

# ML in Economics and Finance: Where Do We Go Now? - Part II

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- 1. What is ML, anyway?
  - 2. Causality in High Dimensions
  - 3. (Seriously) Heterogeneous Partial Effects
  - 4. Solving Large-Scale Dynamic Models
- } Yesterday
- } Today

## Heterogeneous Partial Effects

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## Motivation

Let  $Y$  be an outcome and  $X, Z$  be features (covariates). We frequently want to approximate

$$h(x, z) \equiv \mathbb{E}[Y|X = x, Z = z]$$

and the **partial effects**

$$\frac{\partial}{\partial x} h(x, z) = \frac{\partial}{\partial x} \mathbb{E}[Y|X = x, Z = z].$$

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- Approach 2: use fully nonparametric methods. Pros and cons?
- The third way is the charm: a bit of structure, a bit of ML!

## Example I - Heterogenous Treatment Effects

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- Outcomes  $Y_i$  depend on a treatment  $X_i \in \mathbb{R}$  and covariates  $Z_i \in \mathbb{R}^p$ ;
- The dose  $X_i$  depends on observables  $Z_i$ ;
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- The dose  $X_i$  depends on observables  $Z_i$ ;
- Potential outcomes  $Y_i(x)$  for each dose  $x \in \mathbb{R}$ ;
- The conditional average effect of increasing the dose is  $\tau(x, z) \equiv \frac{\partial}{\partial x} \mathbb{E}[Y(x)|Z = z]$ ;
- If  $\mathbb{E}[Y(x)|X = x, Z = z] = \mathbb{E}[Y(x)|Z = z]$  (common assumption in the literature), then

$$\tau(x, z) = \frac{\partial}{\partial x} \mathbb{E}[Y|X = x, Z = z] = \frac{\partial h(x, z)}{\partial x}$$

## Example II - Grouped Heterogeneity

Consider the following model:

$$Y_i = \alpha(Z_i) + X'_i \beta + \varepsilon_i, \quad \mathbb{E}[\varepsilon_i | X_i, Z_i] = 0,$$

- $X_i$  affects  $Y_i$  homogeneously;
- Intercept  $\alpha(Z_i)$  varies with  $Z_i$ , maybe in a highly nonlinear way;
- Since  $Z_i$  and  $X_i$  can be correlated, this can affect inference about  $\beta$ ;
- [Bonhomme and Manresa \(2015\)](#) studied how democracy affects national income using this model;
- In their case:  $\alpha(Z_i)$  is constant across groups but  $Z_i$  defines membership;
- In our notation:  $h(z, x) = \alpha(z) + x' \beta$

## How can we balance flexibility and interpretability?

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$$h(x, z) = x^\top \beta(z), \quad \frac{\partial h(x, z)}{\partial x} = \beta(z)$$

- The partial effect of  $X$  on  $Y$  varies with  $Z$  through  $\beta(z)$ ;
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- Secret sauce: a variant of the **Random Forest** algorithm!

But what is a Random Forest, anyway? 🤔

**Questions?**

## Quick Intro to Random Forests

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## Random Trees

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Recall the general ML framework:

