Cross-validation for estimator selection

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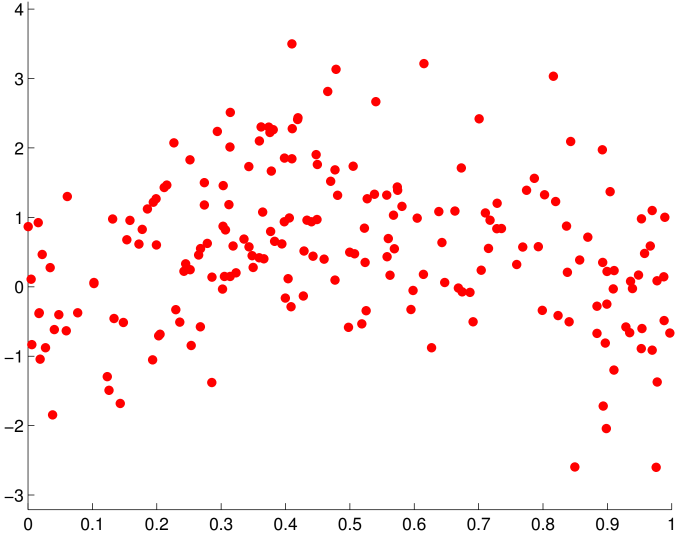
IHP, Paris
April, 9th, 2015

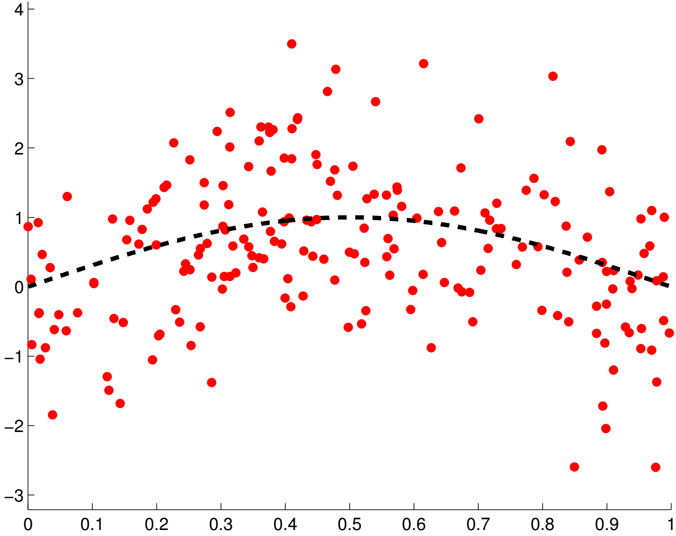
Main reference (survey): arXiv:0907.4728

Outline

Regression: data $(X_1, Y_1), \ldots, (X_n, Y_n)$



Goal: predict Y given X, i.e., denoising



Prediction problem / regression

- Data D_n: $(X_1, Y_1), \ldots, (X_n, Y_n) \in \mathcal{X} \times \mathcal{Y}$ (i.i.d. $\sim P$)
- Contrast $\gamma(t; (x, y))$ measures how well $t(x)$ "predicts" y
- Goal: learn $t \in \mathbb{S} = \{$ measurable functions $\mathcal{X} \to \mathcal{Y}\}$ s.t. $\mathbb{E}_{(X,Y)\sim P}\left[\gamma\left(t; (X, Y)\right)\right] =: P\gamma(t)$ is minimal.

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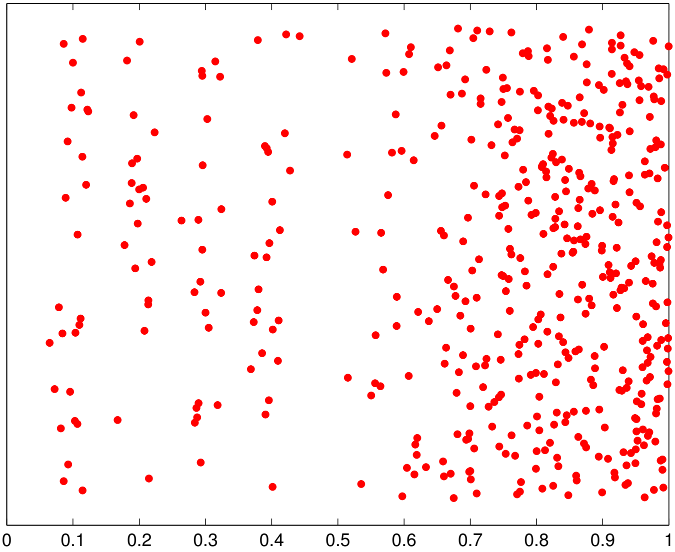
- Example: regression $\mathcal{Y} = \mathbb{R}$, least-squares contrast $\gamma(t; (x, y)) = (t(x) - y)^2$
  $s^\star \in \operatorname{argmin}_{t \in \mathbb{S}} P\gamma(t)$ is the regression function:
  $s^\star(X) = \mathbb{E}[Y \mid X]$

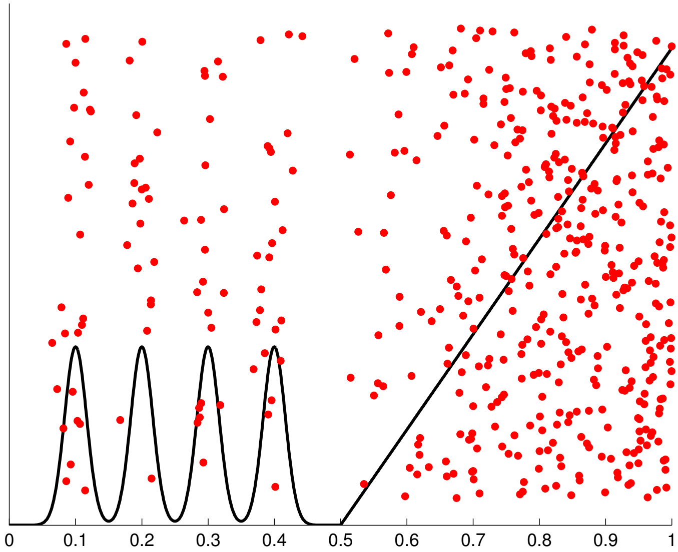
$\Rightarrow$ excess loss

$$\ell\left(s^\star, t\right) := P\gamma(t) - P\gamma(s^\star) = \mathbb{E}\left[\left(t(X) - s^\star(X)\right)^2\right]$$

Density estimation: data $\xi_1, \ldots, \xi_n$



Goal: estimate the common density $s^\star$ of ξ_i



Problem: density estimation

- Data D_n : $\xi_1, \ldots, \xi_n \in \Xi$ (i.i.d. $\sim P$, density $s^\star$ w.r.t. μ)
- Least-squares contrast $\gamma(t, \xi) = \|t\|^2_{L^2(\mu)} - 2t(\xi)$
- Goal: learn $t \in \mathbb{S} = \{$measurable functions $\Xi \to \mathbb{R}\}$ s.t. $\mathbb{E}_{\xi \sim P}\left[\gamma(t; \xi)\right] =: P\gamma(t)$ is minimal.

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$$P\gamma(t) = \int t^2 \, \mathrm{d}\mu - 2 \int t s^\star \, \mathrm{d}\mu = \int (t - s^\star)^2 \, \mathrm{d}\mu - \|s^\star\|^2_{L^2(\mu)}$$

$\Rightarrow$ the true density $s^\star \in \operatorname{argmin}_{t \in \mathbb{S}} P\gamma(t)$ and the excess loss is

$$\ell(s^\star, t) := P\gamma(t) - P\gamma(s^\star) = \|t - s^\star\|^2_{L^2(\mu)}$$

General setting

- Data $\xi_1, \ldots, \xi_n \in \Xi$ i.i.d. with distribution P

  prediction: $\xi_i = (X_i, Y_i) \in \mathcal{X} \times \mathcal{Y}$

- Goal: Estimate some feature $s^\star \in \mathbb{S}$ of P

  density, regression function, Bayes predictor...

