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State-dependent Preconditioning for Data Assimilation

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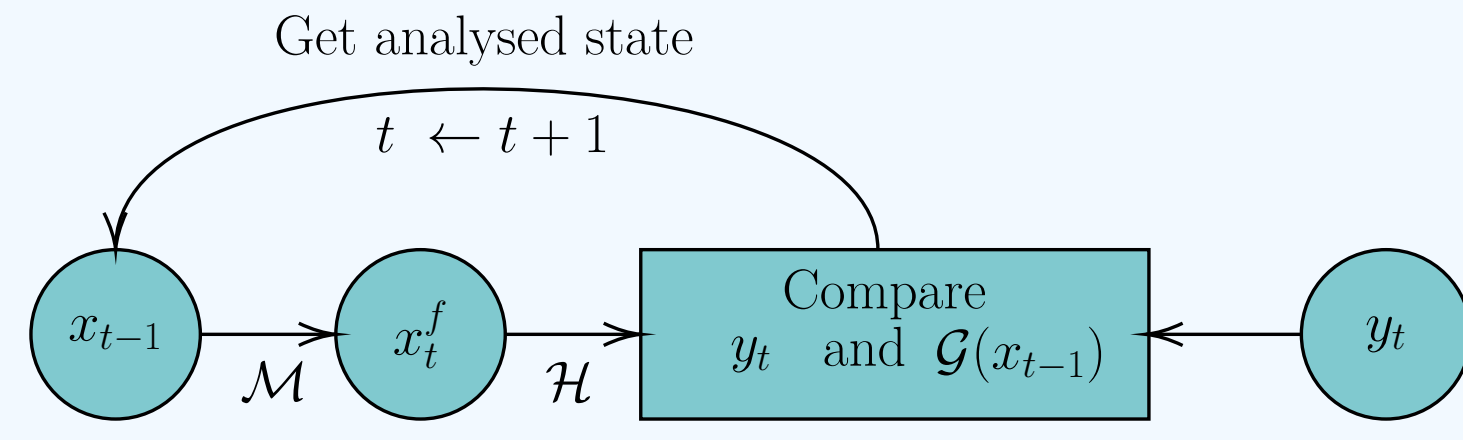
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Variational Data Assimilation

- $x \in \mathbb{R}^n$: state
- $\mathcal{M} : \mathbb{R}^n \rightarrow \mathbb{R}^n$: time propagator
- $\mathcal{H} : \mathbb{R}^n \rightarrow \mathbb{R}^m$: observation operator
- $y \in \mathbb{R}^m$: observations



- \mathcal{G} composes the forward model and the observation operator, to compare with the available observation

$$\mathcal{G} : \mathbb{X} \subseteq \mathbb{R}^n \rightarrow \mathbb{X} \rightarrow \mathbb{R}^m \quad (1)$$

$$x \mapsto \mathcal{M}(x) \mapsto (\mathcal{H} \circ \mathcal{M})(x) = \mathcal{G}(x)$$

- The cost function to optimize in order to get the analysis is

$$J_{4D}(x) = \frac{1}{2} \|\mathcal{G}(x) - y\|_{R^{-1}}^2 + \frac{1}{2} \|x - x^b\|_{B^{-1}}^2 \quad (2)$$

and

$$x_{t-1}^a = \arg \min_{x \in \mathbb{X}} J_{4D}(x) \quad (3)$$

Incremental 4DVar

Outer and Inner loops: Minimization as a sequence of Linear Systems

- Linearize J around x (Linear Inverse Problem):

