

Barron, Schervish, and Wasserman (1999)

The consistency of posterior distributions in nonparametric problems

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Motivating Question and Literature

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- Does nonparametric Bayesian inference possess good **consistency** properties?
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- Doob (1949) showed consistency of the posterior under very weak conditions, but **only almost surely w.r.t. the prior**.
- Schwartz (1965) showed that if the prior puts positive mass in each Kullback-Leibler neighborhood of the true density, then the posterior does accumulate in **weak neighborhoods** of f_0 a.s. w.r.t. the true density. However, weak neighborhoods may contain many distributions that do not resemble the true density.

Main Object of Discussion

- Barron, Schervish, and Wasserman (1999), then, show that, under two assumptions, the posterior accumulates in Hellinger neighborhoods of the true density a.s. $[P_0^\infty]$. Thus, **consistency in Hellinger distance holds**, which is equivalent to consistency in total variation.

General framework

Primitive elements

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- $\mathcal{P} := \{\mu \in \mathcal{Q} : \mu(\mathcal{X}) = 1\}$ set of λ -a.c. probability measures on \mathcal{X}

Hellinger metric

- **Hellinger metric** on \mathcal{Q} :

$$d' : \mathcal{Q}^2 \rightarrow \mathbb{R}_+$$

$$(Q_1, Q_2) \mapsto d'(Q_1, Q_2) = \left\{ \int_{\mathcal{X}} [\sqrt{f_1(x)} - \sqrt{f_2(x)}]^2 d\lambda(x) \right\}^{\frac{1}{2}}$$

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- $A_\epsilon = \{P \in \mathcal{P} : d'(P_0, P) \leq \epsilon\}$

Kullback-Leibler Information

- $\forall P, Q \in \mathcal{P}$ the **Kullback-Leibler information** is defined as:

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- The integrand is intended to be 0 whenever $f_P(x) = 0$
- $N_\epsilon = \{P \in \mathcal{P} : \mathcal{I}(P_0, P) \leq \epsilon\}$ KL neighborhood of P_0

More Primitive Elements

- $(X_n)_{n \geq 1}$ i.i.d. random variables on $(\mathcal{X}, \mathcal{B})$ each with distribution P_0
 λ -a.c. and Radon Nikodym derivative $f_0 = \frac{dP_0}{d\lambda}$

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- $p_n(x^n) = \prod_{i=1}^n f_0(x_i)$ density of the true n -fold product measure of P_0
- For $\delta > 0$, $C \in \mathcal{C}$, we define the δ -**upper metric entropy** as:

$$\mathcal{K}(\delta, C) := \inf \left\{ k : \exists f_1^U, \dots, f_k^U : \begin{array}{l} i) \int_{\mathcal{X}} f_i^U(x) d\lambda(x) \leq 1 + \delta \\ ii) \forall P \in C, \exists i : f_P \leq f_i^U \text{ a.e. } [\lambda] \end{array} \right\}$$

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- $m_n(x^n) = \int_{\mathcal{P}} \prod_{i=1}^n f_P(x_i) d\pi(P)$ **predictive density** of X^n under π
- The **posterior probability** of $B \in \mathcal{C}$ given $X^n = x^n$ is computed as:

$$\pi(B|x^n) = \frac{\int_B \prod_{i=1}^n f_P(x_i) d\pi(P)}{m_n(x^n)}$$

Theoretical Core

Assumptions

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Assumption 2

$\forall \epsilon > 0, \exists (\mathcal{F}_n)_{n \geq 1} \in \mathcal{C}^{\mathbb{N}}, \exists c, c_1, c_2, \delta \in \mathbb{R}_{++} : \delta < \frac{\epsilon^2}{4} ; c < \frac{(\epsilon - \sqrt{\delta})^2 - \delta}{2}$
and, for all but finitely many n ,

- i) $\pi(\mathcal{F}_n^C) \leq c_1 \exp(-nc_2)$
- ii) $\mathcal{K}(\mathcal{F}_n, \delta) \leq nc$

