ where $(\mathbf{E}, \Lambda, \lambda_{q+1})$ is the top- q eigensystem of $K(X, X)$.

Proposition 3. *The following update equations*

$$\mathbf{v}_t \leftarrow K(X_m, X)\beta_t - Y[B] \in \mathbb{R}^m \quad (17a)$$

$$\mathbf{w}_t \leftarrow \mathbf{F} \mathbf{F}^\top \mathbf{H}_B^\top \mathbf{v}_t \in \mathbb{R}^n \quad (17b)$$

$$\alpha_{t+1} \leftarrow \beta_t - \eta_1 \mathbf{H}_B^\top \mathbf{v}_t + \eta_1 \mathbf{w}_t \quad (17c)$$

$$\beta_{t+1} \leftarrow (1 + \gamma)\alpha_{t+1} - \gamma\alpha_t + \eta_2 \mathbf{H}_B^\top \mathbf{v}_t - \eta_2 \mathbf{w}_t \quad (17d)$$

emulate the updates in equation (16) via the relation $f_t := S^ \alpha_t$ and $g_t := S^* \beta_t$.*

Remark 4. In Algorithm 3, lines (11-13) together implement equation (17c), whereas lines (14-16) together implement equation (17d). Note that here we have used the fact that $\mathbf{H}_B \mathbf{F} = \mathbf{F}[B] \in \mathbb{R}^{m \times q}$.

3.4 AxlePro 2: Approximating preconditioner via a Nyström extension

Suppose J is a subset of s distinct indices from $\{1, 2, \dots, n\}$. Define the approximate preconditioner

$$\mathcal{Q} := \mathcal{I} - \sum_{i=1}^q \left(1 - \frac{\delta_{q+1}}{\delta_i}\right) \phi_i \otimes \phi_i. \quad (18)$$

where $(\phi_i, \frac{\delta_i}{s})$ are eigenpairs of \mathcal{K}_J , and (\mathbf{d}_i, δ_i) are eigenpairs of $K(X[J], X[J])$, with $\|\phi_i\|_{\mathbb{H}} = 1$. Note that we still have the relation $\phi_i = \frac{S_J^* \mathbf{d}_i}{\sqrt{\delta_i}}$.

In the context of kernels the preconditioner in (18) is an effective approximation to (15), since it approximate the head of the spectrum well enough. See [3] for a thorough treatment on the approximation error.

Recall Definition 2 of a top- q eigensystem, and define $\mathbf{G} = \mathbf{D} \sqrt{\Delta^{-1}(I_q - \delta_{q+1} \Delta^{-1})} \in \mathbb{R}^{s \times q}$ where $(\mathbf{D}, \Delta, \delta_{q+1})$ is the top- q eigensystem of $K(X[J], X[J])$.

Proposition 4. *The following update equations*

$$\mathbf{v}_t \leftarrow K(X[B], X)\beta_t - Y[B] \in \mathbb{R}^m \quad (19a)$$

$$\mathbf{w}_t \leftarrow \mathbf{G} \mathbf{G}^\top K(X[J], X[B])\mathbf{v}_t \in \mathbb{R}^s \quad (19b)$$

$$\alpha_{t+1} \leftarrow \beta_t - \eta_1 \mathbf{H}_B^\top \mathbf{v}_t + \eta_1 \mathbf{H}_J^\top \mathbf{w}_t \quad (19c)$$

$$\beta_{t+1} \leftarrow (1 + \gamma)\alpha_{t+1} - \gamma\alpha_t + \eta_2 \mathbf{H}_B^\top \mathbf{v}_t - \eta_2 \mathbf{H}_J^\top \mathbf{w}_t \quad (19d)$$

emulate the updates (16) with \mathcal{P} replaced by \mathcal{Q} via the relation $f_t := S^ \alpha_t$ and $g_t := S^* \beta_t$.*

Remark 5. In Algorithm 1, lines 12-14 together implement equation (19c), whereas lines 21-17 together implement equation (19d).

Algorithm 2 AxlePro 4

1: **Input:** positive definite kernel K , batch size m , size of approximate preconditioner s , level of preconditioner q , learning rates $\eta_1, \eta_2 > 0$, damping factor $\gamma \in (0, 1)$, model centers $Z = \{z_i\}_{i=1}^p$.

2: **Output:** $f : \mathcal{X} \rightarrow \mathbb{R}$ solving (9) approximately.

3: **setup:** Sample $J \subset \{1, 2, \dots, n\}$ with $|J| = s$.

4: $(\mathbf{D}, \Delta, \delta_{q+1}) \leftarrow$ top- q eigensystem of $K(X[J], X[J])$

5: $\mathbf{G} \leftarrow \mathbf{D} \sqrt{\Delta^{-1}(I_q - \delta_{q+1} \Delta^{-1})} \in \mathbb{R}^{s \times q}$

6: Initialize $\alpha = \beta = \mathbf{0}_p$, $\mathbf{a} = \mathbf{b} = \mathbf{0}_n$, $\mathbf{c} = \mathbf{d} = \mathbf{0}_s$.

7: **repeat**

8: Fetch batch of indices $B \subset \{1, \dots, n\}$, $|B| = m$

9: $\mathbf{v} \leftarrow K(X[B], Z)\beta - Y[B] \in \mathbb{R}^m$

10: $\mathbf{v} \leftarrow \mathbf{v} + K(X[B], X)\mathbf{b} + K(X[B], X[J])\mathbf{d}$

11: $\mathbf{w} \leftarrow \mathbf{G}\mathbf{G}^\top K(X[J], X[B])\mathbf{v} \in \mathbb{R}^s$

12: $\tilde{\alpha} \leftarrow \alpha$

13: $\tilde{\mathbf{a}} \leftarrow \mathbf{a}$

14: $\tilde{\mathbf{c}} \leftarrow \mathbf{c}$

15: $\alpha \leftarrow \beta$

16: $\beta \leftarrow (1 + \gamma)\alpha - \gamma\tilde{\alpha}$

17: $\mathbf{c} \leftarrow \mathbf{d} + \eta_1 \mathbf{w}$

18: $\mathbf{d} \leftarrow (1 + \gamma)\mathbf{c} - \gamma\tilde{\mathbf{c}} - \eta_2 \mathbf{w}$

19: $\mathbf{a} \leftarrow \mathbf{b}$

20: $\mathbf{a}[B] \leftarrow \mathbf{a}[B] - \eta_1 \mathbf{v}$

21: $\mathbf{b} \leftarrow (1 + \gamma)\mathbf{a} - \gamma\tilde{\mathbf{a}}$

22: $\mathbf{b}[B] \leftarrow \mathbf{b}[B] + \eta_2 \mathbf{v}$

23: **if** projection condition holds **then**

24: $\mathbf{A} \leftarrow K(Z, X)\mathbf{a} + K(Z, X[J])\mathbf{c} \in \mathbb{R}^p$

25: $\alpha \leftarrow \alpha + \text{K.solve}(K, Z, \mathbf{A})$

26: $\mathbf{C} \leftarrow K(Z, X)\mathbf{b} + K(Z, X[J])\mathbf{d} \in \mathbb{R}^n$

27: $\beta \leftarrow \beta + \text{solve}(K, Z, \mathbf{C})$

28: Reset $\mathbf{a} = \mathbf{b} = \mathbf{0}_n$, $\mathbf{c} = \mathbf{d} = \mathbf{0}_s$

29: **end if**

30: **until** Stopping criterion is reached

31: **return** $f(x) = \sum_{i=1}^n \alpha_i K(x, z_i)$

3.5 AxlePro 4: Training general kernel models

Since the model is constrained to be in a subspace $\mathcal{M} = \{K(\cdot, z_i)\}_{i=1}^p \subset \mathbb{H}$, we must apply projected PSGD with momentum acceleration.

However, an approximate projection costs $O(p^2)$ for a model with p centers, whereas the PSGD step with momentum costs $O(mp)$ for a batch of size m . To amortize the cost of projection, we delay the projection step until after $T = \frac{p}{m}$ steps. This leads to a per iteration complexity of $\tilde{O}(mp)$ on average. This idea is similar to the strategy in EigenPro4 from [2].

This leads to the following update equations. For $t = kT + 1, kT + 2, \dots, (k+1)T - 1$

$$f_{t+1} = g_t - \eta_1 \mathcal{Q}\tilde{\nabla} \mathbf{L}(g_t) \quad (20a)$$

$$g_{t+1} = (1 + \gamma)f_{t+1} - \gamma f_t + \eta_2 \mathcal{Q}\tilde{\nabla} \mathbf{L}(g_t) \quad (20b)$$

whereas for $t = kT$, we perform the step

$$f_{kT} = \arg \min_{f \in \mathcal{M}} \|f - f_{kT-1}\|_{\mathbb{H}}^2 \quad (21a)$$

$$g_{kT} = \arg \min_{g \in \mathcal{M}} \|g - g_{kT-1}\|_{\mathbb{H}}^2 \quad (21b)$$

Proposition 5. *Algorithm 2 emulates equations (20) and (21) with $f_0 = g_0 = \mathbf{0}_{\mathbb{H}}$.*

The proof of this proposition has been provided in the Appendix for completeness. Note however, that f_t and g_t for $t \neq kT$ also have components that are not in \mathcal{M} . However they are in $\text{span}(\{K(\cdot, x_i)\}_{i=1}^n)$, and hence can be tracked through the updates.

4 CONVERGENCE ANALYSIS

We provide a convergence for Algorithm 1. Proofs of intermediate results are in the Appendix.

We need to define a few quantities to describe the convergence properties of Algorithm 1. Let $\lambda_1 \geq \lambda_2 \geq \dots \geq \lambda_n > 0$ be the eigenvalues of $K(X, X)$. Let $\mathbf{e}_i = (e_{i1}, e_{i2}, \dots, e_{in}) \in \mathbb{R}^n$ be the eigenvector of $K(X, X)$ corresponding to eigenvalue λ_i . Define

$$L_1 := \max_{j \in [n]} K(x_j, x_j) - \sum_{i=1}^q e_{ij}^2 (\lambda_i - \lambda_{q+1}) \quad (22a)$$

$$L_m := L_1/m + (m-1)\lambda_{q+1}/m \quad (22b)$$

$$\kappa_m := L_m/\lambda_n \quad (22c)$$

$$\tilde{\kappa}_m := n/m + (m-1)/m \quad (22d)$$

Consider hyperparameters,

$$\eta_1^* = \frac{1}{L_m} \quad (23a)$$

$$\eta_2^* = \frac{\eta_1^*(m)\sqrt{\kappa_m \tilde{\kappa}_m}}{\sqrt{\kappa_m \tilde{\kappa}_m} + 1} \left(1 - \frac{1}{\tilde{\kappa}_m}\right) \quad (23b)$$

$$\gamma^* = \frac{\sqrt{\kappa_m \tilde{\kappa}_m} - 1}{\sqrt{\kappa_m \tilde{\kappa}_m} + 1} \quad (23c)$$

Let $\varepsilon > 0$ and $\delta \in (0, 1)$ be parameters for controlling the approximation error of Nyström approximate preconditioner defined in equation (18).