$$Y = f(X) + \varepsilon$$

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- If  $X \in \mathbb{R}^p$ , consider a finite partition  $\{S_1, S_2, \dots, S_m\}$  of  $\mathbb{R}^p$ ;
- Each  $S_i$  is a hyperrectangle defined by recursive binary splits on the covariates;
- On each  $S_i$ ,  $f$  is constant:  $f(x) = \mu_i$  for all  $x \in S_i$ ;
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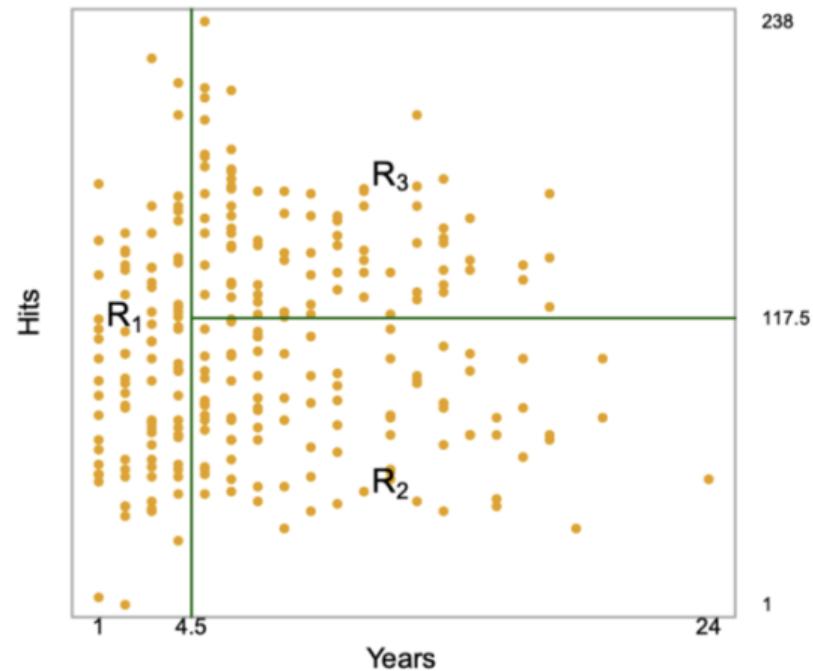
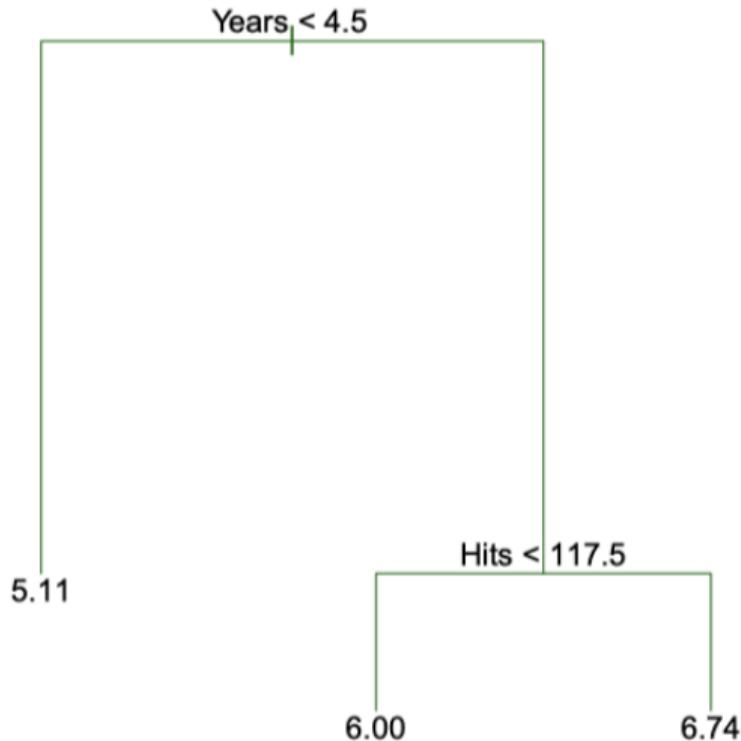
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**Hyafil and Rivest (1976):** this is harder than you think! The problem is NP-complete!

## Example: Predicting Baseball Player Salaries



## How to pick a split point? Use some greed!

Let's say you want to split on feature  $X_j$  at point  $\delta$ :

$$S_1 \equiv \{x \in \mathbb{R}^p : x_j \leq \delta\}, \quad S_2 \equiv \{x \in \mathbb{R}^p : x_j > \delta\}$$

$$\mu_1(\delta) \equiv \sum_{i:x_i \in S_1} \frac{Y_i}{n_1}, \quad \mu_2(\delta) \equiv \sum_{i:x_i \in S_2} \frac{Y_i}{n_2}$$

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- Define  $SSR(\delta) \equiv \sum_{i:x_i \in S_1} (Y_i - \mu_1(\delta))^2 + \sum_{i:x_i \in S_2} (Y_i - \mu_2(\delta))^2$
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- Repeat this for all features  $X_j$  and pick the best one;
- Important: you need some stopping rule! There is a huge literature on this...
- Example: minimum number of observations per leaf;

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This is the so-called the **CART** algorithm due to Breiman et al. (1984).

