

Big Data and Bayesian Nonparametrics

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Big Data

The sample sizes are enormous.

- ▶ we'll see 21 and 200 million today.
- ▶ Data can't fit in memory, or even storage, on a single machine.

The data are super weird.

- ▶ Internet transaction data distributions have a big spike at zero and spikes at other discrete values (e.g., 1 or \$99).
- ▶ Big tails (e.g., \$12 mil/month eBay user spend) that matter.
- ▶ The potential feature space is enormous.
- ▶ We cannot write down or measure believable models.

Both 'Big' and 'Strange' beg for nonparametrics.

Bayesian nonparametrics

In usual BNP you *model* a complex generative process with flexible priors, then apply that model directly in prediction and inference.

$$\text{e.g., } y = f(\mathbf{x}) + \varepsilon \quad \text{or} \quad f(y|\mathbf{x}) = f(\mathbf{x}, y)/f(\mathbf{x})$$

'Flexibility' comes from a huge number of variables,

$$\text{e.g., } f(\mathbf{z}) = \sum_{k=1}^{\infty} \omega_k N(\mathbf{z}; \boldsymbol{\mu}_k, \boldsymbol{\Sigma}_k),$$

and learning requires integration over uncertainty on nuisance parameters, e.g., k_i component membership for observation \mathbf{z}_i .

For years this integration was done via MCMC. But these algorithms did not scale for big data. **Can we do scalable BNP?**

Classical distribution-free nonparametrics

Frequentists are great at finding simple procedures (e.g. $[\mathbf{X}'\mathbf{X}]^{-1}\mathbf{X}'\mathbf{y}$) and describing how they work under a variety of possible true DGP.

(DGP = Data Generating Process)

This is 'distribution free' nonparametrics.

- 1: Find some statistic that is useful regardless of DGP.
- 2: Derive the distribution for this stat under minimal assumptions.

Practitioners apply the simple stat and feel happy that it will work.

Distribution-free Bayesian nonparametrics

Find some *statistic of the DGP* that you care about:

- ▶ derive from first principles, e.g. moment conditions
- ▶ *an algorithm* that we know works, e.g. CART
- ▶ think about geometric projections, e.g. OLS

Call this statistic $\theta(g)$ where $g(\mathbf{z})$ is the DGP (e.g., for $\mathbf{z} = [\mathbf{x}, y]$).

Then you write down a flexible model for the DGP g , and study properties of the posterior on $\theta(g)$ induced by the posterior over g .

A flexible model for the DGP

Say $\mathbf{z} = [\mathbf{x}, y]$ is a single *independent* data point.

Each data point assumes one of a *finite* number of possible values, $[\zeta_1 \dots \zeta_L]$, with probabilities proportional to $[\theta_1 \dots \theta_L]$.

$$g(\mathbf{z}) = \frac{1}{|\boldsymbol{\theta}|} \sum_{l=1}^L \theta_l \mathbb{1}_{[\mathbf{z}=\zeta_l]}$$

We complete specification with a conjugate prior on the weights:

$$\frac{\boldsymbol{\theta}}{|\boldsymbol{\theta}|} \sim \text{Dir}(\mathbf{a}) \propto \frac{1}{|\boldsymbol{\theta}|^{L(a-1)}} \prod_l \theta_l^{a_l-1} \quad \text{where } a, \theta_l > 0.$$

This is the Dirichlet-multinomial sampling model (Ferguson 1973).

Now you've observed some data, say $\mathbf{Z} = \{\mathbf{z}_1 \dots \mathbf{z}_n\}$.
(say every $\mathbf{z}_i = [\mathbf{x}_i, y_i]$ is unique).

The posterior over weights has $\theta_l \stackrel{ind}{\sim} \text{Exp}(a + \mathbb{1}_{[\zeta_l \in \mathbf{Z}]})$.

A convenient limiting case

$a \rightarrow 0$ leads to $p(\theta_l = 0) = 1$ for $\zeta_l \notin \mathbf{Z}$.