Theorem 6. *Fix $\varepsilon > 0$ and $\delta \in (0, 1)$. Suppose X consists of i.i.d. samples from an arbitrary distribution on \mathbb{X} , and J consists of distinct indices chosen from $\{1, 2, \dots, n\}$, independent of X with*

$$|J| \geq c \cdot \frac{\log^4(1+n)}{\varepsilon^4} \log \frac{4}{\delta}.$$

for some universal constant c . Now, suppose Algorithm 1 is run for t iterations with hyperparameters given by equation (23). Then, with probability at least

$1 - \delta$ over the randomness in X , we have the following upper bound for a constant C ,

$$\|f_t - f^*\|_{\mathbb{H}}^2 \leq C \cdot \exp\left(\frac{-t/(1+\varepsilon)^2}{\sqrt{\kappa_m \kappa_m}}\right). \quad (24)$$

Proof of Theorem 6. Note that by Proposition 4, Algorithm 1 is emulating the updates

$$f_{t+1} \leftarrow g_t - \eta_1 \mathcal{Q} \tilde{\nabla}_f \mathcal{L}(g_t), \quad (25a)$$

$$g_{t+1} \leftarrow (1+\gamma)f_{t+1} - \gamma f_t + \eta_2 \mathcal{Q} \tilde{\nabla}_f \mathcal{L}(g_t). \quad (25b)$$

Rewriting the above in terms of $\tilde{\nabla} \mathcal{L}(f_t) = \mathcal{K}_{B_t}(f_t - f^*)$ from (70), and subtracting f^* on both sides in the updates (25), we get

$$f_{t+1} - f^* \leftarrow g_t - f^* - \eta_1 \mathcal{Q} \mathcal{K}_{B_t}(g_t - f^*), \quad (26a)$$

$$g_{t+1} - f^* \leftarrow (1+\gamma)(f_{t+1} - f^*) - \gamma(f_t - f^*) + \eta_2 \mathcal{Q} \mathcal{K}_{B_t}(g_t - f^*). \quad (26b)$$

To proceed, we need the following technical lemma.

Lemma 7. *Consider the data dependent kernel*

$$\hat{K}_q(x, z) = K(x, z) - K(x, X[J]) \mathbf{G} \mathbf{G}^\top K(X[J], z)$$

and $\hat{\mathbb{H}}_q$ be the RKHS associated with \hat{K}_q . Define the operator $T : \mathbb{H} \rightarrow \hat{\mathbb{H}}_q$ such that $T(K(\cdot, x)) = \hat{K}_q(\cdot, x)$.

- (a) $T^* f = f_{\mathbb{H}}$, where $f_{\mathbb{H}} \in \mathbb{H}$ is pointwise the same function as $f \in \hat{\mathbb{H}}_q$.
- (b) $T^* T = \mathcal{Q}$
- (c) $R = ST^*$ is the sampling operator $\hat{\mathbb{H}}_q \rightarrow \mathbb{R}^n$ such that $R\hat{f} = \hat{f}(X) \in \mathbb{R}^n$ for all $\hat{f} \in \hat{\mathbb{H}}_q$.
- (d) $\hat{\mathbb{H}}_q$ is equivalent to \mathbb{H} , i.e., there exist constants a, a' such that $a\|f\|_{\mathbb{H}} \leq \|\hat{f}\|_{\hat{\mathbb{H}}_q} \leq a'\|f\|_{\mathbb{H}}$.
- (e) $TKT^* = \frac{1}{n}R^*R$ is the empirical covariance operator of the kernel \hat{K}_q , and $R^*R = \hat{K}_q(X, X)$.

Proof. (a) Note that by definition

$$\left\langle TK(\cdot, x), \hat{K}_q(\cdot, z) \right\rangle_{\hat{\mathbb{H}}_q} = (TK(\cdot, x))(z) = \hat{K}_q(z, x)$$

$$\left\langle K(\cdot, x), T^* \hat{K}_q(\cdot, z) \right\rangle_{\mathbb{H}} = \left(T^* \hat{K}_q(\cdot, z) \right)(x)$$

which proves the claim in (a). Parts (b), (c), (e) follow immediately. Proof of (d) is in the Appendix. \square

Defining $\hat{f}_t := T^{*-1}(f_t - f^*)$ and $\hat{g}_t := T^{*-1}(g_t - f^*)$, and using the fact that $\mathcal{Q} = T^*T$, we can write (26) as

$$\hat{f}_{t+1} \leftarrow \hat{g}_t - \eta_1 TK_{B_t} T^* \hat{g}_t, \quad (27a)$$

$$\hat{g}_{t+1} \leftarrow (1+\gamma)\hat{f}_{t+1} - \gamma\hat{f}_t + \eta_2 TK_{B_t} T^* \hat{g}_t. \quad (27b)$$

Note that in equation (27), we have that $\mathbb{E}_{B_t} TK_{B_t} T^* = TKT^* = \frac{1}{n}R^*R$. Hence the above iteration is (13) specialized to solve

$$\min_{f \in \hat{\mathbb{H}}_q} \frac{1}{2} \|Rf - Y\|^2. \quad (28)$$

however in this case the stochastic gradients will be $\frac{1}{|B_t|} R_{B_t}^* R_{B_t} = TK_{B_t} T^*$, and expected Hessian TKT^* .

Specializing the convergence result of [20, Thm. 2] for the case of square loss and search space $\hat{\mathbb{H}}_q$, we can conclude that for hyperparameters in equations (23), updates (27) converge as

$$\|\hat{f}_t\|_{\hat{\mathbb{H}}_q}^2 \leq \exp\left(-t/\sqrt{\tilde{c}_m c_m}\right) \|T^{*-1} f^*\|_{\hat{\mathbb{H}}_q}^2 \quad (29)$$

where

$$\tilde{c}_m = \frac{1}{m} \cdot \mathbb{E} \left\| \hat{K}_q(\cdot, x) \right\|_{(TK_q T^*)^{-1}} + \frac{m-1}{m} \quad (30a)$$

$$c_m = d_m / \lambda_n(R^*R) \quad (30b)$$

$$d_m = d_1 / m + (m-1)\lambda_1(R^*R) / m \quad (30c)$$

$$d_1 = \max_{\hat{f} \in \text{range}(R^*)} \left\| \hat{f} \right\|_{\hat{\mathbb{H}}_q}^2 \quad (30d)$$

We also have the following result.

Proposition 8 ([3, Thm. 2]). *Let X and J satisfy assumptions stated in Theorem 6, then with probability at least $1 - \delta$ over the randomness in X and J , the following inequalities hold*

$$\lambda_1(\mathcal{R}) \leq (1+\varepsilon)^2 \lambda_1(\mathcal{PK}) = n(1+\varepsilon)^2 \lambda_{q+1}, \quad (31a)$$

$$\lambda_n(R^*R) \geq (1+\varepsilon)^2 \lambda_n(\mathcal{PK}) = n \frac{1}{(1+\varepsilon)^2} \lambda_n. \quad (31b)$$

Due to the above proposition, we have that $c_m \leq (1+\varepsilon)^4 \kappa_m$. In the Appendix, we show that $d_1 = L_1$ whereby $d_m = L_m$ and we also show that $\tilde{c}_m = \tilde{\kappa}_m$, which leads to the bound

$$\|f_t - f^*\|_{\hat{\mathbb{H}}_q}^2 \leq \exp\left(\frac{-t/(1+\varepsilon)^2}{\sqrt{\tilde{\kappa}_m \kappa_m}}\right) \|T^{*-1} f^*\|_{\hat{\mathbb{H}}_q}^2. \quad (32)$$

Eq. (24) follows due to equivalence of \mathbb{H} and $\hat{\mathbb{H}}_q$. \square

5 NUMERICAL EXPERIMENTS

Due to space limitations, only a few key experiments are presented in the main paper while other variants are provided in the Appendix.

All experiments are solving equation (1) and show the mean squared error (MSE) over the training dataset. Note that all plots use a log-scale on the Y-axis. Experiments were run on a machine with 32GB RAM, 1

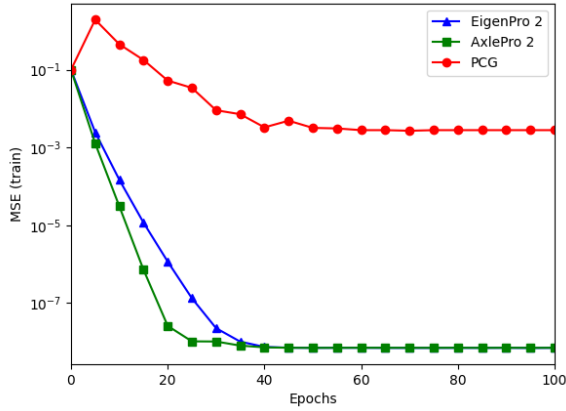


Figure 2: **Numerical stability to low precision.** Convergence comparison on CIFAR10 dataset with Laplacian kernel over single precision arithmetic.

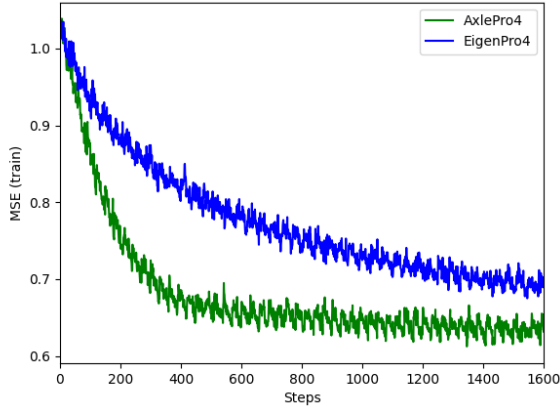


Figure 3: Progress of Algorithm 2 v/s EigenPro 4 from [2] with respect to number of steps on randomly generated dataset ($n = 6000, p = 3000$).

NVIDIA V100 SMX2 with 32GB VRAM, and 1 Xeon Gold 6248 CPU.

Our experiments were conducted on the following datasets: CIFAR-10, Stellar Classification, and EMNIST Digits. We test the performance for both Gaussian kernel and Laplacian kernel. For CIFAR-10 dataset, we also compare the performance with Myrtle-5 kernel [32], which is the state-of-the-art kernel for this dataset. Experiment details are in Appendix D.

The batch size is set to be the same for AxlePro and EigenPro. This batch size is optimized to minimize total computation time by maximizing GPU utilization, see [23] for a detailed discussion on this topic.

For AxlePro, the only hyperparameter needs to be tuned

Dataset	Algorithm	Gaussian	Laplacian
CIFAR10 $n = 50,000$ $d = 3072$	AxlePro	48.35%	58.84%
	EigenPro	49.38%	58.84%
	CG	28.35%	54.11%
	PCG	45.32%	58.84%
	Falkon	53.37%	56.47%
	GPyTorch	10.00%	-
Stellar Classification $n = 95,000$ $d = 13$	AxlePro	95.92%	94.84%
	EigenPro	95.42%	94.84%
	CG	61.78%	94.52%
	PCG	19.68%	94.84%
	Falkon	95.80%	94.90%
	GPyTorch	92.10%	-
EMNIST digits $n = 240,000$ $d = 784$	AxlePro	99.40%	99.12%
	EigenPro	99.40%	99.12%
	CG	95.78%	99.15%
	PCG	98.56%	99.12%
	Falkon	98.94%	98.45%
	GPyTorch	87.31%	-

Table 3: Performance comparison in terms of test accuracy between different methods for training kernel models with Gaussian and Laplacian kernels.

is the smallest eigenvalue of the kernel matrix due to the Nyström approximation and we chose this factor from according to the datasets.

We follow the standard PCG algorithm used in [15], which computes the precondition matrix based on the pivoted Cholesky decomposition [6, 17]. And we set the rank of approximation to be 300.

6 DISCUSSION

In this paper we presented a derivation for an algorithm AxlePro, for training kernel models using a momentum accelerated version of preconditioned SGD in the RKHS. We provided a convergence guarantee in Theorem 6, and compared the performance with other algorithms.

While AxlePro emulates accelerated PSGD with approximate preconditioning, other iterative updates such as ADAM and its variants cannot be emulated as elegantly via finite dimensional updates. This is primarily because we use a spectral preconditioner among other options available for preconditioning. Deriving other emulated algorithms would lead us to the optimal performance for training kernel methods. Extending this work beyond the square loss would also be useful. However going beyond square loss remains unresolved even for the EigenPro family of algorithms. The main challenge in doing so remains managing the complexity of approximating the preconditioner at each iteration.

