

Robust estimation via Minimum Distance Estimation

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Advanced Intelligence Project

Statistical Estimation and Deep Learning in UQ for PDEs
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Contents

- 1 Some problems with the likelihood and how to fix them
 - Some problems with the likelihood
 - Minimum Distance Estimation (MDE)
- 2 Maximum Mean Discrepancy (MMD)
 - Details on the computation of the MMD estimator
 - Complex models
- 3 A Bayesian(?) point of view
 - 1st approach : “generalized posteriors”
 - 2nd approach : ABC

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The Maximum Likelihood Estimator (MLE)

Let X_1, \dots, X_n be i.i.d in \mathcal{X} from a probability distribution P_0 .

Statistical inference :

- propose a model $(P_\theta, \theta \in \Theta)$, assume $P_0 = P_{\theta_0}$.
- compute $\hat{\theta}_n = \hat{\theta}_n(X_1, \dots, X_n)$.

Letting p_θ denote the density of P_θ , then

$$\hat{\theta}_n^{MLE} = \arg \max_{\theta \in \Theta} L_n(\theta), \text{ where } L_n(\theta) = \prod_{i=1}^n p_\theta(X_i).$$

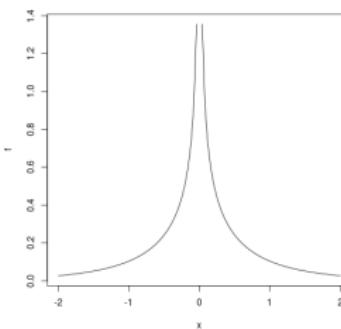
Example : $P_{(m,\sigma)} = \mathcal{N}(m, \sigma^2)$ then

$$\hat{m} = \frac{1}{n} \sum_{i=1}^n X_i \text{ and } \hat{\sigma}^2 = \frac{1}{n} \sum_{i=1}^n (X_i - \hat{m})^2.$$

MLE not unique / not consistent

Example :

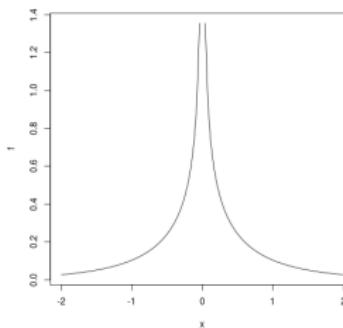
$$p_\theta(x) = \frac{\exp(-|x - \theta|)}{2\sqrt{\pi|x - \theta|}},$$



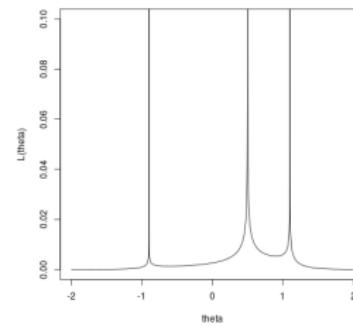
MLE not unique / not consistent

Example :

$$p_\theta(x) = \frac{\exp(-|x - \theta|)}{2\sqrt{\pi|x - \theta|}},$$



$$L_n(\theta) = \frac{\exp(-\sum_{i=1}^n |X_i - \theta|)}{(2\sqrt{\pi})^n \prod_{i=1}^n \sqrt{|X_i - \theta|}}.$$



MLE fails in the presence of outliers

What is an outlier?

Huber proposed the **contamination** model : with probability ε , X_i is not drawn from P_{θ_0} but from Q that can be **anything** :

$$P_0 = (1 - \varepsilon)P_{\theta_0} + \varepsilon Q.$$

Example : $P_\theta = \mathcal{U}nif[0, \theta]$, then

$$L_n(\theta) = \frac{1}{\theta^n} \prod_{i=1}^n \mathbb{1}_{\{0 \leq X_i \leq \theta\}} \Rightarrow \hat{\theta} = \max_{1 \leq i \leq n} X_i.$$

In the case of the following contamination, the MLE is extremely far from the truth :

$$P_0 = (1 - \varepsilon).\mathcal{U}nif[0, 1] + \varepsilon.\mathcal{N}(10^{10}, 1)\dots$$

Minimum Distance Estimation

Minimum Distance Estimation (MDE)

Let $d(\cdot, \cdot)$ be a metric on probability distributions.

$$\hat{\theta}_d := \arg \min_{\theta \in \Theta} d(P_\theta, \hat{P}_n) \text{ where } \hat{P}_n := \frac{1}{n} \sum_{i=1}^n \delta_{X_i}.$$



Wolfowitz, J. (1957). The minimum distance method. *The Annals of Mathematical Statistics*.

