Sequential Monte Carlo methods

Lecture 5 – Basic convergence theory

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2017-08-24

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Outline – Lecture 5

Aim: Provide some insight into the convergence and stability of the bootstrap particle filter.

Outline:

1. Central limit theorem for **importance sampling**
2. Central limit theorem for the **bootstrap particle filter**
3. **Stability** — key difference between the two

CLT for importance sampling

Importance sampling

Importance sampling,

- **Target:** $\pi(x)$
- **Proposal:** $q(x)$
- **Weight function:** $\omega(x) = \frac{\pi(x)}{q(x)}$

Procedure (for $i = 1, \ldots, N$)

1. Sample $x^i \sim q(x)$,
2. Compute $\widetilde{w}^i = \omega(x^i)$,
3. Normalize $w^i = \frac{\widetilde{w}^i}{\sum_{j=1}^N \widetilde{w}^j}$.

N.B. Here, we define ω in terms of the normalized target – no difference algorithmically but simplifies analysis.

Importance sampling bias

From the black board we have,

$$\mathbb{E}\left[\widehat{I}_N^{\text{IS}}(\varphi)\right] = I(\varphi) - \frac{\text{Cov}_q[g(X), \omega(X)]}{N} + \frac{I(\varphi)\,\text{Var}_q[\omega(X)]}{N} + O\left(\frac{1}{N^2}\right)$$

Thus, the **bias** in the importance sampling estimator, **for large N**, is

$$\begin{aligned}
&\mathbb{E}\left[\widehat{I}_N^{\text{IS}}(\varphi)\right] - I(\varphi) \\
&\qquad \approx -\frac{\text{Cov}_q[g(X), \omega(X)]}{N} + \frac{I(\varphi)\,\text{Var}_q[\omega(X)]}{N} \\
&\qquad = \cdots = -\frac{1}{N}\int \frac{\pi(x)^2}{q(x)}(\varphi(x) - I(\varphi))\mathrm{d}x
\end{aligned}$$

Summary – importance sampling

Importance sampling bias (large N):

$$\mathbb{E}\left[\widehat{I}_N^{\text{IS}}(\varphi)\right] - I(\varphi) \approx -\frac{1}{N}\int \frac{\pi(x)^2}{q(x)}(\varphi(x) - I(\varphi))\mathrm{d}x$$

Importance sampling variance (large N):

$$\text{Var}\left[\widehat{I}_N^{\text{IS}}(\varphi)\right] \approx \frac{1}{N}\int \frac{\pi(x)^2}{q(x)}(\varphi(x) - I(\varphi))^2\mathrm{d}x$$

Mean-squared error $=$ bias^2 $+$ variance — Dominated by variance!

CLT for importance sampling

Asymptotically, as $N \to \infty$,

Central limit theorem (CLT) for importance sampler

$$\sqrt{N}\left(\sum_{i=1}^{N} W^i \varphi(X^i) - I_t(\varphi)\right) \xrightarrow{\text{d}} \mathcal{N}\left(0, \int \frac{\pi(x)^2}{q(x)}(\varphi(x) - I(\varphi))^2\mathrm{d}x\right)$$

Importance sampling for filtering

Importance sampling for $\pi(x_{0:t}) = p(x_{0:t} \mid y_{1:t})$, where

$$\underbrace{p(x_{0:t} \mid y_{1:t})}_{\text{target}} = \frac{\overbrace{p(x_{0:t}, y_{1:t})}^{\text{unnormalized target}}}{\underbrace{p(y_{1:t})}_{\text{normalization}}} \propto p(y_{1:t} \mid x_{0:t})p(x_{0:t})$$

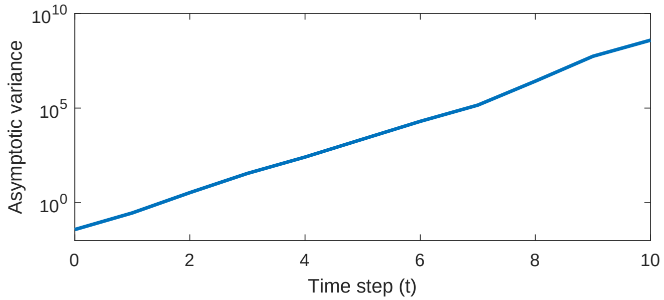
Procedure: (for $i = 1, \ldots, N$)

