

Foundations of machine learning

Debiased Machine Learning

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Outline

- Supervised machine learning as a first stage estimator in econometrics.
- Two problems that arise using a plugin approach.
- Two solutions - orthogonalized scores and sample splitting.
- How to derive orthogonalized scores.
- Examples.
- Asymptotics.

Takeaways for this part of class

- Supervised learning can be useful as a first-stage in econometric estimation problems.
- But simple plug-in estimators are often poorly behaved.
- Well-behaved estimators can be constructed using
 1. Orthogonal scores, and
 2. Sample splitting and averaging.
- Examples:
 1. Partial linear regression.
 2. Average treatment effect und unconfoundedness.
 3. Local average treatment effect under conditional instrument exogeneity.

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Setup

- Many settings in econometrics:
 - The object of interest is low-dimensional (or real-valued),
 - but high-dimensional parameters are of intermediate relevance.
- General two stage structure:
 1. The high-dimensional \mathbf{g}_0 is given by the solution to some supervised learning problem.
 2. The low-dimensional parameter of interest θ_0 then solves

$$E[\phi(W, \theta_0, \mathbf{g}_0)] = 0.$$

- Can we estimate \mathbf{g}_0 using supervised machine learning, and plug it in?

Plugin estimation

- Most obvious estimator of θ_0 :
 1. First estimate g_0 using some supervised ML method.
 2. Then plug in the estimate and solve for $\hat{\theta}$ in

$$E_n \left[\phi(W_i, \hat{\theta}, \hat{g}) \right] = 0.$$

- This causes two **problems**, however:
 1. Bias of \hat{g} might distort $\hat{\theta}_0$.
 2. The statistical dependence of \hat{g} and W_i might distort $\hat{\theta}_0$.
- Both of these issues might cause large biases.
- Let us consider some examples, before solving these problems.

Example 1: Partially linear regression

- Model:

$$Y = D \cdot \theta_0 + g_0(X) + U, \quad E[U|X, D] = 0.$$

- Plugin estimator:
 1. Estimate g_0 , using some supervised ML method.
 2. Then solve $E_n[\phi(W_i, \theta_0, \hat{g})] = 0$, where E_n is the sample average across observations W_i , and

$$\phi(W, \theta, g) = (Y - D \cdot \theta - g(X)) \cdot D,$$

- Thus

$$\hat{\theta} = E_n \left[D_i^2 \right]^{-1} \cdot E_n [D_i \cdot (Y_i - g(X_i))]$$

Example 2: Average treatment effect

- Model:

$$Y = g_0(D, X) + U \qquad E[U|X, D] = 0$$
$$\theta_0 = E[g_0(1, X) - g_0(0, X)].$$

- Under unconfoundedness, θ_0 is the average treatment effect.
- Plugin estimator:
 1. Estimate g_0 , using some supervised ML method.
 2. Then solve $E_n[\phi(W_i, \theta_0, \hat{g})] = 0$, where

$$\phi(W, \theta, g) = g(1, X) - g(0, X) - \theta.$$

Example 3: Local average treatment effect

- Model:

$$Y = g_0^y(Z, X) + U, \quad D = g_0^d(Z, X) + V, \quad E[(U, V)|X, D] = 0,$$
$$\theta_0 = \frac{E[g_0^y(1, X) - g_0^y(0, X)]}{E[g_0^d(1, X) - g_0^d(0, X)]}.$$

- Under conditional instrument exogeneity, exclusion restriction, θ_0 is the local average treatment effect.
- Plugin estimator:
 1. Estimate g_0 , using some supervised ML method.
 2. Then solve $E_n[\phi(W_i, \theta_0, \hat{g})] = 0$, where

$$\phi(W, \theta, g) = g^y(1, X) - g^y(0, X) - (g^d(1, X) - g^d(0, X)) \cdot \theta.$$

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Approximating $\hat{\theta}$