Idea : MDE with an adequate d leads to robust estimation.



Bickel, P. J. (1976). Another look at robustness : a review of reviews and some new developments. *Scandinavian Journal of Statistics. Discussion by Sture Holm*.



Parr, W. C. & Schucany, W. R. (1980). Minimum distance and robust estimation. *JASA*.



Yatracos, Y. G. (1985). Rates of convergence of minimum distance estimators and Kolmogorov's entropy. *Annals of Statistics*.

Integral Probability Semimetrics

Integral Probability Semimetrics (IPS)

Let \mathcal{F} be a set of real-valued, measurable functions and put

$$d_{\mathcal{F}}(P, Q) = \sup_{f \in \mathcal{F}} \left| \mathbb{E}_{X \sim P}[f(X)] - \mathbb{E}_{X \sim Q}[f(X)] \right|.$$



Müller, A. (1997). Integral probability metrics and their generating classes of functions. *Applied Probability*.

- assumptions required in order to ensure that $d_{\mathcal{F}}(P, Q) = 0 \Rightarrow P = Q$ (that is, $d_{\mathcal{F}}$ is a metric).
- assumptions required in order to ensure that $d_{\mathcal{F}} < +\infty$.

Non-asymptotic bound for MDE

Theorem 1

- X_1, \dots, X_n i.i.d from P_0 ,
- for any $f \in \mathcal{F}$, $\sup_{x \in \mathcal{X}} |f(x)| \leq 1$.

Then

$$\mathbb{E} \left[d_{\mathcal{F}}(P_{\hat{\theta}_{d_{\mathcal{F}}}}, P_0) \right] \leq \inf_{\theta \in \Theta} d_{\mathcal{F}}(P_{\theta}, P_0) + 4 \cdot \text{Rad}_n(\mathcal{F}).$$

Rademacher complexity

$$\text{Rad}_n(\mathcal{F}) := \sup_P \mathbb{E}_{Y_1, \dots, Y_n \sim P} \mathbb{E}_{\epsilon_1, \dots, \epsilon_n} \left[\sup_{f \in \mathcal{F}} \frac{1}{n} \sum_{i=1}^n \epsilon_i f(Y_i) \right].$$

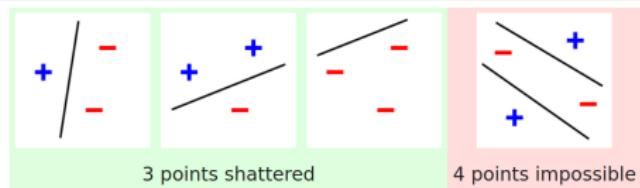
where $\epsilon_1, \dots, \epsilon_n$ are i.i.d Rademacher variables :

$$\mathbb{P}(\epsilon_1 = 1) = \mathbb{P}(\epsilon_1 = -1) = 1/2.$$

Example 1 : set of indicators

$$\mathbb{1}_A(x) = \begin{cases} 1 & \text{if } x \in A, \\ 0 & \text{if } x \notin A. \end{cases}$$

Image from Wikipedia.



Reminder - Vapnik-Chervonenkis dimension

Assume that $\mathcal{F} = \{\mathbb{1}_A, A \in \mathcal{A}\}$ for some $\mathcal{A} \subseteq \mathcal{P}(\mathcal{X})$,

- $S_{\mathcal{F}}(x_1, \dots, x_n) := \{(f(x_1), \dots, f(x_n)), f \in \mathcal{F}\}$,
- $\text{VC}(\mathcal{F}) := \max \{n : \exists x_1, \dots, x_n, |S_{\mathcal{F}}(x_1, \dots, x_n)| = 2^n\}$.