Main Result

Theorem 1

Let A_ϵ be an Hellinger neighborhood of the true density. Under assumptions 1 and 2, $\forall \epsilon > 0$:

$$\lim_{n \rightarrow \infty} \pi(A_\epsilon | x^n) = 1 \quad a.s. [P_0^\infty]$$

Important Implication

Corollary 1

Let $\hat{f}_n(\cdot) = \int f_P(\cdot) d\pi(P|x^n)$. Under assumptions 1 and 2:

$$\lim_{n \rightarrow \infty} d(f_0, \hat{f}_n) = 0 \quad a.s. [P_0^\infty]$$

Where d is the Hellinger pseudo-metric on the set of non-negative functions that are integrable w.r.t. λ .

Conditions to Check

Lemma 8

Let $(\mathcal{T}_n)_{n \geq 1}$ be a sequence of finite measurable partitions of \mathcal{X} and let $N_n = |\mathcal{T}_n|$. $\forall n$, let $a_n > 0$ and suppose $\lambda(A) = \frac{1}{N_n} \forall A \in \mathcal{T}_n$. Define $\mathcal{F}_n := \{P \in \mathcal{P} : \forall A \in \mathcal{T}_n, \forall x, y \in A, |f_P(x) - f_P(y)| \leq a_n\}$. Then

$$\mathcal{K}(\mathcal{F}_n, 2a_n) \leq N_n \left[1 + \log \left(1 + \frac{1}{2N_n a_n} \right) \right]$$

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Corollary 2

$\forall \epsilon > 0$, $n \in \mathbb{N}$, let $N_n \leq \frac{n\epsilon^2}{10}$, $a_n = \frac{\epsilon^2}{32}$, $\delta = \frac{\epsilon^2}{16}$. If $\lim_{n \rightarrow \infty} N_n = \infty$, then $(\mathcal{F}_n)_{n \geq 1}$ as defined in lemma 8 satisfies $\mathcal{K}(\mathcal{F}_n, \delta) \leq \frac{n\epsilon^2}{5}$ ultimately, thus satisfying assumption 2 part ii).

Histograms Example

Histograms I

- We focus on **real-valued random variables**. Formally $(\mathcal{X}, \mathcal{B}) = ([0, 1], \mathcal{B}([0, 1]))$ and, $\forall n \in \mathbb{N}$, $\omega \in [0, 1]$, we have $X_n : \omega \mapsto \omega$

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$$\mathcal{T}_n = \left\{ \left[0, \frac{1}{N_n} \right), \left[\frac{1}{N_n}, \frac{2}{N_n} \right), \dots, \left[\frac{N_n - 1}{N_n}, 1 \right] \right\}$$

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- Let $\mathcal{U}_n \in \mathcal{C}$ be the collection of all distributions that have **constant density on every interval** in \mathcal{T}_n

Histograms II

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- Let $a_n > 0$. Conditional on $P \in \mathcal{U}_n$ we assign P/N_n the Dirichlet distribution $Dir(a_n, \dots, a_n)$
- By careful choice of N_n and p_n **this prior distribution satisfies the conditions of Theorem 1**. In particular, we set $N_n = 2^{m_n}$, with $m_n = \lfloor \log_2(n) - \log_2(\log(n)) \rfloor$, and $p_n = (1-a)a^n$ for some $0 < a < 1$. Notice that the choice of N_n implies that, when going from n to $n+1$, each time we either split each interval into two or keep the same partition.

