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Interfere: Intervention Response Simulation and Prediction for Stochastic Nonlinear Dynamics

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Summary

The vision of Interfere is simple: What if we used high quality scientific models to benchmark causal prediction tools? Randomized experimental data and counterfactuals are essential for testing methods that attempt to infer causal relationships from data, but obtaining such datasets can be expensive and difficult. Mechanistic models have been developed to simulate scenarios and predict the response of systems to interventions across economics, neuroscience, ecology, systems biology and other areas (Baker et al., 2018; Banks et al., 2017; Brayton et al., 2014; Izhikevich & Edelman, 2008) . Because these models are painstaking calibrated with the real world, they have the ability to generate diverse and complex synthetic counterfactual data that are characteristic of the real processes they emulate. Interfere offers the first steps towards implementing a vision that leverages such models to test causal prediction tools, combining (1) a general interface for simulating the effect of interventions on dynamic simulation models, (2) a suite of predictive methods and cross validation tools, and (3) an initial benchmark set of dynamic counterfactual scenarios.

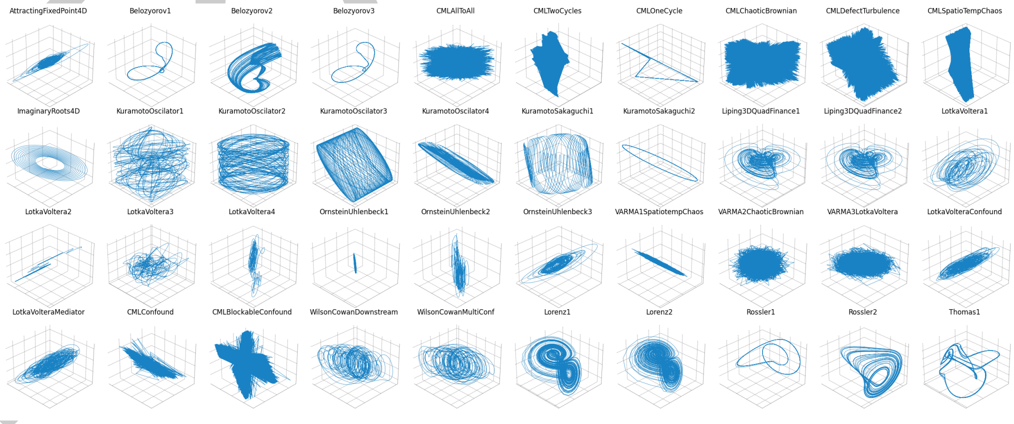

Figure 1: Three dimensional trajectories of forty scenarios simulated with the Interfere package. Many of the models pictured have more than three dimensions (in such cases, only the three components of the trajectory with highest variance are shown). **(I'm going to add intervention response trajectories to this)**

Statement of Need

Over the past twenty years there has been an emergence of multiple frameworks for identifying causal relationships in observational data (Imbens & Rubin, 2015; Pearl, 2009; Wieczorek & Roth, 2019). The most influential frameworks are probabilistic and, while is not a requirement of all frameworks, in practice a linear relationship is often assumed (Runge, 2022). However, when attempting to anticipate the response of complex systems in the medium and long term, linear models are insufficient. For example, static linear models cannot predict scenarios where things get worse before they get better. However, there are relatively few techniques that are able to fit causal dynamic nonlinear models to data. Because of this, we see an opportunity to bring together the insights from recent breakthroughs in causal inference with the descriptive power of mechanistic modeling.

In order to facilitate this cross pollination, we focus on a key causal problem — predicting how a complex system responds to a previously unobserved intervention — **(double check em dashes rendered correctly)** and designed the Interfere package for benchmarking tools aimed at intervention response prediction. The dynamic models contained in Interfere present challenges for causal inference that can likely only be addressed with the incorporation of mechanistic assumptions. As such, the Interfere package creates a much-needed link between the causal inference community and mechanistic modeling community. **(Add cookbook, pedantic description of what the problem is and what exactly we want to do so that a CS person can understand.) (Think about adding Forward Euler)**