- Contrast function $\gamma : \mathbb{S} \times \Xi \to \mathbb{R}$ such that

$$s^\star \in \operatorname*{argmin}_{t \in \mathbb{S}} \left\{ P\gamma(t) \right\} \qquad \text{with} \qquad P\gamma(t) := \mathbb{E}_{\xi \sim P}\left[\gamma(t; \xi) \right]$$

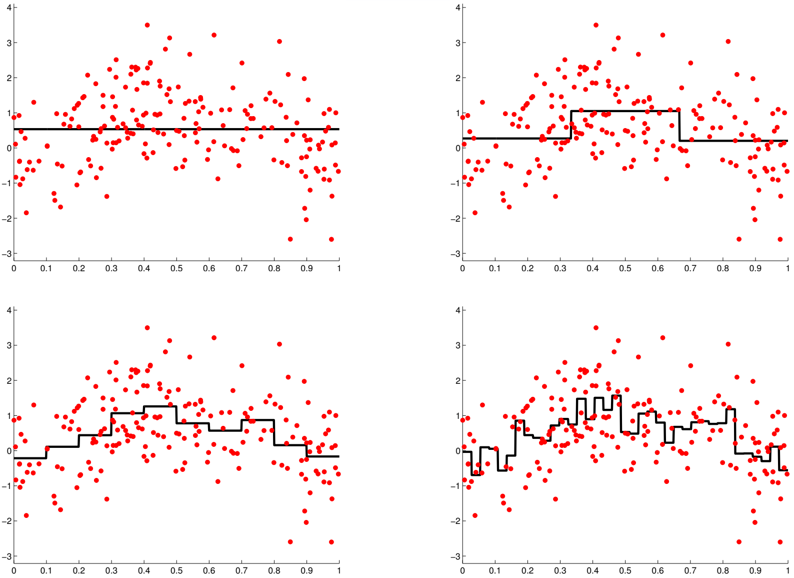
- Excess loss

$$\ell\left(s^\star, t\right) := P\gamma(t) - P\gamma(s^\star) \geqslant 0$$

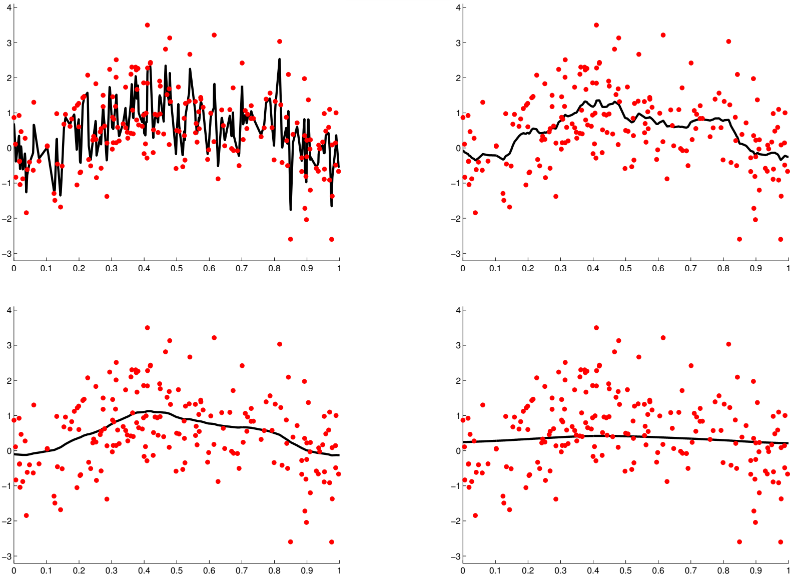
Examples

- Prediction: $\xi_i = (X_i, Y_i)$
  $X_{n+1} \quad \rightsquigarrow \quad$ "predict" Y_{n+1} with $t(X_{n+1})$?
  $\gamma(t; (x, y))$ quantifies the "distance" between $t(x)$ and y
- Regression ($\mathcal{Y} = \mathbb{R}$), least squares:
  $$\gamma(t; (x, y)) = (t(x) - y)^2 \qquad s^\star(X) = \mathbb{E}[Y|X]$$
- Binary classification ($\mathcal{Y} = \{0, 1\}$), 0–1 contrast:
  $$\gamma(t; (x, y)) = 1_{t(x) \neq y}$$
- Density estimation (reference measure μ):
  least squares: $\gamma(t; \xi) = \|t\|^2_{L^2(\mu)} - 2t(\xi)$
  log-likelihood: $\gamma(t; \xi) = -\log(t(\xi))$

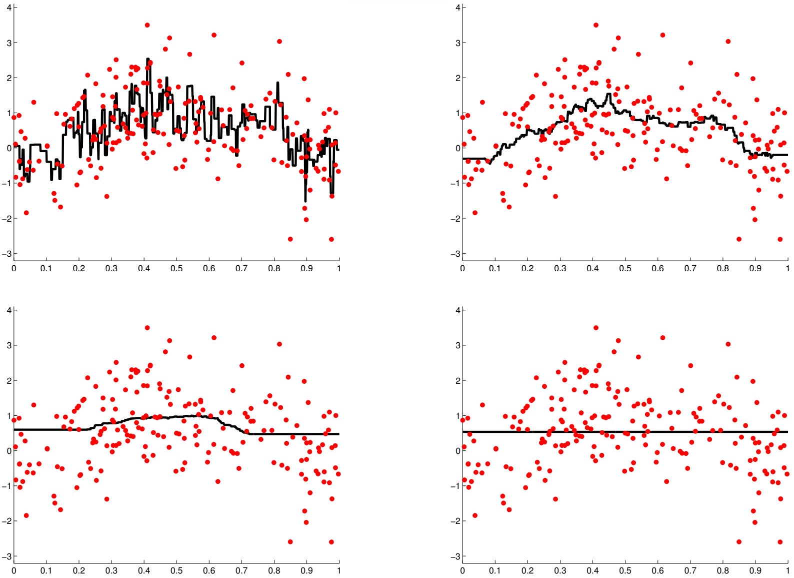
Estimator selection (regression): regular regressograms



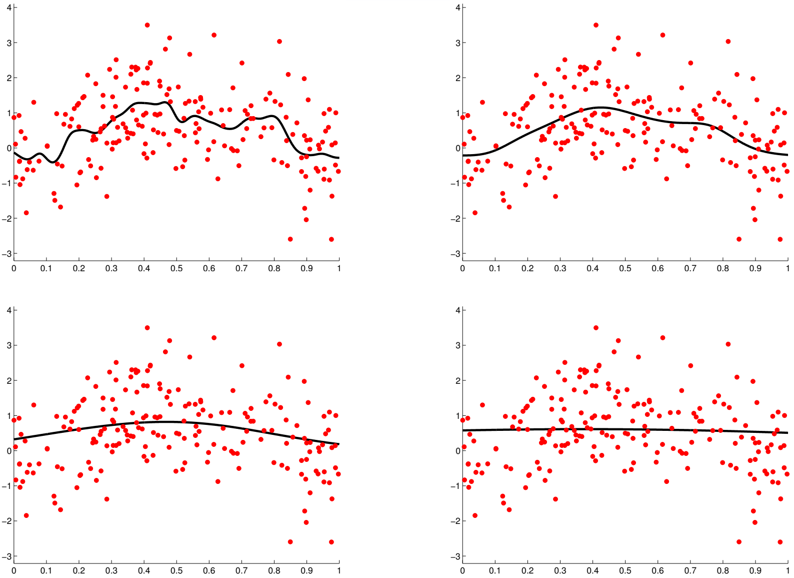
Estimator selection (regression): kernel ridge



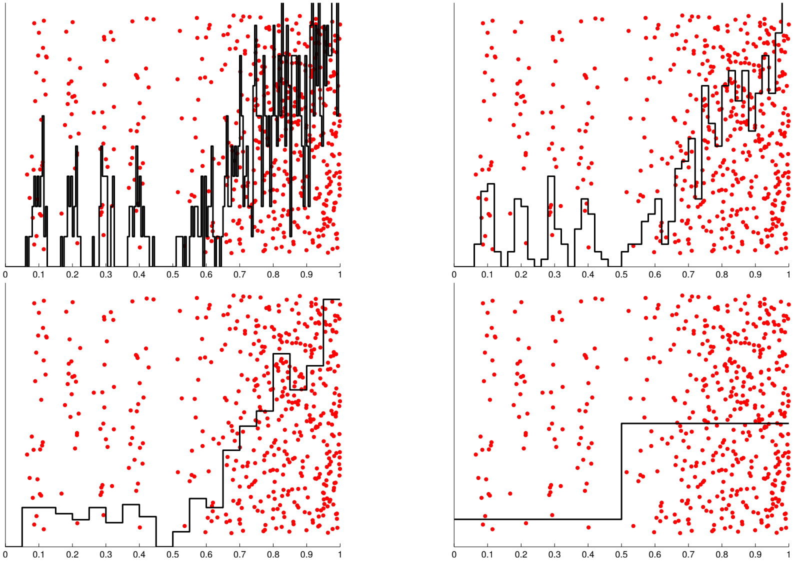
Estimator selection (regression): k nearest neighbours



