How Inductive Bias in Machine Learning Aligns with Optimality in Economic Dynamics

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July 8, 2024

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Motivation

> **In the long run, we are all dead—***J.M. Keynes, A Tract on Monetary Reform (1923)*

- Numerical solutions to dynamical systems are central to many quantitative fields in economics.

- Dynamical systems in economics are **boundary value** problems:

    1. The boundary is at **infinity**.
    2. The values at the boundary are potentially **unknown**.

- Resulting from **forward looking** behavior of agents.

- Examples include the transversality and the no-bubble condition.

- Without them, the problems are **ill-posed** and have infinitely many solutions:

    - These forward-looking boundary conditions are a key limitation on increasing dimensionality.

Contribution

1. **Inductive bias alignment**:
   - The minimum-norm implicit bias of modern ML models automatically satisfies economic boundary conditions at infinity.

2. **Learning the right set of steady-states**:
   - Deep neural networks and kernel machines learn the boundary values, thereby extrapolating very accurately.

3. **Robustness and speed**:
   - Competitive in speed and more stable than traditional methods.

4. **Consistency of ML estimates**.

Intuition

- **Minimum-norm implicit bias**:
  - Over-parameterized models (e.g., large neural networks) have more parameters than data points and potentially interpolate the data.
  - They are biased towards interpolating functions with smallest norm.

- **Violation of economic boundary conditions**:
  - Sub-optimal solutions diverge (explode) over time.
  - They have large or explosive norms.
  - This is due to the **saddle-path** nature of econ problems.
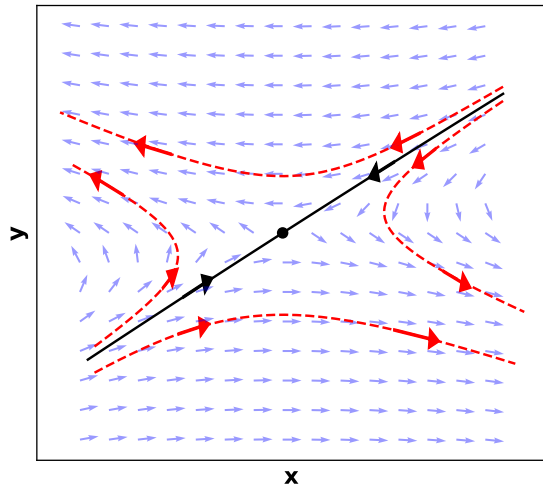
The Problem

The class of problems

A differential-algebraic system of equations, coming from an economic optimization problem:

$$\dot{\mathbf{x}}(t) = \mathbf{F}(\mathbf{x}(t), \mathbf{y}(t)) \qquad (1)$$

$$\dot{\mathbf{y}}(t) = \mathbf{G}(\mathbf{x}(t), \mathbf{y}(t)) \qquad (2)$$

$$\mathbf{0} = \mathbf{H}(\mathbf{x}(t), \mathbf{y}(t)) \qquad (3)$$

$\mathbf{x} \in \mathbb{R}^{N_x}$: state variables, $\mathbf{y} \in \mathbb{R}^{N_y}$: jump variables. Initial value $\mathbf{x}(0) = \mathbf{x}_0$ and boundary conditions (at infinity)

$$\mathbf{0} = \lim_{t \to \infty} \mathbf{B}(t, \mathbf{x}(t), \mathbf{y}(t)) \qquad (4)$$

Goal: finding an approximation for $\mathbf{x}(t)$ and $\mathbf{y}(t)$.

What is the problem?

- $\mathbf{y}_0$ is unknown.

- The optimal solutions is a **saddle-path**: unstable nature

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Method

Method

- Pick a set of points $\mathcal{D} \equiv \{t_1, \cdots, t_N\}$ for some fixed interval $[0, T]$

- Large machine learning models to learn $\hat{\mathbf{x}}(t)$ and $\hat{\mathbf{y}}(t)$

$$\min_{\hat{\mathbf{x}}, \hat{\mathbf{y}}} \sum_{t_i \in \mathcal{D}} \left[\eta_1 \left\| \dot{\hat{\mathbf{x}}}(t_i) - \mathbf{F}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)(t_i)) \right\|_2^2 + \eta_2 \left\| \dot{\hat{\mathbf{y}}}(t_i) - \mathbf{G}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)) \right\|_2^2 \right.$$
$$\left. + \eta_3 \left\| \mathbf{H}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)) \right\|_2^2 + \eta_4 \left\| \hat{\mathbf{x}}(0) - \mathbf{x}_0 \right\|_2^2 \right],$$

- This optimization **ignores** the boundary conditions.