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- Since $p_n = (1 - a)a^n$ for some $0 < a < 1$, then, [Assumption 2](#) part i) holds
- Finally, given that N_n behaves asymptotically as $\frac{n}{\log(n)}$, we can apply Corollary 2, so that also Assumption 2 part ii) holds

Main Proof

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- Let $\epsilon > 0$ and let $(\mathcal{F}_n)_{n \geq 1}$, c , c_1 , c_2 , and δ be as guaranteed by Assumption 2. We'll show that $\pi(A_\epsilon^C | \mathcal{X}^n)$ goes to 0 a.s. $[P_0^\infty]$

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- Write:

$$\pi(A_\epsilon^C | x^n) = \pi(A_\epsilon^C \cap \mathcal{F}_n | x^n) + \pi(A_\epsilon^C \cap \mathcal{F}_n^C | x^n)$$

Next, observe that, by Assumption 2, $\pi(\mathcal{F}_n^C) \leq c_1 \exp(-nc_2)$ ultimately. [Lemma 5](#), then, assures us that $\pi(A_\epsilon^C \cap \mathcal{F}_n^C | x^n)$ goes to 0 a.s. $[P_0^\infty]$.

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- Let then $C_n = A_\epsilon^C \cap \mathcal{F}_n$. We can focus on $\pi(C_n | x^n)$

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- Lemma 4 will take care of the ratio multiplying the integral, so we can focus on the latter, for now.

Proof III

- [Assumption 2](#), again, allows us to define $r \equiv r(n, \delta) = \exp(\mathcal{K}(\mathcal{F}_n, \delta))$.
Let $\{f_1^U, \dots, f_r^U\}$. For $j = 1, \dots, r$ define:

$$\tilde{E}_j = \{P \in \mathcal{F}_n : f_P \leq f_j^U \text{ a.e. } [\lambda]\}$$

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- Let $E_1 = \tilde{E}_1$ and for $j > 1$ let $E_j = \{P \in \tilde{E}_j : P \notin \tilde{E}_s \forall s < j\}$, so that the sets $\{E_1, \dots, E_r\}$ are disjoint and cover C_n . Hence, we have constructed a partition of C_n . Moreover, if $P \in E_j$, then $f_P \leq f_j^U$ a.e. $[\lambda]$. Using these two facts, we can write:

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- By contraposition, then, we can conclude that, for all j s.t. $d(f_0, f_j^U) < \epsilon - \sqrt{\delta}$, then $E_j \cap C_n = \emptyset$

Proof V

- $\forall n, j$ such that $d(f_0, f_j^U) \geq \epsilon - \sqrt{\delta}$, we can apply [Lemma 6](#) with $g = f_j^U$, $\gamma = d(f_0, f_j^U)^2 \geq [\epsilon - \sqrt{\delta}]^2$, and β as defined above.

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- Thus, $P_0^\infty(F_{n,j}) \leq \exp(-nv)$, with $v > c$. Combined with the previous inequality, Assumption 2 part ii) and the fact that $\sum_j \pi(E_j \cap \mathcal{C}_n) \leq 1$, this implies that, for all but finitely many n :

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Proof VI

- First Borel-Cantelli lemma, then, implies:

$$P_0^\infty \left(x^n : \int_{C_n} \prod_{i=1}^n \frac{f_P(x_i)}{f_0(x_i)} d\pi(P) \geq \exp \left\{ -\frac{n\beta}{2} \right\}, i.o. \right) = 0$$

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- [Lemma 4](#) grants:

$$P_0^\infty \left(x^\infty : \frac{p_n(x^n)}{m_n(x^n)} \geq \exp \left\{ \frac{n\beta}{4} \right\}, i.o. \right) = 0$$

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- Combining these last two equations with the previous decomposition of the posterior, we finally get:

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- Which implies that $\lim_{n \rightarrow \infty} \pi(C_n | x^n) = 0$, a.s. $[P_0^\infty]$

