

Solving Models of Economic Dynamics with Ridgeless Kernel Regressions

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Motivation

- 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

Using kernel methods to solve a class of infinite-horizon, deterministic, continuous-time models

1. Minimum-norm alignment:

- The minimum-norm kernel method aligns with asymptotic boundary conditions.

2. Learning the correct set of steady-states:

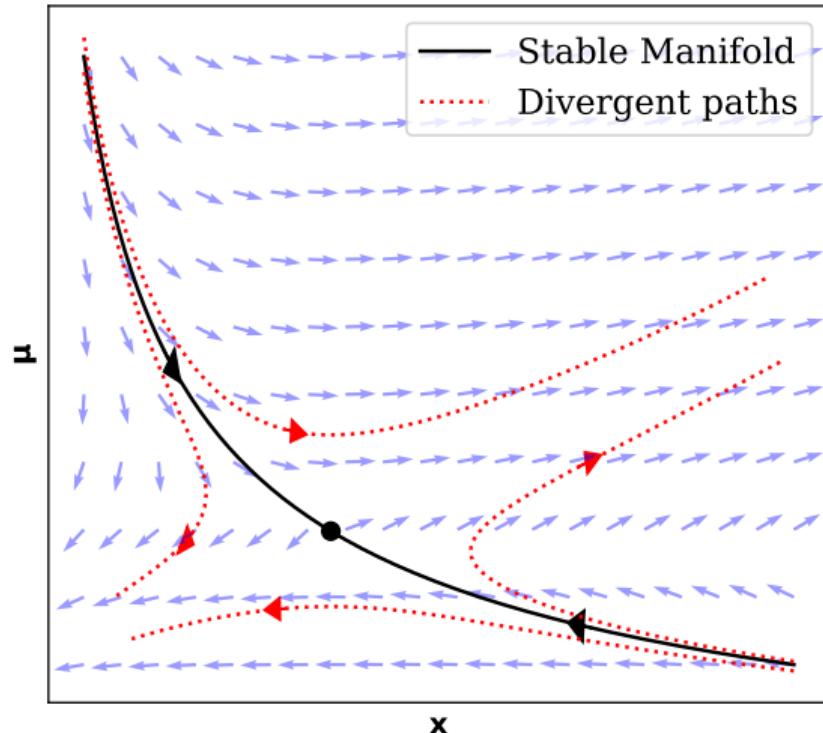
- Kernel machines learn the boundary values, thereby extrapolating outside the training data.

3. Robustness and speed:

- Competitive in speed and more stable than traditional methods.

4. Consistency of the kernel estimates.

- **Violation of the boundary conditions:**
 - Sub-optimal solutions explode over time.
 - They have large derivatives.
 - This behavior is due to the **saddle-path** nature of the problem.
- **Minimum-norm solution :**
 - Penalizing large derivatives rules out explosive paths.
 - The remaining solution is the optimal solution.



The Problem

The class of problems

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

$$\dot{\mathbf{x}}(t) = \mathbf{F}(\mathbf{x}(t), \boldsymbol{\mu}(t), \mathbf{y}(t)) \quad (1)$$

$$\dot{\boldsymbol{\mu}}(t) = r\boldsymbol{\mu}(t) - \boldsymbol{\mu}(t) \odot \mathbf{G}(\mathbf{x}(t), \boldsymbol{\mu}(t), \mathbf{y}(t)) \quad (2)$$

$$\mathbf{0} = \mathbf{H}(\mathbf{x}(t), \boldsymbol{\mu}(t), \mathbf{y}(t)), \quad (3)$$

boundary conditions (at infinity)

$$\mathbf{0} = \lim_{t \rightarrow \infty} e^{-rt} \mathbf{x}(t) \odot \boldsymbol{\mu}(t), \quad (4)$$

initial value $\mathbf{x}(0) = \mathbf{x}_0$.

- $\mathbf{x} \in \mathbb{R}^M$: state variables.
- $\boldsymbol{\mu} \in \mathbb{R}^M$: co-state variables.
- $\mathbf{y} \in \mathbb{R}^P$: jump variables.

Challenges

Goal: Find an approximation to $\mathbf{x}(t)$, $\boldsymbol{\mu}(t)$, and $\mathbf{y}(t)$.

What is the problem?

- Initial conditions \mathbf{y}_0 and $\boldsymbol{\mu}_0$ are unknown.
- The optimal solution follows a **saddle path**.
 - If T is small, solutions are inaccurate due to premature enforcement of the steady state.
 - If T is large, the algorithms become increasingly numerically unstable.