In this case, we can focus on only the *observed support* and write the posterior for our DGP

$$g(\mathbf{z}) = \frac{1}{|\theta|} \sum_{i=1}^n \theta_i \mathbb{1}[\mathbf{z} = \mathbf{z}_i], \quad \theta_i \stackrel{iid}{\sim} \text{Exp}(1).$$

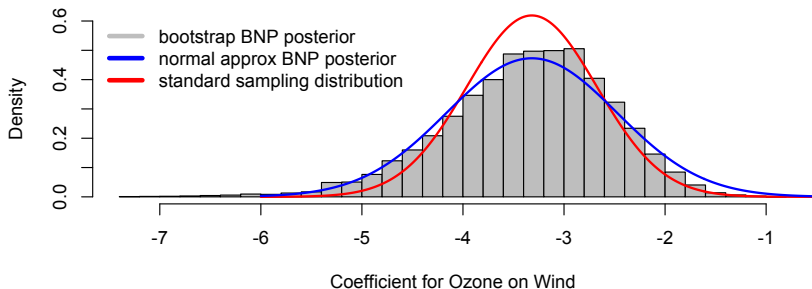
This is just the Bayesian bootstrap. (Rubin 1981)

Example: Ordinary Least Squares

Population OLS is a posterior functional

$$\beta = (\mathbf{X}'\Theta\mathbf{X})^{-1}\mathbf{X}'\Theta\mathbf{y}$$

where $\Theta = \text{diag}(\theta)$. This is a random variable. (sample via BB)



What is the blue line?

BB sampling is great, but analytic approximations are also useful.

Consider a first-order Taylor series approximation,

$$\tilde{\beta} = \hat{\beta} + \nabla\beta|_{\theta=1}(\theta - 1)$$

where $\hat{\beta} = [\mathbf{X}'\mathbf{X}]^{-1}\mathbf{X}'\mathbf{y} = \beta|_{\theta=1}$ is the sample OLS line.

We can derive *exact* posterior moments for $\tilde{\beta}$. e.g.,

$$\text{var}(\beta) \approx \text{var}(\tilde{\beta}) = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\text{diag}(\mathbf{e}^2)\mathbf{X}'(\mathbf{X}'\mathbf{X})^{-1}$$

where $\mathbf{e} = \mathbf{y} - \mathbf{X}[\mathbf{X}'\mathbf{X}]^{-1}\mathbf{X}'\mathbf{y}$ are the sample OLS residuals.

This is the economist's Huber-White 'Sandwich' variance formula.

(Lancaster 2003 or Poirier 2011.)

Example: Heterogeneous Treatment Effects

eBay runs lots of experiments: they make changes to the marketplace (website) for random samples of users.

Every experiment has response y and treatment d [0/1].

In our illustrative example, $d_i = 1$ for bigger pictures in my eBay.

$i \in \text{control} : d_i = 0$

$i \in \text{treatment} : d_i = 1$



This is a typical 'A/B experiment'.

What is 'heterogeneity in treatment effects'? (HTE)

Different units [people, devices] respond differently to some treatment you apply [change to website, marketing, policy].

I imagine it exists.

We know \mathbf{x}_i about user i . About 400 features in our example.

- ▶ Their previous spend, items bought, items sold...
- ▶ Page view counts, items watched, searches, ...
- ▶ All of the above, broken out by product, fixed v. auction, ...

Can we accurately measure heterogeneity: index it on \mathbf{x} ?

Potential outcomes:

- ▶ $v_i(d)$ is the response for user i if $d_i = d$.
- ▶ The *treatment effect* is $v_i(1) - v_i(0)$
- ▶ We only observe one of $v_i(1)$ and $v_i(0)$: ' y '.

We'd love to model $\mathbb{E}[v_i(1) - v_i(0)|\mathbf{x}_i]$, but we can't directly.