- The implicit bias automatically satisfy the boundary conditions.

- Recent works suggest the implicit bias is toward smallest Sobolev semi-norms.

Ridgeless kernel regression

$$\hat{\dot{\mathbf{x}}}(t) = \sum_{j=1}^{N} \boldsymbol{\alpha}_j^x K(t, t_j), \quad \hat{\dot{\mathbf{y}}}(t) = \sum_{j=1}^{N} \boldsymbol{\alpha}_j^y K(t, t_j)$$

$$\hat{\mathbf{x}}(t) = \mathbf{x}_0 + \int_0^t \hat{\dot{\mathbf{x}}}(\tau)d\tau, \quad \hat{\mathbf{y}}(t) = \hat{\mathbf{y}}_0 + \int_0^t \hat{\dot{\mathbf{y}}}(\tau)d\tau$$

- $\mathbf{x}_0$ is given.

- $\hat{\mathbf{y}}_0$, $\boldsymbol{\alpha}_j^x$, and $\boldsymbol{\alpha}_j^y$ are learnable parameters.

- $K(\cdot, \cdot)$: Matérn Kernel, with smoothness parameter ν and length scale ℓ.

Ridgeless kernel regression: minimum Sobolev seminorm solutions

We also solve the ridgeless kernel regression

$$\lim_{\lambda \to 0} \min_{\hat{\mathbf{x}}, \hat{\mathbf{y}}} \sum_{t_i \in \mathcal{D}} \left[\eta_1 \left\| \hat{\mathbf{x}}(t_i) - \mathbf{F}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)(t_i)) \right\|_2^2 + \eta_2 \left\| \hat{\mathbf{y}}(t_i) - \mathbf{G}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)) \right\|_2^2 \right.$$

$$\left. + \eta_3 \left\| \mathbf{H}(\hat{\mathbf{x}}(t_i), \hat{\mathbf{y}}(t_i)) \right\|_2^2 \right] + \eta_4 \left\| \hat{\mathbf{x}}(0) - \hat{\mathbf{x}}_0 \right\|_2^2 + \lambda \left[\sum_{m=1}^{N_x} \| \hat{\mathbf{x}}^{(m)} \|_{\mathcal{H}}^2 + \sum_{m=1}^{N_y} \| \hat{\mathbf{y}}^{(m)} \|_{\mathcal{H}}^2 \right]$$

- Targeting Sobolev semi-norm.

- This choice is very natural: it solves the instability issues of the classical algorithm.

Applications

Linear asset pricing

$$\dot{\mathbf{x}}(t) = c + g\mathbf{x}(t) \tag{5}$$

$$\dot{\mathbf{y}}(t) = r\mathbf{y}(t) - \mathbf{x}(t) \tag{6}$$

$$0 = \lim_{t \to \infty} e^{-rt}\mathbf{y}(t) \tag{7}$$

- $\mathbf{x}(t) \in \mathbb{R}$: dividends, $\mathbf{y}(t) \in \mathbb{R}$: prices, and $\mathbf{x}_0$ given.

- Equation (5): how the dividends evolve in time.

- Equation (6): how the prices evolve in time.

- Equation (7): "no-bubble" condition, the boundary condition at infinity.

Why do we need the boundary condition?

$$\dot{\mathbf{x}}(t) = c + g\mathbf{x}(t)$$
$$\dot{\mathbf{y}}(t) = r\mathbf{y}(t) - \mathbf{x}(t)$$

- The solutions:

$$\mathbf{y}(t) = \mathbf{y}_f(t) + \zeta e^{rt}$$

- $\mathbf{y}_f(t) = \int_0^\infty e^{-r\tau}\mathbf{x}(t+s)ds$: price based on the fundamentals.

- ζe^{rt}: explosive bubble terms, it has to be **ruled out** by the boundary condition.

- Triangle inequality: $\|\mathbf{y}_f\| < \|\mathbf{y}\|$.