Example: Neoclassical Growth Model

$$\dot{x}(t) = f(x(t)) - \delta x(t) - y(t) := F(x(t), \mu(t), y(t))$$

$$\dot{\mu}(t) = r\mu(t) - \mu(t) \underbrace{(f'(x(t)) - \delta)}_{:= G(x(t), \mu(t), y(t))}$$

$$0 = \mu(t)y(t) - 1 := H(x(t), \mu(t), y(t))$$

$$x(0) = x_0, \quad \lim_{t \rightarrow \infty} e^{-rt} \mu(t)x(t) = 0$$

capital $x(t)$, consumption $y(t)$, utility $\log(y)$, present-value co-state variable $\mu(t)$, discount rate $r > 0$, depreciation rate $0 < \delta < 1$, and production function $f(x)$.

Method

Method: approximation

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

$$\hat{\mathbf{x}}(t) = \sum_{j=1}^N \alpha_j^x k(t, t_j), \quad \hat{\boldsymbol{\mu}}(t) = \sum_{j=1}^N \alpha_j^\mu k(t, t_j), \quad \hat{\mathbf{y}}(t) = \sum_{j=1}^N \alpha_j^y k(t, t_j),$$

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

- α_j^x , α_j^μ , α_j^y , $\boldsymbol{\mu}_0$, and \mathbf{y}_0 are parameters to be found.
- $k(t, t_j)$ is a kernel that measures how close (or similar) t is to t_j .
- We use a Matérn kernel with smoothness ν and length ℓ .

► Matérn kernel

Method: Ridgeless kernel regression

We solve

$$\min_{\hat{\mathbf{x}}, \hat{\boldsymbol{\mu}}, \hat{\mathbf{y}}} \left(\sum_{m=1}^M \|\hat{\mathbf{x}}^{(m)}\|_{\mathcal{H}}^2 + \sum_{m=1}^M \|\hat{\boldsymbol{\mu}}^{(m)}\|_{\mathcal{H}}^2 \right)$$

$$\text{s.t. } \hat{\mathbf{x}}(t_i) = \mathbf{F}(\hat{\mathbf{x}}(t_i), \hat{\boldsymbol{\mu}}(t_i), \hat{\mathbf{y}}(t_i)), \quad \text{for all } t_i \in \mathcal{D}$$

$$\hat{\boldsymbol{\mu}}(t_i) = r\hat{\boldsymbol{\mu}}(t_i) - \hat{\boldsymbol{\mu}}(t_i) \odot \mathbf{G}(\hat{\mathbf{x}}(t_i), \hat{\boldsymbol{\mu}}(t_i), \hat{\mathbf{y}}(t_i)), \quad \text{for all } t_i \in \mathcal{D}$$

$$\mathbf{0} = \mathbf{H}(\hat{\mathbf{x}}(t_i), \hat{\boldsymbol{\mu}}(t_i), \hat{\mathbf{y}}(t_i)), \quad \text{for all } t_i \in \mathcal{D}.$$

- $\|\hat{\mathbf{x}}^{(m)}\|_{\mathcal{H}}^2 = \sum_{i=1}^N \sum_{j=1}^N \alpha_i^{x^{(m)}} \alpha_j^{x^{(m)}} k(t_i, t_j)$ and $\|\hat{\boldsymbol{\mu}}^{(m)}\|_{\mathcal{H}}^2 = \sum_{i=1}^N \sum_{j=1}^N \alpha_i^{\mu^{(m)}} \alpha_j^{\mu^{(m)}} k(t_i, t_j)$
- TVC is **not imposed**.
- The minimization term (objective) is used to control the smoothness of the approximating functions.
- For Matérn kernels, it also controls the smoothness of derivatives.

Applications

Neoclassical growth model

$$\begin{aligned} & \max_{y(t)} \int_0^{\infty} e^{-rt} \ln(y(t)) dt \\ \text{s.t. } & \dot{x}(t) = f(x(t)) - y(t) - \delta x(t) \end{aligned}$$

for a given x_0 .

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

Constructing the Hamiltonian ...