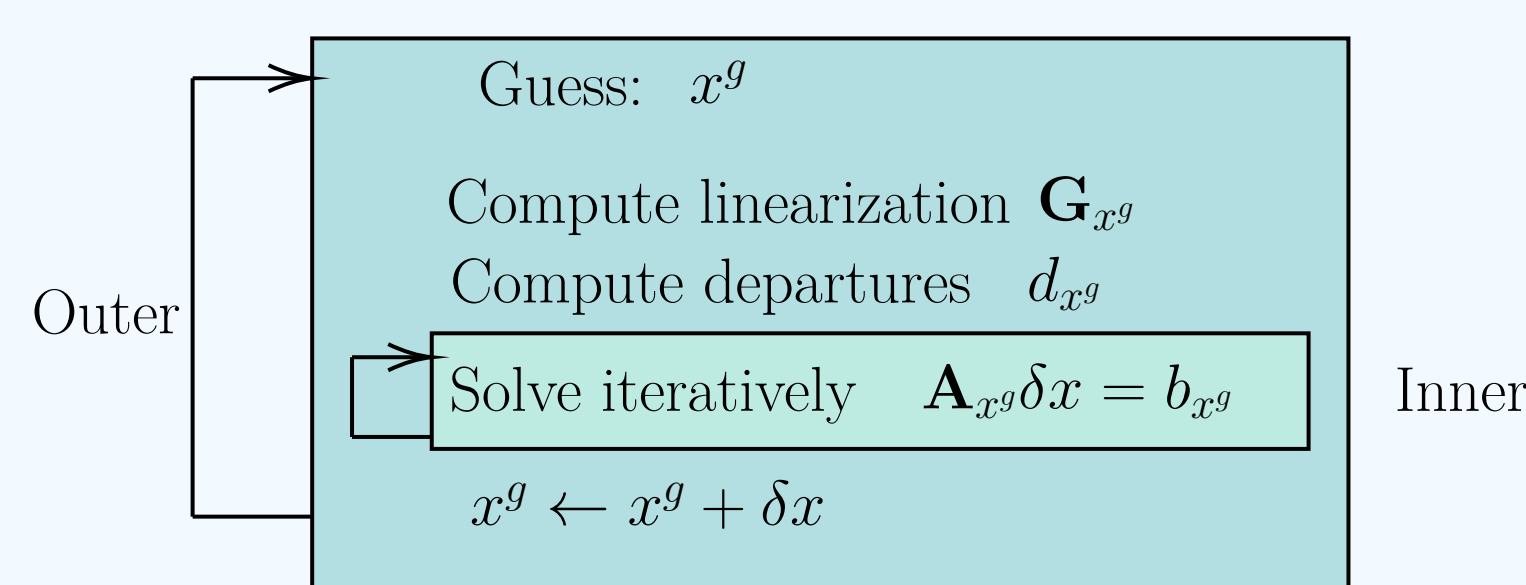
$$J_{\text{incr}}(x, \delta x) = \frac{1}{2} \|\mathbf{G}_x \delta x + \underbrace{(\mathcal{G}(x) - y)}_{-d_x}\|_{R^{-1}}^2 + \frac{1}{2} \|\delta x + x - x^b\|_{B^{-1}}^2 \quad (4)$$

- The optimal increment solves

$$\underbrace{(\mathbf{G}_x^T R^{-1} \mathbf{G}_x + B^{-1})}_{\mathbf{A}_x} \delta x = \underbrace{-\mathbf{G}_x^T R^{-1} d_x - B^{-1} (x - x^b)}_{b_x} \quad (5)$$

where \mathbf{A}_x Gauss-Newton Matrix \iff Inverse posterior covariance Matrix

$$\mathbf{A}_x = \mathbf{G}_x^T R^{-1} \mathbf{G}_x + B^{-1} \in \mathbb{R}^{n \times n} \text{ symmetric and spd} \quad (6)$$



In the Inner Loop

- \mathbf{A}_x is spd, so **Conjugate Gradient** can be used
- Convergence rate depends on the spectrum of \mathbf{A}_x
 - Condition number: $\sigma_{\max}/\sigma_{\min} = \|\mathbf{A}\| \|\mathbf{A}^{-1}\|$
 - Clustering of eigenvalues at 1

State Dependent Preconditioner

Preconditioning

Instead of solving $\mathbf{A}_x \delta x = b$, solve $H \mathbf{A}_x \delta x = H b$ instead

- H symmetric, positive definite, cheap to compute and to apply
- H should be close to \mathbf{A}_x^{-1}
- $1 \leq \kappa(H \mathbf{A}_x) \leq \kappa(\mathbf{A}_x)$

But "one-fits-all" preconditioner do not exist, most include information on *spectrum* of \mathbf{A}_x .

State-dependent preconditioner

We propose to construct a mapping

$$x \mapsto H(x) \quad (7)$$

where $H(x)$ is a preconditioner well-suited for the linear system $\mathbf{A}_x \delta x = b_x$

Challenges

- $H(x) \in \mathbb{R}^{n \times n}$ is spd (ie $n(n+1)/2$ "free" parameters)
- \mathbf{A}_x is not stored explicitly (only accessible as $\text{TL}(x, z) = \mathbf{A}_x z$) and high-dimensional
- Independence with respect to the observations (thus to b_x)
- $H(x)$ should contain spectral information of \mathbf{A}_x

ML framework

Objective

- Construct a preconditioner $x \mapsto H_\theta$ using DNN, which require **no** call to \mathbf{A}_x when in use
- No access to \mathbf{A}_x^{-1} during the training

Limited Memory Preconditioners [4]/Balancing Preconditioners

Let $S, S' \in \mathbb{R}^{n \times r}$, $S' = \mathbf{A}_x S$

$$H_{\text{LMP}}(S, S') = (I_n - S(S^T S')^{-1} S'^T)(I_n - S'(S^T S')^{-1} S^T) + S(S^T S')^{-1} S'^T \quad (8)$$