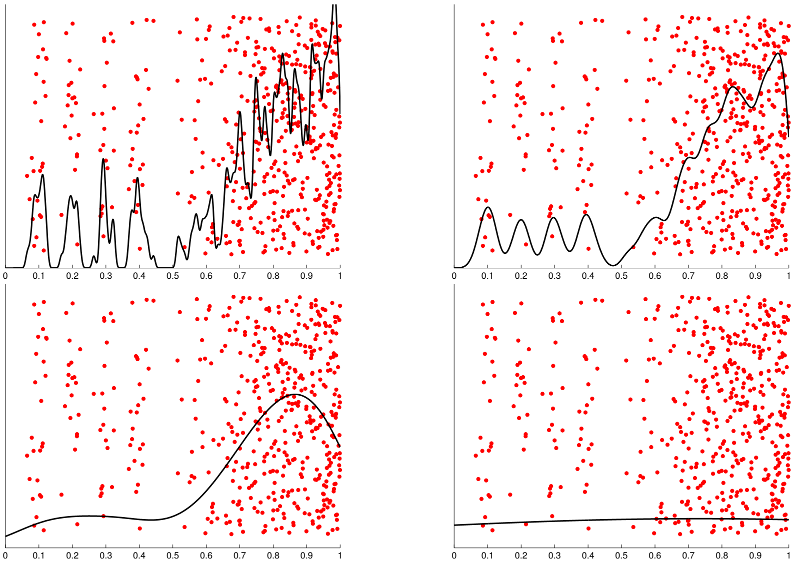
Estimator selection (regression): Nadaraya-Watson



Estimator selection (density): regular histograms



Estimator selection (density): Parzen, Gaussian kernel



Estimator selection

- Estimator/Learning algorithm: $\widehat{s} : D_n \mapsto \widehat{s}(D_n) \in \mathbb{S}$
- Example: least-squares estimator on some model $S_m \subset \mathbb{S}$

$$\widehat{s}_m \in \operatorname*{argmin}_{t \in S_m} \left\{ P_n \gamma(t) \right\} \quad \text{where} \quad P_n \gamma(t) := \frac{1}{n} \sum_{\xi \in D_n} \gamma(t; \xi)$$

Examples of models: histograms, span$\{\varphi_1, \ldots, \varphi_D\}$

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Examples of models: histograms, $\operatorname{span}\{\varphi_1, \ldots, \varphi_D\}$

- Estimator collection $(\widehat{s}_m)_{m \in \mathcal{M}} \Rightarrow$ choose $\widehat{m} = \widehat{m}(D_n)$?
- Examples:
  - model selection
  - calibration of tuning parameters (choosing k or the distance for k-NN, choice of a regularization parameter, choice of a kernel, etc.)
  - choice between different methods
    ex.: k-NN vs. smoothing splines?

Estimator selection: two possible goals

- Estimation goal: minimize the risk of the final estimator, i.e., Oracle inequality (in expectation or with a large probability):

$$\ell\left(s^{\star}, \widehat{s}_{\widehat{m}}\right) \leqslant C \inf_{m \in \mathcal{M}} \left\{ \ell\left(s^{\star}, \widehat{s}_m\right) \right\} + R_n$$

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- Identification goal: select the (asymptotically) best model/estimator, assuming it is well-defined, i.e., Selection consistency:

$$\mathbb{P}\left(\widehat{m}(D_n) = m^\star\right) \xrightarrow[n \to \infty]{} 1 \, .$$

Equivalent to estimation in the parametric setting.

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  Equivalent to estimation in the parametric setting.

- Both goals with the same procedure (AIC-BIC dilemma)? No in general (Yang, 2005). Sometimes possible.

Estimation goal: Bias-variance trade-off

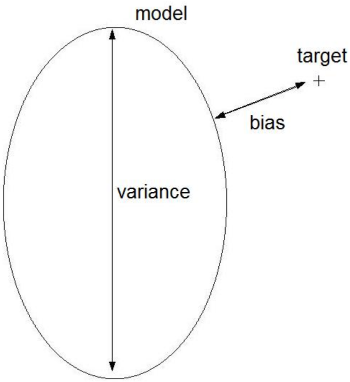
$$\mathbb{E}\left[\ell\left(s^\star, \widehat{s}_m\right)\right] = \text{Bias} + \text{Variance}$$

Bias or Approximation error

$$\ell\left(s^\star, s^\star_m\right) = \inf_{t \in S_m} \ell\left(s^\star, t\right)$$

Variance or Estimation error

OLS in regression: $$\frac{\sigma^2 \dim(S_m)}{n}$$



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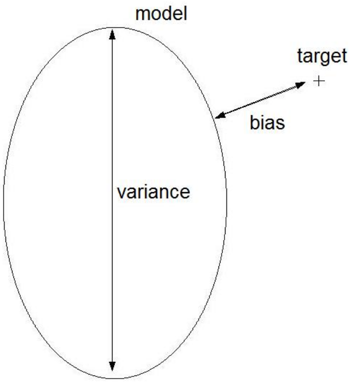
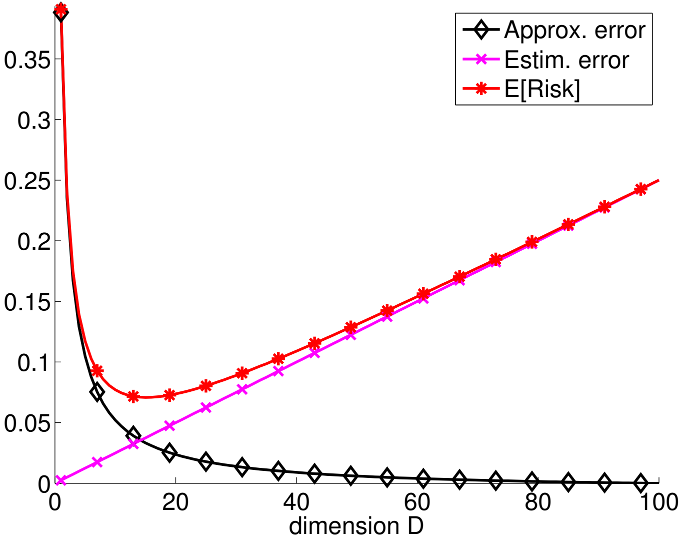


Bias-variance trade-off

$\Leftrightarrow$ avoid overfitting and underfitting

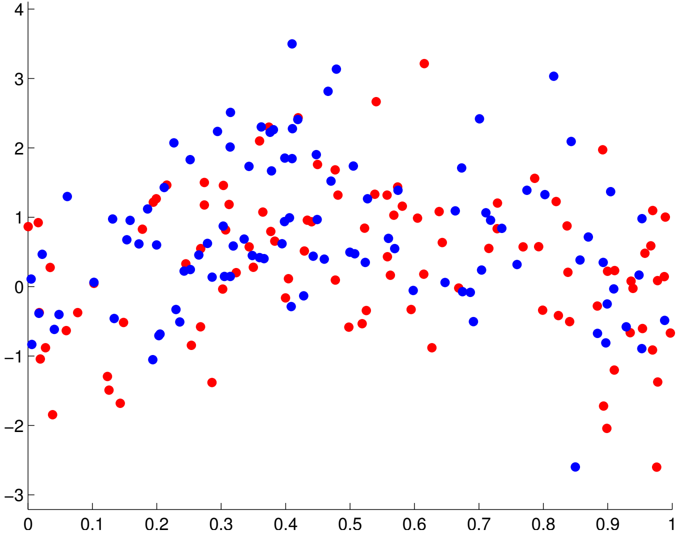
Estimation goal: Bias-variance trade-off