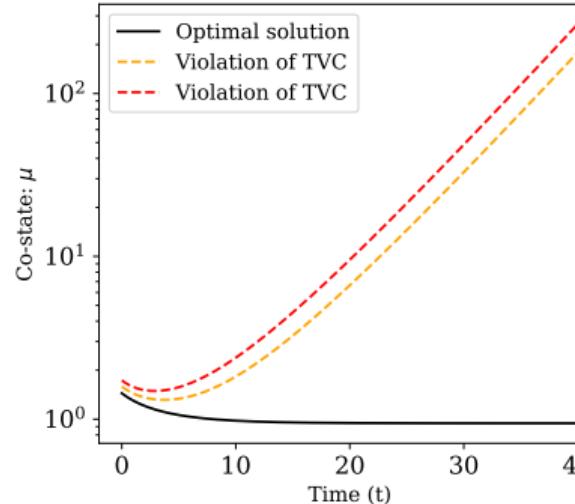
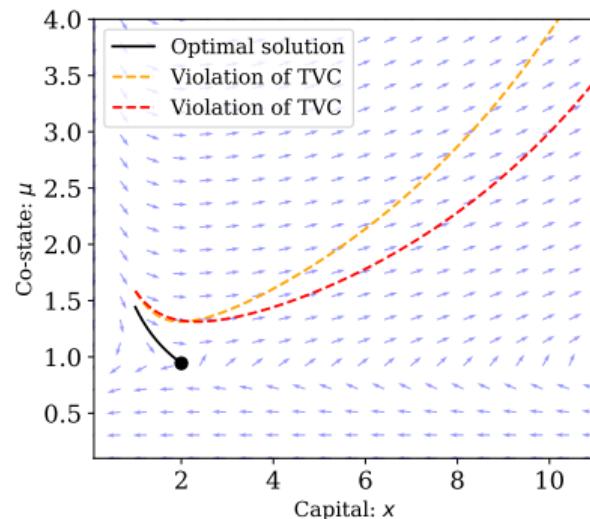
$$\begin{aligned} \dot{x}(t) &= f(x(t)) - \delta x(t) - y(t), \\ \dot{\mu}(t) &= r\mu(t) - \mu(t)(f'(x(t)) - \delta), \\ 0 &= \mu(t)y(t) - 1, \\ x(0) &= x_0, \quad \lim_{t \rightarrow \infty} e^{-rt}\mu(t)x(t) = 0. \end{aligned}$$

- Last Equation : transversality condition (TVC)

Why do we need the boundary condition?

Ignoring the transversality condition:

$$\begin{aligned}\dot{x}(t) &= f(x(t)) - \delta x(t) - y(t), \\ \dot{\mu}(t) &= r\mu(t) - \mu(t)(f'(x(t)) - \delta), \\ 0 &= \mu(t)y(t) - 1, \\ x(0) &= x_0.\end{aligned}$$



Neoclassical Growth Model: algorithm

$$\begin{aligned} & \min_{\hat{x}, \hat{\mu}, \hat{y}} \left(\|\hat{x}\|_{\mathcal{H}}^2 + \|\hat{\mu}\|_{\mathcal{H}}^2 \right) \\ \text{s.t. } & \hat{x}(t_i) = f(\hat{x}(t_i)) - \delta \hat{x}(t_i) - \hat{y}(t_i), \quad \text{for all } t_i \in \mathcal{D} \\ & \hat{\mu}(t_i) = r \hat{\mu}(t_i) - \hat{\mu}(t_i) (f'(\hat{x}(t_i) - \delta)), \quad \text{for all } t_i \in \mathcal{D} \\ & 0 = \hat{\mu}(t_i) \hat{y}(t_i) - 1, \quad \text{for all } t_i \in \mathcal{D}. \end{aligned}$$

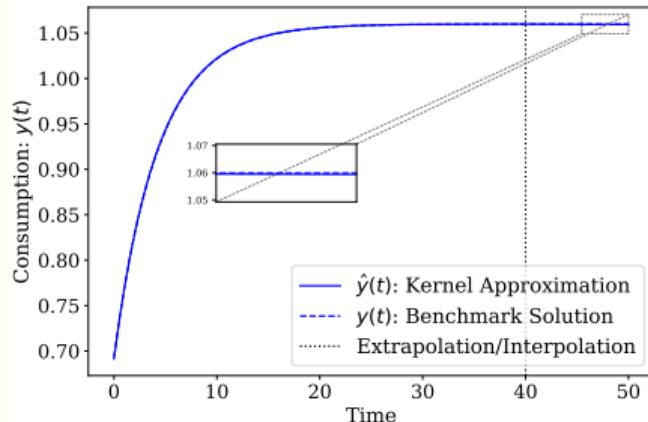
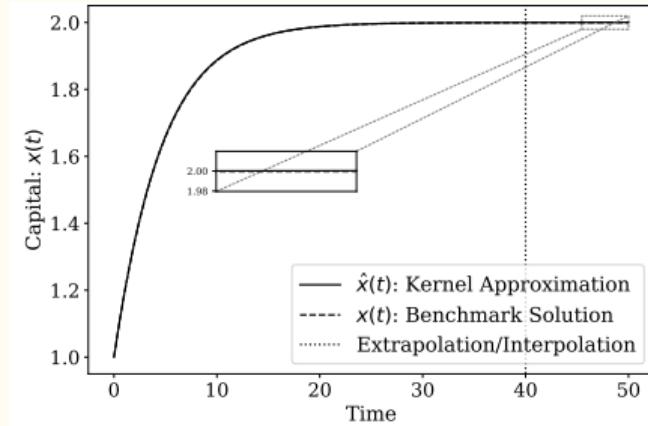
- $\|\hat{x}\|_{\mathcal{H}}^2 = \sum_{i=1}^N \sum_{j=1}^N \alpha_i^x \alpha_j^x k(t_i, t_j)$ and $\|\hat{\mu}\|_{\mathcal{H}}^2 = \sum_{i=1}^N \sum_{j=1}^N \alpha_i^\mu \alpha_j^\mu k(t_i, t_j)$
- TVC is **not imposed**.