- The price based on the fundamentals has the **lowest norm**.
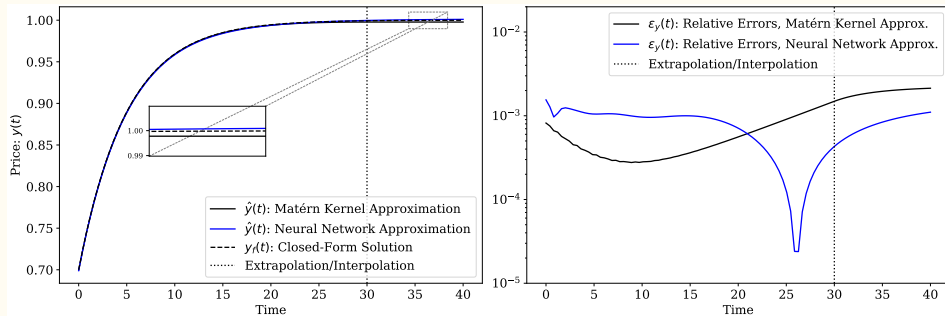
$$\mathcal{D} = \{0, 1, \cdots, 30\}$$

- The explosive solutions are ruled out without directly imposing the boundary condition.

- Very accurate approximations, both in the short- and medium-run.

- Learns the steady-state.

Neoclassical growth model: the agent's problem

$$\max_{\mathbf{y}(t)} \int_0^\infty e^{-rt} \ln(\mathbf{y}(t)) dt$$

$$\text{s.t.} \quad \dot{\mathbf{x}}(t) = f(\mathbf{x}(t)) - \mathbf{y}(t) - \delta \mathbf{x}(t)$$

for a given $\mathbf{x}_0$.

- $\mathbf{x}(t) \in \mathbb{R}$: capital, $\mathbf{y}(t) \in \mathbb{R}$: consumption, and a concave production function $f(x) = x^a$.

Constructing the Hamiltonian ...

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t)) - \mathbf{y}(t) - \delta \mathbf{x}(t) \tag{8}$$

$$\dot{\mathbf{y}}(t) = \mathbf{y}(t)\big[f'(\mathbf{x}(t)) - \delta - r\big] \tag{9}$$

$$0 = \lim_{t \to \infty} e^{-rt} \frac{\mathbf{x}(t)}{\mathbf{y}(t)} \tag{10}$$
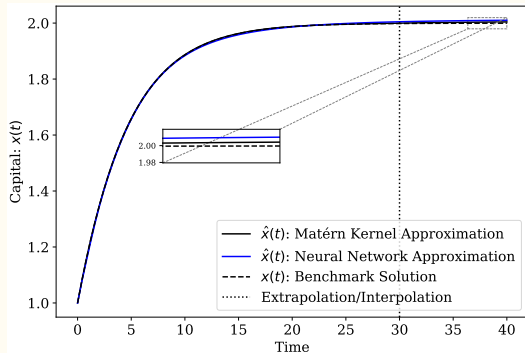
- Equation (10) : transversality condition (TVC)

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Ignoring the transversality condition:

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t)) - \mathbf{y}(t) - \delta\mathbf{x}(t)$$
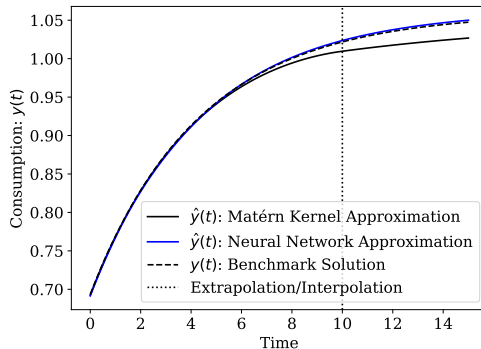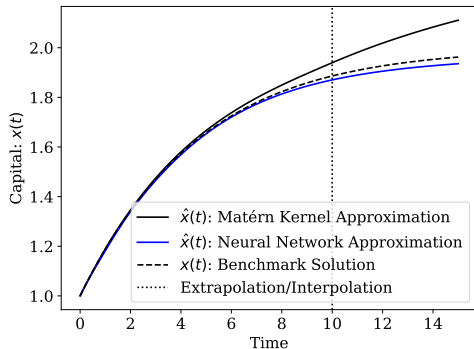$$\dot{\mathbf{y}}(t) = \mathbf{y}(t)\big[f'(\mathbf{x}(t)) - \delta - r\big]$$
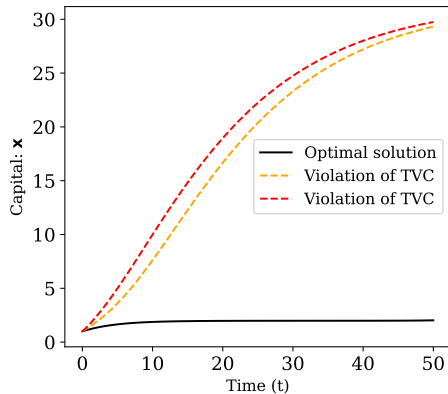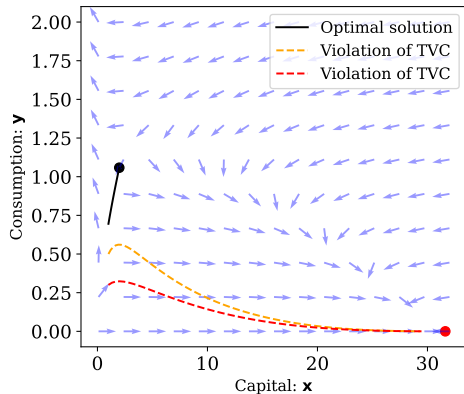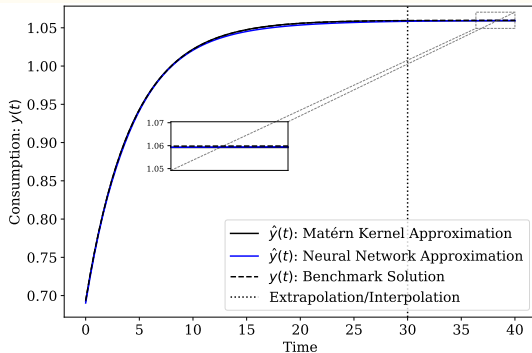
$$\mathcal{D} = \{0, 1, \cdots, 30\}$$

- The explosive solutions are ruled out without directly imposing the boundary condition.

- Very accurate approximations, both in the short- and medium-run.

- Learns the **right steady-state**. ▸▸ Relative errors

$$\mathcal{D} = \{0, 1, \cdots, 10\}$$

- The explosive solutions are ruled out without directly imposing the boundary condition.

- Provides a very accurate approximation in the short-run.

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Extensions

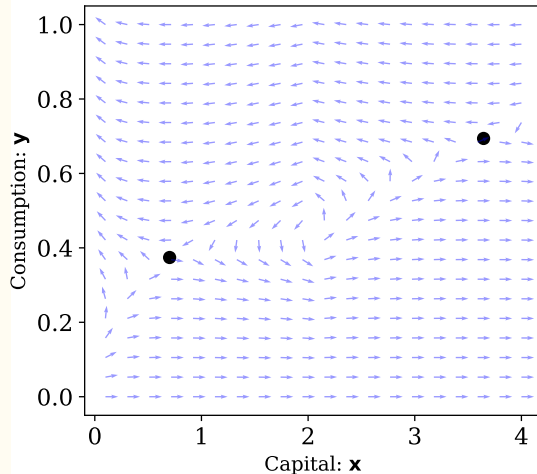## Neoclassical Growth Model: Concave-Convex Production Function

- So far we have had a **unique** saddle-path converging to a unique **saddle** steady state.

- What if we have **two** saddle steady states, very close to each other (equilibrium multiplicity)?

- Neoclassical growth model with a concave-convex production function:
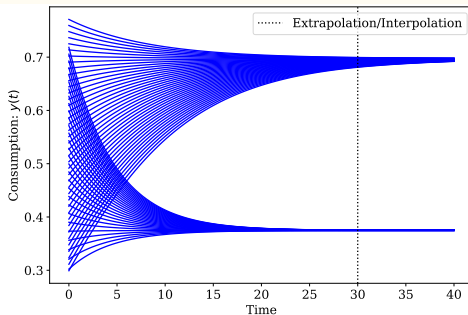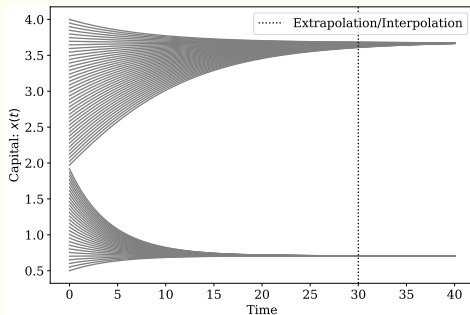
$$f(x) = A \max\{x^a, b_1 x^a - b_2\}$$