Appendix I: Histograms Assumption 1

Histograms Assumption 1 I

Lemma 9

Let $(\mathcal{X}, \mathcal{B}, \lambda)$ be a probability space, and let \mathcal{R} be a collection of measurable real-valued functions defined on \mathcal{X} . $\forall b > 0$, define

$$\mathcal{R}_b = \{f \in \mathcal{R} : \text{esssup}|f| \leq b\}$$

$$L_b = \{f : \text{esssup}|f| \leq b\}$$

where the essential supremum is relative to λ . Suppose $\exists r > 1$ such that \mathcal{R}_{rb} is dense [in the sense of $L_1(\lambda)$] in $L_b \forall b$ large. Let $P_0 \ll \lambda$ be another probability on $(\mathcal{X}, \mathcal{B})$ such that $\mathcal{I}(P_0, \lambda) < \infty$. Then $\forall \epsilon > 0$, \exists a bounded function $g \in \mathcal{R}$ such that $\mathcal{I}(P_0, P_g) < \epsilon$, where P_g is the distribution with density

$$p_g(x) = \frac{\exp(g(x))}{\int \exp(g(y)) d\lambda(y)}$$

Histograms Assumption 1 II

- Let \mathcal{R} be the set of all step functions that are constant on all of the intervals in at least one of the \mathcal{T}_n partitions, and let λ be Lebesgue measure.
- Step functions are dense in the collection of bounded measurable functions and \mathcal{R} is dense in the collection of step functions.
- Thus, $\forall \epsilon, \exists n$ and $P_\epsilon \in \mathcal{U}_n$ such that $\mathcal{I}(P_0, P_\epsilon) < \frac{\epsilon}{2}$
- Since the Dirichlet distribution over \mathcal{U}_n assigns positive probability to every open neighborhood of P_ϵ and $\mathcal{I}(P_0, P)$ is continuous as a function of P for distributions with densities in \mathcal{R} , then Assumption 1 holds.

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Appendix II: Preliminary Lemmas

Preliminary Lemmas I

Lemmas 1 and 2

Under Assumption 1,

$$P_0^\infty(x^\infty : \exists n \text{ such that } m_n(x^n) \in \{0, \infty\}) = 0$$

$$P_0^\infty(x^\infty : \exists n \text{ such that } p_n(x^n) \in \{0, \infty\}) = 0$$

where m_n is the predictive density of X^n and p_n the density of the n -fold product measure of P_0 .

Lemma 3

\exists a set $B \subseteq \mathcal{X}^\infty$ such that $P_0^\infty(B) = 1$ and such that $\forall x^\infty \in B$, there is a set $G_{x^\infty} \in \mathcal{C}$ such that $\pi(G_{x^\infty}) = 1$ and $\forall P \in G_{x^\infty}$, $\lim_{n \rightarrow \infty} D_n(x^n, P) = \mathcal{I}(P_0, P)$.

Preliminary Lemmas II

Lemma 4

Under Assumption 1, $\forall \epsilon > 0$,

$$P_0^\infty \left(x^\infty : \frac{m_n(x^n)}{p_n(x^n)} \leq \exp(n\epsilon), \text{ i.o.} \right) = 0$$

where, again, m_n is the predictive density of X^n and p_n the density of the n -fold product measure of P_0 .

Lemma 5

Suppose that Assumption 1 holds. Let $c_1, c_2 > 0$. Suppose that $(B_n)_{n=1}^\infty$ is a sequence of subset of \mathcal{P} such that $\pi(B_n) < c_1 \exp(-c_2 n)$ for all but finitely many n . Then $\lim_{n \rightarrow \infty} \pi(B_n | x^n) = 0$ a.s. $[P_0^\infty]$

Preliminary Lemmas III

Lemma 6

Let g be a non-negative, integrable function, $\beta > 0$, $d(f_0, g) = \sqrt{\gamma}$, $\int g(x) d\lambda(x) \leq 1 + \delta$ and $\delta \leq \gamma$. Then

$$P_0^n \left(x^n : \prod_{i=1}^n \frac{g(x_i)}{f_0(x_i)} \geq \exp[-n\beta] \right) \leq \exp \left(-n \frac{\gamma - \beta - \delta}{2} \right)$$

Lemma 7

Let $P \in \mathcal{P}$ and $g \in \mathcal{G}$ be such that $f_p \leq g$ a.e. $[\lambda]$ and $\int g(x) d\lambda(x) \leq 1 + \delta$. Then $d(f_p, g) \leq \sqrt{\delta}$.

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