Neoclassical growth model: results

- $\mathcal{D} = \{0, 1, \dots, 40\}$. ► sparse grids
- $f(x) = x^{\frac{1}{3}}$, $\delta = \frac{1}{3}$, and $r = 0.11$.
- The explosive solutions are ruled out without directly imposing the boundary condition.

Conclusion

- For short- and medium-run accuracy, we do not need to know the steady state (global condition).
- It suffices that sub-optimal paths diverge from the optimal path (local condition).
- Learns the **correct steady state**. ► Relative errors



Neoclassical growth model: learning the steady state

Why does it learn the **correct steady state**?

- A straight line is the “smoothest” solution: it has zero derivatives.
- The kernels we use are zero-reverting:

$$\lim_{t \rightarrow \infty} k(t, t_j) = 0.$$

- We approximate the derivatives using kernels:

$$\lim_{t \rightarrow \infty} \hat{x}(t) = \hat{\mu}(t) = \hat{y}(t) = 0.$$

- This behavior is mainly driven by choosing a large t_N (e.g., $t_N = 40$) in \mathcal{D} .
- **Question:** How accurate are the short-run dynamics when t_N is small?

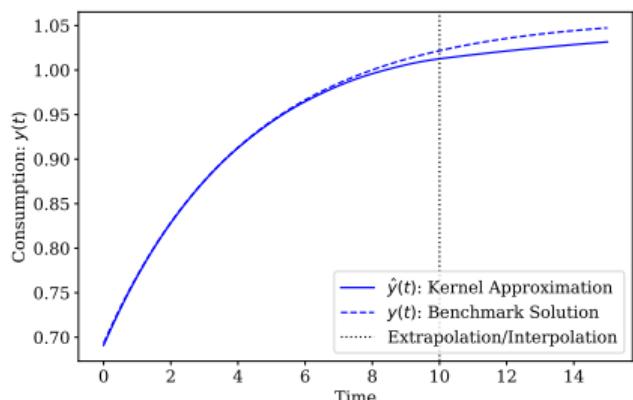
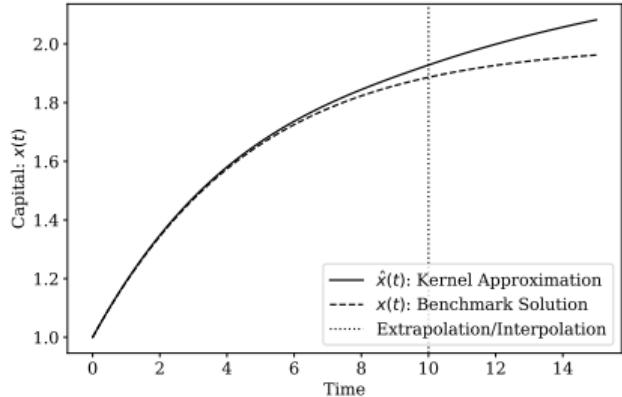
Neoclassical growth model: short-run results

- $\mathcal{D} = \{0, 1, \dots, 10\}$.
- $f(x) = x^{\frac{1}{3}}$, $\delta = \frac{1}{3}$, and $r = 0.11$.
- Very accurate short-run dynamics.

Conclusion

- For short-run accuracy, we do not need to use large T (global condition).
- It suffices that sub-optimal paths diverge fast enough from the optimal path (local condition).

▶ Relative errors



Neoclassical Growth Model: Non-Concave 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 (steady-state multiplicity)?
- Neoclassical growth model with a non-concave production function (threshold externalities):