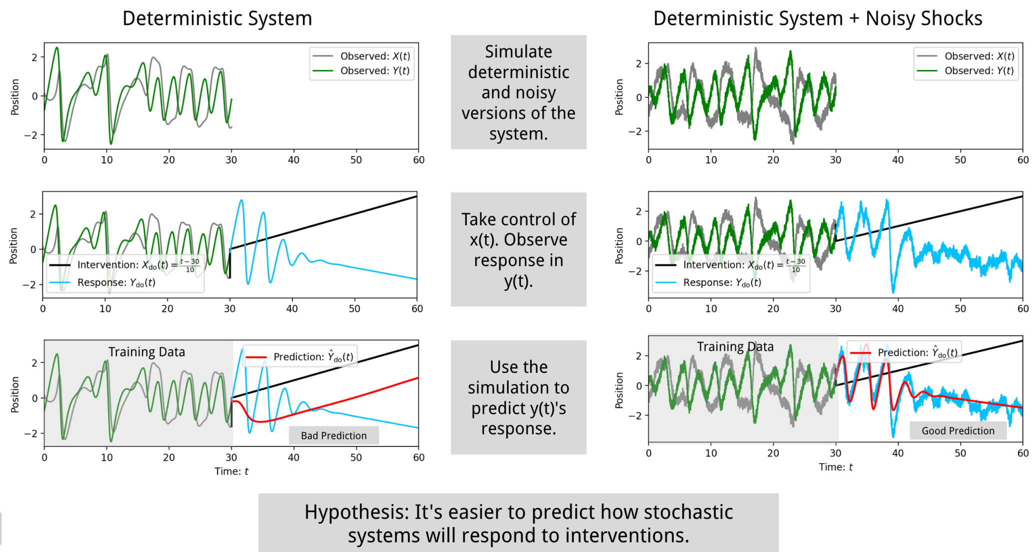

Figure 2: Example experimental setup possible with Interfere: Comparing intervention response prediction for deterministic and stochastic systems.

Usage

The Interfere package is designed around four tasks: Simulation, intervention, forecasting method optimization and intervention response prediction. This section will walk through each task in detail.

1. Simulation.

Each dynamic model has a simulate function availible. The models implemented in the interfere package are mainly stochastic differential equations simulated with Ito's method (e.g. $d\mathbf{X} = A\mathbf{X} + d\mathbf{W}$) or difference equations (e.g. $x[n+1] = 0.25x[n] - 0.5x[n-1]$), simulated via initial conditions and stepping forward in time. To run a simulation, the package requires an array of equally spaced time values and an initial condition or past observations.

```
import numpy as np
import interfere
```

```python
import optuna

# Set up simulation parameters
initial_cond = np.random.rand(3)
t_train = np.arange(0, 10, 0.05)
dynamics = interfere.dynamics.Belozyorov3DQuad()

# Generate trajectory
sim_states = dynamic_model.simulate(t_train, initial_cond)
```

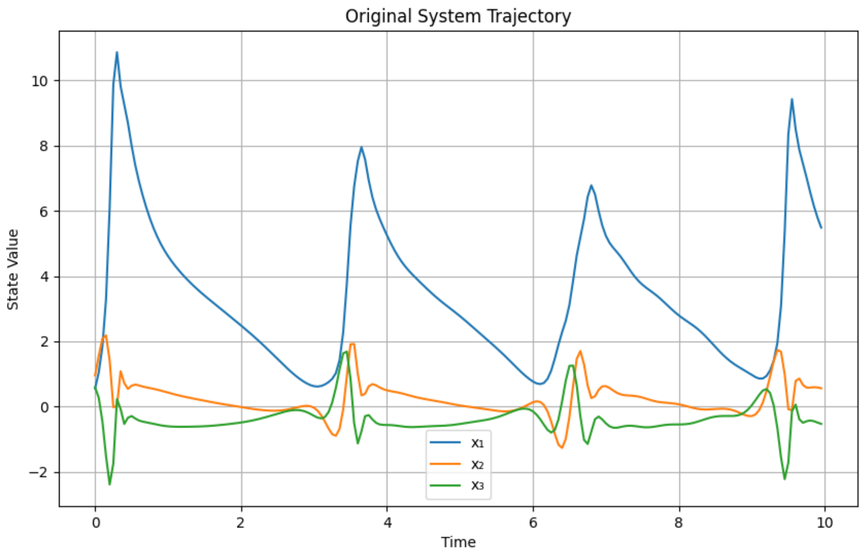

Figure 3: Original System Trajectory Simulation of natural, uninterupted evolution of a chaotic system studied in (Belozyorov, 2015). We've let $x = x_1$ and $y = x_2$ here and do not plot x_0 for simplicity.