1. Generate $x_{0:t}^i \sim p(x_{0:t})$ by simulating the system dynamics
2. Compute weights $\widetilde{w}_t^i = p(y_{1:t} \mid x_{0:t}^i)$ and normalize $\Rightarrow w_t^i$

ex) Importance sampling for filtering

ex) Very simple state space model where the states are independent over time (no dynamics),

$$X_t \sim \mathcal{N}(0,1), \quad t = 0,1,\dots,$$
$$Y_t \mid (X_t = x_t) \sim \mathcal{N}(x_t, \sigma^2), \quad t = 1,2,\dots$$



CLT for bootstrap particle filter

CLT for bootstrap particle filter

Test function: $I_t(\varphi) = \mathbb{E}[\varphi(X_t) \mid y_{1:t}]$.

Let

$$I_{k,t}(\varphi \mid x_k) = \mathbb{E}[\varphi(X_t) \mid y_{k+1:t}, x_k] \stackrel{k<t}{=} \int \varphi(x_t) p(x_t \mid x_k, y_{k+1:t}) \mathrm{d}x_t.$$

Theorem: CLT for bootstrap particle filter

$$\sqrt{N}\left(\sum_{i=1}^N W_t^i \varphi(X_t^i) - I_t(\varphi)\right) \xrightarrow{\mathrm{d}} \mathcal{N}(0, V_t(\varphi))$$

with

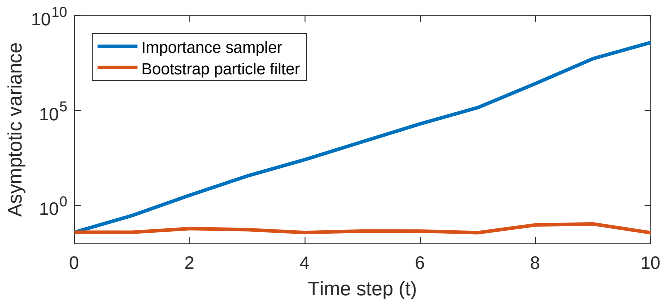
$$V_t(\varphi) = \sum_{k=0}^t \int \frac{p(x_k \mid y_{1:t})^2}{p(x_k \mid y_{1:k-1})} \left(I_{k,t}(\varphi \mid x_k) - I_t(\varphi)\right)^2 \mathrm{d}x_k.$$

ex) Very simple model, cont'd

Simple model with $X_t \sim \mathcal{N}(0,1)$, independent over time.

$$I_{k,t}(\varphi \mid x_k) = \mathbb{E}[\varphi(X_t) \mid y_{k+1:t}, x_k] = \begin{cases} \mathbb{E}[\varphi(X_t) \mid y_t] & k < t, \\ \varphi(x_t) & k = t, \end{cases}$$

It follows that all terms $k < t$ in the definition of $V_t(\varphi)$ are zero!



Particle filter stability

Often the distant past has little effect on the future (and vice versa) — referred to as **forgetting**

Exponential forgetting of **exact filter**:

$$\frac{1}{2}\int |p(x_t \mid x_k, y_{k+1:t}) - p(x_t \mid x_k', y_{k+1:t})| \mathrm{d}x_t \leq \rho^{t-k}$$

Furthermore, it often holds that,

$$\frac{p(x_k \mid y_{1:t})^2}{p(x_k \mid y_{1:k-1})} \approx \frac{p(x_k \mid y_{1:k+\Delta})^2}{p(x_k \mid y_{1:k-1})} \leq A$$

Thus, for bounded $|\varphi| < B$, it holds that $V_t(\varphi) \leq C$, independent of t!

The bootstrap particle filter is **stable**, in the sense that the estimator variance does not increase (unboundedly) with t.