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Appendices

A Notation

Table 4: **Notation**

n	number of samples
$x_i \in \mathcal{X}, y_i \in \mathbb{R}$	input, target
$Y \in \mathbb{R}^n$	vector of targets $(y_i) \in \mathbb{R}^n$
$X = (x_1, x_2, \dots, x_n)$	tuple of inputs
$K : \mathcal{X} \times \mathcal{X} \rightarrow \mathbb{R}$	positive definite kernel with \mathbb{H} as its RKHS.
$S : \mathbb{H} \rightarrow \mathbb{R}^n$	Sampling operator, defined as $S(f) = f(X) = (f(x_i)) \in \mathbb{R}^n$
$S^* : \mathbb{R}^n \rightarrow \mathbb{H}$	Adjoint of sampling operator, defined as $S^* \alpha = \sum_{i=1}^n K(\cdot, x) \alpha_i$
\mathcal{K}	empirical covariance operator using n samples, defined as $\frac{1}{n} S S^* : \mathbb{H} \rightarrow \mathbb{H}$
$K(X, X)$	kernel matrix. Also equals $S S^*$
B	mini-batch of indices, subset of $\{1, 2, \dots, n\}$
$m = B $	batch size
$X[B] \in \mathcal{X}^m$	minibatch of size m
$\mathbf{v}[B] \in \mathbb{R}^m$	subvector of $\mathbf{v} \in \mathbb{R}^n$ corresponding to indices B
\mathbf{H}_B	selector matrix, rows of I_n corresponding to B , so that $\mathbf{v}[B] = \mathbf{H}_B \mathbf{v}$.
q	level of preconditioner
$(\mathbf{E}, \Lambda, \lambda_{q+1})$	top- q eigensystem of $K(X, X)$
$\mathcal{P} : \mathbb{H} \rightarrow \mathbb{H}$	preconditioner in \mathbb{H} defined as $\mathcal{I} - \sum_{i=1}^q \left(1 - \frac{\lambda_{q+1}}{\lambda_i}\right) \psi_i \otimes_{\mathbb{H}} \psi_i$ where $\psi_i = S^* \mathbf{e}_i / \sqrt{\lambda_i} \in \mathbb{H}$ are top- q eigenfunction of \mathcal{K} with eigenvalues $\frac{1}{n} \lambda_i$
\mathbf{F}	rescaled eigenvectors defined as $\mathbf{E} \sqrt{I_q - \lambda_{q+1} \Lambda^{-1}}$
$\mathbf{F}[B]$	rows of \mathbf{F} corresponding to the mini-batch B
J	subset of indices $\{1, 2, \dots, n\}$ to obtain Nyström approximation of \mathcal{P}
$s = J $	size of Nyström subset
$X[J]$	Nyström subsample of size s
$(\mathbf{D}, \Delta, \delta_{q+1})$	top- q eigensystem of $\frac{1}{n} K(X[J], X[J])$
$\mathcal{Q} : \mathbb{H} \rightarrow \mathbb{H}$	Nyström approximation of \mathcal{P} defined as $\mathcal{I} - \sum_{i=1}^q \left(1 - \frac{\delta_{q+1}}{\delta_i}\right) \phi_i \otimes_{\mathbb{H}} \phi_i$ where $(\delta_i/s, \phi_i)$ is an eigen-pair of $\frac{1}{s} S_J^* S_J$
\mathbf{G}	rescaled eigenvectors defined as $\mathbf{D} \sqrt{(I_q - \delta_{q+1} \Delta^{-1}) \Delta^{-1}}$

B EigenPro algorithms

Lemma 9. Suppose Algorithm 3 is run for t iterations with hyperparameters given by equation (23), then we have,

$$\|f_t - f^*\|_{\mathbb{H}}^2 \leq \exp\left(-t/\sqrt{\tilde{\kappa}_m \kappa_m}\right) \|f^*\|_{\mathbb{H}}^2. \quad (33)$$

Proof. This is an immediate corollary of [20, Theorem 2] and the discussion that ensues therein on the convergence rate of MaSS. Preconditioning only changes the largest eigenvalue from λ_1 to λ_{q+1} . This can via the following reduction commonly applied to analyze spectral preconditioning: (16) is actually (13) with the following modified kernel,

$$\tilde{K}(x, z) := K(x, z) - K(x, X) \mathbf{E} \mathbf{Q} \mathbf{E}^\top K(X, z), \quad (34)$$

where $\mathbf{Q} = \Lambda^{-1}(I_q - \lambda_{q+1} \Lambda^{-1})$, where $(\mathbf{E}, \Lambda, \lambda_{q+1})$ is the top- q eigensystem of $K(X, X)$. An interested reader can find this reduction argument in [22, 23]. The largest eigenvalue of $\tilde{K}(X, X)$ can be verified to be λ_{q+1} .

The other key difference is the quantities L_1 and $\tilde{\kappa}_m$ defined in [20]. Using elementary properties of our Hilbert space \mathbb{H} , we can easily show that our L_1 and $\tilde{\kappa}_m$ are upper bounds to these quantities in [20]. \square

Algorithm 3 AxlePro

1: **Input:** positive definite kernel K , batch size m , learning rates $\eta_1, \eta_2 > 0$, damp factor $\gamma \in (0, 1)$.
2: **Output:** $f : \mathcal{X} \rightarrow \mathbb{R}$ solving (9) approximately.
3: **setup:** $\alpha \leftarrow \mathbf{0}_n$, and $\beta \leftarrow \mathbf{0}_n$.
4: $(\mathbf{E}, \Lambda, \lambda_{q+1}) \leftarrow$ top- q eigensystem of $K(X, X)$
5: $\mathbf{F} \leftarrow \mathbf{E} \sqrt{I_q - \lambda_{q+1} \Lambda^{-1}} \in \mathbb{R}^{n \times q}$
6: **repeat**
7: Fetch batch of indices $B \subset \{1, \dots, n\}$, $|B| = m$
8: $\mathbf{v} \leftarrow K(X[B], X)\beta - Y[B] \in \mathbb{R}^m$
9: $\mathbf{w} \leftarrow \mathbf{F} \mathbf{F}[B]^\top \mathbf{v} \in \mathbb{R}^n$
10: $\tilde{\alpha} \leftarrow \alpha$ {copy state for momentum}
11: $\alpha \leftarrow \beta$
12: $\alpha[B]^- \leftarrow \eta_1 \mathbf{v}$ {gradient step-1}
13: $\alpha^+ \leftarrow \eta_1 \mathbf{w}$ {correction-1}
14: $\beta \leftarrow \alpha + \gamma(\alpha - \tilde{\alpha})$ {momentum}
15: $\beta[B]^+ \leftarrow \eta_2 \mathbf{v}$ {gradient step-2}
16: $\beta^- \leftarrow \eta_2 \mathbf{w}$ {correction-2}
17: **until** Stopping criterion is reached
18: **return** $f(x) = \sum_{i=1}^n \alpha_i K(x, x_i)$

Algorithm	FLOPS/batch	memory
EigenPro 2	$nm + sm + 2sq + m + s$	$n + sq$
AxlePro 2	$nm + sm + 2sq + \mathbf{2m} + \mathbf{2s} + \mathbf{n}$	$\mathbf{2n} + sq$
EigenPro 3	$2pm + ps + ms + 2sq + m + p$	$p + sq$
AxlePro 3	$2pm + ps + ms + 2sq + \mathbf{2m} + \mathbf{2p}$	$\mathbf{2p} + sq$

Table 5: The bolded quantities indicate overheads due to preconditioning. Here $s = |J|$. We have omitted the lower-order terms of n and $2n$ in the per iteration time since they are dominated by mn . Memory requirement and per iteration complexity of EigenPro and AxlePro. The algorithm AxlePro is based on applying momentum acceleration to EigenPro [22], whereas AxlePro 2 is based on applying momentum acceleration to EigenPro 2 [23]. The overhead of storing the previous parameter is n as seen the last column.

C Numerical Experiments (continued)

See Table 6, Table 7, Table 8, Table 9, Table 10 for experiment comparisons.

D Details on Numerical Experiments

Hardware. Experiments were run on the SDSC Expanse GPU cluster with 32GB RAM, with 1 NVIDIA V100 SMX2 with 32GB VRAM, and 1 Xeon Gold 6248 CPU.

Datasets and Kernels. Our experiments were conducted on the following datasets: Cifar-10($n = 50,000, d = 3072$), Stellar Classification($n = 95,000, d = 13$), and EMNIST Digits($n = 240,000, d = 784$). We test the performance for both Gaussian kernel and Laplacian kernel. And for Cifar-10 dataset, we also compare the performance with Myrtle-5 kernel [32], which is the state-of-the-art kernel for this dataset.

1. **EigenPro.** We select the precondition level based on the GPU memory so that the batch size at the linear rate regime critical point m_1^* fully exploits GPU memory. This step involves computing eigenpairs of the kernel matrix and we use Nyström approximation with $20k$ subsamples. The optimal learning rate can also be computed using the computed eigenpairs.

2. **AxlePro.** For the precondition level, we follow the same way as in Eigenpro. The only hyperparameter needs to be tuned is the smallest eigenvalue of the kernel matrix due to the Nyström approximation and we choose this factor according to the datasets.

3. **FALKON.** According to the GPU memory, we set the number of inducing points to be $20k$ with the uniform

Algorithm 4 AxlePro 3

1: **Input:** positive definite kernel K , batch size m , size of approximate preconditioner s , learning rates $\eta_1, \eta_2 > 0$, damping factor $\gamma \in (0, 1)$, model centers $Z = \{z_i\}_{i=1}^p$.
2: **Output:** $f : \mathcal{X} \rightarrow \mathbb{R}$ solving (9) approximately.
3: **setup:** Sample $J \subset \{1, 2, \dots, n\}$ with $|J| = s$.
4: $(\mathbf{D}, \Delta, \delta_{q+1}) \leftarrow$ top- q eigensystem of $K(X[J], X[J])$
5: $\mathbf{G} \leftarrow \mathbf{D} \sqrt{\Delta^{-1}(I_q - \delta_{q+1}\Delta^{-1})} \in \mathbb{R}^{s \times q}$
6: Initialize $\alpha = \beta = \mathbf{0}_p$.
7: **repeat**
8: Fetch batch of indices $B \subset \{1, \dots, n\}$, $|B| = m$
9: $\mathbf{v} \leftarrow K(X[B], Z)\beta + K(X[B], X)\mathbf{b} + K(X[B], X[J])\mathbf{d} - Y[B] \in \mathbb{R}^m$ {gradient}
10: $\mathbf{w} \leftarrow \mathbf{G}\mathbf{G}^\top K(X[J], X[B])\mathbf{v} \in \mathbb{R}^s$ {correction}
11: $\tilde{\alpha} \leftarrow \alpha$
12: $\tilde{\mathbf{c}} \leftarrow \mathbf{c}$
13: $\alpha \leftarrow \beta$
14: $\beta \leftarrow (1 + \gamma)\alpha - \gamma\tilde{\alpha}$ {momentum-1}
15: $\mathbf{A} \leftarrow K(Z, X)\mathbf{a} + K(Z, X[J])\mathbf{c} \in \mathbb{R}^p$
16: $\alpha \leftarrow \alpha + \text{K_solve}(K, Z, \mathbf{A})$
17: $\mathbf{C} \leftarrow K(Z, X)\mathbf{b} + K(Z, X[J])\mathbf{d} \in \mathbb{R}^n$
18: $\beta \leftarrow \beta + \text{solve}(K, Z, \mathbf{C})$
19: **until** Stopping criterion is reached
20: **return** $f(x) = \sum_{i=1}^n \alpha_i K(x, z_i)$

Algorithm 5 EigenPro 1 [22]

Input: kernel K , batch size m , learning rate $\eta_0 > 0$.
Output: $f : \mathcal{X} \rightarrow \mathbb{R}$ that solves (9) approximately.
setup: $\alpha \leftarrow \mathbf{0}_n$.
 $(\mathbf{E}_q, \Lambda, \lambda_{q+1}) \leftarrow$ top- q eigensystem of $K(X, X)$
 $\mathbf{F}_q \leftarrow \mathbf{E}_q \sqrt{I_q - \lambda_{q+1}\Lambda^{-1}}$
repeat
 Fetch a batch of indices $B \subset \{1, 2, \dots, n\}$
 $\mathbf{v} \leftarrow K(X[B], X)\alpha - Y[B] \in \mathbb{R}^m$
 $\mathbf{w} \leftarrow \mathbf{F}_q \mathbf{F}_q[B]^\top \mathbf{v} \in \mathbb{R}^n$
 $\alpha[B] \leftarrow \alpha[B] - \eta_0 \mathbf{v}$ {gradient step}
 $\alpha \leftarrow \alpha + \eta_0 \mathbf{w}$ {correction}
until Stopping criterion is reached
return $f_t(x) = \sum_{i=1}^n \alpha_i K(x, x_i)$

sampling. We do not use any regularization. We comment here that even in our experiments the MSE does not decrease significantly due to the subsampling, the classification accuracy is indeed increasing during training.