Theorem (Bartlett and Mendelson)

$$\text{Rad}_n(\mathcal{F}) \leq \sqrt{\frac{2 \cdot \text{VC}(\mathcal{F}) \log(n+1)}{n}}.$$



Bartlett, P. L. & Mendelson, S. (2002). Rademacher and Gaussian complexities : Risk bounds and structural results. *JMLR*.

Example 1 : KS and TV distances

Two classical examples :

- $\mathcal{A} = \{\text{all measurable sets in } \mathcal{X}\}$, then $d_{\mathcal{F}}(\cdot, \cdot)$ is the total variation distance $\text{TV}(\cdot, \cdot)$.
 - $\text{VC}(\mathcal{F}) = +\infty$ when $|\mathcal{X}| = +\infty$,
 - in general, $\text{Rad}_n(\mathcal{F}) \not\rightarrow 0$.
- $\mathcal{X} = \mathbb{R}$, $\mathcal{A} = \{(-\infty, x] \text{, } x \in \mathbb{R}\}$, then $d_{\mathcal{F}}(\cdot, \cdot)$ is the Kolmogorov-Smirnov distance $\text{KS}(\cdot, \cdot)$.
 - KS distance was actually proposed by S. Holm for robust estimation,
 - $\text{VC}(\mathcal{F}) = 1$.

$$\mathbb{E} [\text{KS}(P_{\hat{\theta}_{\text{KS}}}, P_0)] \leq \inf_{\theta \in \Theta} \text{KS}(P_\theta, P_0) + 4 \cdot \sqrt{\frac{2 \log(n+1)}{n}}.$$

Example 2 : Maximum Mean Discrepancy (MMD)

- Let $(\mathcal{H}, \langle \cdot, \cdot \rangle_{\mathcal{H}})$ be a RKHS with kernel

$$k(x, y) = \langle \phi(x), \phi(y) \rangle_{\mathcal{H}}.$$

- If $\|\phi(x)\|_{\mathcal{H}} = k(x, x) \leq 1$ then $\mathbb{E}_{X \sim P}[\phi(X)]$ is well-defined .
- The map $P \mapsto \mathbb{E}_{X \sim P}[\phi(X)]$ is one-to-one if k is *characteristic*.
- For example, $k(x, y) = \exp(-\|x - y\|^2/\gamma^2)$ works.

Definition - MMD

$$\begin{aligned} \text{MMD}_k(P, Q) &= \sup_{\substack{f \in \mathcal{H} \\ \|f\|_{\mathcal{H}} \leq 1}} \left| \mathbb{E}_{X \sim P}[f(X)] - \mathbb{E}_{X \sim Q}[f(X)] \right| \\ &= \left\| \mathbb{E}_{X \sim P}[\phi(X)] - \mathbb{E}_{X \sim Q}[\phi(X)] \right\|_{\mathcal{H}}. \end{aligned}$$

Example 2 : MMD

$$\mathcal{F} = \{f \in \mathcal{H} : \|f\|_{\mathcal{H}} \leq 1\} \Rightarrow \text{Rad}_n(\mathcal{F}) \leq \sqrt{\frac{\sup_x k(x, x)}{n}}.$$

Theorem 2

For k bounded by 1 and characteristic,

$$\mathbb{E} \left[\text{MMD}_k(P_{\hat{\theta}_{\text{MMD}_k}}, P_0) \right] \leq \inf_{\theta \in \Theta} \text{MMD}_k(P_\theta, P_0) + \frac{2}{\sqrt{n}}.$$



Joint work with Badr-Eddine Chérief-Abdellatif (Oxford).



Chérief-Abdellatif, B.-E. and Alquier, P. Finite Sample Properties of Parametric MMD Estimation : Robustness to Misspecification and Dependence. Bernoulli, 2022.