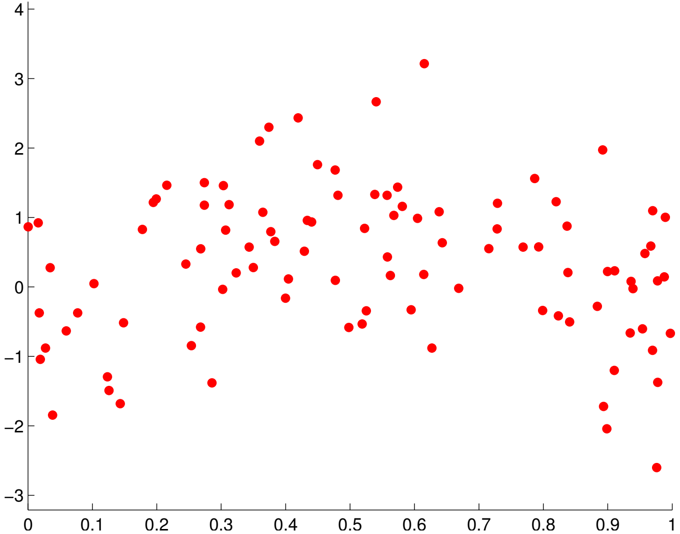
Outline

1. Estimator selection
2. Cross-validation
3. Cross-validation for risk estimation
4. Cross-validation for estimator selection
5. Large $\mathcal{M}$
6. Conclusion

Validation principle



Validation principle: learning sample



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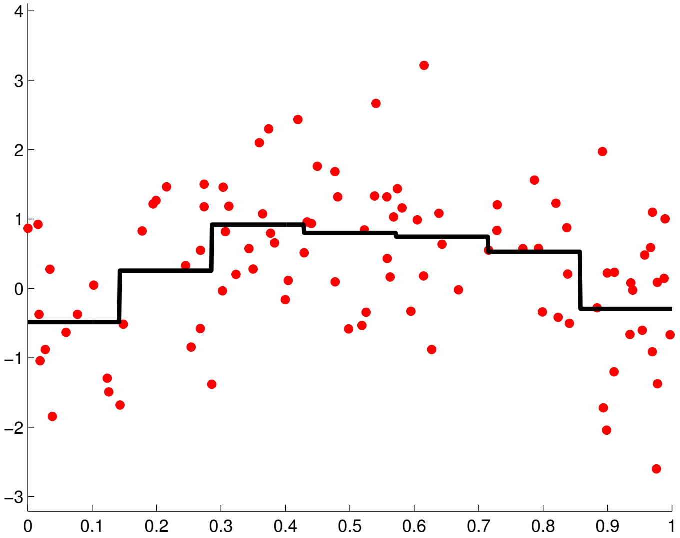

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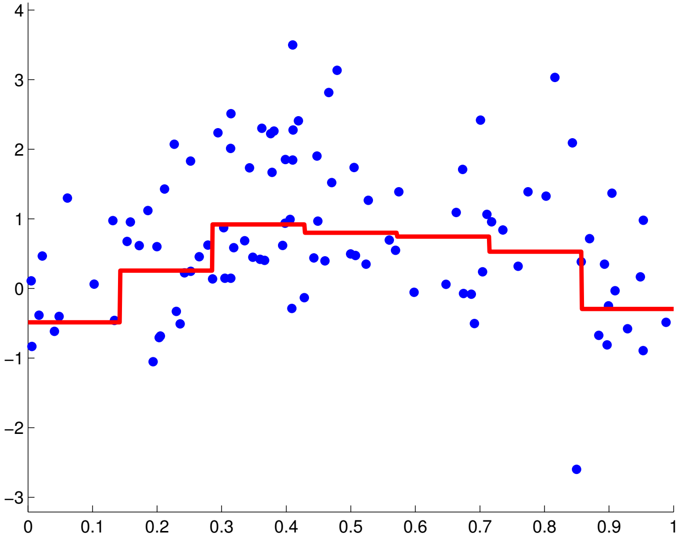

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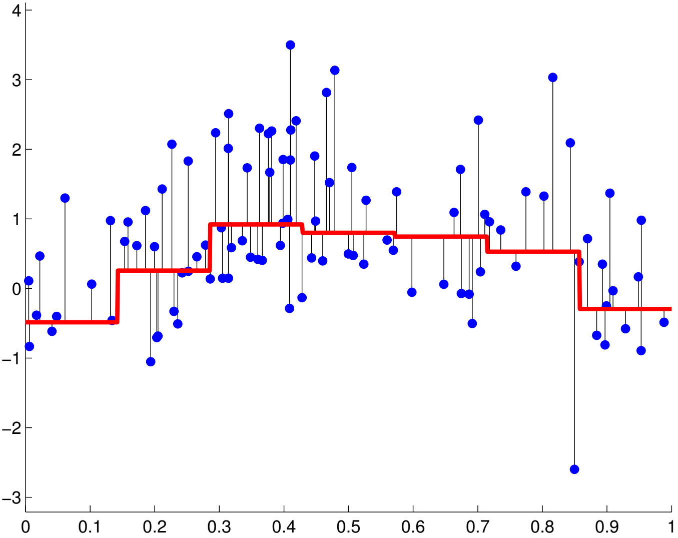

Cross-validation

$$\underbrace{(X_1, Y_1), \ldots, (X_{n_t}, Y_{n_t})}_{\text{Training set } D_n^{(t)} \Rightarrow \widehat{s}_m^{(t)} = \widehat{s}_m\left(D_n^{(t)}\right)} \quad \underbrace{(X_{n_t+1}, Y_{n_t+1}), \ldots, (X_n, Y_n)}_{\text{Validation set } D_n^{(v)} \Rightarrow \text{ evaluate risk}}$$

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- hold-out estimator of the risk:

$$P_n^{(v)} \gamma \left(\widehat{s}_m^{(t)} \right) = \frac{1}{n_v} \sum_{\xi \in D_n^{(v)}} \gamma \left(\widehat{s}_m^{(t)} ; \xi \right) \qquad n_v = |D_n^{(v)}| = n - n_t$$

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- cross-validation: average several hold-out estimators

$$\widehat{\mathcal{R}}^{\mathrm{cv}} \left(\widehat{s}_m ; D_n ; (I_j^{(t)})_{1 \leqslant j \leqslant B} \right) = \frac{1}{B} \sum_{j=1}^{B} P_n^{(v,j)} \gamma \left(\widehat{s}_m^{(t,j)} \right) \qquad D_n^{(t,j)} = (\xi_i)_{i \in I_j^{(t)}}$$

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- estimator selection:

$$\widehat{m} \in \operatorname*{argmin}_{m \in \mathcal{M}} \left\{ \widehat{\mathcal{R}}^{\mathrm{cv}}\left(\widehat{s}_m; D_n\right) \right\}$$

Cross-validation: examples

- Exhaustive data splitting: all possible subsets of size n_t
  $\Rightarrow$ leave-one-out ($n_t = n - 1$)

$$\widehat{\mathcal{R}}^{\mathrm{loo}}\left(\widehat{s}_m; D_n\right) = \frac{1}{n}\sum_{j=1}^{n}\gamma\left(\widehat{s}_m^{(-j)}; \xi_j\right)$$

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- V-fold cross-validation: $\mathcal{B} = (B_j)_{1 \leqslant j \leqslant V}$ partition of $\{1, \ldots, n\}$

$$\Rightarrow \widehat{\mathcal{R}}^{\mathrm{vf}}\left(\widehat{s}_m; D_n; \mathcal{B}\right) = \frac{1}{V}\sum_{j=1}^{V} P_n^j \gamma\left(\widehat{s}_m^{(-j)}\right)$$

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- Monte-Carlo CV / Repeated learning testing:

$$I_1^{(t)}, \ldots, I_B^{(t)} \text{ i.i.d. uniform}$$

Outline

Bias of cross-validation

- In this talk, we always assume: $\forall j$, $\operatorname{Card}\left(D_n^{(t,j)}\right) = n_t$
  For V-fold CV: $\operatorname{Card}(B_j) = n/V$.
- Ideal criterion: $P\gamma\left(\widehat{s}_m(D_n)\right)$

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- Note: $D_n \to \widehat{s}_m(D_n)$ must be fixed before seeing any data; otherwise, stronger bias.

