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## Scalability and uncertainty of Gaussian processes

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# Bibliography

- Arbel, J., Gayraud, G., and Rousseau, J. (2013). Bayesian optimal adaptive estimation using a sieve prior. *Scandinavian Journal of Statistics*, 40(3):549–570.
- Balder, E., Gilliland, D., and van Houwelingen, J. (1983). On the essential completeness of Bayes empirical Bayes decision rules. *Statistics & Risk Modeling*, 1(4–5):503–510.
- Belitser, E. (2017). On coverage and local radial rates of credible sets. *Ann. Statist.*, 45(3):1124–1151.
- Belitser, E. and Enikeeva, F. (2008). Empirical Bayesian test of the smoothness. *Math. Methods Statist.*, 17(1):1–18.
- Bényi, A. and Oh, T. (2013). The sobolev inequality on the torus revisited. *Publications Mathematicae Debrecen*, 83:359–374.
- Berlinet, A. and C. Thomas-Agnan, C. (2004). *RKHS and Stochastic Processes*, pages 55–108. Springer US.
- Bernardo, J. and Smith, A. (1994). *Bayesian Theory*. John Wiley, New York.
- Bhattacharya, A. and Pati, D. (2015). Adaptive Bayesian inference in the Gaussian sequence model using exponential-variance priors. *Statist. Prob. Letters*, 103:100–104.
- Bhattacharya, A., Pati, D., and Yang, Y. (2017). Frequentist coverage and sup-norm convergence rate in gaussian process regression. *arXiv e-prints*.
- Bickel, P. J. (1982). On Adaptive Estimation. *The Annals of Statistics*, 10(3):647 – 671.
- Bickel, P. J. and Doksum, K. A. (1977). *Mathematical Statistics: Basic Ideas and Selected Topics*. Holden-Day Company, Oakland, California.
- Box, G. (1976). Science and statistics. *Journal of the American Statistical Association*, 71(356):791–799.
- Brown, L. and Low, M. (1996). A constrained risk inequality with applications to nonparametric function estimation. *Ann. Statist.*, 24:2524–2535.
- Cai, T. and Low, M. (2004). An adaptation theory for nonparametric confidence intervals. *Ann. Statist.*, 32:1805–1840.
- Cao, Y. and Fleet, D. (2014). Generalized product of experts for automatic and principled fusion of gaussian process predictions. *arXiv e-prints*.

- Castillo, I. and Nickl, R. (2013). Nonparametric Bernstein-von Mises theorems in gaussian white noise. *Ann. Statist.*, 41(4):1999–2028.
- Castillo, I. and Nickl, R. (2014). On the Bernstein-von Mises phenomenon for nonparametric bayes procedures. *Ann. Statist.*, 42(5):1941–1969.
- Choudhuri, N., Ghosal, S., and Roy, A. (2007). Nonparametric binary regression using a Gaussian process prior. *Statistical Methodology*, 4:227–243.
- Cobos, F., Kühn, T., and Sickel, W. (2015). Optimal approximation of multivariate periodic Sobolev functions in the sup-norm. *Journal of Functional Analysis*, 270.
- Cox, D. D. (1993). An analysis of bayesian inference for nonparametric regression. *Ann. Statist.*, 21(2):903–923.
- de Jonge, R. and van Zanten, J. H. (2009). Adaptive nonparametric bayesian inference using location-scale mixture priors. Technical report.
- Diaconis, P. and Freedman, D. (1986). On the consistency of Bayes estimates. *Ann. Statist.*, 14:1–26.
- Donoho, D. L. (1994). Statistical estimation and optimal recovery. *Ann. Statist.*, 22(1):238–270.
- Doob, J. L. (1949). Application of the theory of martingales. In *Le calcul des probabilités et ses applications*, number 13 in CNRS International Colloquia, pages 23–27. CNRS, Paris.
- Ferrari-Trecate, G., Williams, C., and Opper, M. (1998). Finite-dimensional approximation of gaussian processes. In Kearns, M., Solla, S., and Cohn, D., editors, *Advances in Neural Information Processing Systems*, volume 11. MIT Press.
- Freedman, D. (1963). On the asymptotic behavior of Bayes’ estimates in the discrete case. *The Annals of Mathematical Statistics*, 34(4):1386 – 1403.
- Gal, Y., van der Wilk, M., and Rasmussen, C. E. (2014). Distributed variational inference in sparse Gaussian process regression and latent variable models. *arXiv:1402.1389*.
- Ghosal, S., Ghosh, J. K., and van der Vaart, A. (2000). Convergence rates of posterior distributions. *Ann. Statist.*, 28:500–531.
- Ghosal, S. and van der Vaart, A. (2007). Convergence rates of posterior distributions for non iid observations. *Ann. Statist.*, 35(1):192–223.
- Ghosal, S. and Van der Vaart, A. (2017). *Fundamentals of nonparametric Bayesian inference*, volume 44. Cambridge University Press.
- Gibbs, N., Jr, W. P., and Stockmeyer, P. (1976). An algorithm for reducing the bandwidth and profile of a sparse matrix. *SIAM J. Numer. Anal.*, 13(2):236–250.
- Giné, E. and Nickl, R. (2010). Confidence bands in density estimation. *Ann. Statist.*, 38(2):1122–1170.