4. PCG. We choose the rank to be 100 for the pivoted Cholesky decomposition.

5. GPYTORCH. We use instances of the class `IndependentMultitaskGPMModel` in order to deal with multiclass classification problems. The optimizer was set to be ‘Adam’ with learning rate 0.05. As in the case of Falkon, while it is hard to notice significant decrease in the logarithmic scale plot of MSE, the classification accuracy is improved during optimization.

Unless otherwise specified, we do not tune λ_n for AxlePro and use the following setup for our experiments.

For Cifar-10 dataset, we scale the data by a factor of 0.05 as our bandwidth selection. With Gaussian kernel, we set $(m, q, s) = (2000, 500, 20, 000)$, while for Laplacian kernel, we use $q = 300$ instead. For the Myrtle5 kernel experiment, we follow the original paper [32] to use ZCA preprocessing (without Leave-One-Outtilting and ZCA augmentation) and store the kernel matrix before performing regression. For this kernel, we set $(m, q, s) = (2000, 300, 10, 000)$.

Algorithm 6 EigenPro 2 [23]

Input: kernel K , batch size m , indices $J = \{j_\ell\}_{\ell=1}^s \subset \{1, 2, \dots, n\}$, learning rate $\eta_0 > 0$.
Output: $f : \mathcal{X} \rightarrow \mathbb{R}$ that solves (9) approximately.
setup: $\alpha \leftarrow \mathbf{0}_n$.
 $(D, \Delta, \delta_{q+1}) \leftarrow$ top- q eigensystem of $K(X[J], X[J])$
 $G \leftarrow D\sqrt{\Delta^{-1}(I_q - \delta_{q+1}\Delta^{-1})}$
repeat
 Fetch a batch of indices $B \subset \{1, 2, \dots, n\}$
 $v \leftarrow K(X[B], X)\alpha - Y[B] \in \mathbb{R}^m$
 $w \leftarrow GG^\top K(X[J], X[B])v \in \mathbb{R}^s$
 $\alpha[B] \leftarrow \alpha[B] - \eta_0 v$ {gradient step}
 $\alpha[J] \leftarrow \alpha[J] + \eta_0 w$ {correction}
until Stopping criterion is reached
return $f_t(x) = \sum_{i=1}^n \alpha_i K(x, x_i)$

Algorithm 7 EigenPro 3 [1]

Input: kernel K , batch size m , centers $Z = \{z_i\}$, indices $J = \{j_\ell\}_{\ell=1}^s \subset \{1, 2, \dots, n\}$, learning rate $\eta_0 > 0$.
Output: $f : \mathcal{X} \rightarrow \mathbb{R}$ that solves (9) approximately.
setup: $\alpha \leftarrow \mathbf{0}_p$.
 $(D, \Delta, \delta_{q+1}) \leftarrow$ top- q eigensystem of $K(X[J], X[J])$
 $G \leftarrow D\sqrt{\Delta^{-1}(I_q - \delta_{q+1}\Delta^{-1})}$
repeat
 Fetch a batch of indices $B \subset \{1, 2, \dots, n\}$
 $v \leftarrow K(X[B], Z)\alpha - Y[B] \in \mathbb{R}^m$ {gradient}
 $w \leftarrow GG^\top K(X[J], X[B])v \in \mathbb{R}^s$ {correction}
 $h \leftarrow K(Z, X[B])v - K(Z, X[J])w$
 $\theta \leftarrow \text{K_solve}(K, Z, h)$ {projection}
 $\alpha \leftarrow \alpha - \eta_0 \cdot \theta$
until Stopping criterion is reached
return $f_t(x) = \sum_{i=1}^n \alpha_i K(x, z_i)$

For Star Classification dataset, we use $(m, q, s) = (2000, 150, 20,000)$ for Gaussian kernel (bandwidth=2) and $(m, q, s) = (2000, 600, 20,000)$ for Laplacian kernel (bandwidth=4). We preprocess the data with mean subtraction and standard deviation normalization.

For EMNIST Digits dataset, we preprocess the data by mean subtraction and scale by a factor of 0.001. We set $(m, q, s) = (700, 600, 20,000)$ for Gaussian kernel (bandwidth=1) and $(m, q, s) = (800, 600, 20,000)$ for Laplacian kernel (bandwidth=1).

E Exact preconditioner

Calculating the exact preconditioner requires finding the top- q eigensystem of $K(X, X)$ which can cost n^2q FLOPs. Instead, we can use a Nyström extension. Let $J = \{j_1, j_2, \dots, j_s\} \subseteq \{1, 2, \dots, n\}$. Next, let $(\tilde{E}, \Lambda, \lambda_{q+1})$ be the top- q eigensystem of $K(X[J], X[J])$, where the columns of $\tilde{E} \in \mathbb{R}^{s \times q}$ are the eigenvectors of $K(X[J], X[J])$. Finally, obtain approximate eigenvectors $E \in \mathbb{R}^{n \times q}$ of $K(X, X)$ as

$$E \leftarrow K(X, X[J])\tilde{E}$$

Due to the matrix multiplication, the vectors E obtained as such are not orthonormal. Hence we run a thin QR decomposition to refine E as,

$$E, _ \leftarrow \text{thinQR}(E).$$

This only has a total complexity $s^2q + qsn + nq^2$, where s^2q is the cost of getting eigenvectors \tilde{E} , and sqn is the cost of Nyström extension, and nq^2 is the cost of thin QR decomposition. Since $q \leq s \leq n$, the term nsq dominates.

Algorithm 8 EigenPro 4 [2]

Input: kernel K , batch size m , centers $Z = \{z_i\}$, indices $J = \{j_\ell\}_{\ell=1}^s \subset \{1, 2, \dots, n\}$, learning rate $\eta_0 > 0$.

Output: $f : \mathcal{X} \rightarrow \mathbb{R}$ that solves (9) approximately.

setup: $\alpha \leftarrow \mathbf{0}_p, \mathbf{a} \leftarrow \mathbf{0}_n, \mathbf{c} \leftarrow \mathbf{0}_{|J|}, \mathbf{h} \leftarrow \mathbf{0}_0$

$(\mathbf{D}, \Delta, \delta_{q+1}) \leftarrow \text{top-}q \text{ eigensystem of } K(X[J], X[J])$

$\mathbf{G} \leftarrow \mathbf{D} \sqrt{\Delta^{-1}} (\mathbf{I}_q - \delta_{q+1} \Delta^{-1})$

repeat

Fetch a batch of indices $B \subset \{1, 2, \dots, n\}$

$\mathbf{v} \leftarrow K(X[B], Z)\alpha + K(X[B], X)\mathbf{a} + K(X[B], X[J])\mathbf{c} - Y[B] \in \mathbb{R}^m$

{gradient}

$\mathbf{w} \leftarrow \mathbf{G}\mathbf{G}^\top K(X[J], X[B])\mathbf{v} \in \mathbb{R}^s$

{correction}

$\mathbf{a}[B] \leftarrow -\eta_0 \mathbf{v}$

{update temporary weights-1}

$\mathbf{c} \leftarrow \mathbf{c} + \eta_0 \mathbf{w}$

{update temporary weights-2}

$\mathbf{h} \leftarrow \mathbf{h} - \eta_0 (K(Z, X[B])\mathbf{v} + K(Z, X[J])\mathbf{w})$

{accumulate gradients}

if projection condition holds **then**

$\boldsymbol{\theta} \leftarrow \text{K_solve}(K, Z, \mathbf{h})$

{delayed projection}

$\alpha \leftarrow \alpha - \eta_0 \cdot \boldsymbol{\theta}$

Reset $\mathbf{a} \leftarrow \mathbf{0}_n, \mathbf{c} \leftarrow \mathbf{0}_s, \mathbf{h} \leftarrow \mathbf{0}_p$,

end if

until Stopping criterion is reached

return $f_t(x) = \sum_{i=1}^n \alpha_i K(x, z_i)$

F Details on convergence analysis

Proof of Lemma 7(d). We consider the norms restricted to the subspace $\text{span}(\{K(\cdot, x_i)\}_{i=1}^n)$ since we only care about $\|f\|_{\mathbb{H}}$ and $\|\hat{f}\|_{\mathbb{H}_q}$ for $f = \sum_{i=1}^n \alpha_i K(\cdot, x_i)$.

Now, suppose $f = \hat{f} = \sum_{i=1}^n \alpha_i \hat{K}_q(\cdot, x_i)$.

Claim: $\text{span}(\{K(\cdot, x_i)\}_{i=1}^n) = \text{span}(\{\hat{K}_q(\cdot, x_i)\}_{i=1}^n)$.

W.L.O.G, we assume $J = (1, 2, \dots, s)$. Denote $\mathbf{v}_i := \mathbf{G}\mathbf{G}^\top K(X[J], x_i) \in \mathbb{R}^s$

$$\begin{aligned} \hat{K}_q(\cdot, x_i) &= K(\cdot, x_i) - K(\cdot, X[J])\mathbf{G}\mathbf{G}^\top K(X[J], x_i) \\ &= K(\cdot, X)(e_i - [\mathbf{v}_i \ \mathbf{0}_{n-s}]^T) \end{aligned}$$

So $\sum_{i=1}^n \alpha_i \hat{K}_q(\cdot, x_i) = \hat{K}_q(\cdot, X)\alpha = K(\cdot, X)A\alpha$, where $A := \mathbf{I}_n - \begin{pmatrix} \mathbf{G}\mathbf{G}^\top K(J, X) \\ \mathbf{0}_{(n-s) \times n} \end{pmatrix} = \begin{pmatrix} \mathbf{I}_s - \mathbf{G}\mathbf{G}^\top K(J, J) & -\mathbf{G}\mathbf{G}^\top K(J, J^C) \\ \mathbf{0}_{(n-s) \times s} & \mathbf{I}_{(n-s) \times (n-s)} \end{pmatrix} = \begin{pmatrix} \mathbf{I}_s - \mathbf{D}(\mathbf{I}_q - \delta_{q+1}\Delta^{-1})\mathbf{D}^\top & -\mathbf{G}\mathbf{G}^\top K(J, J^C) \\ \mathbf{0}_{(n-s) \times s} & \mathbf{I}_{(n-s) \times (n-s)} \end{pmatrix}$. Since A is an upper triangular block matrix, we can easily get $\frac{\delta_{q+1}}{\delta_1} = \min(\frac{\delta_{q+1}}{\delta_1}, 1) \leq \lambda(A) \leq \max(\frac{\delta_{q+1}}{\delta_q}, 1) = 1$. This also implies A is invertible and hence our Claim holds.