Bias of cross-validation: generic example

Assume

$$\mathbb{E}\left[P\gamma\left(\widehat{s}_m(D_n)\right)\right] = \alpha(m) + \frac{\beta(m)}{n}$$

(e.g., LS/ridge/k-NN regression, LS/kernel density estimation).

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Bias of cross-validation: generic example

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$\Rightarrow$ V-fold: bias decreases when V increases, vanishes as $V \to +\infty$.

Variance of cross-validation

- Hold-out (Nadeau & Bengio, 2003):

$$\operatorname{var}\left(P_n^{(v)} \gamma\left(\widehat{s}_m^{(t)}\right)\right) = \frac{1}{n_v} \mathbb{E}\left[\operatorname{var}\left(\gamma(u;\xi) \,\middle|\, u = \widehat{s}_m^{(t)}\right)\right] + \operatorname{var}\left(P\gamma\left(\widehat{s}_m(D_{n_t})\right)\right)$$

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- *V-fold CV*: B, n_t, n_v related
  leave-one-out: related to stability? (empirical results)

Variance of the V-fold CV criterion

- Least-squares density estimation (A. & Lerasle 2012), exact computation (non-asymptotic):

$$\operatorname{var}\left(\widehat{\mathcal{R}}^{\mathrm{vf}}\left(\widehat{s}_m; D_n; \mathcal{B}\right)\right) = \frac{1+\mathcal{O}(1)}{n}\operatorname{var}_P(s_m^\star) + \frac{2}{n^2}\left[1 + \frac{4}{V-1} + \mathcal{O}\left(\tfrac{1}{V}+\tfrac{1}{n}\right)\right] A(m)$$

(simplified formula, histogram model with bin size d_m^{-1}, $A(m) \approx d_m$)

- Linear regression, specific setting, asymptotic formula (Burman, 1989):

$$\operatorname{var}\left(\widehat{\mathcal{R}}^{\mathrm{vf}}\left(\widehat{s}_m; D_n; \mathcal{B}\right)\right) = \frac{2\sigma^2}{n} + \frac{4\sigma^4}{n^2}\left[4 + \frac{4}{V-1} + \frac{2}{(V-1)^2} + \frac{1}{(V-1)^3}\right] + \mathrm{o}\left(n^{-2}\right)$$

$\Rightarrow$ decreasing with V, dependence only in second order terms.

Outline

Risk estimation and estimator selection are different goals

$$\widehat{m} \in \operatorname*{argmin}_{m \in \mathcal{M}} \left\{ \widehat{\mathcal{R}}^{\mathrm{cv}} \left(\widehat{s}_m \right) \right\} \quad \text{vs.} \quad m^{\star} \in \operatorname*{argmin}_{m \in \mathcal{M}} \left\{ P\gamma \left(\widehat{s}_m(D_n) \right) \right\}$$

- For any Z (deterministic or random),

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Bias and estimator selection: generic example

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(e.g., LS/ridge/k NN regression, LS/kernel density estimation).

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- Key quantities:

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$$\mathbb{E}\left[\widehat{\mathcal{R}}^{\mathrm{cv}}\left(\widehat{s}_m\right) - \widehat{\mathcal{R}}^{\mathrm{cv}}\left(\widehat{s}_{m'}\right) \right] = \alpha(m) - \alpha(m') + \frac{n}{n_t} \frac{\beta(m) - \beta(m')}{n}$$

$\Rightarrow$ CV favours m with smaller complexity $\beta(m)$, more and more as n_t decreases.

CV with an estimation goal: the big picture ($\mathcal{M}$ "small")

- At first order, the bias drives the performance of:
  leave-p-out, V-fold CV,
  Monte-Carlo CV if $B \gg n^2$
  or if n_v large enough (including hold-out)
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$\Rightarrow$ first-order optimality if $n_t \sim n$

$\Rightarrow$ suboptimal otherwise
e.g., V-fold CV with V fixed.

- Theoretical results for least-squares regression and density estimation at least.

Bias-corrected VFCV / V-fold penalization

- Bias-corrected V-fold CV (Burman, 1989):

$$\widehat{\mathcal{R}}^{\mathrm{vf,corr}}\left(\widehat{s}_m; D_n; \mathcal{B}\right) := \widehat{\mathcal{R}}^{\mathrm{vf}}\left(\widehat{s}_m; D_n; \mathcal{B}\right) + P_n\gamma\left(\widehat{s}_m\right) - \frac{1}{V}\sum_{j=1}^{V} P_n\gamma\left(\widehat{s}_m^{(-j)}\right)$$

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- In least-squares density estimation (A. & Lerasle, 2012):

$$\widehat{\mathcal{R}}^{\mathrm{vf}}(\widehat{s}_m; D_n; \mathcal{B}) = P_n\gamma\big(\widehat{s}_m(D_n)\big) + \underbrace{\left(1 + \frac{1}{2(V-1)}\right)}_{\text{overpenalization factor}} \mathrm{pen}_{\mathrm{VF}}(\widehat{s}_m; D_n; \mathcal{B})$$

$$\widehat{\mathcal{R}}^{\ell\mathrm{po}}(\widehat{s}_m; D_n; \mathcal{B}) = P_n\gamma\big(\widehat{s}_m(D_n)\big) + \overbrace{\left(1 + \frac{1}{2\left(\frac{n}{p} - 1\right)}\right)} \mathrm{pen}_{\mathrm{VF}}(\widehat{s}_m; D_n; \mathcal{B}_{\mathrm{loo}})$$

Variance and estimator selection

$$\Delta(m, m', V) = \widehat{\mathcal{R}}^{\mathrm{vf,corr}}(\widehat{s}_m) - \widehat{\mathcal{R}}^{\mathrm{vf,corr}}(\widehat{s}_{m'})$$

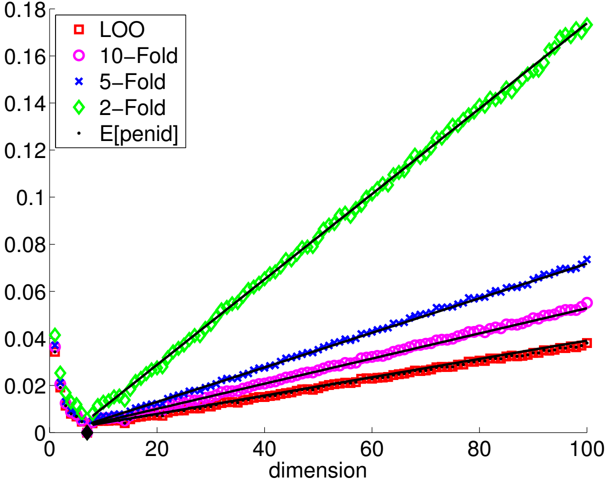
Theorem (A. & Lerasle 2012, least-squares density estimation)

$$\operatorname{var}(\Delta(m, m', V)) = 4\left(1 + \frac{2}{n} + \frac{1}{n^2}\right)\frac{\operatorname{var}_P\left(s_m^\star - s_{m'}^\star\right)}{n} + 2\left(1 + \frac{4}{V-1} - \frac{1}{n}\right)\underbrace{\frac{B(m, m')}{n^2}}_{\geqslant 0}$$

If $S_m \subset S_{m'}$ are two histogram models with constant bin sizes $d_m^{-1}, d_{m'}^{-1}$, then, $B(m, m') \propto \left\| s_m^\star - s_{m'}^\star \right\| d_m$.