Since $d \perp\!\!\!\perp [\mathbf{x}, \mathbf{v}]$, a good alternative is to consider

$$\mathbb{E}[v_i(1)|d_i = 1, \mathbf{x}_i] - \mathbb{E}[v_i(0)|d_i = 0, \mathbf{x}_i].$$

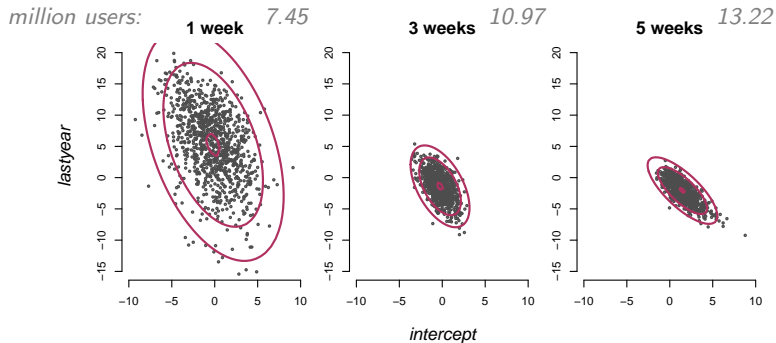
Even simpler, just diff the OLS projections for each group

$$\beta_t - \beta_c = (\mathbf{X}'_t \Theta_t \mathbf{X}_t)^{-1} \mathbf{X}'_t \Theta_t \mathbf{y}_t - (\mathbf{X}'_c \Theta_c \mathbf{X}_c)^{-1} \mathbf{X}'_c \Theta_c \mathbf{y}_c$$

See Taddy, Gardner, Chen, Draper 2014 for alternative linear projections.

Since $\beta_t \perp\!\!\!\perp \beta_c$, our results on BNP analysis of OLS apply directly.
Or you can bootstrap, but it takes a long time.

e.g., coefficient on *[made purchase this year]* vs an intercept:



Sample is from posterior, contours are normal approximation.

$\beta_t - \beta_c$ is a statistic we care about, even if the truth is nonlinear.

The most basic application of an A/B experiment is estimating the average treatment effect,

$$ATE = \mathbb{E}[v(t)] - \mathbb{E}[v(c)]$$

The usual estimator is $\bar{y}_t - \bar{y}_c$. But many authors advocate instead the 'regression adjusted' $\bar{\mathbf{x}}'(\hat{\beta}_t - \hat{\beta}_c)$ (Lin, Berk+, Deng+, 2013).

Both are [frequentist] unbiased.

But quantifying uncertainty about the regression adjustment, and any variance reduction it provides, is tough without assumptions.

From our BNP perspective, both the usual and adjusted ATE estimators are random functions of the DGP.

$$\begin{aligned} \text{ATE}_g^{\text{obs}} &= \frac{1}{|\boldsymbol{\theta}_t|} \boldsymbol{\theta}_t' \mathbf{y}_t - \frac{1}{|\boldsymbol{\theta}_c|} \boldsymbol{\theta}_c' \mathbf{y}_c \\ \text{ATE}_g^{\text{lin}} &= \frac{1}{|\boldsymbol{\theta}|} \boldsymbol{\theta}' \mathbf{X} \left((\mathbf{X}_t' \boldsymbol{\Theta}_t \mathbf{X}_t)^{-1} \mathbf{X}_t' \boldsymbol{\Theta}_t \mathbf{y}_t - (\mathbf{X}_c' \boldsymbol{\Theta}_c \mathbf{X}_c)^{-1} \mathbf{X}_c' \boldsymbol{\Theta}_c \mathbf{y}_c \right). \end{aligned}$$

Using our usual tricks, we can resolve any *controversy*:

$$\text{var} \left(\text{ATE}_g^{\text{lin}} \right) \approx \text{var}(\text{ATE}_g^{\text{obs}}) - \left(\frac{R_t^2 s_{\mathbf{y}_{td}}^2}{n_t^2} + \frac{R_c^2 s_{\mathbf{y}_c}^2}{n_c^2} \right),$$

so that big variance reduction comes only for small sample n_d or large $R_d^2 = \text{cor}(y_d, \hat{y}_d)$. In digital experiments we have big samples and low signal, so we shouldn't expect much variance reduction.