We define the preconditioner as

$$H_\theta : x \mapsto H_{\text{LMP}}(S_\theta(x), \tilde{A}_\theta(x) S_\theta(x)) \quad (9)$$

and H_θ^{-1} available in a similar way

Loss function, Estimation of Frobenius norm

If we constrain the norm of $\|H_\theta\|$ (e.g. by choosing S_θ as eigenvectors)

$$\text{"minimize } \|\mathbf{A}_x - H_\theta^{-1}(x)\|_{\text{F}}^2 \text{"} \quad (10)$$

Sample n_z random $z_j \sim \mathcal{N}(0, I_n)$, and an estimation of the loss at a state x_i is

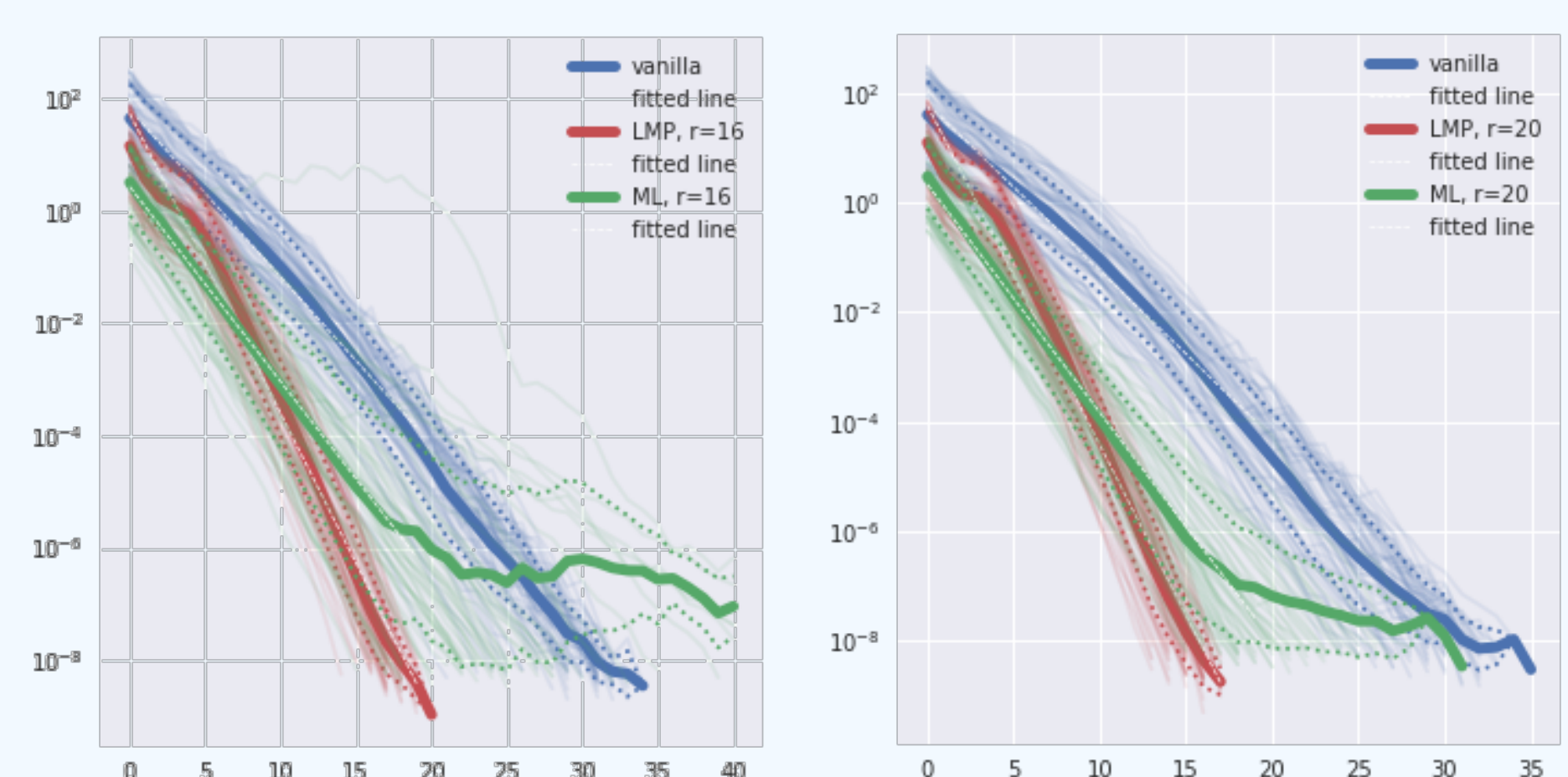
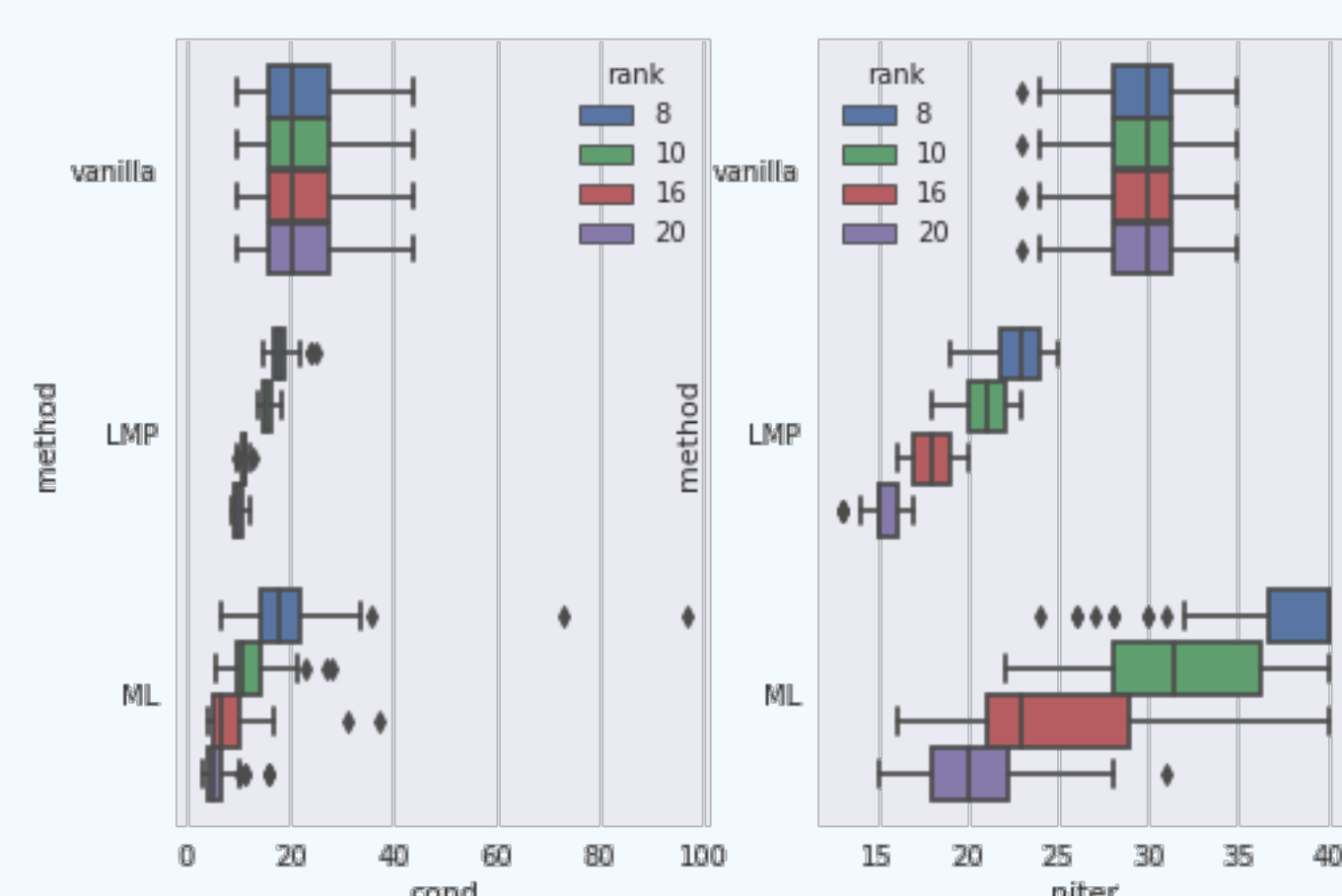
$$\hat{\mathcal{L}}(\theta, x_i) = \frac{1}{n_z} \sum_{j=1}^{n_z} \|\mathbf{A}_x z_j - H_\theta^{-1}(x_i) z_j\|_2^2 + \text{regul}(\theta) \quad (11)$$

Possibility of **online training**:

- In a DA system, when \mathbf{A}_x is available, evaluate $\mathbf{A}_x z_j$
- Less storage required

Numerical Results

Lorenz96 system, n dimension, state is "spatially" distributed and periodic \implies CNN



Conclusion and further work

- We propose to use DNN in order to build a preconditioner for inverting the Gauss-Newton matrix, which is **state-dependent** (or parametrized spd matrices in general)
- Use of different metric/regularization for the training of the DNN (Förstner distance...)
- Directly looking for a low-rank / spectral decomposition of \mathbf{A}_x might be of interest
- Use this information for dimension reduction (with Bayesian inverse problem point of view) [2]

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