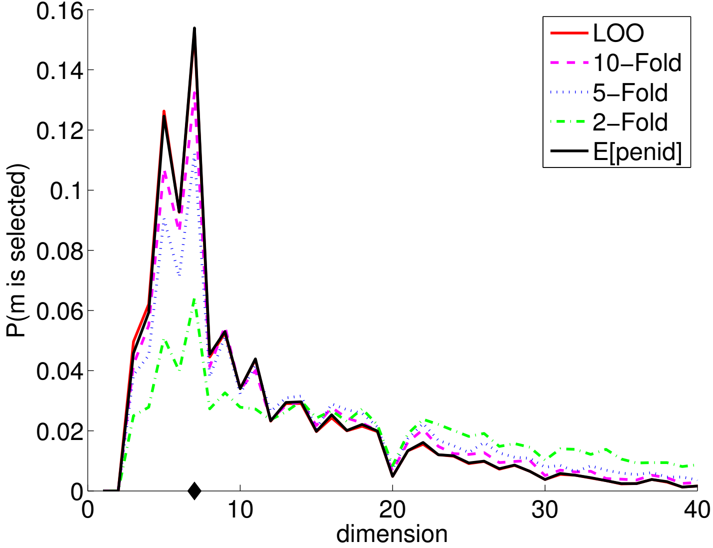
The two terms are of the same order if $\left\| s_m^\star - s_{m'}^\star \right\| \approx d_m / n$.

Variance of $\widehat{\mathcal{R}}^{\mathrm{vf,corr}}(\widehat{s}_m) - \widehat{\mathcal{R}}^{\mathrm{vf,corr}}(\widehat{s}_{m^\star})$ vs. (d_m, V)

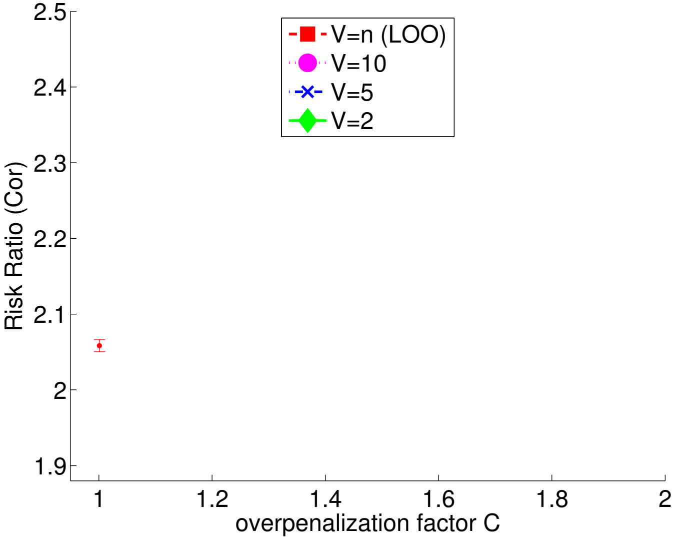


$$\operatorname{var}(\Delta(m, m', V)) \approx n^{-2}\left[29\left(1 + \frac{0.8}{V-1}\right) + 3.7\left(1 + \frac{3.8}{V-1}\right)(d_m - d_{m^\star})\right]$$

Probability of selection of every m



Experiment (LS density estimation): V-fold CV



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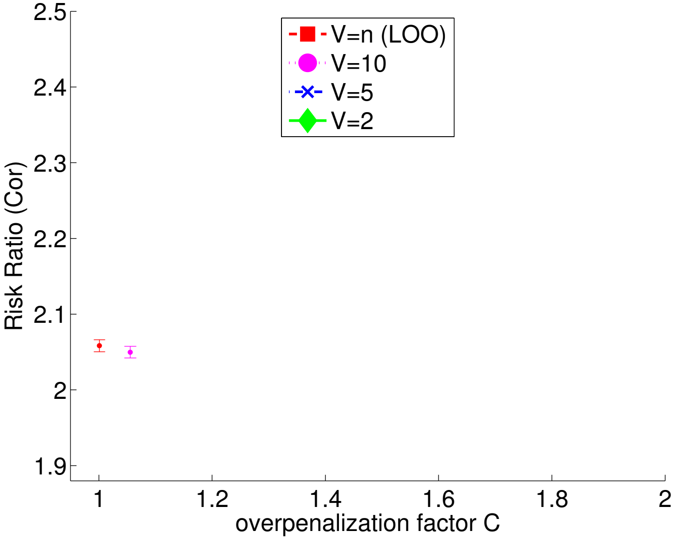

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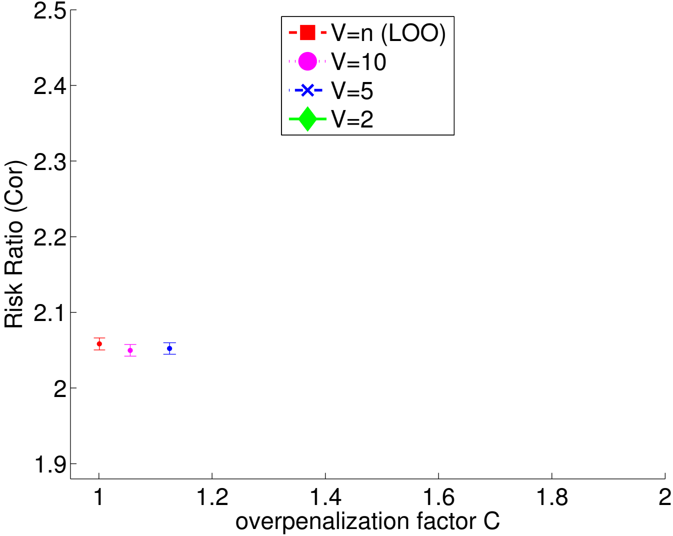

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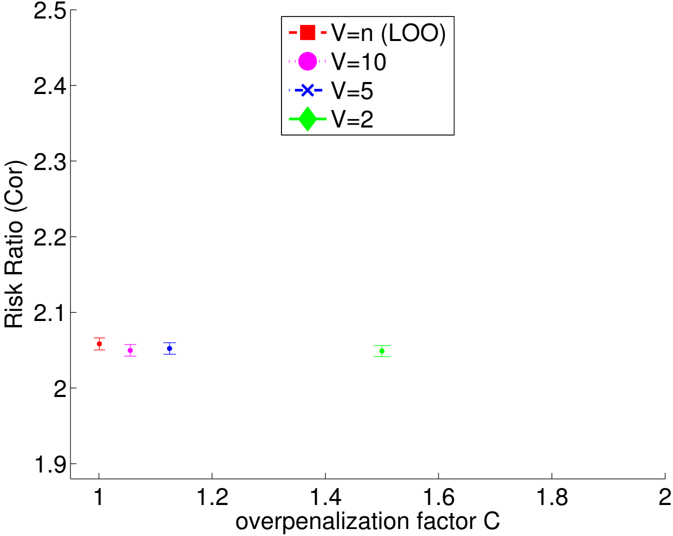
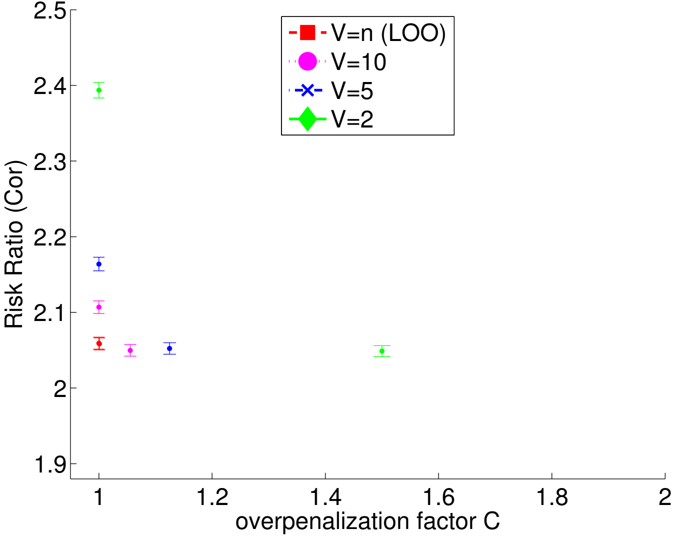
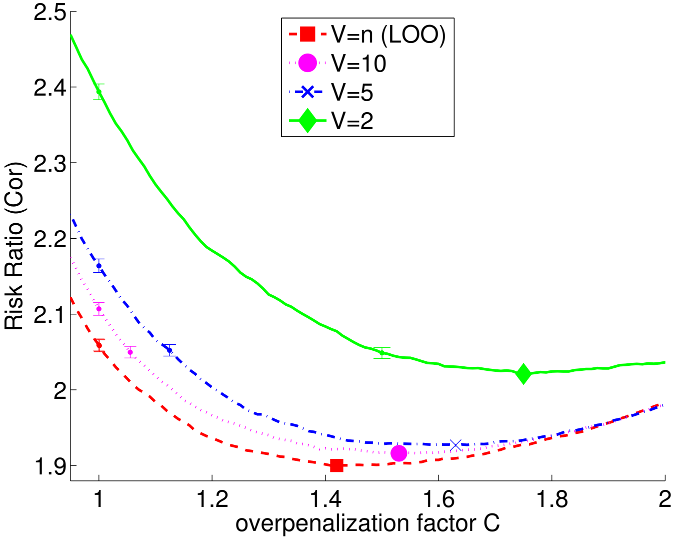