Example 3 : Wasserstein

Another classical metric belongs to the IPS family :

$$W_\delta(P, Q) = \sup_{\substack{f : \mathcal{X} \rightarrow \mathbb{R} \\ \text{Lip}(f) \leq 1}} \left| \mathbb{E}_{X \sim P}[f(X)] - \mathbb{E}_{X \sim Q}[f(X)] \right|$$

where $\text{Lip}(f) := \sup_{x \neq y} |f(x) - f(y)|/\delta(x, y)$.

- In general, $\text{Rad}_n(\mathcal{F}) \not\rightarrow 0$, so will not converge in full generality as with MMD and KS.
- However, nice results can be proven under additional assumptions :



Bernton, E., Jacob, P. E., Gerber, M. & Robert, C. P. (2019). On parameter estimation with the Wasserstein distance. *Information and Inference : A Journal of the IMA*.

MDE and robustness : Huber's contamination

Reminder

$$\mathbb{E} \left[d_{\mathcal{F}}(P_{\hat{\theta}_{d_{\mathcal{F}}}}, P_0) \right] \leq \inf_{\theta \in \Theta} d_{\mathcal{F}}(P_{\theta}, P_0) + 4 \cdot \text{Rad}_n(\mathcal{F}).$$

Huber's contamination model : $P_0 = (1 - \varepsilon)P_{\theta_0} + \varepsilon Q$.

$$\begin{aligned} d_{\mathcal{F}}(P_{\theta_0}, P_0) &= \sup_{f \in \mathcal{F}} |\mathbb{E}_{X \sim P_{\theta_0}} f(X) - (1 - \varepsilon)\mathbb{E}_{X \sim P_{\theta_0}} f(X) - \varepsilon\mathbb{E}_{X \sim Q} f(X)| \\ &= \sup_{f \in \mathcal{F}} |\varepsilon\mathbb{E}_{X \sim P_{\theta_0}} f(X) - \varepsilon\mathbb{E}_{X \sim Q} f(X)| \\ &= \varepsilon \cdot d_{\mathcal{F}}(P_{\theta_0}, Q) \leq 2\varepsilon \quad \text{if for any } f \in \mathcal{F}, \sup_x |f(x)| \leq 1 \end{aligned}$$

Corollary - in Huber's contamination model

$$\mathbb{E} \left[d_{\mathcal{F}}(P_{\hat{\theta}_{d_{\mathcal{F}}}}, P_{\theta_0}) \right] \leq 4\varepsilon + 4 \cdot \text{Rad}_n(\mathcal{F}).$$

MDE and robustness : toy experiment

Model : $\mathcal{N}(\theta, 1)$, X_1, \dots, X_n i.i.d $\mathcal{N}(\theta_0, 1)$, $n = 100$ and we repeat the exp. 200 times. Kernel $k(x, y) = \exp(-|x - y|)$.

	$\hat{\theta}_{MLE}$	$\hat{\theta}_{MMD_k}$	$\hat{\theta}_{KS}$
mean abs. error	0.081	0.094	0.088

Now, $\varepsilon = 2\%$ of the observations drawn from a Cauchy.

mean abs. error	0.276	0.095	0.088
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Now, $\varepsilon = 1\%$ are replaced by 1,000.

mean abs. error	10.008	0.088	0.082
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Reminder

$k(x, x') = \langle \phi(x), \phi(x') \rangle_{\mathcal{H}}$, k bounded by 1 and characteristic.

Reminder - MMD

$$\begin{aligned} \text{MMD}_k(P, Q) &= \sup_{\substack{f \in \mathcal{H} \\ \|f\|_{\mathcal{H}} \leq 1}} \left| \mathbb{E}_{X \sim P}[f(X)] - \mathbb{E}_{X \sim Q}[f(X)] \right| \\ &= \left\| \mathbb{E}_{X \sim P}[\phi(X)] - \mathbb{E}_{X \sim Q}[\phi(X)] \right\|_{\mathcal{H}}. \end{aligned}$$