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Key insight:

- Each tree is noisy and biased, but averaging them reduces variance dramatically;
- Randomness *decorrelates* the trees, making averaging powerful;

**Questions?**

**Back to Partial Effects**

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## The Main Insight

We have a random sample  $\{(Y_i, X_i, Z_i)\}_{i=1}^n$  from

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Pick  $\delta$  to minimize  $SSR(\delta)$ !

## The Algorithm

Pick a number of trees  $B$  and a minimum leaf size  $k$ . For  $b = 1, \dots, B$ :

1. Draw a bootstrap sample of size  $s \leq n$  from the data;
2. Divide the data into two halves  $\mathcal{A}$  and  $\mathcal{B}$ ;
3. Using  $\mathcal{B}$ , keep splitting at random dimensions  $j$  using the previous criterion;
4. Stop when all leaves have less than  $2k - 1$  and more than  $k$  observations;
5. Using  $\mathcal{A}$ , estimate  $\beta(z)$  using only observations in the leaf where  $z$  falls;

The final estimate is

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This algorithm uses **honest trees!** Similar intuition to cross-fitting.

## Cool Properties and Limitations

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### Cool properties:

- Highly interpretable and relatively mild assumptions on  $\beta(z)$ ;
- Easy confidence intervals for  $\beta(z)$  at any point  $z$ :

$$\Omega^{-1/2}(z) \left( \hat{\beta}(z) - \beta(z) \right) \xrightarrow{d} \mathcal{N}(0, I_q)$$

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## Limitations:

- The dimension of  $X_i$  should be small relative to  $n$ ;
- The dimension of  $Z_i$  cannot be *that* large relative to  $n$ ;
- Pointwise inference only;
- It can be computationally demanding in large datasets;

**Questions?**

**Take a deep breath... we are changing topics!**



## Solving Large Models Through Deep Learning

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- Main challenge: computational cost increases exponentially with state space dimension;
- Traditional practice: simpler economics, simpler models;
- In practice: forget solving models with more than  $\approx 10\text{-}15$  state variables;

Deep Learning to the rescue!

## The Three Musketeers

Let  $\mathbf{s} \in \mathbb{R}^n$  be a state vector,  $\mathbf{c} \in \mathbb{R}^m$  be a control vector, and  $\mathbf{u} \in \mathbb{R}^k$  be shocks:

$$V(\mathbf{s}) = \max_{\mathbf{c}} \left\{ u(\mathbf{c}) + e^{-\rho} \mathbb{E} [V(\mathbf{s}') \mid \mathbf{s}, \mathbf{c}] \right\}$$
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Following [Powell \(2011\)](#)

- **The curse of representation:** a Cartesian grid for  $\mathbf{s}$  grows exponentially with  $n$ ;
  - Ex: 100 grid points per dimension  $\implies 10^{2n}$  total points;
  - Ex:  $n = 26$ , 100 points per dimension =  $O(10^{40})$  TB of RAM (AWS  $\approx 10^9$  TB);

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$$\mathbb{E} [V(\mathbf{s}') \mid \mathbf{s}, \mathbf{c}] = \int_{u_1} \int_{u_2} \cdots \int_{u_k} V(f(\mathbf{s}, \mathbf{c}(\mathbf{s}), \mathbf{u})) \phi(\mathbf{u}) du_1 du_2 \cdots du_k$$

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- **The curse of optimization:** Given  $V(\cdot)$ ,  $10^{2n}$  optimizations to find  $\mathbf{c}(\mathbf{s})$ ;

## Can Ito Calculus Save Us?

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- Typical approach from engineering: **Finite Differences** or **Finite Elements**;
- Let  $n = 1$  (scalar state) and an equally spaced grid  $\{\mathbf{s}_1, \mathbf{s}_2, \dots, \mathbf{s}_M\}$ . Then:

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- Drawback: we need very fine grids to approximate derivatives well;

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$$V(s_1, \dots, s_n) = \sum_{k_1=0}^K \cdots \sum_{k_n=0}^K a_{k_1, \dots, k_n} \prod_{j=1}^n T_{k_j}(s_j)$$

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- Number of coefficients grows exponentially with  $n$ :

$$(K + 1)^n$$

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  - **Richness:** be able to approximate a wide variety of functions;
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## But why?