- Giné, E. and Nickl, R. (2016). *Mathematical foundations of infinite-dimensional statistical models*. Cambridge series in statistical and probabilistic mathematics.
- Goldenshluger, A. and Nemirovski, A. (1997). On spatial adaptive estimation of nonparametric regression. *Math. Meth. Statistics*, 6:135–170.
- Guhaniyogi, R., Li, C., Savitsky, T. D., and Srivastava, S. (2017). A divide-and-conquer bayesian approach to large-scale kriging. *arXiv preprint arXiv:1712.09767*.
- Hadji, A. and Szabo, B. (2021). Can we trust bayesian uncertainty quantification from gaussian process priors with squared exponential covariance kernel? *SIAM/ASA Journal on Uncertainty Quantification*, 9(1):185–230.
- Hensman, J., Fusi, N., and Lawrence, N. D. (2013). Gaussian processes for big data. UAI'13, page 282–290, Arlington, Virginia, USA. AUAI Press.
- Huang, T.-M. (2004). Convergence rates for posterior distributions and adaptive estimation. *The Annals of Statistics*, 32(4):1556 – 1593.
- Hunter, J. (2013). Distributions and sobolev spaces. Lecture Notes: Analysis Prelim Workshop. Department of Mathematics of the University of California Davis.
- Isserlis, L. (1916). On certain probable errors and correlation coefficients of multiple frequency distributions with skew regression. *Biometrika*, 11(3):185–190.
- Jiang, W. and Zhang, C.-H. (2009). General maximum likelihood empirical bayes estimation of normal means. *Ann. Statist.*
- Johnstone, I. and Silverman, B. (2005). Empirical bayes selection of wavelet thresholds. *Ann. Statist.*, 33:1700–1752.
- Jordan, M. and Jacobs, R. (1994). Hierarchical mixtures of experts and the em algorithm. *Neural Comput.*, 6(2):181–214.
- Karhunen, K. (1947). über lineare Methoden in der Wahrscheinlichkeitsrechnung. *Annales Academiae Scientiarum Fennicae Series A. I. Mathematica*, (37):1–79.
- Kim, H.-M., Mallick, B. K., and Holmes, C. C. (2005). Analyzing nonstationary spatial data using piecewise gaussian processes. *Journal of the American Statistical Association*, 100(470):653–668.
- Kim, Y. and Lee, J. (2001). On posterior consistency of survival models. *The Annals of Statistics*, 29(3):666 – 686.
- Knapik, B., van der Vaart, A. W., and van Zanten, J. H. (2011). Bayesian inverse problems with Gaussian priors. *Ann. Statist.*, 39(5):2626–2657.
- Knapik, B. T., Szabó, B. T., van der Vaart, A. W., and van Zanten, J. H. (2016). Bayes procedures for adaptive inference in inverse problems for the white noise model. *Probability Theory and Related Fields*, 164(3):771–813.
- Lehmann, E. and Casella, G. (1998). *Theory of Point Estimation (revised edition)*. Springer-Verlag, New York.