As a consequence,

$$\begin{aligned} \|f\|_{\mathbb{H}}^2 &= (A\alpha)^\top K(X, X)(A\alpha) \\ &\leq \lambda_{\max}(K(X, X)) \|A\alpha\|_2^2 \\ &\leq \lambda_{\max}(K(X, X)) \lambda_{\max}^2(A) \|\alpha\|_2^2 \\ &\leq \lambda_{\max}(K(X, X)) \|\alpha\|_2^2. \end{aligned}$$

Similarly, $\|f\|_{\mathbb{H}}^2 \geq \lambda_{\min}(K(X, X)) \lambda_{\min}^2(A) \|\alpha\|_2^2 \geq \lambda_{\min}(K(X, X)) \frac{\delta_{q+1}^2}{\delta_1^2} \|\alpha\|_2^2$

On the other hand,

$$\|\hat{f}\|_{\mathbb{H}_q}^2 = \alpha^\top \hat{K}_q(X, X)\alpha \leq \lambda_{\max}(\hat{K}_q(X, X)) \|\alpha\|_2^2.$$

Similarly, $\|\hat{f}\|_{\mathbb{H}_q}^2 \geq \lambda_{\min}(\widehat{K}_q(X, X)) \|\alpha\|_2^2$.

So by proposition 8, with high probability, there exist constants a, a' depending (polynomially) on the eigenvalues of $K(X, X)$ such that $a\|f\|_{\mathbb{H}} \leq \|\hat{f}\|_{\mathbb{H}_q} \leq a'\|f\|_{\mathbb{H}}$. \square

F.1 Condition numbers for analysis of MaSS

Let λ_1 and λ_n be the largest and smallest non-zero eigenvalues of \mathcal{K} .

Let a mini-batch of size m be $\{(\tilde{x}_i, \tilde{y}_i)\}_{i=1}^m$. Defining mini-batch covariance operator as follows

$$\tilde{\mathcal{K}}^{(m)} := \frac{1}{m} \sum_{i=1}^m K(\tilde{x}_i, \cdot) \otimes K(\tilde{x}_i, \cdot) \quad (35)$$

$$\tilde{\mathcal{K}}_{\mathcal{P}}^{(m)} := \frac{1}{m} \sum_{i=1}^m k_{\mathcal{P}}(\tilde{x}_i, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}_i, \cdot) \quad (36)$$

where $\tilde{\mathcal{K}}_{\mathcal{P}}$ is the covariance operator after preconditioning. The kernel function $k_{\mathcal{P}}$ can be defined in the same way as in Lemma 7 with the exact preconditioner.

F.2 Identifying quantities defined by [20]

Suppose we run MaSS to solve $\min_{f \in \mathbb{H}} \frac{1}{n} \sum_{i=1}^n (S_{\{i\}} f - Y_i)^2$, with Hessian $H = \mathcal{K}$. Note that $S_{\{i\}} f = \langle K(x_i, \cdot), f \rangle_{\mathbb{H}}$. The authors define the quantities L, μ to be the largest and smallest eigenvalues of the Hessian $H : \mathbb{H} \mapsto \mathbb{H}$, and $\kappa = L/\mu$ to be the condition number. In our case, $L = \lambda_1/n$, $\mu = \lambda_n/n$ and $\kappa = \frac{\lambda_1}{\lambda_n}$.

They also define the quantity L_1 to be the smallest number such that

$$\mathbb{E}[\|K(\tilde{x}, \cdot)\|_{\mathbb{H}}^2 K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot)] \lesssim L_1 H \quad (37)$$

where \mathbb{E} is over the random variable \tilde{x} from the empirical distribution. Note that in our case $\|K(\tilde{x}, \cdot)\|_{\mathbb{H}}^2 = K(\tilde{x}, \tilde{x})$ since,

$$\|K(x, \cdot)\|_{\mathbb{H}}^2 = \langle K(x, \cdot), K(x, \cdot) \rangle_{\mathbb{H}} = K(x, x) \leq \beta := \max_i K(x_i, x_i) \quad (38)$$

Then we have $L_1 \leq \beta$, since

$$\mathbb{E}[\|K(\tilde{x}, \cdot)\|^2 K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot)] \preceq \beta \mathbb{E}[K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot)] = \beta \mathcal{K}$$

Thus

$$L_m := \frac{L_1}{m} + \frac{(m-1)L}{m} \leq \frac{\beta + (m-1)\frac{\lambda_1}{n}}{m} \quad (39)$$

Defining $\tilde{\kappa}$ as the smallest positive real number such that

$$\mathbb{E}[\|K(\tilde{x}, \cdot)\|_{\mathcal{K}^{-1}}^2 K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot)] \preceq \tilde{\kappa} \mathcal{K} \quad (40)$$

Deriving $\|K(x_i, \cdot)\|_{\mathcal{K}^{-1}}^2$. Recall that $\psi_i = S^* \mathbf{e}_i / \sqrt{\lambda_i}$. Also note that $\mathcal{K}^{-1} = \sum_{i=1}^n \frac{n}{\lambda_i} \psi_i \otimes \psi_i$.

$$\begin{aligned} \|K(x_i, \cdot)\|_{\mathcal{K}^{-1}}^2 &= \langle K(x_i, \cdot), \mathcal{K}^{-1} K(x_i, \cdot) \rangle_{\mathbb{H}} \\ &= \left\langle K(x_i, \cdot), \left(\sum_{j=1}^n \frac{n}{\lambda_j} \psi_j \otimes \psi_j \right) K(x_i, \cdot) \right\rangle_{\mathbb{H}} \\ &= \sum_{j=1}^n \frac{n}{\lambda_j} \langle \psi_j, K(x_i, \cdot) \rangle_{\mathbb{H}}^2 = \sum_{j=1}^n \frac{n}{\lambda_j} \psi_j^2(x_i) \stackrel{(a)}{=} \sum_{j=1}^n \frac{1}{\lambda_j} n \lambda_j e_{ji}^2 \end{aligned} \quad (41a)$$

$$= n \sum_{j=1}^n e_{ji}^2 = n \|\mathbf{e}_j\|^2 = n \quad (41b)$$

where (a) follows from the fact that $\psi_j(x_i) = S_{\{i\}}\psi_j = S_{\{i\}}S^*e_j/\sqrt{\lambda_j} = \mathbf{H}_{\{i\}}SS^*e_j/\sqrt{\lambda_j} = \mathbf{H}_{\{i\}}e_j\sqrt{\lambda_j}$.

Deriving $\tilde{\kappa}$

$$\mathbb{E} \left[\|K(\tilde{x}, \cdot)\|_{\mathcal{K}^{-1}}^2 K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot) \right] \stackrel{(a)}{=} n \mathbb{E} [K(\tilde{x}, \cdot) \otimes K(\tilde{x}, \cdot)] = n \mathbb{E} [\tilde{\mathcal{K}}^{(1)}] = n \mathcal{K} \stackrel{(b)}{\Rightarrow} \tilde{\kappa} = n$$

where (a) follows from equation (41b) and (b) from definition of $\tilde{\kappa}$ in equation (40). This also implies $\tilde{c}_m = \tilde{\kappa}_m$ in lemma 7 since (b) holds for any kernel function.

F.3 Formulae for hyperparameters

$$L_1 = \beta, L = \frac{\lambda_1}{n}, \tilde{\kappa} = n$$

$$L_m = \frac{L_1}{m} + \frac{(m-1)L}{m} = \frac{\beta + (m-1)\frac{\lambda_1}{n}}{m} \quad (42a)$$

$$\kappa_m = \frac{nL_m}{\lambda_n} \quad (42b)$$

$$\tilde{\kappa}_m = \frac{\tilde{\kappa}}{m} + \frac{m-1}{m} = 1 + \frac{n-1}{m} \quad (42c)$$

$$\eta_1(m) = \frac{1}{L_m} = \frac{m}{\beta + (m-1)\frac{\lambda_1}{n}} \quad (42d)$$

$$\eta_2(m) = \eta_1 \frac{\sqrt{\kappa_m \tilde{\kappa}_m}}{1 + \sqrt{\kappa_m \tilde{\kappa}_m}} \left(1 - \frac{1}{\tilde{\kappa}_m} \right) \quad (42e)$$

$$\gamma(m) = \frac{\sqrt{\kappa_m \tilde{\kappa}_m} - 1}{\sqrt{\kappa_m \tilde{\kappa}_m} + 1} \quad (42f)$$

F.4 Condition numbers after preconditioning

Note that after preconditioning we are operating in Hilbert space $\mathbb{H}_{\mathcal{P}}$. Also, the largest eigenvalue of $\mathcal{K}_{\mathcal{P}}$ is λ_{q+1} i.e., $L = \lambda_{q+1}$

Similar to equation (37), defining L_1 as the smallest positive number such that

$$\mathbb{E} \left[\|k_{\mathcal{P}}(\tilde{x}, \cdot)\|^2 k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot) \right] \preceq L_1 \mathcal{K}_{\mathcal{P}} \quad (43)$$

Deriving $\|k_{\mathcal{P}}(\mathbf{x}_i, \cdot)\|^2$

$$\begin{aligned} \|k_{\mathcal{P}}(\mathbf{x}_i, \cdot)\|^2 &= \langle k_{\mathcal{P}}(\mathbf{x}_i, \cdot), k_{\mathcal{P}}(\mathbf{x}_i, \cdot) \rangle_{\mathbb{H}_{\mathcal{P}}} \\ &= k_{\mathcal{P}}(\mathbf{x}_i, \mathbf{x}_i) \\ &\stackrel{(a)}{=} K(\mathbf{x}_i, \mathbf{x}_i) - \sum_{j=1}^q \left(1 - \frac{\lambda_{q+1}}{\lambda_j} \right) \lambda_j e_{ji}^2 \\ &= K(\mathbf{x}_i, \mathbf{x}_i) - \sum_{j=1}^q (\lambda_j - \lambda_{q+1}) e_{ji}^2 \end{aligned} \quad (44)$$

where (a) is from the definition of $k_{\mathcal{P}}$.

Define $\beta_{\mathcal{P}}$ as the maximum norm of $k_{\mathcal{P}}(\mathbf{x}_i, \cdot)$ among the samples

$$\beta_{\mathcal{P}} := \max_i \|k_{\mathcal{P}}(\mathbf{x}_i, \cdot)\|^2 = \max_i \left\{ K(\mathbf{x}_i, \mathbf{x}_i) - n \sum_{j=1}^q (\lambda_j - \lambda_{q+1}) e_{ji}^2 \right\} \quad (45)$$

Deriving L_1

$$\mathbb{E} \left[\|k_{\mathcal{P}}(\tilde{x}, \cdot)\|^2 k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot) \right] \preceq \beta_{\mathcal{P}} \mathbb{E} [k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot)] = \beta_{\mathcal{P}} \mathbb{E} [\tilde{\mathcal{K}}_{\mathcal{P}}^{(1)}] = \beta_{\mathcal{P}} \mathcal{K}_{\mathcal{P}}$$

which implies $L_1 \leq \beta_{\mathcal{P}}$ due to the definition of L_1 in equation (43).