More explicit formulas for the MMD

We actually have

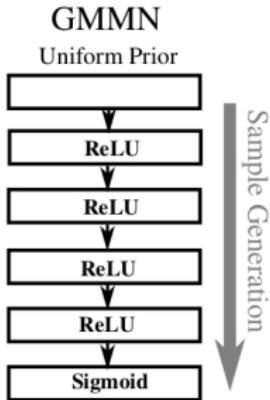
$$\text{MMD}_k^2(P_\theta, \hat{P}_n) = \mathbb{E}_{X, X' \sim P_\theta} [k(X, X')] - \frac{2}{n} \sum_{i=1}^n \mathbb{E}_{X \sim P_\theta} [k(X_i, X)] + \frac{1}{n^2} \sum_{1 \leq i, j \leq n} k(X_i, X_j)$$

and so

$$\begin{aligned} & \nabla_\theta \text{MMD}_k^2(P_\theta, \hat{P}_n) \\ &= 2\mathbb{E}_{X, X' \sim P_\theta} \left\{ \left[k(X, X') - \frac{1}{n} \sum_{i=1}^n k(X_i, X) \right] \nabla_\theta [\log p_\theta(X)] \right\} \end{aligned}$$

that can be approximated by sampling from P_θ .

Generative Adversarial Networks (GAN, 1/2)



Generative model $X \sim P_\theta$:

- $U \sim \text{Unif}[0, 1]^d$,
- $X = F_\theta(U)$ where F_θ is some NN with weights θ .



Dziugaite, G. K., Roy, D. M. & Ghahramani, Z. (2015). Training generative neural networks via maximum mean discrepancy optimization. *UAI*.



Li, Y., Swersky, K. & Zemel, R. (2015). Generative Moment Matching Networks. *ICML*.

→ proposed to minimize the MMD to learn θ .

GAN (2/2)

Results from Dziugaite et al. (2015).



Inference for Systems of SDEs (1/2)



Briol, F. X., Barp, A., Duncan, A. B., & Girolami, M. (2019). Statistical Inference for Generative Models with Maximum Mean Discrepancy. *Preprint arXiv :1906.05944*.

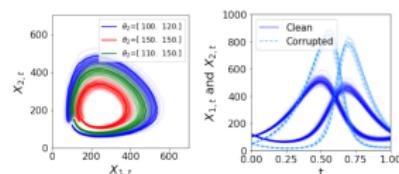
$$dX_t = b(X_t, \theta_1)dt + \sigma(X_t, \theta_2)dW_t$$

- easy to sample from the model with a given $\theta = (\theta_1, \theta_2)$,
- they propose a method to approximate the gradient of the MMD criterion.

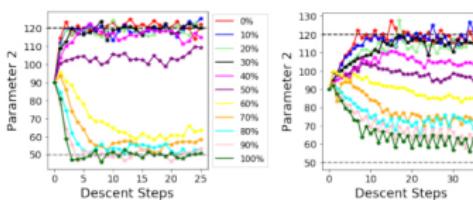
Inference for Systems of SDEs (2/2)

Example in a (stochastic) Lotka-Volterra model.

$$\begin{aligned} d \begin{pmatrix} X_{1,t} \\ X_{2,t} \end{pmatrix} = & \left[\begin{pmatrix} 1 \\ 0 \end{pmatrix} \theta_{11} X_{1,t} + \begin{pmatrix} -1 \\ 1 \end{pmatrix} \theta_{12} X_{1,t} X_{2,t} + \begin{pmatrix} 0 \\ -1 \end{pmatrix} \theta_{13} X_{2,t} \right] dt \\ & + \begin{pmatrix} 1 \\ 0 \end{pmatrix} \sqrt{\theta_{11} X_{1,t}} dW_t^{(1)} + \begin{pmatrix} -1 \\ 1 \end{pmatrix} \sqrt{\theta_{12} X_{1,t} X_{2,t}} dW_t^{(2)} + \begin{pmatrix} 0 \\ -1 \end{pmatrix} \sqrt{\theta_{13} X_{2,t}} dW_t^{(3)}, \end{aligned}$$



Results from Briol et al. (2019) : compare MMD minimization to Wasserstein minimization.