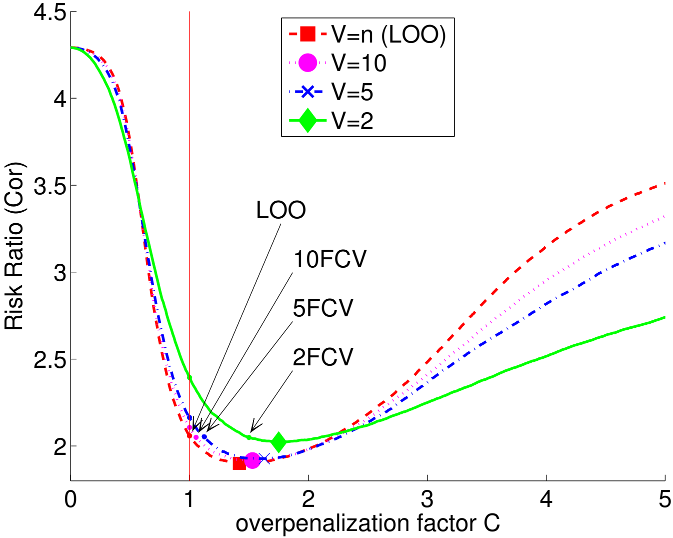
Experiment (LS density estimation): V-fold penalization



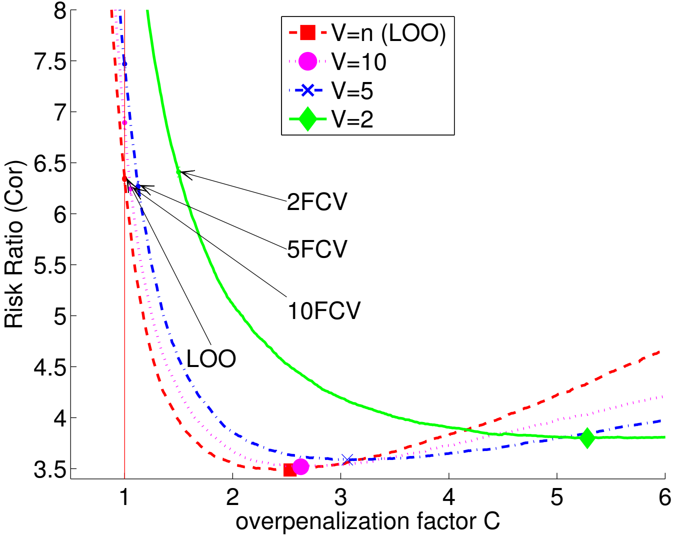
Experiment (LS density estimation): overpenalization



Experiment (LS density estimation): conclusion



Experiment (LS density estimation): other setting



Estimator selection with V-fold: conclusion

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- V-fold penalization:
  - Decoupling of bias and variance $\Rightarrow$ easier to understand.
  - Bias: chosen directly through C, without any constraint.
  - Variance: decreases with V / almost minimal with $V \in [5, 10]$.

Outline

Large collection of estimators/models

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- Solution: group the models $\Rightarrow$ one estimator per dimension (e.g., empirical risk minimizer)
  works for change-point detection (A. & Celisse, 2010).

Change-point detection and model selection

$$Y_i = \eta(t_i) + \sigma(t_i)\varepsilon_i \quad \text{with} \quad \mathbb{E}[\varepsilon_i] = 0 \quad \mathbb{E}\left[\varepsilon_i^2\right] = 1$$

- Goal: detect the change-points of the mean η of the signal Y

⇒ Model selection, collection of regressograms with $\mathcal{M}_n = \mathfrak{P}_{\mathrm{interv}}(\{t_1, \ldots, t_n\})$ (partitions of $\mathcal{X}$ into intervals)

- No assumption on the variance $\sigma(t_i)^2$

Classical approach (Lebarbier, 2005; ...)

- "Birgé-Massart" penalty (assumes $\sigma(t_i) \equiv \sigma$):

$$\widehat{m} \in \operatorname*{argmin}_{m \in \mathcal{M}_n} \left\{ P_n \gamma\left(\widehat{s}_m\right) + \frac{C \sigma^2 D_m}{n} \left(5 + 2 \log \left(\frac{n}{D_m} \right) \right) \right\}$$

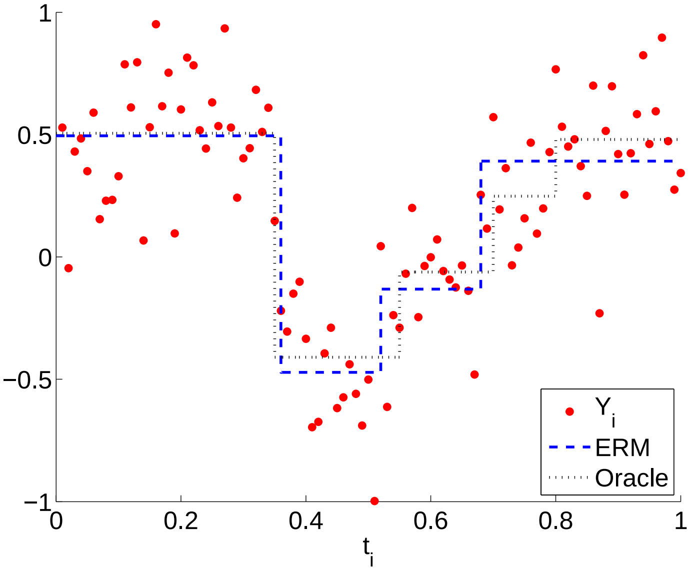
- Equivalent to aggregating models of the same dimension:

$$\widetilde{S}_D := \bigcup_{m \in \mathcal{M}_n \, , \, D_m = D} S_m$$

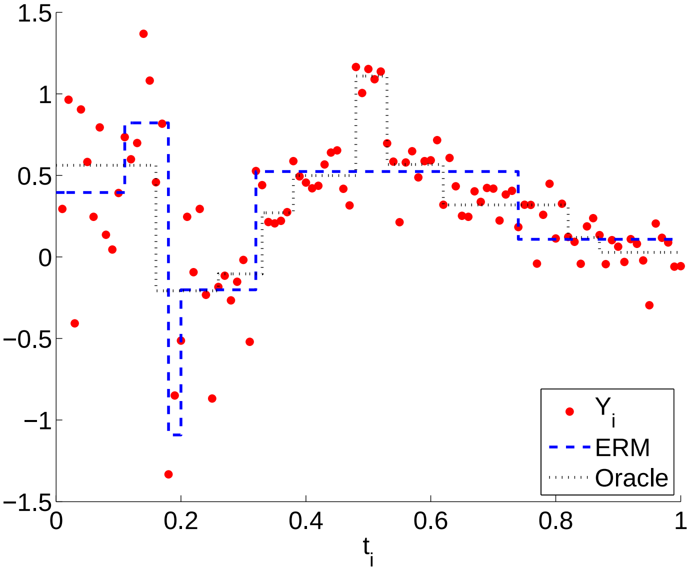
$$\widehat{s}_D \in \operatorname*{argmin}_{t \in \widetilde{S}_D} \left\{ P_n \gamma\left(t\right) \right\} \qquad \text{dynamic programming}$$

$$\widehat{D} \in \operatorname*{argmin}_{1 \leqslant D \leqslant n} \left\{ P_n \gamma\left(\widehat{s}_D\right) + \frac{C \sigma^2 D}{n} \left(5 + 2 \log \left(\frac{n}{D} \right) \right) \right\}$$