Deriving L_m

$$L_m := \frac{L_1}{m} + \frac{(m-1)L}{m} \leq \frac{\beta_{\mathcal{P}} + (m-1)\lambda_{q+1}}{m} \quad (46)$$

Defining $\tilde{\kappa}$ as the smallest positive real number such that

$$\mathbb{E} \left[\|k_{\mathcal{P}}(\tilde{x}, \cdot)\|_{\mathcal{K}_{\mathcal{P}}^{-1}}^2 k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot) \right] \preceq \tilde{\kappa} \mathcal{K}_{\mathcal{P}} \quad (47)$$

Deriving $\|k_{\mathcal{P}}(\mathbf{x}_i, \cdot)\|_{\mathcal{K}_{\mathcal{P}}^{-1}}^2$

$$\begin{aligned} \|k_{\mathcal{P}}(\mathbf{x}_i, \cdot)\|_{\mathcal{K}_{\mathcal{P}}^{-1}}^2 &= \langle k_{\mathcal{P}}(\mathbf{x}_i, \cdot), \mathcal{K}_{\mathcal{P}}^{-1} k_{\mathcal{P}}(\mathbf{x}_i, \cdot) \rangle_{\mathbb{H}_{\mathcal{P}}} \\ &\stackrel{(a)}{=} \left\langle k_{\mathcal{P}}(\mathbf{x}_i, \cdot), \left(\sum_{j=1}^q \frac{1}{\lambda_{q+1}} \psi'_j \otimes \psi'_j + \sum_{j=q+1}^n \frac{1}{\lambda_j} \psi'_j \otimes \psi'_j \right) k_{\mathcal{P}}(\mathbf{x}_i, \cdot) \right\rangle_{\mathbb{H}_{\mathcal{P}}} \\ &= \sum_{j=1}^q \frac{1}{\lambda_{q+1}} \langle \psi'_j, k_{\mathcal{P}}(\mathbf{x}_i, \cdot) \rangle_{\mathbb{H}_{\mathcal{P}}}^2 + \sum_{j=q+1}^n \frac{1}{\lambda_j} \langle \psi'_j, k_{\mathcal{P}}(\mathbf{x}_i, \cdot) \rangle_{\mathbb{H}_{\mathcal{P}}}^2 \\ &\stackrel{(b)}{=} n \left\{ \sum_{j=1}^q e_{ji}^2 + \sum_{j=q+1}^n e_{ji}^2 \right\} \\ &\stackrel{(c)}{=} n \end{aligned} \quad (48)$$

where (a) is from the eigendecomposition of $\mathcal{K}_{\mathcal{P}}$, (b) follows from using eigenfunction evaluation with ψ' in $\mathbb{H}_{\mathcal{P}}$ and (c) follows from the fact that $\mathbf{E} = [\mathbf{e}_1 \ \mathbf{e}_2 \ \dots \ \mathbf{e}_n]$ is an orthonormal matrix which implies $\mathbf{E}^\top \mathbf{E} = \mathbf{I} = \mathbf{E} \mathbf{E}^\top$.

Deriving $\tilde{\kappa}$

$$\mathbb{E} \left[\|k_{\mathcal{P}}(\tilde{x}, \cdot)\|_{\mathcal{K}_{\mathcal{P}}^{-1}}^2 k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot) \right] \quad (49)$$

$$\stackrel{(a)}{=} n \mathbb{E} [k_{\mathcal{P}}(\tilde{x}, \cdot) \otimes k_{\mathcal{P}}(\tilde{x}, \cdot)] \quad (50)$$

$$\begin{aligned} &= n \mathbb{E} \left[\widetilde{\mathcal{K}_{\mathcal{P}}}^{(1)} \right] \\ &= n \mathcal{K}_{\mathcal{P}} \end{aligned} \quad (51)$$

$$\stackrel{(b)}{\implies} \tilde{\kappa} = n \quad (52)$$

where (a) follows from equation (48) and (b) from definition of $\tilde{\kappa}$ in equation (47).

F.5 MaSS parameters after preconditioning

Using (46), η_1 defined in (23a) can be written as

$$\eta_1^*(m) = \frac{m}{\beta_{\mathcal{P}} + (m-1)\lambda_{q+1}}$$

Using (52), (42), we can write η_2, γ defined in (23b), (23c) as

$$\begin{aligned} \eta_2^*(m) &= \frac{\eta_1^*(m) \sqrt{(\beta_{\mathcal{P}} + (m-1)\lambda_{q+1})(n+m-1)}}{\sqrt{(\beta_{\mathcal{P}} + (m-1)\lambda_{q+1})(n+m-1)} + m\sqrt{\lambda_n}} \\ \gamma^*(m) &= \frac{\sqrt{(\beta_{\mathcal{P}} + (m-1)\lambda_{q+1})(n+m-1)} - m\sqrt{\lambda_n}}{\sqrt{(\beta_{\mathcal{P}} + (m-1)\lambda_{q+1})(n+m-1)} + m\sqrt{\lambda_n}} \end{aligned}$$

Since the kernel matrix is positive definite we see that $\lambda_{q+1} \geq \beta/n$ and using (52) we get regime critical points

m_1^*, m_2^* defined in [20] as

$$m_1^* = \min \left(\frac{\beta_{\mathcal{P}}}{\lambda_{q+1}}, n \right) = \frac{\beta_{\mathcal{P}}}{\lambda_{q+1}}$$

$$m_2^* = \max \left(\frac{\beta_{\mathcal{P}}}{\lambda_{q+1}}, n \right) = n$$

Note that there is no saturation regime for kernel methods

If optimal mini-batch size for linear regime $m_* := m_1^*$ is used, then optimal MaSS parameters are

$$\eta_1^* = \frac{m_*^2}{\beta_{\mathcal{P}}(2m_* - 1)}$$

$$\eta_2^* = \frac{m_*^2 \sqrt{n + m_* - 1}}{\beta_{\mathcal{P}}(2m_* - 1) \sqrt{n + m_* - 1} + m_* \sqrt{m_* \lambda_n \beta_{\mathcal{P}}(2m_* - 1)}}$$

$$\gamma^* = \frac{\sqrt{\beta_{\mathcal{P}}(2m_* - 1)} \sqrt{n + m_* - 1} - m_* \sqrt{m_* \lambda_n}}{\sqrt{\beta_{\mathcal{P}}(2m_* - 1)} \sqrt{n + m_* - 1} + m_* \sqrt{m_* \lambda_n}}$$

Informal: Assume large natural image dataset with gaussian/laplacian kernel. Due to the eigenvalue decay, m_* is reasonably large and $\beta_{\mathcal{P}}$ is usually very close to 1. The MaSS parameters can be approximated as follows

$$\eta_1^* \approx \frac{m_*}{2}$$

$$\eta_2^* \approx \frac{m_* \sqrt{n + m_* - 1}}{2 \sqrt{n + m_* - 1} + m_* \sqrt{2 \lambda_n}}$$

$$\gamma^* \approx \frac{\sqrt{2} \sqrt{n + m_* - 1} - m_* \sqrt{\lambda_n}}{\sqrt{2} \sqrt{n + m_* - 1} + m_* \sqrt{\lambda_n}}$$

Proposition 10. Suppose $m \leq \frac{n}{2}$, we have

$$m \sqrt{\tilde{\kappa}_m \kappa_m} \leq n \sqrt{\kappa}$$

Proof. According to the definitions of $\tilde{\kappa}_m$ and κ_m , the statement is equivalent to

$$m^2 \left(\frac{n}{m} + \frac{m-1}{m} \right) \left(\frac{L_1 + (m-1)\lambda_{q+1}}{\lambda_n m} \right) \leq n^2 \frac{\lambda_1}{\lambda_n},$$

i.e.

$$(n + m - 1)(L_1 + (m - 1)\lambda_{q+1}) \leq n^2 \lambda_1.$$

Since $L_1 = \max_i K(x_i, x_i) \leq \lambda_1$, we have

$$\begin{aligned} (n + m - 1)(L_1 + (m - 1)\lambda_{q+1}) &\leq 2n(\lambda_1 + (m - 1)\lambda_1) \\ &\leq 2mn\lambda_1 \\ &\leq n^2 \lambda_1. \end{aligned}$$

□

G Acceleration of EigenPro 4

Accelerated iteration of EigenPro 3 in RKHS:

$$f_{t+1} \leftarrow \text{proj}_{\mathcal{Z}}(g_t - \eta_1 \mathcal{P}_s \tilde{\nabla}_f \mathcal{L}(g_t))$$

$$g_{t+1} \leftarrow \text{proj}_{\mathcal{Z}}((1 + \gamma)f_{t+1} - \gamma f_t + \eta_2 \mathcal{P}_s \tilde{\nabla}_f \mathcal{L}(g_t))$$

Suppose you project after every T iterations.

Consider the AxlePro2 iterations

$$f_{t+1} = g_t - \eta \mathcal{P}_s \tilde{\nabla}_f \mathbf{L}(g_t) \quad (53)$$

$$g_{t+1} = (1 + \gamma)f_{t+1} - \gamma f_t + \eta_2 \mathcal{P}_s \tilde{\nabla}_f \mathbf{L}(g_t) \quad (54)$$

for $t = 1, 2, \dots, T$ and $f_T = \text{proj}_{\mathcal{Z}}(f_T)$ which requires $f_T(Z)$ and $g_T(Z)$ which will be computed iteratively.

Suppose B_t is the batch at step t , define $C_t := C_{t-1} \cup B_t$ and $C_0 = \emptyset$ and let $f_t = S_Z^* \alpha_t^Z + S_{C_t}^* \alpha_t^X + S_J^* \alpha_t^J$ and $g_t = S_Z^* \beta_t^Z + S_{C_t}^* \beta_t^X + S_J^* \beta_t^J$.

Then $\tilde{\nabla}_f \mathbf{L}(g_t) \in \text{range}(S_{B_{t+1}}^*)$ given by

$$\begin{aligned} \tilde{\nabla}_f \mathbf{L}(g_t) &= S_{B_{t+1}}^* \mathbf{v}_t \\ \mathbf{v}_t &:= g_t(X[B_{t+1}]) - y_t \\ g_t(X[B_{t+1}]) &= K(X[B_{t+1}], Z) \beta_t^Z + K(X[B_{t+1}], X[C_t]) \beta_t^X + K(X[B_{t+1}], X[J]) \beta_t^J \\ \mathbf{w}_t &:= \mathbf{G} \mathbf{G}^\top K(X[J], X[B_{t+1}]) \mathbf{v}_t \\ \mathcal{P}_s \tilde{\nabla}_f \mathbf{L}(g_t) &= S_{B_{t+1}}^* \mathbf{v}_t - S_J^* \mathbf{w}_t \end{aligned}$$

$$\begin{aligned} S_Z^* \alpha_{t+1}^Z + S_{C_{t+1}}^* \alpha_{t+1}^X + S_J^* \alpha_{t+1}^J &\leftarrow S_Z^* \beta_t^Z + S_{C_t}^* \beta_t^X + S_J^* \beta_t^J - \eta_1 (S_{B_{t+1}}^* \mathbf{v}_t - S_J^* \mathbf{w}_t) \\ S_Z^* \beta_{t+1}^Z + S_{C_{t+1}}^* \beta_{t+1}^X + S_J^* \beta_{t+1}^J &\leftarrow (1 + \gamma)(S_Z^* \alpha_{t+1}^Z + S_{C_t}^* \alpha_{t+1}^X + S_J^* \alpha_{t+1}^J) - \gamma(S_Z^* \alpha_t^Z + S_{C_t}^* \alpha_t^X + S_J^* \alpha_t^J) \\ &\quad + \eta_2 (S_{B_{t+1}}^* \mathbf{v}_t - S_J^* \mathbf{w}_t) \end{aligned}$$