$$\dot{\mathbf{x}}(t) = f(\mathbf{x}(t)) - \mathbf{y}(t) - \delta\mathbf{x}(t)$$
$$\dot{\mathbf{y}}(t) = \mathbf{y}(t)\big[f'(\mathbf{x}(t)) - \delta - r\big]$$

- The approximate solutions approach the right steady states.

- The transversality conditions are satisfied without being directly imposed.

- The steady states are learned. ⏩ Full DAE

Conclusion

- The minimum-norm implicit bias of large ML models aligns with optimality in economic dynamic models.

- Long-run (global) conditions can be replaced with local conditions (regularization) to achieve the optimal solution.

- Both kernel and neural network approximations accurately learn the right steady state(s).

- Proceeding with **caution**: can regularization be thought of as an equilibrium selection device?

Appendix

Back
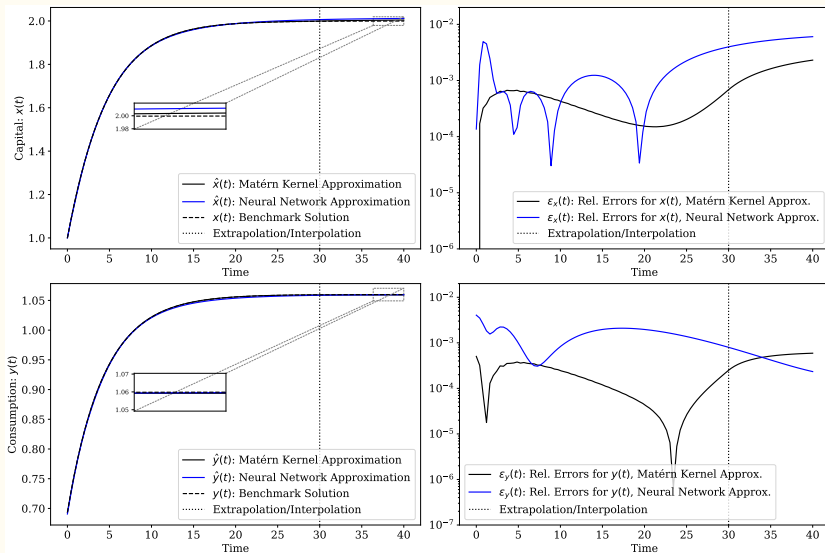
$$\dot{\mathbf{x}}_k(t) = \mathbf{y}_k(t) - \delta_k \mathbf{x}_k(t),$$
$$\dot{\mathbf{x}}_h(t) = \mathbf{y}_h(t) - \delta_k \mathbf{x}_h(t)$$
$$\dot{\mathbf{y}}_c(t) = \mathbf{y}_c(t) \left[f_1 \left(\mathbf{x}_k(t), \mathbf{x}_h(t) \right) - \delta_k - r \right],$$
$$0 = f \left(\mathbf{x}_k(t), \mathbf{x}_h(t) \right) - \mathbf{y}_c(t) - \mathbf{y}_k(t) - \mathbf{y}_h(t),$$
$$0 = f_2 \left(\mathbf{x}_k(t), \mathbf{x}_h(t) \right) - f_1 \left(\mathbf{x}_k(t), \mathbf{x}_h(t) \right) + \delta_k - \delta_h.$$
$$0 = \lim_{t \to \infty} e^{-rt} \frac{\mathbf{x}_k(t)}{\mathbf{y}_c(t)}, \ 0 = \lim_{t \to \infty} e^{-rt} \frac{\mathbf{x}_h(t)}{\mathbf{y}_c(t)}.$$

- $\mathbf{x}_k$: physical capital, $\mathbf{x}_h$: human capital, $\mathbf{y}_c$: consumption, $\mathbf{y}_k$: investment in physical capital, $\mathbf{y}_h$: investment in human capital

- $f \left(x_k, x_h \right) = x_k^{a_k} x_h^{a_h}$

Results