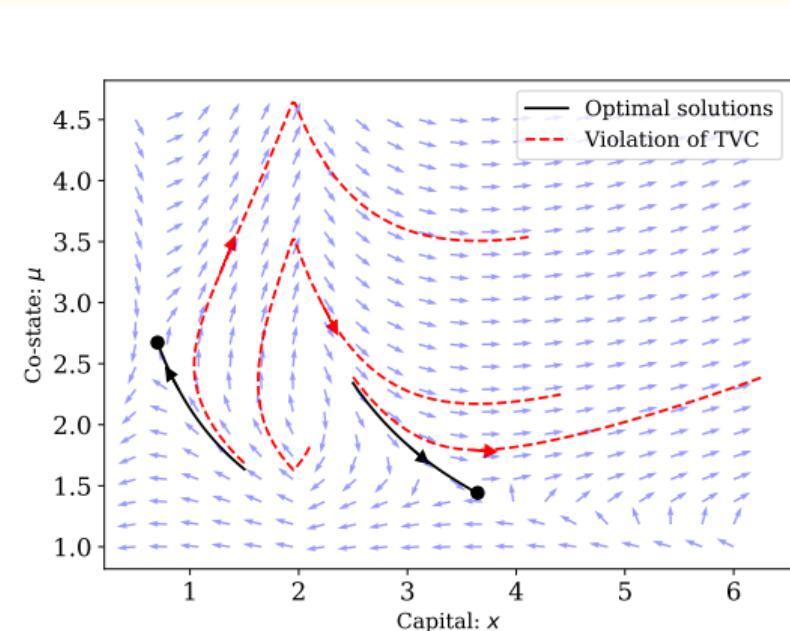
$$f(x) = A \max\{x^a, b_1 x^a - b_2\}$$

- The production function has a kink.

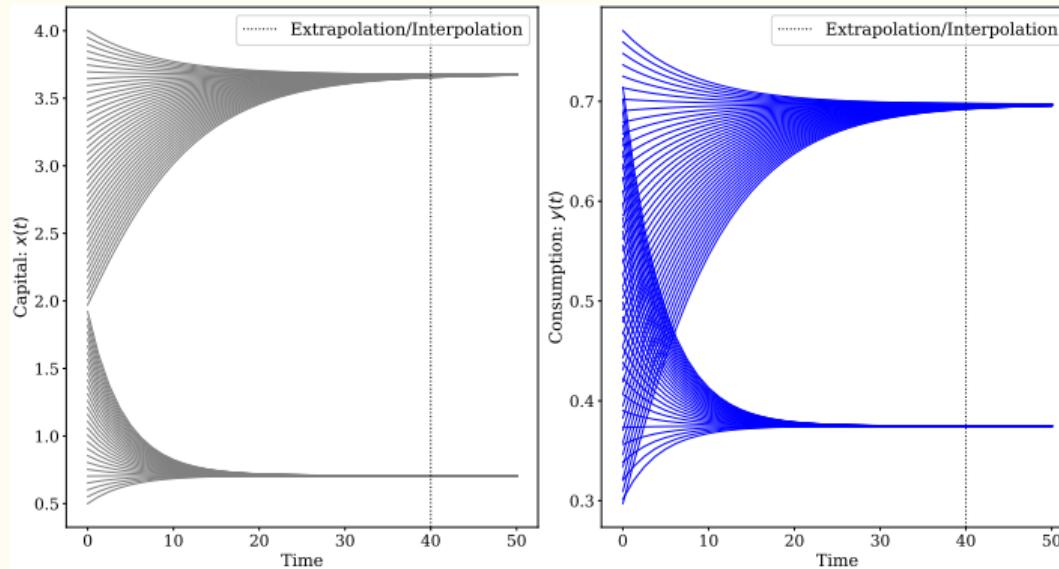
Non-concave production function: vector field

$$\begin{aligned}\dot{x}(t) &= f(x(t)) - \delta x(t) - y(t), \\ \dot{\mu}(t) &= r\mu(t) - \mu(t)(f'(x(t)) - \delta), \\ 0 &= \mu(t)y(t) - 1, \\ x(0) &= x_0.\end{aligned}$$

- The model is identical to the concave case, except that $f(\cdot)$ is now non-concave.
- This problem is very challenging for traditional methods such as shooting.



Results



- The approximate solutions approach the right steady states.
- The transversality conditions are satisfied without being directly imposed.
- The steady states are learned.

Extensions

Linear asset pricing

Linear asset pricing model

$$\dot{x}(t) = c + gx(t)$$

$$\dot{\mu}(t) = r\mu(t) - x(t) := r\mu(t) - \mu(t)\frac{x(t)}{\mu(t)}$$

$$0 = \lim_{t \rightarrow \infty} e^{-rt} \mu(t)x(t).$$

- $x(t) \in \mathbb{R}$: flow payoffs from a claim to an asset.
- $\mu(t) \in \mathbb{R}$ be the price of a claim to that asset.
- x_0 given.