Regression

- problem with regression : we want to specify and estimate a parametric model $P_{\theta(X)}$ for $Y|X$. MMD requires to specify a model for (X, Y) .
- natural idea : estimate the distribution of X by $\frac{1}{n} \sum_{i=1}^n \delta_{X_i}$ and use the MMD procedure on $P_{\theta(X)}$.
- the previous theory shows directly that we estimate the distribution of (X, Y) consistently.
- it is far more difficult to prove that we estimate the distribution of $Y|X$.



Joint work with M. Gerber (Bristol).



Alquier, P. and Gerber, M. (2020). *Universal Robust Regression via Maximum Mean Discrepancy*. Preprint arXiv.

Copulas

- another semi-parametric model, MMD approach can be adapted.



With B.-E. Chérief-Abdellatif (Oxford), J.-D. Fermanian (ENSAE Paris), A. Derumigny (TU Delft).

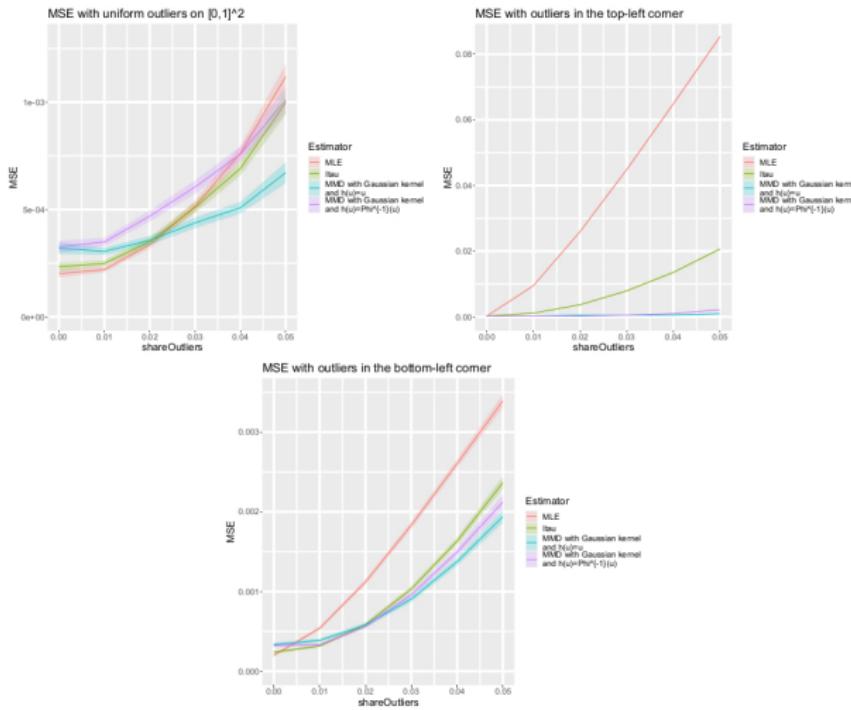


Alquier, P., Chérif-Abdellatif, B.-E., Derumigny, A. and Fermanian, J.-D. Estimation of copulas via Maximum Mean Discrepancy. *JASA*, to appear.