- Neural networks can approximate almost any function;
- Computing gradients is super fast due to breakthroughs in *Automatic Differentiation*;
- If we use *deep* Neural Nets, we need few parameters!

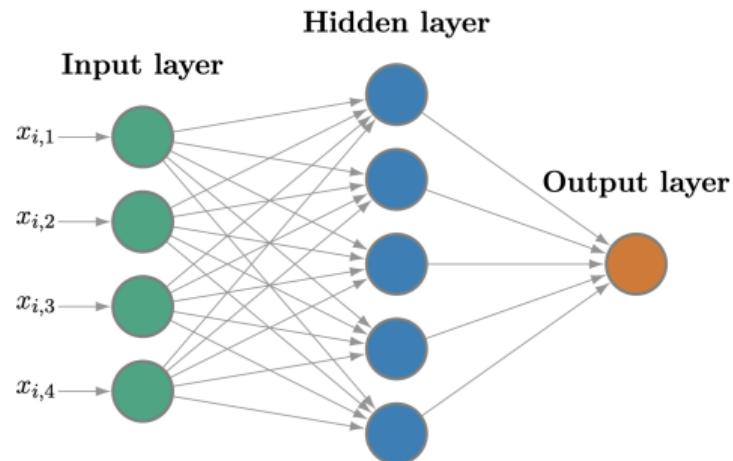
**Questions?**

**But what is a Neural Network?**

---

# A Smart Way of Composing Functions

- Each node is equipped with weights  $w$ , a bias  $b$ , and an activation function  $\sigma(\cdot)$ ;
- Hidden nodes compute  $\sigma(w^\top x + b)$ ;
- Examples of  $\sigma(\cdot)$ :  $\underbrace{\max\{0, x\}}_{\text{ReLU}}$ ,  $\tanh(x)$ ;
- Output of hidden layer:  
$$\mathbf{h}(\mathbf{x}, \theta) = \sigma(W\mathbf{x} + \mathbf{b});$$
- Final output:  $\hat{y} = w_{out}^\top \mathbf{h}(\mathbf{x}, \theta) + b_{out}$ ;
- Abuse notation:  $\theta \equiv (W, b, w_{out}, b_{out})$
- *Shallow neural network* = 1 hidden layer;



## Does it have good properties?

Cybenko (1989), Hornik et al. (1989), and Hornik (1991) proved that this basis of functions is rich:

### Theorem (Universal Approximation)

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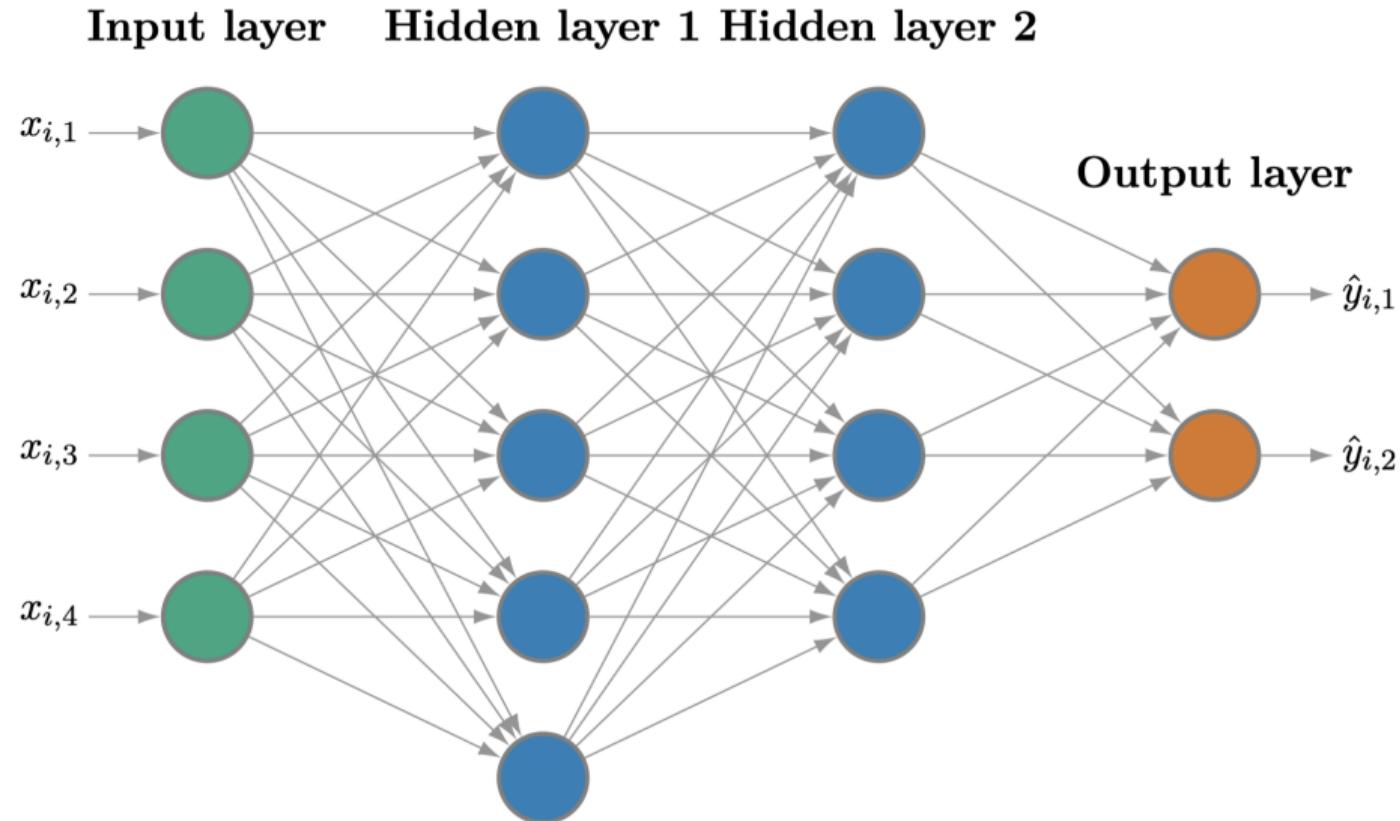
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### Theorem (Lu et al. (2017))

*For any Lebesgue integrable function  $f \in L^1(\mathbb{R}^n)$ , there exists a ReLU deep neural network with width at most  $n + 4$  in every hidden layer that approximates  $f$  to arbitrary precision.*

# What is a Deep Neural Network?



## How do we find these parameters?

---

*Training the network* = picking  $\theta$  to minimize some loss function:

$$\mathcal{L}(\theta) = \frac{1}{n} \sum_{i=1}^n (y_i - f(\mathbf{x}_i, \theta))^2$$

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**Questions?**

**Back to Solving Models!**

---

## Big Picture

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- Key insight in [Duarte et al. \(2024\)](#): approximate  $V(\mathbf{s})$  and  $\mathbf{c}(\mathbf{s})$  using DNNs;
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- Notation:  $HJB(\mathbf{s}, \mathbf{c}(\mathbf{s}, \theta_c), V(\mathbf{s}, \theta_V)) \equiv HJB(\mathbf{s}, \theta_c, \theta_V)$ ;

## The Algorithm

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- Step 1:** sample  $l$  points  $\{\mathbf{s}_i\}_{i=1}^l$  from the state space  $\mathcal{S}$  (for example, uniformly);  
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**Step 4:** Define the loss function  $\mathcal{L}(\boldsymbol{\theta}_V)$  and compute its gradient:

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**Step 5:** Update  $\theta_V$  using Gradient Descent:

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Summarizing:

- DNNs are a rich basis of functions with cheap derivatives and not so many parameters;
- They are an extremely flexible class;

## Wrap-Up

In two days, we covered a lot of ground!

- Always think about ML methods as an array of *functional bases*;
- A bit of LASSO and how to use it when we have many controls
- A bit of Random Forests and how to use them to estimate heterogeneous partial effects;
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**Important: I hope you had fun!**

# Thank you! 🙏

Scan below to get in touch!