- Lember, J. and van der Vaart, A. (2007). On universal bayesian adaptation. *Statistics & Decisions*, 25(2):127–152.
- Lepski, O. V. and Spokoiny, V. G. (1997). Optimal pointwise adaptive methods in nonparametric estimation. *The Annals of Statistics*, 25(6):2512 – 2546.
- Loève, M. (1978). *Probability theory Vol. II*, volume 46 of *Graduate Texts in Mathematics*. Springer-Verlag.
- Mallasto, A. and Feragen, A. (2017). Learning from uncertain curves: The 2-Wasserstein metric for Gaussian processes. In Guyon, I., Luxburg, U. V., Bengio, S., Wallach, H., Fergus, R., Vishwanathan, S., and Garnett, R., editors, *Advances in Neural Information Processing Systems 30*, pages 5660–5670. Curran Associates, Inc.
- Meeds, E. and Osindero, S. (2006). An alternative infinite mixture of gaussian process experts. In Weiss, Y., Schölkopf, B., and Platt, J., editors, *Advances in Neural Information Processing Systems*, volume 18. MIT Press.
- Mercer, J. (1909). Functions of positive and negative type, and their connection with the theory of integral equations. *Philosophical Transactions of the Royal Society, London*, 209:415–446.
- Minsker, S., Srivastava, S., Lin, L., and Dunson, D. (2014). Robus and scalable Bayes via a media of subset posterior measures. *arXiv preprint*.
- Nadaraya, E. A. (1964). On estimating regression. *Theory of Probability and its Applications*, 9:141–142.
- Ng, J. and Deisenroth, M. (2014). Hierarchical mixture-of-experts model for large-scale gaussian process regression. *arXiv e-prints*.
- Ng, J. and Deisenroth, M. (2015). In *Proceedings of the 32nd International Conference on Machine Learning*, volume 37 of *Proceedings of Machine Learning Research*, pages 1481–1490.
- Nussbaum, M. (1996). Asymptotic equivalence of density estimation and gaussian white noise. *Ann. Statist.*, 24(6):2399–2430.
- Opper, M. and Vivarelli, F. (1999). General bounds on bayes errors for regression with gaussian processes. In Kearns, M., Solla, S., and Cohn, D., editors, *Advances in Neural Information Processing Systems II*, pages 302–308. MIT Press.
- Park, C. and Apley, D. W. (2018). Patchwork kriging for large-scale gaussian process regression. *J. Mach. Learn. Res.*, 19:7:1–7:43.
- Park, C. and Huang, J. Z. (2016). Efficient computation of gaussian process regression for large spatial data sets by patching local gaussian processes. *Journal of Machine Learning Research*, 17(174):1–29.
- Quiñonero-Candela, J. and Rasmussen, C. E. (2005). A unifying view of sparse approximate gaussian process regression. *J. Machine Learning Research*, 6:1939–1959.

- Rasmussen, C. and Ghahramani, Z. (2002). Infinite mixtures of gaussian process experts. In Dietterich, T., Becker, S., and Ghahramani, Z., editors, *Advances in Neural Information Processing Systems*, volume 14. MIT Press.
- Rasmussen, C. and Williams, C. (2006). *Gaussian processes for machine learning*. MIT Press, Boston.
- Rasmussen, C. E. (2004). Gaussian processes in machine learning. In *Advanced lectures on machine learning*, pages 63–71. Springer.
- Ray, K. (2017). Adaptive bernstein-von mises theorems in gaussian white noise. *Ann. Statist.*, 45(6):2511–2536.
- Robert, C. (2001). *The Bayesian Choice*. Springer-Verlag, New York, second edition.
- Robins, J. and van der Vaart, A. (2006). Adaptive nonparametric confidence sets. *Ann. Statist.*, 34(1):229–253.
- Rousseau, J. and Szabo, B. (2017). Asymptotic behaviour of the empirical bayes posteriors associated to maximum marginal likelihood estimator. *Ann. Statist.*, 45:833–865.
- Rousseau, J. and Szabo, B. (2020). Asymptotic frequentist coverage properties of bayesian credible sets for sieve priors. *Annals of Statistics*, 48(4):2155–2179.
- Saad, Y. (1990). Sparskit: a basic tool kit for sparse matrix computations.
- Samo, Y.-L. K. and Roberts, S. J. (2016). String and membrane gaussian processes. *Journal of Machine Learning Research*, 17(131):1–87.
- Schwartz, L. (1965). On Bayes procedures. *Z. Warsch. Verw. Gebiete*, 4:10–26.
- Scott, S., Blocker, A., Bonassi, F., Chipman, H., George, E., and McCulloch, R. (2016). Bayes and big data: The consensus monte carlo algorithm. *International Journal of Management Science and Engineering Management*, 11(2):78–88.
- Serra, P. and Krivobokova, T. (2017). Adaptive empirical bayesian smoothing splines. *Bayesian Anal.*, 12(1):219–238.
- Sniekers, S. and van der Vaart, A. (2015a). Adaptive Bayesian credible sets in regression with a Gaussian process prior. *Electron. J. Stat.*, 9(2):2475–2527.
- Sniekers, S. and van der Vaart, A. (2015b). Credible sets in the fixed design model with Brownian motion prior. *Journal of Statistical Planning and Inference*, 166:78–86.
- Srivastava, S., Cevher, V., Dinh, Q., and Dunson, D. (2015). WASP: Scalable Bayes via barycenters of subset posteriors. In Lebanon, G. and Vishwanathan, S., editors, *Proceedings of the Eighteenth International Conference on Artificial Intelligence and Statistics*, volume 38 of *Proceedings of Machine Learning Research*, pages 912–920, San Diego, California, USA. PMLR.

