A Tree-based Model Averaging Approach for Personalized Treatment Effect Estimation from Heterogeneous Data Sources

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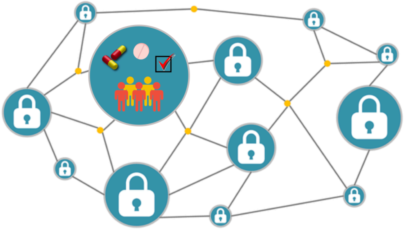
Joint work with Drs. Joyce Chang, Ling Zhou, and Lu Tang

Motivation: to improve CATE estimation in a target site

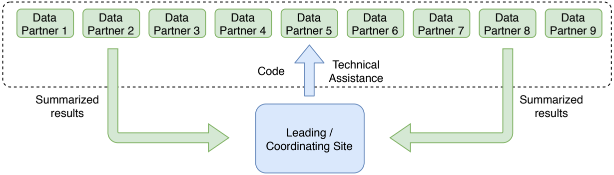
- Interested in causal effects conditional on subject characteristics, i.e. conditional average treatment effects (CATE)
- A site is under-powered, hope to borrow information across site

Challenges of information borrowing in distributed data networks



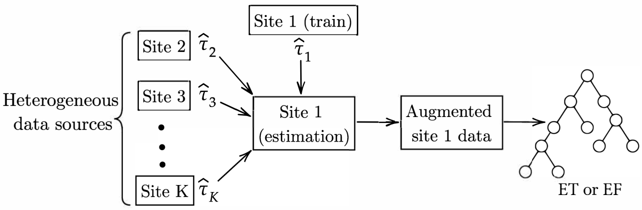
- Data are highly heterogeneous across sites
- Privacy concerns of subject-level data sharing across sites
- Challenging in causal inference settings: no “ground truth” outcome

Possible solution: leveraging models from different sites



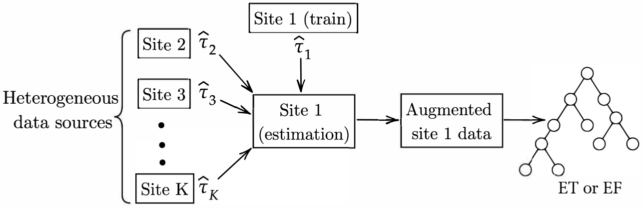
- Model averaging framework in distributed data networks
- Multiple sites collectively contribute to the tasks of statistical modeling without sharing sensitive subject-level data
- There is no established model averaging approach with the goal of improving the estimation of CATE

Sketch of the proposed framework



- Without loss of generality, let site 1 to be the target/coordinating site
- Local stage: each of the K sites estimate τ_k independently
    - can use any CATE estimator
    - in parallel
- Sites pass $\{\tau_k(\boldsymbol{x})\}_{k=1}^{K}$ to site 1

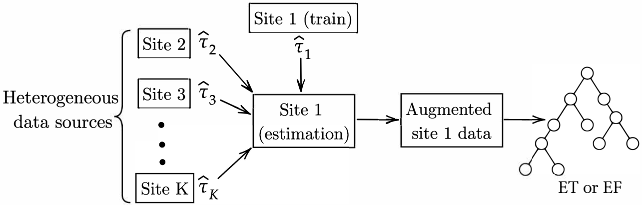
Sketch of the ensemble algorithm



- Create the augmented data in site 1

Subject	Site	$\boldsymbol{X}$	S	τ
1	1	$\boldsymbol{x}_1$	1	$\tau_1(\boldsymbol{x}_1)$
		$\vdots$		
1	1	$\boldsymbol{x}_1$	K	$\tau_K(\boldsymbol{x}_1)$
2	1	$\boldsymbol{x}_2$	1	$\tau_1(\boldsymbol{x}_2)$
		$\vdots$		