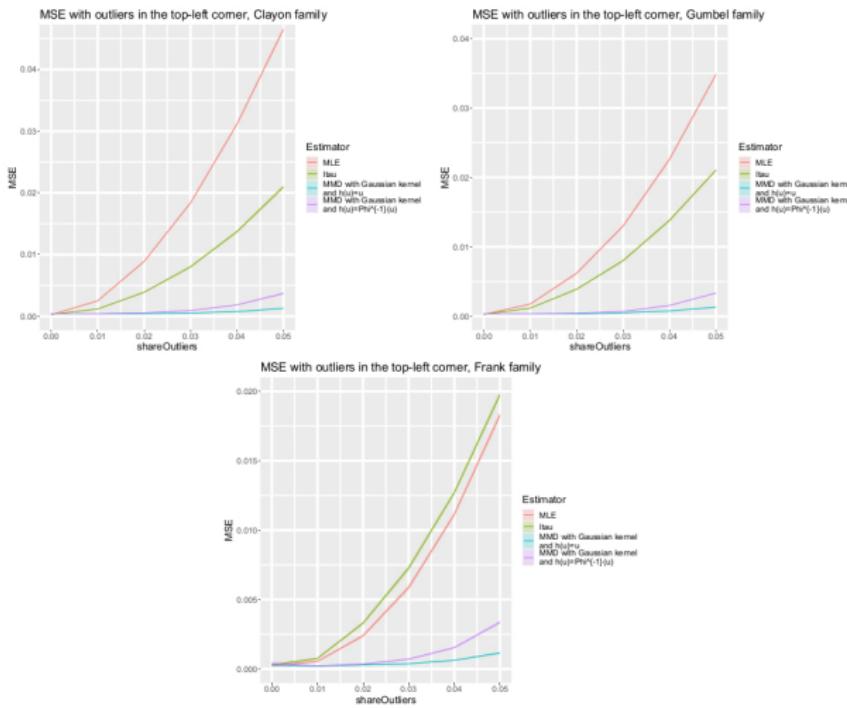


PRISCapital: Robust Estimation of Copulas by Maximum Mean Discrepancy	
Provides functions for the robust estimation of parameters of copulas using minimization of the Maximum Mean Discrepancy, following the article Aguera y Alcalde et al. (2019) .	
Depends	0.1.1
R (≥ 3.4.0)	
Imports	stats
ImportsFrom	MASS
Published	2019-10-13
Author	Guilherme G. da Cunha [aut, cre], Jean-David Fermanian [aut], Both-Ericz Chantal-Aléat [aut]
Maintainer	Guilherme G. da Cunha < GdaCunha@est.ufsc.br >
License	MIT + file LICENSE
NeedsCompilation	no
Packaged	2019-10-13
Repository	https://CRAN.R-project.org/package=PRISCapital
CRAN checks	https://CRAN.R-project.org/checks/PRISCapital.html
Details	
Reference manual	https://CRAN.R-project.org/manuals.html?file=PRISCapital.pdf
Data sources	None. PRISCapital performs robust estimation of parametric copula models by MMD minimization.
Package source	https://CRAN.R-project.org/src/contrib/PRISCapital_0.1.1.tar.gz
BiocDossier	None. PRISCapital_0.1.1.tar.gz + version PRISCapital_0.1.1.tar.gz + version PRISCapital_0.1.1.pdf
BiocTestfile	None. PRISCapital_0.1.1.tar.gz + version PRISCapital_0.1.1.pdf
LinkingTo	
Please use the citation from https://doi.org/10.5281/zenodo.3530884 to cite this package.	

Example : Gaussian copulas



Example : other models



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Generalized posteriors

Posterior

$$\pi(\theta | X_1, \dots, X_n) \propto L_n(\theta) \pi(\theta).$$

Generalized posterior

$$\hat{\pi}_{\beta, R_n}(\theta) \propto \exp(-\beta \cdot R_n(\theta)) \pi(\theta).$$

- old idea in ML (PAC-Bayes, forecasting with expert advice...) and in statistics (Gibbs posteriors...)
- popularized / extended and studied by :



Bissiri, P. G., Holmes, C. C. & Walker, S. G. (2016). A general framework for updating belief distributions. *JRSSB*.



Knoblauch, J., Jewson, J. & Damoulas, T. (2022). An Optimization-centric View on Bayes' Rule : Reviewing and Generalizing Variational Inference. *JMLR* (to appear).

Generalizing the posterior with IPS

Generalized posterior with IPS

$$\hat{\pi}_{\beta, R_n}(\theta) \propto \exp(-\beta \cdot d_{\mathcal{F}}(P_\theta, \hat{P}_n)) \pi(\theta).$$

- in the MMD case : non-asymptotic result in



Chérief-Abdellatif, B.-E. and Alquier, P. (2020). MMD-Bayes : Robust Bayesian Estimation via Maximum Mean Discrepancy. *Proceedings of AABI*.



- asymptotic results to come very soon in a joint paper with Takuo Matsubara (Newcastle) and Jeremias Knoblauch (UCL).

- both papers discuss computation via variational approximations or MCMC.