Why do we need the boundary condition?

$$\dot{x}(t) = c + gx(t)$$

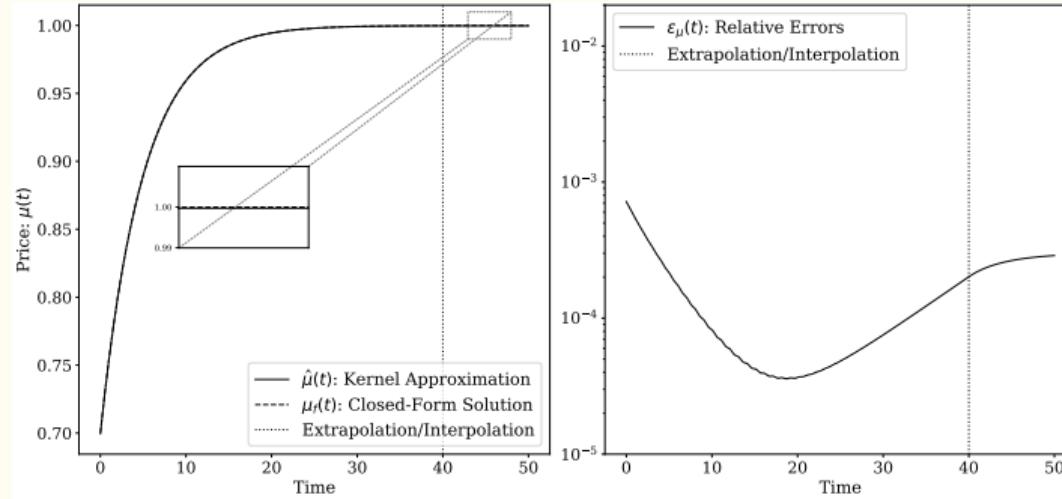
$$\dot{\mu}(t) = r\mu(t) - x(t)$$

- The solutions:

$$\mu(t) = \mu_f(t) + \zeta e^{rt}$$

- $\mu_f(t) = \int_0^\infty e^{-r\tau} x(t+\tau) d\tau$: price based on the fundamentals.
- ζe^{rt} : explosive bubble terms, it has to be **ruled out** by the boundary condition.
- The price based on the fundamentals is the “**smoothest**”.

Results



$$\mathcal{D} = \{0, 1, \dots, 30\}$$

- 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.

Conclusion

- Long-run (**global**) conditions can be replaced with appropriate regularization (**local**) to achieve the optimal solutions.
- The minimum-norm kernels aligns with optimality in economic dynamic models.
- The minimum-norm kernels accurately learn the correct steady state(s).

Conclusion: explicit and implicit Regularization

Machine learning methods:

$$\underbrace{\frac{1}{N} \sum_{i=1}^N \mathcal{L}(y_i, f_\theta(x_i))}_{\text{loss}} + \underbrace{\lambda \Omega(f_\theta)}_{\text{regularization term}}$$

- $f_\theta(\cdot)$: parametric function (kernel methods, neural networks, etc.).
- In this paper, regularization is used to rule out sub-optimal solutions and enforce stability.
- What other roles can regularization play in solving economic models with modern ML methods?

Appendix

Matérn kernel

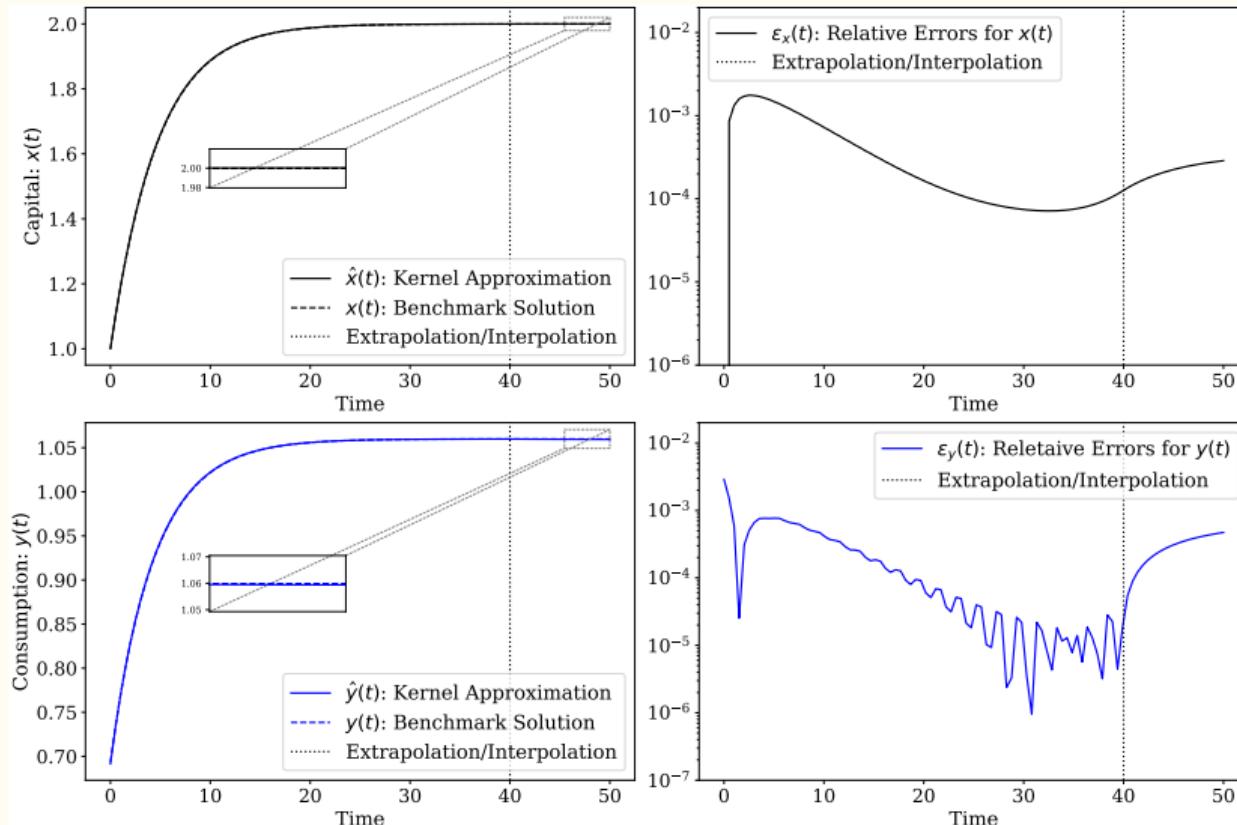
$$K(t, t_j) = C_{\frac{1}{2}}(t, t_j) = \sigma^2 \exp\left(-\frac{|t - t_j|}{\ell}\right),$$