Sketch of the proposed framework



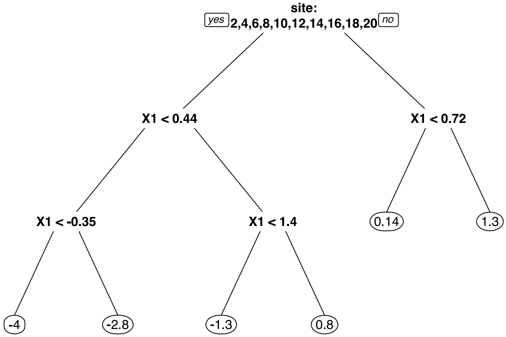
- Ensemble stage: either a **E**nsemble **T**ree (ET) or a **E**nsemble **F**orest (EF)

$$\text{causal estimand } \mathcal{T}(\boldsymbol{x}, s)$$

A site indicator of which individual model is used, S, along with the patient characteristics $\boldsymbol{X}$ are used as covariates

Visualization of the proposed tree-based estimator

- Suppose there are $K = 20$ sites in total
- CATE function $\tau(\boldsymbol{x}, k) = \mathbb{1}\{x_1 > 0\} \cdot x_1 + (x_1 - 3) \cdot c \cdot U_k$



Asymptotic properties

We provide the consistency guarantee of $\widehat{\mathcal{T}}_{\mathrm{EF}}$ for the true target τ_1

Theorem

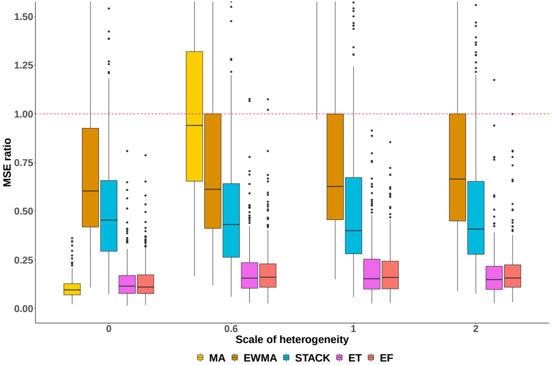
Suppose the subsamples used to build each tree in an ensemble forest are drawn from different subjects in the augmented site 1 data. Under the following conditions:

1. *Bounded covariates: Features $\boldsymbol{X}_i$ and the site indicator S_i are independent and have a density that is bounded away from 0 and infinity*
2. *Lipschitz response: the conditional mean function $\mathbb{E}[\mathcal{T}|\boldsymbol{X}=\boldsymbol{x}, S=k]$ is Lipschitz-continuous*
3. *Honest trees: trees in the random forest use different data for placing splits and estimating leaf-wise responses*

Then $\widehat{\mathcal{T}}_{EF}(\boldsymbol{x}, s) \xrightarrow{p} \tau_s(\boldsymbol{x})$, for all $\boldsymbol{x}$ and s, as $\min_k n_k \to \infty$
Hence, $\widehat{\tau}^*_{EF}(\boldsymbol{x}) \xrightarrow{p} \tau_1(\boldsymbol{x})$

Comparison among various methods

- Compare the proposed estimators with local estimator (LOC) and multiple existing model averaging or ensemble approaches

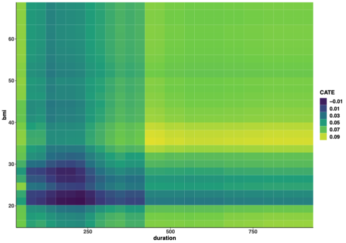


Application: oxygen therapy on survival

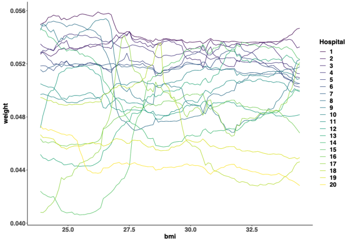
- **Our goal:** estimate CATE of oxygen saturation SpO_2 within 94-98% range on hospital mortality among critically ill patients with respiratory disease and with at least 48-hour of oxygen therapy
- eICU database: data from critical care units throughout the U.S.
- $K = 20$ hospitals, $N = 7,022$
- Earlier studies considered using random effects to model site heterogeneity (van den Boom et al., 2020)

Decision rule	Avg. survival rate
Baseline	0.762
LOC-based	0.772
EF-based	0.791

(a)



(b)



(c)

Discussion

- We have proposed an efficient and interpretable tree-based model averaging framework to enhance the estimation of CATE
- Our work facilitates practical collaboration within distributed research networks
- Can be extended beyond causal inference to a general $f(\boldsymbol{x})$
- R package `ifedtree` is built and available at GitHub (`https://github.com/ellenxtan/ifedtree`)

Thank you!