- Telescope sum; Taylor approximation; approximating sample averages by expectations:

$$\begin{aligned} 0 &= E_n [\phi(W_i, \hat{\theta}, \hat{g})] = E_n [\phi(W_i, \hat{\theta}, \hat{g}) - \phi(W_i, \hat{\theta}, g_0)] \\ &\quad + E_n [\phi(W_i, \hat{\theta}, g_0) - \phi(W_i, \theta_0, g_0)] + E_n [\phi(W_i, \theta_0, g_0)] \\ &\approx E[\partial_g \phi(W_i, \theta_0, g_0) \cdot (\hat{g} - g_0)] \\ &\quad + E[\partial_\theta \phi(W_i, \theta_0, g_0)] \cdot (\hat{\theta} - \theta_0) + E_n [\phi(W_i, \theta_0, g_0)]. \end{aligned}$$

- Solving for $\hat{\theta} - \theta_0$:

$$\begin{aligned} (\hat{\theta} - \theta_0) &\approx E[\partial_\theta \phi(W_i, \theta_0, g_0)]^{-1} \cdot [E_n [\phi(W_i, \theta_0, g_0)] + \\ &\quad + E[\partial_g \phi(W_i, \theta_0, g_0) \cdot (\hat{g} - g_0)]] \end{aligned}$$

- We can further decompose the last term, which is the cause of bias:

$$\begin{aligned} &E[\partial_g \phi(W_i, \theta_0, g_0) \cdot (\hat{g} - g_0)] \\ &= E[\partial_g \phi(W_i, \theta_0, g_0)] \cdot (E[\hat{g}] - g_0) + E[\partial_g \phi(W_i, \theta_0, g_0) \cdot (\hat{g} - E[\hat{g}])] \end{aligned}$$

Practice problem

Write out this decomposition for average treatment effect estimation and the plugin estimator.

1. Recall what is ϕ and g here.
2. What is $\partial_{\theta}\phi$, what is $\partial_g\phi$?
3. What do we get for the red and magenta terms?

Problem 1: Bias in the first stage

- As we discussed previously, ML estimators use regularization, and therefore are **biased**: $E[\hat{g}] \neq g_0$.
- Suppose however that we had a score function which satisfies “**Neyman orthogonality**.”

$$E[\partial_g \phi(W_i, \theta_0, g_0)] = 0.$$

- Then

$$E[\partial_g \phi(W_i, \theta_0, g_0)] \cdot (E[\hat{g}] - g_0) = 0.$$

- \Rightarrow Bias of \hat{g} does not matter to first order.

Problem 2: Statistical dependence of first stage and data

- In general, W_i and \hat{g} are not statistically independent, and \hat{g} has non-negligible **variance**.
- Therefore $E[\partial_g \phi(W_i, \theta_0, g_0) \cdot (\hat{g} - E[\hat{g}])] \neq 0$.
- Suppose however we used sample splitting:
 1. Estimate \hat{g} on one part of the data.
 2. Average $\phi(W_i, \hat{\theta}, \hat{g})$ over the remaining data.
- Then this term automatically vanishes!

Debiased Machine Learning

Combining these two ideas: (*Definition 3.2 in the paper.*)

1. Start with an estimation problem of the form $E[\phi(W, \theta_0, g_0)] = 0$.
2. Derive an orthogonal Neyman score ψ , which satisfies

$$\begin{aligned} E[\psi(W, \theta_0, \eta_0)] &= 0, \\ E[\partial_\eta \psi(W_i, \theta_0, \eta_0)] &= 0. \end{aligned}$$

We will discuss next how to do this.

3. Split the sample into K subsamples I_k .
Estimate $\hat{\eta}_k$ based on I_k^c . Denote $E_{n,k}$ the sample average over I_k .
4. Estimate θ by solving

$$\sum_{k=1}^k E_{n,k} [\psi(W, \hat{\theta}, \hat{\eta}_k)] = 0.$$

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How to derive orthogonal scores

- Suppose that

$$(\theta_0, \beta_0) = \operatorname{argmax}_{\theta, \beta} E[L(W, \theta, \beta)].$$

- Two approaches to deriving an orthogonal score
 1. Construction from moment functions.
 2. Concentrating out.