2. Intervention

Next, we can take exogenous control of x by pinning it to $sin(t)$ and simulate the response of y. The resulting simulation describes how the behavior of the system is altered by this intervention. See 4 for an example.

```python
t_test = np.arange(t_train[-1], 12, 0.05)
intervention = interfere.SignalIntervention(iv_idxs=1, signals=np.sin)
interv_states = dynamics.simulate(
    t_test,
    prior_states=sim_states,
    intervention=intervention,
)
```

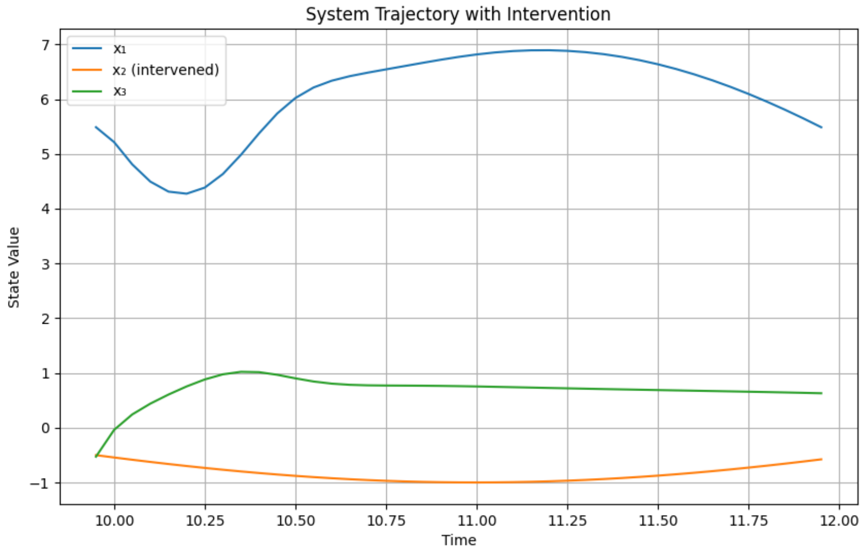

Figure 4: System Trajectory with Intervention The figure above demonstrates the effect that taking exogenous control of x has on y. The intervention and response, plotted as dotted lines depict a clear departure from the natural evolution behavior of the system.

3. Cross Validation and Hyperparameter Optimization

We can fit a method to the observation period generated in the previous section using Interfere's cross validation objective function along with a hyperparameter optimizer (Optuna). Every Interfere method comes with preset hyperparameter ranges to explore.

The "CrossValObjetive" class is designed to break the training data into training and forecasting chunks and return a methods average performance on all chunks. The objective supports several chunking strategies.

```python
# Select the SINDy method for optimization.
method_type = interfere.SINDY

# Create an objective function that aims to minimize cross validation error
# over different hyper parameter configurations for SINDy
cv_obj = interfere.CrossValObjective(
    method_type=method_type,
    data=sim_states,
    times=t_train,
    train_window_percent=0.3,
    num_folds=5,
    exog_idxs=intervention.iv_idxs,
)

# Run the study using optuna.
study = optuna.create_study()
study.optimize(cv_obj, n_trials=25)

# Collect the best hyperparameters into a dictionary.
best_param_dict = study.best_params
```

4. Intervention Response Prediction

Using the best parameters from the hyperparameter optimization run, we can fit a method to the observation data, treating the states we plan to manipulate as exogenous. This way, the method expects to be given exogenous data about the intervention variable(s). We then supply an the desired intervention to the method as an exogenous signal forecast a response.

```
 method = interfere.SINDY(**study.best_params)

Y_endog, Y_exog = intervention.split_exog(sim_states)
method.fit(t_train, Y_endog, Y_exog)

pred_traj = method.simulate(
    t_test, prior_states=sim_states, intervention=intervention
)
```

Primary Contributions

The Interfere package provides three primary contributions to the scientific community.

1. Dynamically Diverse Counterfactuals at Scale

The "dynamics" submodule in the interfere package contains over fifty dynamic models. It contains a mix of linear, nonlinear, chaotic, continuous time, discrete time, stochastic, and deterministic models. The models come from a variety of diciplines including economics, finance, ecology, biology, neuroscience and public health. Each model inherits the from the Interfere BaseDynamics type and gains the ability to take exogenous control of any observed state and to add measurement noise. Most models also gain the ability to make any observed state stochastic where magnitude of stochasticity can be controlled by a simple scalar parameter or fine tuned with a covariance matrix.