Example: Decision Trees

Trees are great: nonlinearity, deep interactions, heteroskedasticity.



The 'optimal' decision tree is a statistic we care about (s.w.c.a).

CART: greedy growing with optimal splits

Given node $\{\mathbf{x}_i, y_i\}_{i=1}^n$ and DGP weights θ , find x to minimize

$$\begin{aligned} |\theta| \sigma^2(x, \theta) = & \sum_{k \in \text{left}(x)} \theta_k (y_k - \mu_{\text{left}(x)})^2 \\ & + \sum_{k \in \text{right}(x)} \theta_k (y_k - \mu_{\text{right}(x)})^2 \end{aligned}$$

for a regression tree. Classification impurity can be Gini, etc.

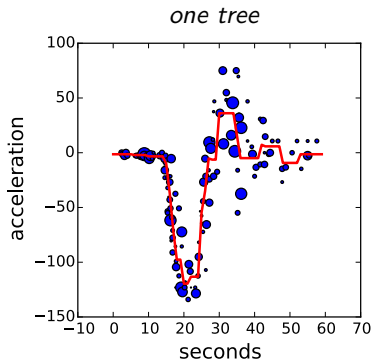
Population-CART might be a statistic we care about.

Or, in settings where greedy CART would do poorly (big p), a randomized splitting algorithm might be a better s.w.c.a.

Bayesian Forests: a posterior for CART trees

For $b = 1 \dots B$:

- draw $\theta^b \stackrel{iid}{\sim} \text{Exp}(\mathbf{1})$
- run weighted-sample CART to get $\mathcal{T}_b = \mathcal{T}(\theta^b)$



Random Forest \approx Bayesian forest \approx posterior over CART fits.

Theoretical **trunk** stability

Given forests as a posterior, we can start talking about *variance*.
Consider the first-order approximation

$$\begin{aligned}\sigma^2(x, \boldsymbol{\theta}) &\approx \sigma^2(x, \mathbf{1}) + \nabla \sigma^2|_{\boldsymbol{\theta}=\mathbf{1}}(\boldsymbol{\theta} - \mathbf{1}) \\ &= \frac{1}{n} \sum_i \theta_i [y_i - \bar{y}_i(x)]^2\end{aligned}$$

with $\bar{y}_i(x)$ the sample mean in i 's node when splitting on x .

Based on this approx, we can say that for data at a given node,

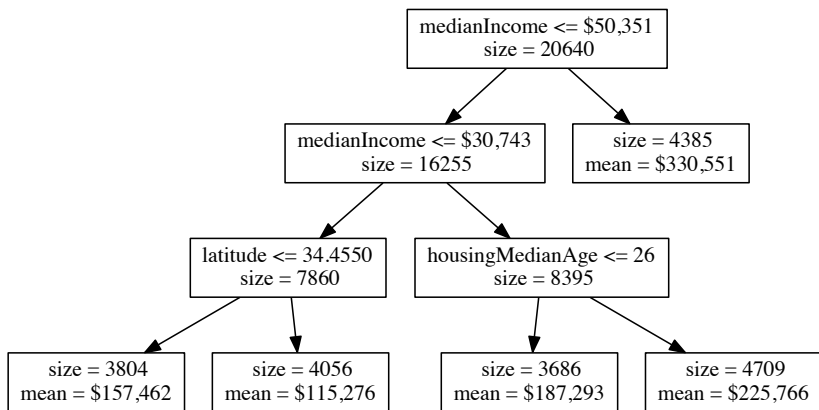
$$p \text{ (optimal split matches sample CART)} \gtrsim 1 - \frac{p}{\sqrt{n}} e^{-n},$$

with p split locations and n observations.

(Taddy, Chen, Yu, Wyle 2015)

California Housing Data

20k observations on median home prices in zip codes.



Above is the trunk you get setting min-leaf-size of 3500.