Proof sketch

Three steps of the approximation

··· → Weighting → Resampling → Propagation → Weighting → Resampling → ···

$\sum_{i=1}^N w_{t-1}^i \varphi(x_{t-1}^i)$ approximates $\mathbb{E}[\varphi(X_{t-1}) \mid y_{1:t-1}]$

Resampling: $a_t^i \sim \text{Discrete}(\{w_{t-1}^j\}_{j=1}^N)$

Propagation: $x_t^i \sim p(x_t \mid x_{t-1}^{a_t^i})$

Weighting: $\widetilde{w}_t^i = p(y_t \mid x_t^i)$ and normalize $\Rightarrow w_t^i$

Three steps of the approximation

··· → Weighting → Resampling → Propagation → Weighting → Resampling → ···

$\sum_{i=1}^N w_{t-1}^i \varphi(x_{t-1}^i)$ approximates $\mathbb{E}[\varphi(X_{t-1}) \mid y_{1:t-1}]$

Resampling: $\frac{1}{N}\sum_{i=1}^N \varphi(x_{t-1}^{a_t^i})$ approximates $\mathbb{E}[\varphi(X_{t-1}) \mid y_{1:t-1}]$

Propagation: $\frac{1}{N}\sum_{i=1}^N \varphi(x_t^i)$ approximates $\mathbb{E}[\varphi(X_t) \mid y_{1:t-1}]$

Weighting: $\sum_{i=1}^N w_t^i \varphi(x_t^i)$ approximates $\mathbb{E}[\varphi(X_t) \mid y_{1:t}]$

Inductive proof idea (I/II)

Inductive hypothesis:

$$\sqrt{N}\left(\sum_{i=1}^{N} W_{t-1}^{i}\varphi(X_{t-1}^{i}) - \mathbb{E}[\varphi(X_{t-1}) \mid y_{1:t-1}]\right) \xrightarrow{\mathrm{d}} \mathcal{N}(0, V_{t-1}(\varphi))$$

Resampling:

$$\sqrt{N}\left(\frac{1}{N}\sum_{i=1}^{N} \varphi(X_{t-1}^{A_t^i}) - \mathbb{E}[\varphi(X_{t-1}) \mid y_{1:t-1}]\right) \xrightarrow{\mathrm{d}} \mathcal{N}(0, \widetilde{V}_{t-1}(\varphi))$$

with $\widetilde{V}_{t-1}(\varphi) = V_{t-1}(\varphi) + \mathrm{Var}[\varphi(X_{t-1}) \mid y_{1:t-1}]$ follows from a conditional CLT.

Inductive proof idea (II/II)

Propagation:

$$\sqrt{N}\left(\frac{1}{N}\sum_{i=1}^{N} \varphi(X_{t}^{i}) - \mathbb{E}[\varphi(X_{t}) \mid y_{1:t-1}]\right) \xrightarrow{\mathrm{d}} \mathcal{N}(0, \bar{V}_{t}(\varphi))$$

with $\bar{V}_t(\varphi) = \widetilde{V}_{t-1}(\mathbb{E}[\varphi(X_t) \mid x_{t-1}]) + \mathbb{E}[\mathrm{Var}[\varphi(X_t) \mid X_{t-1}] \mid y_{1:t-1}]$, again, follows from a conditional CLT.

Weighting:

$$\sqrt{N}\left(\sum_{i=1}^{N} W_{t}^{i}\varphi(X_{t}^{i}) - \mathbb{E}[\varphi(X_{t}) \mid y_{1:t}]\right) \xrightarrow{\mathrm{d}} \mathcal{N}(0, V_{t}(\varphi))$$

with $V_t(\varphi) = \bar{V}_t\left(\frac{p(y_t \mid x_t)}{p(y_t \mid y_{1:t-1})} \cdot \{\varphi(x_t) - \mathbb{E}[\varphi(X_t) \mid y_{1:t}]\}\right)$ follows from the delta method.

References

A non-exhaustive list of references:

- Arnaud Doucet and Adam M. Johansen. **A Tutorial on Particle Filtering and Smoothing: Fifteen years Later.** *The Oxford Handbook of Nonlinear Filtering, Oxford University Press*, 656–704, 2011.
- Pierre Del Moral. **Feynman-Kac Formulae - Genealogical and Interacting Particle Systems with Applications.** *Springer*, 2004.
- Nicolas Chopin. **Central limit theorem for sequential Monte Carlo methods and its application to Bayesian inference.** *The Annals of Statistics*, 32:2385–2411, 2004.
- Nick Whiteley. **Stability properties of some particle filters.** *Annals of Applied Probability*, 23(6):2500–2537, 2013.

A few concepts to summarize lecture 5

Bias and variance: both of order $\frac{1}{N}$ — mean squared error dominated by variance! (Holds for both importance sampling and particle filter.)

Exponential forgetting: A property of the dynamical model — the influence of historical states on the future diminishes exponentially fast.

Particle filter stability: Under forgetting conditions, errors *do not* accumulate with time.