Construction from moment functions

- Suppose that

$$(\theta_0, \eta_0) = \operatorname{argmax}_{\theta, \beta} E[L(W, \theta, \beta)],$$

and thus

$$E[\partial_\theta L(W, \theta, \beta)] = 0, \quad E[\partial_\eta L(W, \theta, \beta)] = 0.$$

- Define

$$\psi(W, \theta, \eta) = \partial_\theta L(W, \theta, \beta) - \mu \cdot \partial_\beta L(W, \theta, \beta),$$

where $\eta = (\mu, \beta)$, and μ solves

$$\partial_\beta E[\partial_\theta L(W, \theta, \beta)] - \mu \cdot \partial_\beta E[\partial_\beta L(W, \theta, \beta)] = 0.$$

- Then

$$\begin{aligned} E[\psi(W, \theta_0, \eta_0)] &= 0, \\ E[\partial_\eta \psi(W_i, \theta_0, \eta_0)] &= 0. \end{aligned}$$

Construction by concentrating out

- Suppose again that

$$(\theta_0, \eta_0) = \operatorname{argmax}_{\theta, \beta} E[L(W, \theta, \beta)].$$

- Define

$$\begin{aligned}\psi(W, \theta, \eta) &= \partial_{\theta} (L(W, \theta, \beta(\theta))) \\ &= \partial_{\theta} L(W, \theta, \beta) + \partial_{\theta} \beta(\theta) \cdot \partial_{\beta} L(W, \theta, \beta),\end{aligned}$$

where $\eta = (\beta, \partial_{\theta} \beta(\theta))$.

- Then, again

$$\begin{aligned}E[\psi(W, \theta_0, \eta_0)] &= 0, \\ E[\partial_{\eta} \psi(W_i, \theta_0, \eta_0)] &= 0.\end{aligned}$$

Example 1: Partially linear regression

- Recall the model

$$Y = D \cdot \theta_0 + g_0(X) + U, \quad E[U|X, D] = 0.$$

- Define

$$m_0(X) = E[D|X].$$

- Then

$$\psi(W, \theta, \eta) = (Y - D \cdot \theta + g(X)) \cdot (D - m(X))$$

satisfies the orthogonality condition.

- In the first stage, we need to estimate $g_0(X)$ and $m(X)$.

Example 2: Average treatment effect

- Recall the model

$$Y = g_0(D, X) + U \quad E[U|X, D] = 0$$
$$\theta_0 = E[g_0(1, X) - g_0(0, X)].$$

- Define

$$m_0(X) = E[D|X].$$

- Then

$$\begin{aligned} \psi(W, \theta, \eta) = & (g(1, X) - g(0, X)) + \left(\frac{DY}{m(X)} - \frac{(1-D)Y}{1-m(X)} \right) \\ & - \left(\frac{Dg(1, X)}{m(X)} - \frac{(1-D)g(0, X)}{1-m(X)} \right) - \theta \end{aligned}$$

satisfies the orthogonality condition.

- This is the famous “doubly robust” estimation approach.

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Asymptotics for debiased ML estimators

Theorem 3.3.

- Assume a number of regularity conditions.
- Consider a Debiased Machine Learning estimator.
- Then

$$\sqrt{n}(\hat{\theta} - \theta) \sim^A N(0, \sigma^2),$$

- where

$$\sigma^2 = J^{-1} \cdot \text{Var}(\psi(W, \theta_0, \eta_0)) \cdot J^{-1},$$

for

$$J = \partial_{\theta} E[\psi(W, \theta_0, \eta_0)].$$

Intuition of proof

- Recall our earlier expansion

$$(\hat{\theta} - \theta_0) \approx E[\partial_{\theta} \psi(W_i, \theta_0, \eta_0)]^{-1} \cdot [E_n[\psi(W_i, \theta_0, \eta_0)] + E[\partial_{\eta} \psi(W_i, \theta_0, \eta_0) \cdot (\hat{\eta} - \eta_0)]] .$$

- Using the Debiased Machine Learning approach, we have killed the blue term.
- The other terms give asymptotic normality and the variance by standard arguments.

References

Chernozhukov, V., Chetverikov, D., Demirer, M., Duflo, E., Hansen, C., Newey, W., and Robins, J. (2018). Double/debiased machine learning for treatment and structural parameters. The Econometrics Journal, 21(1):C1–C68.