$$K(t, t_j) = C_{\frac{3}{2}}(t, t_j) = \sigma^2 \left(1 + \frac{\sqrt{3}|t - t_j|}{\ell}\right) \exp\left(-\frac{\sqrt{3}|t - t_j|}{\ell}\right),$$

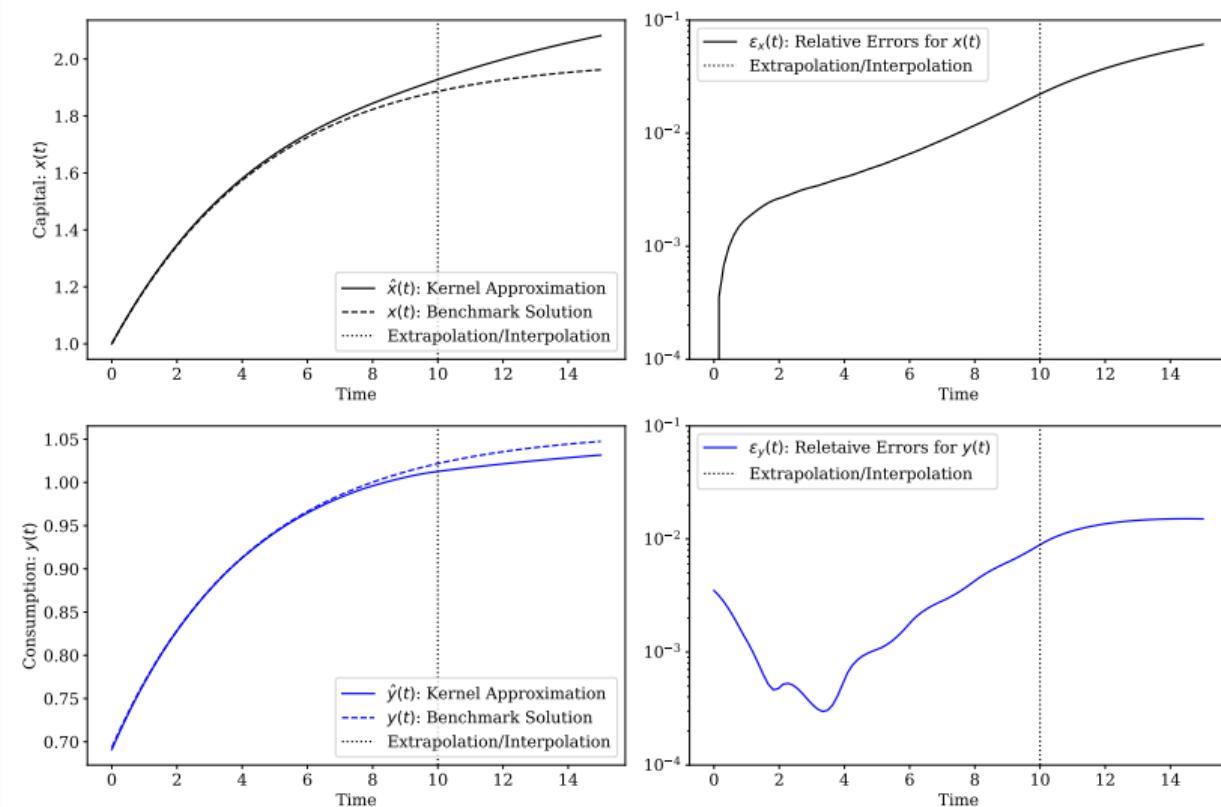
$$K(t, t_j) = C_{\frac{5}{2}}(t, t_j) = \sigma^2 \left(1 + \frac{\sqrt{5}|t - t_j|}{\ell} + \frac{5|t - t_j|^2}{3\ell^2}\right) \exp\left(-\frac{\sqrt{5}|t - t_j|}{\ell}\right).$$