- ▶ sample tree occurs 62% of the time.
- ▶ 90% of trees split on income twice, and then latitude.
- ▶ 100% of trees have 1st 2 splits on median income.

Empirically and theoretically: trees are stable, at the trunk.

Empirical Bayesian Forests (**EBF**)

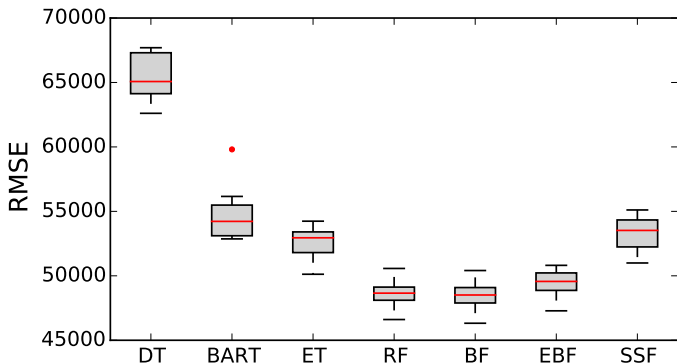
RFs are expensive. Sub-sampling hurts bad.

Instead:

- ▶ fit a single tree to a shallow **trunk**.
- ▶ Map data to each **branch**.
- ▶ Fit a full forest on the smaller branch datasets.

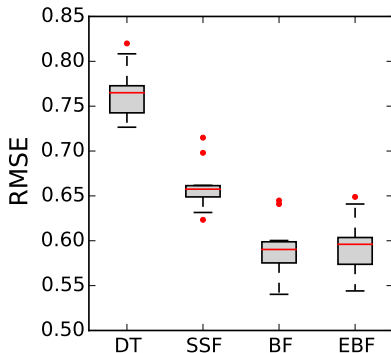
Empirical Bayes: fix plug-in estimates at high levels in a hierarchical model, focus effort at learning the hard bits.

Since the trunks are all the same for each tree in a full forest, our EBF looks nearly the same at a fraction of computational cost.



Here EBF and BF give nearly the same results. *SSF does not.*

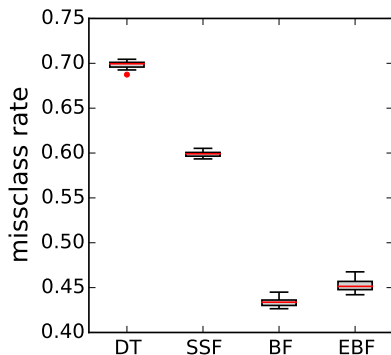
EBFs work all over the place



RMSE	% WTB	
0.5905	0.0	BF
0.5953	0.8	EBF
0.6607	11.9	SSF
0.7648	29.5	DT

Predicting wine rating from chemical profile

EBFs work all over the place



MCR	% WTB	
0.4341	0.0	BF
0.4531	4.4	EBF
0.5989	38.0	SSF
0.6979	60.8	DT

or beer choice from demographics

Choosing the trunk depth

Distributed computing perspective: **fix only as deep as you must!**

How big is each machine? Make that your branch size.

	CA housing			Wine			Beer		
<i>Min Leaf Size in 10^3</i>	6	3	1.5	2	1	0.5	20	10	5
<i>% Worse Than Best</i>	1.6	2.4	4.3	0.3	0.8	2.2	1.0	4.4	7.6

Still, open questions: e.g., more trees vs shallower trunk?

Catching Bad Buyer Experiences at eBay

BBE: 'not as described', delays, etc.

$p(\text{BBE})$ is an input to search rankings.

Best way to improve prediction is more data.

EBFs via Spark: more data in less time.

On 200 million transactions, EBF with 32 branches yields a 1.5% drop in misclassification over the SSF alternatives.

Putting it into production requires some careful engineering, but this really is a very simple algorithm. **Big gain, little pain.**

Back to HTE: Treatment Effect Trees

Recall our earlier example: A/B experiment with user covariates \mathbf{x}_i .