This gives us

$$\alpha_{t+1}^Z \leftarrow \beta_t^Z \quad (55a)$$

$$\beta_{t+1}^Z \leftarrow (1 + \gamma) \alpha_{t+1}^Z - \gamma \alpha_t^Z \quad (55b)$$

$$\alpha_{t+1}^J \leftarrow \beta_t^J + \eta_1 \mathbf{w}_t \quad (55c)$$

$$\beta_{t+1}^J \leftarrow (1 + \gamma) \alpha_{t+1}^J - \gamma \alpha_t^J - \eta_2 \mathbf{w}_t \quad (55d)$$

$$\alpha_{t+1}^X[C_t] \leftarrow \beta_t^X[C_t] \quad (55e)$$

$$\alpha_{t+1}^X[B_{t+1}] \leftarrow -\eta_1 \mathbf{v}_t \quad (55f)$$

$$\beta_{t+1}^X[C_t] \leftarrow (1 + \gamma) \alpha_{t+1}^X[C_t] - \gamma \alpha_t^X[C_t] \quad (55g)$$

$$\beta_{t+1}^X[B_{t+1}] \leftarrow (1 + \gamma) \alpha_{t+1}^X[B_{t+1}] + \eta_2 \mathbf{v}_t = (\eta_2 - (1 + \gamma) \eta_1) \mathbf{v}_t \quad (55h)$$

Claim 1. If we run the extrapolation iteration $a_{t+1} = (1 + \gamma)a_t - \gamma a_{t-1}$ initialized at $a_1 \neq a_0$, then

$$a_t = a_0 + \frac{1 - \gamma^t}{1 - \gamma} (a_1 - a_0). \quad (56)$$

Proof. We will prove this by induction. Observe that the $t = 1$ case hold trivially. Assume that the formula is true for $t \leq \tau$ for some $\tau \geq 1$. If we prove that the formula holds for $t = \tau + 1$, we are done.

$$a_{\tau+1} = (1 + \gamma)a_\tau - \gamma a_{\tau-1} = (1 + \gamma) \left(a_0 + \frac{1 - \gamma^\tau}{1 - \gamma} (a_1 - a_0) \right) - \gamma \left(a_0 + \frac{1 - \gamma^{\tau-1}}{1 - \gamma} (a_1 - a_0) \right) \quad (57)$$

$$= a_0 + \frac{a_1 - a_0}{1 - \gamma} ((1 + \gamma)(1 - \gamma^\tau) - \gamma(1 - \gamma^{\tau-1})) \quad (58)$$

$$= a_0 + \frac{a_1 - a_0}{1 - \gamma} (1 + \gamma - \gamma^\tau - \gamma^{\tau+1} - \gamma + \gamma^\tau) = a_0 + \frac{1 - \gamma^{\tau+1}}{1 - \gamma} (a_1 - a_0). \quad (59)$$

which proves the claim. \square

Let t_B be the time step when batch B is chosen for the first time, i.e., $B_t = B$.

$$\beta_t^X[B] = c_t \mathbf{v}_{t_B} \quad \text{where} \quad c_t = \begin{cases} 0 & t < t_B \\ c_1 & t = t_B \\ (c_1 + \frac{1-\gamma^{(t-t_B+1)}}{1-\gamma} c_2) & t > t_B \end{cases} \quad (60)$$

where $c_1 = -(1+\gamma)\eta_1 - \eta_2$, and $c_2 = \eta_2 - \eta_1$

Finally, after T iterations, we need to project f_T and g_T back onto $\text{span}(S_Z^*)$. To that end, we must calculate $g_T(Z)$. To that end, consider

$$f_T(Z) = K(Z, Z)\alpha_T^Z + K(Z, X[C_T])\alpha_T^X + K(Z, X[J])\alpha_T^J \quad (61)$$

$$g_T(Z) = K(Z, Z)\beta_T^Z + K(Z, X[C_T])\beta_T^X + K(Z, X[J])\beta_T^J \quad (62)$$

We can compute

$$f_{T+1} = \text{proj}_Z(f_T) \quad (63)$$

$$g_{T+1} = \text{proj}_Z(g_T) \quad (64)$$

by

$$f_{T+1} = S_Z^* K(Z, Z)^{-1} f_T(Z) \quad (65)$$

$$g_{T+1} = S_Z^* K(Z, Z)^{-1} g_T(Z) \quad (66)$$

which can be implemented as

$$\alpha_{T+1}^Z = K(Z, Z)^{-1} f_T(Z) = \alpha_T^Z + K(Z, Z)^{-1} (K(Z, X[C_T])\alpha_T^X + K(Z, X[J])\alpha_T^J) \quad (67)$$

$$\beta_{T+1}^Z = K(Z, Z)^{-1} g_T(Z) = \beta_T^Z + K(Z, Z)^{-1} (K(Z, X[C_T])\beta_T^X + K(Z, X[J])\beta_T^J) \quad (68)$$

$$\mathbf{v}_t \leftarrow K(X[B], Z)\beta_t - Y[B] \in \mathbb{R}^m \quad (69a)$$

$$\mathbf{w}_t \leftarrow K(Z, X[B])\mathbf{v}_t - K(Z, X[J])\mathbf{G}\mathbf{G}^\top K(X[J], X[B])\mathbf{v}_t \in \mathbb{R}^{|Z|} \quad (69b)$$

$$\mathbf{u}_t \leftarrow \text{solve } K(Z, Z)\mathbf{u}_t = \mathbf{w}_t \quad (69c)$$

$$\alpha_{t+1} \leftarrow \beta_t - \eta_1 \mathbf{u}_t \quad (69d)$$

$$\beta_{t+1} \leftarrow (1+\gamma)\alpha_{t+1} - \gamma\alpha_t + \eta_2 \mathbf{u}_t \quad (69e)$$

emulate the updates Acceleration algorithm of EigenPro 3.

H ADDITIONAL PROOFS

Proof of Proposition 1. For $f_t = S^* \alpha_t$, a stochastic gradient with respect to the mini-batch $(X[B], Y[B])$ is given by

$$\tilde{\nabla}_f \mathcal{L}(f_t) = \frac{1}{|B|} S_B^* (S_B f_t - Y[B]) \quad (70a)$$

$$= \frac{1}{|B|} S_B^* (S_B S^* \alpha_t - Y[B]) = S_B^* \mathbf{v}_t \quad (70b)$$

Observe that $S_B = \mathbf{H}_B S$, whereby $S_B^* = S^* \mathbf{H}_B^\top$. The claim follows immediately. \square

Proof of Proposition 3. We start by showing that

$$\mathcal{P} S_B^* = S_B^* - S^* \mathbf{F} \mathbf{F}^\top \mathbf{H}_B^\top. \quad (71)$$

For a vector $\mathbf{u} \in \mathbb{R}^m$, observe that

$$\mathcal{P}S_B^* \mathbf{u} = S_B^* \mathbf{u} - \sum_{i=1}^q \left(1 - \frac{\lambda_{q+1}}{\lambda_i}\right) \psi_i \otimes_{\mathbb{H}} \psi_i S_B^* \mathbf{u} \quad (72)$$

Now the term $\psi_i \otimes_{\mathbb{H}} \psi_i S_B^* \mathbf{u}$ simplifies as

$$\begin{aligned} \psi_i \langle \psi_i, S_B^* \mathbf{u} \rangle_{\mathbb{H}} &= \frac{1}{\lambda_i} S^* \mathbf{e}_i \langle S^* \mathbf{e}_i, S_B^* \mathbf{u} \rangle_{\mathbb{H}} \\ &= \frac{1}{\lambda_i} S^* \mathbf{e}_i \langle \mathbf{e}_i, S S^* \mathbf{H}_B^{\top} \mathbf{u} \rangle_{\mathbb{R}^n} \\ &= \frac{1}{\lambda_i} S^* \mathbf{e}_i \mathbf{e}_i^{\top} K(X, X) \mathbf{H}_B^{\top} \mathbf{u} \\ &= S^* \mathbf{e}_i \mathbf{e}_i^{\top} \mathbf{H}_B^{\top} \mathbf{u} \end{aligned}$$

where we have used the definition of adjoint and the fact that $S_B^* = (\mathbf{H}_B S)^* = S^* \mathbf{H}_B^{\top}$. Summing the q terms, and observing that $\mathbf{F} = \sum_{i=1}^q (1 - \frac{\lambda_{q+1}}{\lambda_i}) \mathbf{e}_i \mathbf{e}_i^{\top}$, we have $\mathcal{P}S_B^* \mathbf{u} = S_B^* \mathbf{u} - S^* \mathbf{F} \mathbf{F}^{\top} \mathbf{H}_B^{\top} \mathbf{u}$ for all $\mathbf{u} \in \mathbb{R}^m$. Since \mathbf{u} is arbitrary, this proves the claim in equation (71).

Next, observe that $\mathcal{P}\tilde{\nabla}_f \mathbf{L}(g_t) = \mathcal{P}S_B^* (S_B S^* \boldsymbol{\beta}_t - Y[B]) = \mathcal{P}S_B^* \mathbf{v}_t$, and rewriting the updates in equation (27a) using the relation $f_t = S^* \boldsymbol{\alpha}_t$ and $g_t = S^* \boldsymbol{\beta}_t$, we get

$$\begin{aligned} S^* \boldsymbol{\alpha}_{t+1} &\leftarrow S^* \boldsymbol{\beta}_t - \eta_1 \mathcal{P}S_B^* \mathbf{v}_t \\ &= S^* \boldsymbol{\beta}_t - \eta_1 S_B^* \mathbf{v}_t + \eta_1 S^* \mathbf{F} \mathbf{F}^{\top} \mathbf{H}_B^{\top} \mathbf{v} \\ &= S^* (\boldsymbol{\beta}_t - \eta_1 \mathbf{H}_B^{\top} \mathbf{v}_t + \eta_1 \mathbf{w}_t) \end{aligned}$$

which is indeed equation (17c). A similar calculation can also show equation (17d) emulates equation (27b). \square

Proof of Proposition 4. We start by showing that

$$\mathcal{Q}S_B^* = S_B^* - S_J^* \mathbf{G} \mathbf{G}^{\top} K(X[J], X[B]). \quad (73)$$

For a vector $\mathbf{u} \in \mathbb{R}^m$, observe that

$$\mathcal{Q}S_B^* \mathbf{u} = S_B^* \mathbf{u} - \sum_{i=1}^q \left(1 - \frac{\delta_{q+1}}{\delta_i}\right) \phi_i \otimes_{\mathbb{H}} \phi_i S_B^* \mathbf{u} \quad (74)$$

Now the term $\phi_i \otimes_{\mathbb{H}} \phi_i S_B^* \mathbf{u}$ simplifies as

$$\begin{aligned} \phi_i \langle \phi_i, S_B^* \mathbf{u} \rangle_{\mathbb{H}} &= \frac{1}{\delta_i} S_J^* \mathbf{d}_i \langle S_J^* \mathbf{d}_i, S_B^* \mathbf{u} \rangle_{\mathbb{H}} \\ &= \frac{1}{\delta_i} S_J^* \mathbf{d}_i \langle \mathbf{d}_i, S_J S_J^* \mathbf{u} \rangle_{\mathbb{R}^m} \\ &= \frac{1}{\delta_i} S_J^* \mathbf{d}_i \mathbf{d}_i^{\top} K(X[J], X[B]) \mathbf{u}. \end{aligned}$$