$D = 4$, homoscedastic; $n = 100$, $\sigma = 0.25$



$D = 6$, heteroscedastic; $n = 100$, $\|\sigma\| = 0.30$



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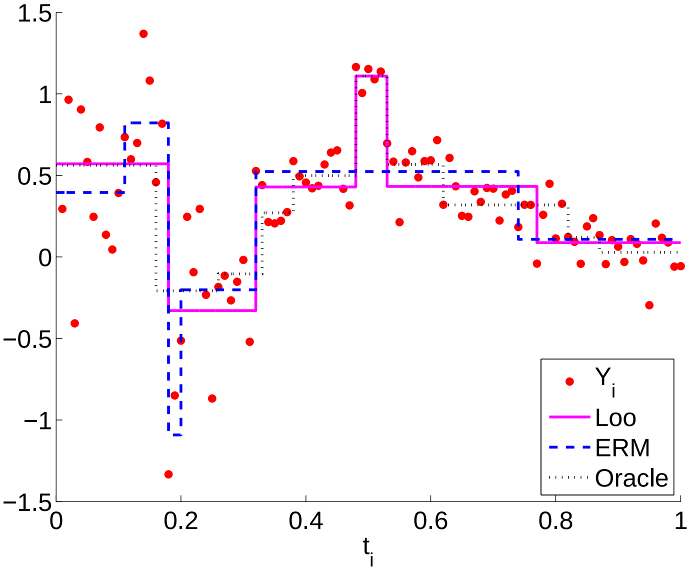

Change-point detection algorithms (A. & Celisse, 2010)

1. $\forall D \in \{1, \ldots, D_{\max}\}$, select

$$\widehat{m}(D) \in \operatorname*{argmin}_{m \in \mathcal{M}_n,\, D_m = D} \left\{ \operatorname{crit}_1\left(m; (t_i, Y_i)_i\right) \right\}$$

Examples for crit_1: empirical risk, or leave-p-out or V-fold estimators of the risk (dynamic programming)

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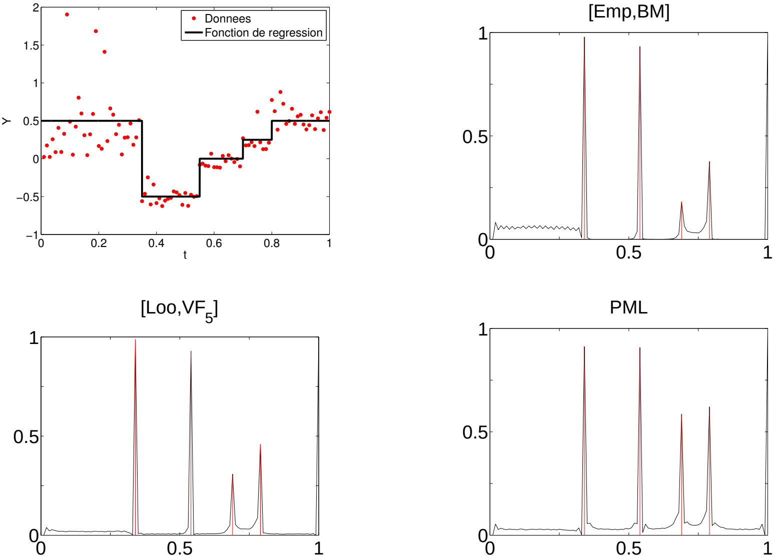
Examples for crit_1: empirical risk, or leave-p-out or V-fold estimators of the risk (dynamic programming)

2. Select

$$\widehat{D} \in \operatorname*{argmin}_{D \in \{1, \ldots, D_{\max}\}} \left\{ \mathrm{crit}_2 \left(D; (t_i, Y_i)_i; \mathrm{crit}_1(\cdot) \right) \right\}$$

Examples for crit_2: penalized empirical criterion, V-fold estimator of the risk

Simulations: position of the change-points



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- Variance: different behaviours can occur in other settings (experiments).
- Everything can be checked on synthetic data: plot

$$n \to \mathbb{E}\Big[P\gamma\big(\widehat{s}_m(D_n)\big)\Big] \qquad \text{and} \qquad m \to \operatorname{var}\Big(\widehat{\mathcal{R}}^{\mathrm{cv}}(\widehat{s}_m) - \widehat{\mathcal{R}}^{\mathrm{cv}}(\widehat{s}_{m^\star})\Big) \enspace .$$

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- Remark: estimation goal, parametric setting $\Rightarrow$ similar behaviour.

Dependent data

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- Solution for short-term dependence:
  remove some data at each split $\Rightarrow$ gap between training and validation samples.

Questions?

Part I

Appendix

Outline

Competitors

- [Emp, BM]: assume $\sigma(\cdot) \equiv \sigma$

$$\operatorname*{argmin}_{m \in \mathcal{M}_n} \left\{ P_n \gamma\left(\widehat{s}_m\right) + \frac{C \widehat{\sigma}^2 D_m}{n} \left(5 + 2 \log\left(\frac{n}{D_m} \right) \right) \right\}$$

- BGH (Baraud, Giraud & Huet 2009): multiplicative penalty, $\sigma(\cdot) \equiv \sigma$

$$\operatorname*{argmin}_{m \in \mathcal{M}_n} \left\{ P_n \gamma\left(\widehat{s}_m\right) \left[1 + \frac{\mathrm{pen}_{\mathrm{BGH}}(m)}{n - D_m} \right] \right\}$$

- ZS (Zhang & Siegmund, 2007): modified BIC, $\sigma(\cdot) \equiv \sigma$
- PML (Picard *et al.*, 2005): penalized maximum likelihood, looks for change-points of (η, σ), assuming a Gaussian model

$$\operatorname*{argmin}_{m \in \mathcal{M}_n} \left\{ \sum_{\lambda \in m} n \widehat{p}_\lambda \log\left(\frac{1}{n \widehat{p}_\lambda} \sum_{t_i \in \lambda} \left(Y_i - \widehat{s}_m(t_i) \right)^2 \right) + \widehat{C}'' D_m \right\}$$

Simulations: comparison to the oracle (quadratic risk)

$$\frac{\mathbb{E}\left[\ell\left(s^\star, \widehat{s}_{\widehat{m}}\right)\right]}{\mathbb{E}\left[\inf_{m \in \mathcal{M}_n} \left\{\ell\left(s^\star, \widehat{s}_m\right)\right\}\right]}$$

$N = 10\,000$ sample

$\mathcal{L}(\varepsilon)$ / $\sigma(\cdot)$ / η	Gaussian homosc. s_2	Gaussian heterosc. s_2	Gaussian heterosc. s_3
$[\mathrm{Loo}, \mathrm{VF}_5]$	4.02 ± 0.02	4.95 ± 0.05	5.59 ± 0.02
$[\mathrm{Emp}, \mathrm{VF}_5]$	3.99 ± 0.02	5.62 ± 0.05	6.13 ± 0.02
$[\mathrm{Emp}, \mathrm{BM}]$	3.58 ± 0.02	9.25 ± 0.06	6.24 ± 0.02
BGH	3.52 ± 0.02	10.13 ± 0.07	6.31 ± 0.02
ZS	3.62 ± 0.02	6.50 ± 0.05	6.61 ± 0.02
PML	4.34 ± 0.02	2.73 ± 0.03	4.99 ± 0.03

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$\mathcal{L}(\varepsilon)$ / $\sigma(\cdot)$ / η	Gaussian homosc. s_2	Exponential heterosc. s_2	Exponential heterosc. s_3
$[\mathrm{Loo}, \mathrm{VF}_5]$	4.02 ± 0.02	4.47 ± 0.05	5.11 ± 0.03
$[\mathrm{Emp}, \mathrm{VF}_5]$	3.99 ± 0.02	5.98 ± 0.07	6.22 ± 0.04
$[\mathrm{Emp}, \mathrm{BM}]$	3.58 ± 0.02	10.81 ± 0.09	6.45 ± 0.04
BGH	3.52 ± 0.02	11.67 ± 0.09	6.42 ± 0.04
ZS	3.62 ± 0.02	9.34 ± 0.09	6.83 ± 0.04
PML	4.34 ± 0.02	5.04 ± 0.06	5.40 ± 0.03