- Szabó, B. and van Zanten, H. (2019). An asymptotic analysis of distributed nonparametric methods. *Journal of Machine Learning Research*, 20(87):1–30.
- Szabo, B. T., van der Pas, S., and van der Vaart, A. W. (2017). Uncertainty quantification for the horseshoe (with discussion). *Bayesian Analysis*, 12(4):1221 – 1274.
- Szabo, B. T., van der Vaart, A. W., and van Zanten, J. H. (2013). Empirical bayes scaling of gaussian priors in the white noise model. *Electron. J. Statist.*, 7:991–1018.
- Szabo, B. T., van der Vaart, A. W., and van Zanten, J. H. (2015). Frequentist coverage of adaptive nonparametric Bayesian credible sets. *Annals of Statistics*, 43(4):1391–1428.
- Titsias, M. (2009). Variational learning of inducing variables in sparse Gaussian Processes. In *Artificial Intelligence and Statistics*, pages 567–574.
- Tokdar, S. and Ghosal, S. (2005). Posterior consistency of Gaussian process priors in density estimation. *J. Statist. Plann. Inference*, 137:34–42.
- Tresp, V. (2000). The generalized bayesian committee machine. In *Proceedings of the Sixth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, page 130–139, New York, NY, USA. Association for Computing Machinery.
- Tresp, V. (2001). Mixtures of gaussian processes. In Leen, T., Dietterich, T., and Tresp, V., editors, *Advances in Neural Information Processing Systems*, volume 13. MIT Press.
- Tsybakov, A. B. (2009). Introduction to nonparametric estimation. revised and extended from the 2004 french original. translated by vladimir zaiats.
- van der Pas, S., Szabo, B., and van der Vaart, A. (2017). Adaptive posterior contraction rates for the horseshoe. *Electron. J. Statist.*, 11(2):3196–3225.
- van der Vaart, A. and van Zanten, J. H. (2007). Bayesian inference with rescaled Gaussian process priors. *Electron. J. Statist.*, 1:433–448.
- van der Vaart, A. and van Zanten, J. H. (2009a). Adaptive Bayesian estimation using a Gaussian random field with inverse Gamma bandwidth. *Ann. Statist.*, 37:2655–2675.
- van der Vaart, A. and van Zanten, J. H. (2011). Information rates of nonparametric Gaussian process methods. *Journal of Machine Learning Research*, 12:2095–2119.
- van der Vaart, A. W. and van Zanten, J. H. (2008). Rates of contraction of posterior distributions based on Gaussian process priors. *Ann. Statist.*, 36(3):1435–1463.
- van der Vaart, A. W. and van Zanten, J. H. (2009b). Adaptive bayesian estimation using a gaussian random field with inverse gamma bandwidth. *Ann. Statist.*, 37(5B):2655–2675.
- Van Der Vaart, A. W. and Wellner, J. A. (1996). Weak convergence. In *Weak convergence and empirical processes*, pages 16–28. Springer.

- Wasserman, L. (2006). *All of Nonparametric Statistics*. Springer-Verlag, Berlin, Heidelberg.
- Watson, G. S. (1964). Smooth regression analysis. *Sankhyā Ser.*, 26:359–372.
- Yoo, W. W. and Ghosal, S. (2016). Supremum norm posterior contraction and credible sets for nonparametric multivariate regression. *Ann. Statist.*, 44(3):1069–1102.