Athey+Imbens propose indexing user HTE by fitting CART to

$$y_i^* = y_i \frac{d_i - q}{q(1 - q)} = \begin{cases} y_i / (1 - q) & \text{if } d_i = 0 \\ y_i / q & \text{if } d_i = 1 \end{cases}$$

where q is the probability of treatment (2/3 in our example).

This works because

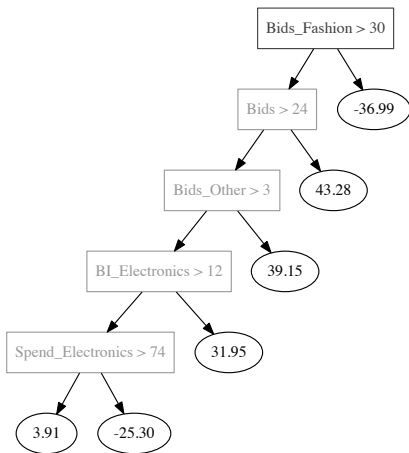
$$\mathbb{E}[y_i^* | \mathbf{v}_i] = v_i(1) - v_i(0)$$

where $v_i(d)$ is the potential outcome for user i if $d_i = d$.

We only get to observe one of these: $y_i = v_i(d_i)$.

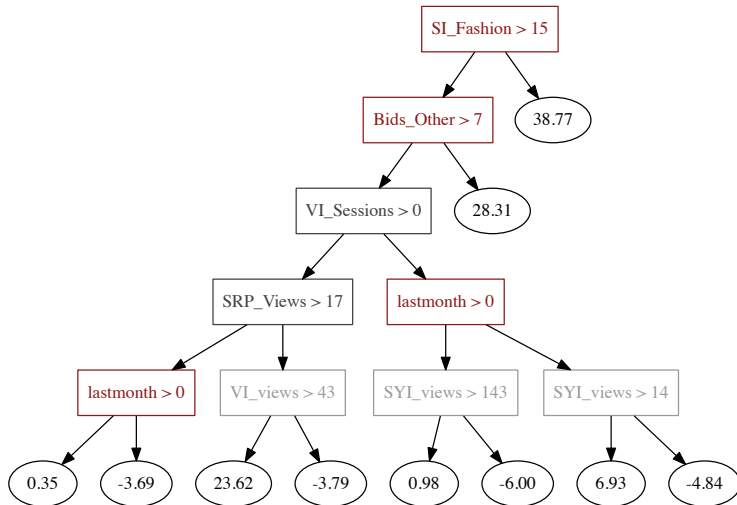
We can apply the Bayesian bootstrap (i.e., fit a BF) to assess *posterior uncertainty* about these treatment-effect trees.

e.g., sample depth-5 CART with min-leaf-size- 10^5 after one week:



prob variable is node in tree: $p < \frac{1}{3}$, $p \in [\frac{1}{3}, \frac{1}{2})$, and $p \geq \frac{1}{2}$.

After 5 weeks the tree is much more stable.



We can quantify uncertainty about all sorts of structure.

Posterior probability of CART splitting on variable

Week 5	depth in tree				
	1	≤ 2	≤ 3	≤ 4	≤ 5
<i>SI Fashion</i>	.45	.50	.50	.50	.50
<i>Bids Other</i>	.30	.75	.75	.75	.75
<i>VI sessions</i>	.05	.05	.05	.10	.35
<i>lastmonth</i>	.05	.10	.15	.40	.65
<i>SRP views</i>	.00	.10	.15	.25	.40
<i>VI views</i>	.00	.00	.10	.20	.25
<i>SYI views</i>	.00	.00	.05	.15	.25

⇒ easy scalable uncertainty quantification for complex algorithms.

Big Data and distribution-free BNP

I think about BNP as a way to analyze (and improve) algorithms.
Decouple action/prediction from the full generative process model.

Efficient Big Data analysis

To cut computation without hurting performance, we need to think about what portions of the 'model' are **hard** or **easy** to learn.

Once we figure this out, we can use a little bit of the data to learn the easy stuff and direct our full data at the hard stuff.

thanks!