# Appendix and References

# References

-  Bonhomme, Stéphane and Elena Manresa (May 2015). "Grouped Patterns of Heterogeneity in Panel Data: Grouped Patterns of Heterogeneity". In: *Econometrica* 83.3, pp. 1147–1184. ISSN: 0012-9682. DOI: [10.3982/ecta11319](https://doi.org/10.3982/ECTA11319). URL: <http://dx.doi.org/10.3982/ECTA11319>.
-  Breiman, Leo, Jerome H. Friedman, Richard A. Olshen, and Charles J. Stone (1984). *Classification and Regression Trees*. en.
-  Cybenko, G. (Dec. 1989). "Approximation by superpositions of a sigmoidal function". In: *Mathematics of Control, Signals, and Systems* 2.4, pp. 303–314. ISSN: 1435-568X. DOI: [10.1007/bf02551274](https://doi.org/10.1007/bf02551274). URL: <http://dx.doi.org/10.1007/BF02551274>.
-  Duarte, Victor, Diogo Duarte, and Dejanir H Silva (Sept. 2024). "Machine Learning for Continuous-Time Finance". In: *The Review of Financial Studies* 37.11. Ed. by Itay Goldstein, pp. 3217–3271. ISSN: 1465-7368. DOI: [10.1093/rfs/hhae043](https://doi.org/10.1093/rfs/hhae043). URL: <http://dx.doi.org/10.1093/rfs/hhae043>.
-  Hornik, Kurt (1991). "Approximation capabilities of multilayer feedforward networks". In: *Neural Networks* 4.2, pp. 251–257. ISSN: 0893-6080. DOI: [10.1016/0893-6080\(91\)90009-t](https://doi.org/10.1016/0893-6080(91)90009-t). URL: [http://dx.doi.org/10.1016/0893-6080\(91\)90009-t](http://dx.doi.org/10.1016/0893-6080(91)90009-t).
-  Hornik, Kurt, Maxwell Stinchcombe, and Halbert White (Jan. 1989). "Multilayer feedforward networks are universal approximators". In: *Neural Networks* 2.5, pp. 359–366. ISSN: 0893-6080. DOI: [10.1016/0893-6080\(89\)90020-8](https://doi.org/10.1016/0893-6080(89)90020-8). URL: [http://dx.doi.org/10.1016/0893-6080\(89\)90020-8](http://dx.doi.org/10.1016/0893-6080(89)90020-8).
-  Hyafil, Laurent and Ronald L. Rivest (May 1976). "Constructing optimal binary decision trees is NP-complete". In: *Information Processing Letters* 5.1, pp. 15–17. ISSN: 0020-0190. DOI: [10.1016/0020-0190\(76\)90095-8](https://doi.org/10.1016/0020-0190(76)90095-8). URL: [http://dx.doi.org/10.1016/0020-0190\(76\)90095-8](http://dx.doi.org/10.1016/0020-0190(76)90095-8).
-  Lu, Zhou, Hongming Pu, Feicheng Wang, Zhiqiang Hu, and Liwei Wang (2017). "The Expressive Power of Neural Networks: A View from the Width". In: *Advances in Neural Information Processing Systems*. Ed. by I. Guyon, U. Von Luxburg, S. Bengio, H. Wallach, R. Fergus, S. Vishwanathan, and R. Garnett. Vol. 30. Curran Associates, Inc. URL: [https://proceedings.neurips.cc/paper\\_files/paper/2017/file/32cbf687880eb1674a07bf717761dd3a-Paper.pdf](https://proceedings.neurips.cc/paper_files/paper/2017/file/32cbf687880eb1674a07bf717761dd3a-Paper.pdf).
-  Masini, Ricardo and Marcelo Medeiros (2025). *Balancing Flexibility and Interpretability: A Conditional Linear Model Estimation via Random Forest*. DOI: [10.48550/ARXIV.2502.13438](https://arxiv.org/abs/2502.13438). URL: <https://arxiv.org/abs/2502.13438>.
-  Powell, Warren B (Sept. 2011). *Approximate dynamic programming*. en. 2nd ed. Wiley Series in Probability and Statistics. Wiley-Blackwell.