Summing the q terms, and observing that $\mathbf{G} = \sum_{i=1}^q \frac{1}{\delta_i} (1 - \frac{\delta_{q+1}}{\delta_i}) \mathbf{d}_i \mathbf{d}_i^{\top}$ we have $\mathcal{Q}S_B^* \mathbf{u} = S_B^* \mathbf{u} - S_J^* \mathbf{G} \mathbf{G}^{\top} K(X[J], X[B]) \mathbf{u}$ for all $\mathbf{u} \in \mathbb{R}^m$. Since \mathbf{u} is arbitrary, this proves the claim in equation (73). The rest of the proof proceeds similar to the proof of Proposition 3. \square

Table 6: Laplacian Kernel

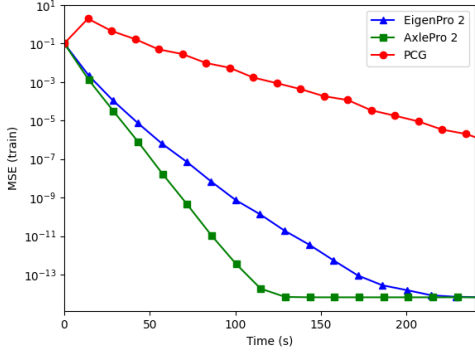
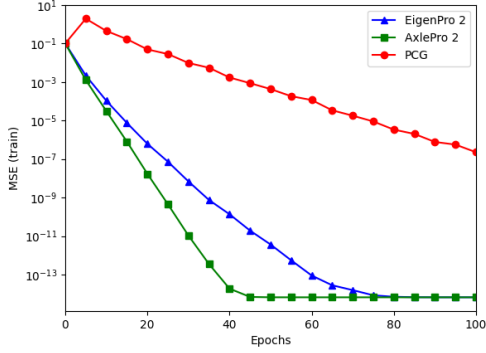
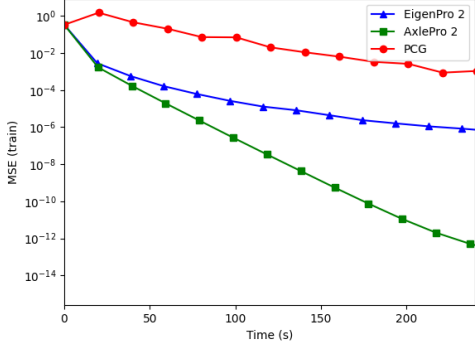
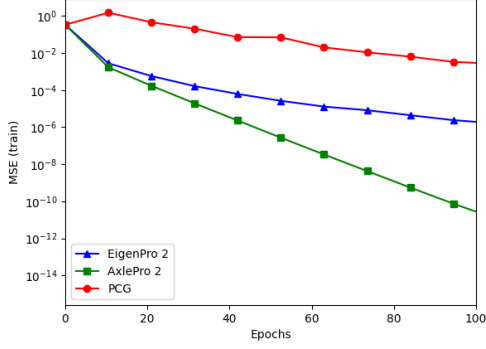
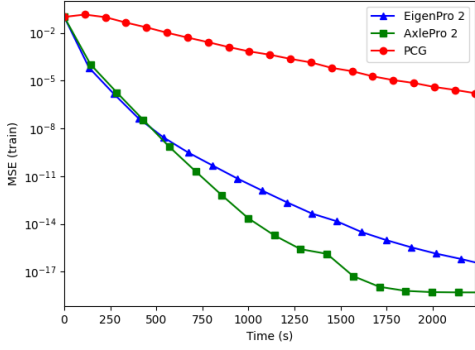
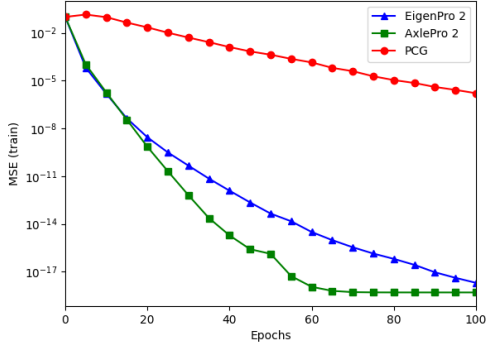
Dataset	MSE v/s Time	MSE v/s Epochs
CIFAR10		
Stellar Classification		
EMNIST Digits		

Table 7: Gaussian Kernel

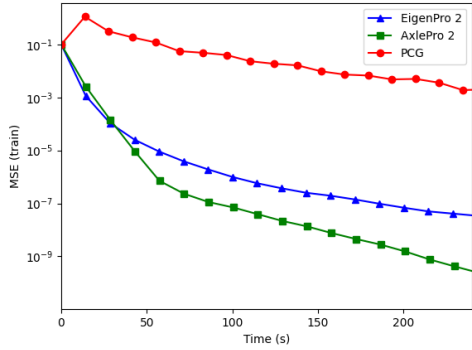
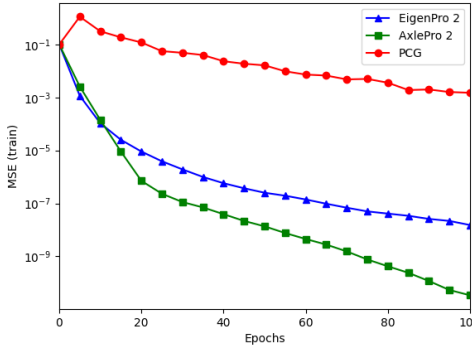
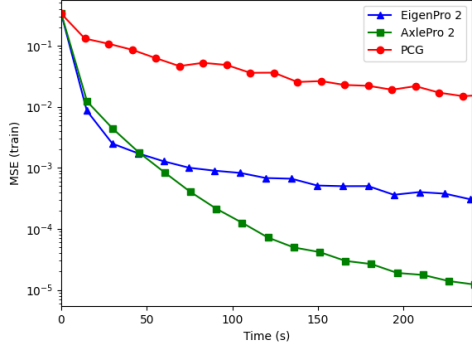
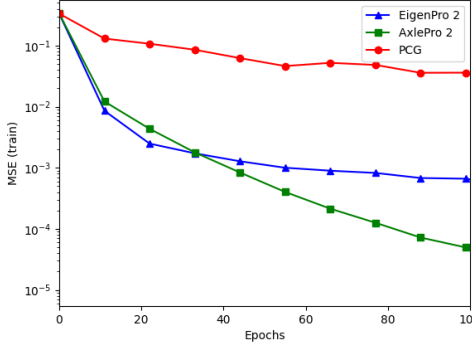
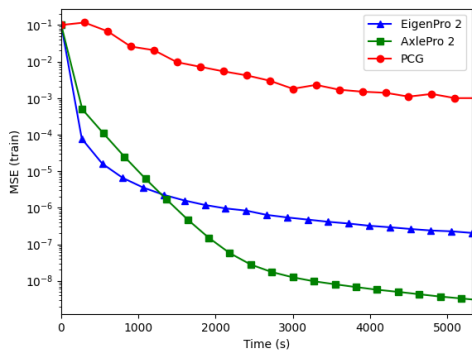
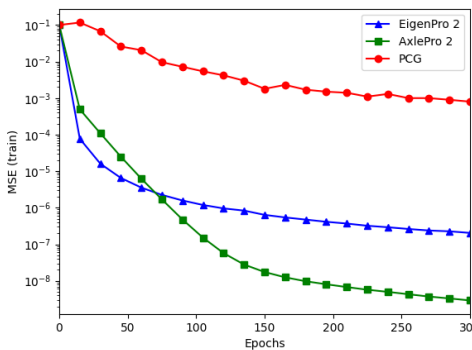
Dataset	MSE v/s Time	MSE v/s Epochs
CIFAR10		
Stellar Classification		
EMNIST Digits		

Table 8: Laplacian Kernel with single precision

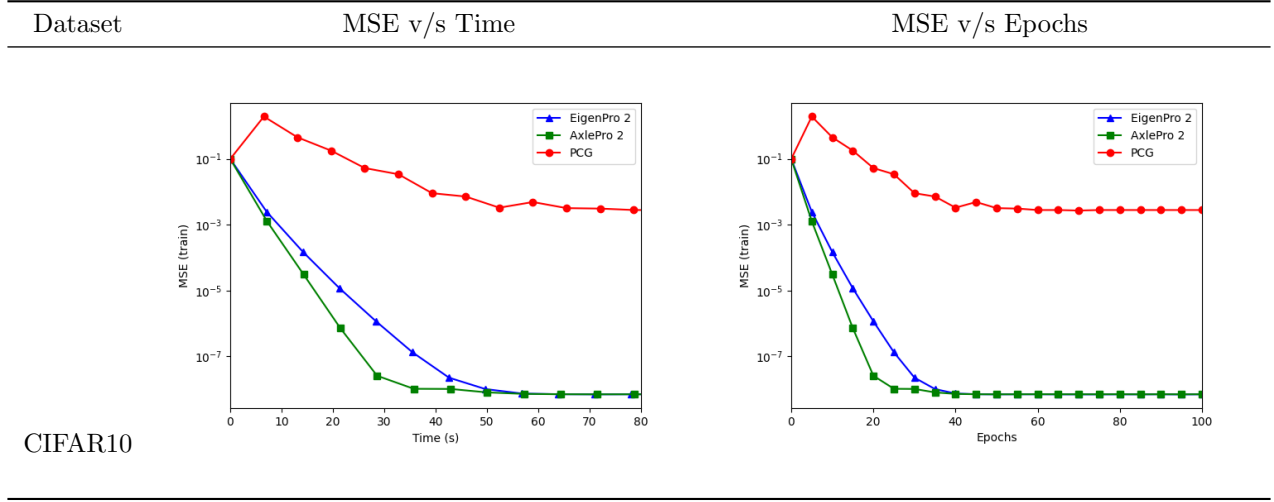


Table 9: Myrtle5 Kernel with stored kernel matrix

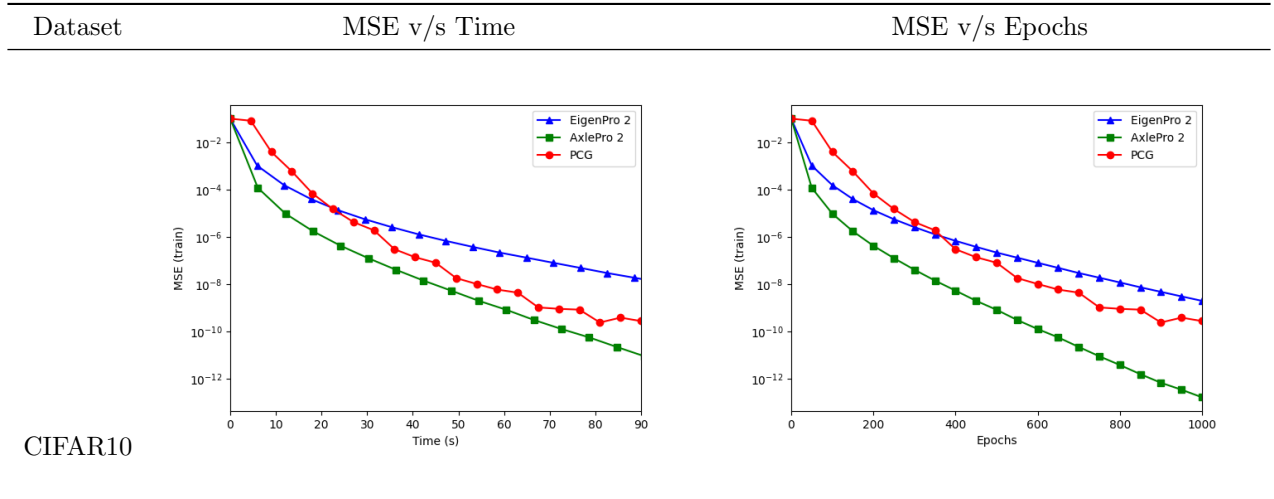


Table 10: Acceleration by Nyström approximation

Dataset	MSE v/s Time	MSE v/s Epochs
$n = 5k,$ $s = 800$		