Reminder on ABC

Approximate Bayesian Computation (ABC)

input : sample $X_1^n = (X_1, \dots, X_n)$, model $(P_\theta, \theta \in \Theta)$, prior π , statistic S , distance δ and threshold ϵ .

- (i) sample $\theta \sim \pi$,
- (ii) sample $Y_1^n = (Y_1, \dots, Y_n)$ i.i.d. from P_θ :
 - if $\delta(S(X_1^n), S(Y_1^n)) \leq \epsilon$ return θ ,
 - else goto (i).
- how close is the distribution of the output to the posterior $\pi(\theta|X_1, \dots, X_n)$?
- reverse point of view : what are the properties of the “generalized posterior” we sample from ?

ABC with IPS

Here, we study the situation :

- $S(x_1, \dots, x_n) = \frac{1}{n} \sum_{i=1}^n \delta_{x_i}$ the empirical distribution,
- $\delta(P, Q) = d_{\mathcal{F}}(P, Q)$.

IPS-ABC

input : sample $X_1^n = (X_1, \dots, X_n)$, model $(P_\theta, \theta \in \Theta)$, prior π , set of functions \mathcal{F} and threshold ϵ . Put $\hat{P}_n = \frac{1}{n} \sum_{i=1}^n \delta_{X_i}$.

- sample $\theta \sim \pi$,
- sample $Y_1^n = (Y_1, \dots, Y_n)$ i.i.d. from P_θ and put $\hat{P}_n^Y = \frac{1}{n} \sum_{i=1}^n \delta_{Y_i}$,
 - if $d_{\mathcal{F}}(\hat{P}_n, \hat{P}_n^Y) \leq \epsilon$ return θ ,
 - else goto (i).

Notation : the output $\vartheta \sim \hat{\pi}_{n,\epsilon}^{\mathcal{F}}(\cdot)$.

Properties of $\hat{\pi}_{n,\epsilon}^{\mathcal{F}}(\cdot)$

In a forthcoming joint paper with S. Legramanti (University of Bergamo) and D. Durante (Bocconi University, Milan) we study 3 questions :



- ① $\hat{\pi}_{n,\epsilon}^{\mathcal{F}}(\theta) \xrightarrow[\epsilon \searrow ?]{?} \pi(\theta|X_1^n).$
- ② $\hat{\pi}_{n,\epsilon}^{\mathcal{F}}(\theta) \xrightarrow[n \rightarrow \infty]{?} ?$
- ③ $\hat{\pi}_{n,\epsilon_n}^{\mathcal{F}}(\cdot) \xrightarrow[n \rightarrow \infty]{?} \delta_{\theta_0}$ if $P_0 = P_{\theta_0}.$

Contraction of the ABC posterior

$$\epsilon_* := \inf_{\theta \in \Theta} d_{\mathcal{F}}(P_\theta, P_0).$$

Theorem 3

Assume :

- for all $\epsilon > 0$, $\pi(\{\theta : d_{\mathcal{F}}(P_\theta, P_0) \leq \epsilon_* + \epsilon\}) \geq c\epsilon^d$.
- $\forall f \in \mathcal{F}, \sup_{x \in \mathcal{X}} |f(x)| \leq 1$.
- $\text{Rad}_n(\mathcal{F}) \xrightarrow[n \rightarrow \infty]{} 0$.

Let ϵ_n be any sequence such that $\epsilon_n/\text{Rad}_n(\mathcal{F}) \rightarrow 0$ and $n\epsilon_n \rightarrow \infty$. Then, with probability $\rightarrow 1$ on the sample, for any $M_n \rightarrow \infty$,

$$\hat{\pi}_{n,\epsilon_*+\epsilon_n}^{\mathcal{F}} \left(d_{\mathcal{F}}(P_\theta, P_0) \leq \epsilon_* + \frac{4\epsilon_n}{3} + \text{Rad}_n(\mathcal{F}) + \sqrt{\frac{\log \frac{M_n}{\epsilon_n^d}}{n}} \right) \geq 1 - \frac{2.3^d}{cM_n}.$$

La fin

終わり

ありがとうございます。