▶ Back

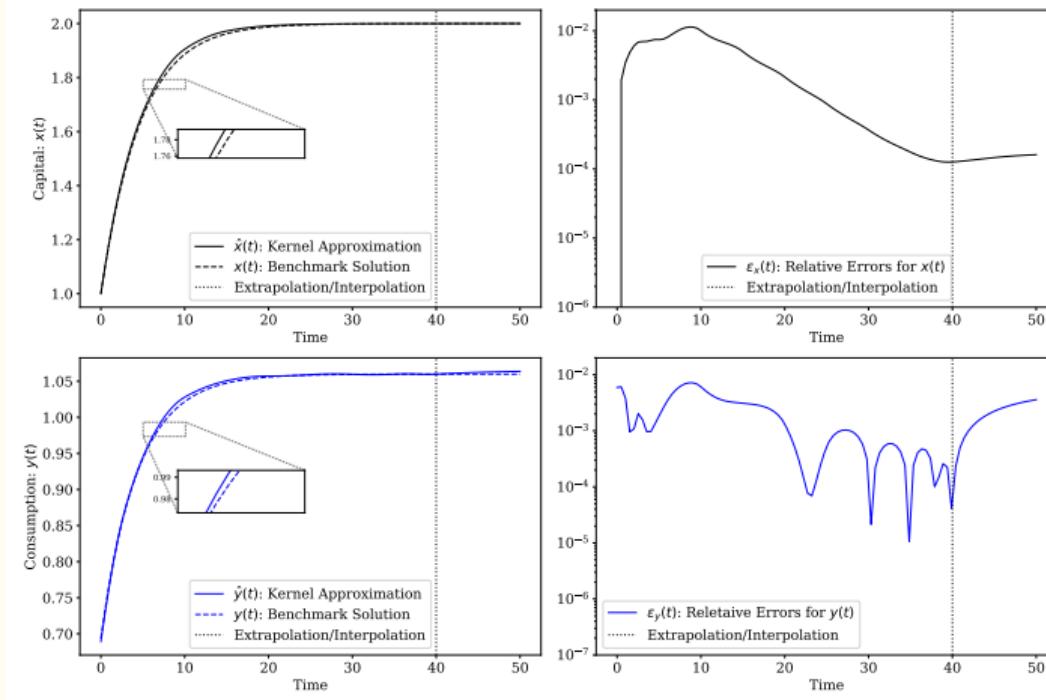
Neoclassical growth: relative errors



Neoclassical growth: short-run relative errors



Neoclassical growth: sparse sampling



$$\mathcal{D} = \{0, 1, 3, 5, 10, 15, 20, 25, 30, 35, 38, 40\}$$

Human capital and growth

$$\begin{aligned}\dot{x}_k(t) &= y_k(t) - \delta_k x_k(t), \\ \dot{x}_h(t) &= y_h(t) - \delta_h x_h(t), \\ \dot{\mu}_k(t) &= r\mu_k(t) - \mu_k(t)[f_1(x_k(t), x_h(t)) - \delta_k], \\ \dot{\mu}_h(t) &= r\mu_h(t) - \mu_h(t)[f_2(x_k(t), x_h(t)) - \delta_h], \\ 0 &= \mu_k(t)y_c(t) - 1, \\ 0 &= \mu_k(t) - \mu_h(t), \\ 0 &= f(x_k(t), x_h(t)) - y_c(t) - y_k(t) - y_h(t), \\ 0 &= \lim_{t \rightarrow \infty} e^{-rt} x_k(t) \mu_k(t), \\ 0 &= \lim_{t \rightarrow \infty} e^{-rt} x_h(t) \mu_h(t),\end{aligned}$$

for given initial conditions $x_k(0) = x_{k_0}$, $x_h(0) = x_{h_0}$.

- Human capital is $x_h(t)$, physical capital $x_k(t)$, consumption $y_c(t)$, investment in human capital $y_h(t)$, and investment in physical capital $y_k(t)$, $\mu_k(t)$ and $\mu_h(t)$ are the co-state variables.

Results