Because of the difficulty of building models of complex systems, predictive methods for complex dynamics are typically benchmarked on less than ten dynamical systems (Brunton et al., 2016; Challu et al., 2023; Pathak et al., 2018; Prasse & Van Mieghem, 2022; Vlachas et al., 2020). As such, Interfere offers a clear improvement over current benchmarking methods for prediction in complex dynamics.

Most importantly, Interfere is built around interventions: the ability to take exogenous control of the state of a complex system and observe the response. Imbuing scientific models with general exogenous control is no small feat because models can be complex and are implemented in a variety of ways. Thus Interfere offers the ability to produce multiple complex dynamic *counterfactual scenarios* at scale. This unqiue feature enables large scale evaluation of dynamic causal prediction methods—tested against systems with properties of interest to scientists.

2. Cross Disciplinary Forecast Methods

A second contribution of interfere is the integration of dynamic *forecasting* methodologies from deep learning, applied mathematics and social science. The Interere "ForecastingMethod" class is expressive enough to describe, fit and predict with multivariate dynamic models and intervene on the states of the models during prediction. This cross diciplinary mix of techniques affords new insights into the problem of intervention response prediction.

3. Opening Up Intervention Response to the Scientific Community

The third major contribution of Interfere is that it poses the intervention response problem—a highly applicable question, to the broader community. The Interfere Benchmark 1.0.0 has the potential provide simple comprehensive evaluation of computational methods on the intervention response problem and therefore streamline future progress towards correctly anticipating how complex systems will respond to new scenarios.

Related Software and Mathematical Foundations

Predictive Methods

The Interfere package draws extensively on the Nixtla open source ecosystem for time series forecasting. Nixtla's NeuralForecast proves three of the methods that are integrated with Interfere's interface and StatsForecast provides one of the methods (Azul Garza, 2022; Olivares et al., 2022). Nixtla also provided the inspiration for the cross validation and hyperparameter optimization workflow. Interfere also integrates with predictive methods from the PySINDy and StatsModels packages (Kaptanoglu et al., 2022; Seabold & Perktold, 2010). An additional reservoir computing method for global forecasts comes from (Harding et al., 2024). Hyperparameter optimization is designed around the Optuna framework (Akiba et al., 2019).

Finding forecasting methods to integrate with Interfere was difficult due to the (1) lack of multivariate dynamic forecasting methods (2) lack of dynamic methods that allow exogenous variables (3) the fact that many methods only offer a fixed forecast window do not implement recursive prediction.

Dynamic Models

See the table below for a full list of dynamic models with attributions that are currently implemented in the interfere package. The dynamic models in were implemented directly from mathematical descriptions except for two which adapt existing simulations from the PyClustering package (Novikov, 2019).

Dynamic Model Class	Description and Source	Properties
Arithmetic Brownian Motion	Brownian motion with linear drift and constant diffusion (Øksendal, 2005)	Stochastic, Linear
Coupled Logistic Map	Discrete-time logistic map with spatial coupling (Lloyd, 1995)	Nonlinear, Chaotic
Stochastic Coupled Map Lattice	Coupled map lattice with stochastic noise (Kaneko, 1991)	Nonlinear, Stochastic, Chaotic
Michaelis Menten	Model for enzyme kinetics and biochemical reaction networks (Srinivasan, 2022)	Nonlinear, Stochastic
Lotka Voltera SDE	Stochastic Lotka-Volterra predator-prey model (Hening & Nguyen, 2018)	Nonlinear, Stochastic
Kuramoto	Coupled oscillator model to study synchronization (Rodrigues et al., 2016)	Nonlinear, Stochastic
Kuramoto Sakaguchi	Kuramoto model variant with phase frustration (Sakaguchi & Kuramoto, 1986)	Nonlinear, Stochastic
Hodgkin Huxley Pyclustering	Neuron action-potential dynamics based on Hodgkin-Huxley equations (Hodgkin & Huxley, 1952)	Nonlinear
Stuart Landau Kuramoto	Coupled oscillators with amplitude-phase dynamics (Cliff et al., 2023)	Nonlinear, Stochastic
Mutualistic Population	Dynamics of interacting mutualistic species (Prasse & Van Mieghem, 2022)	Nonlinear

Dynamic Model Class	Description and Source	Properties
Ornstein Uhlenbeck	Mean-reverting stochastic differential equation (Gardiner, 2009)	Stochastic, Linear
Belozyorov 3D Quad	3-dimensional quadratic chaotic system (Belozyorov, 2015)	Nonlinear, Chaotic
Liping 3D Quad Finance	Chaotic dynamics applied in financial modeling (Liping et al., 2021)	Nonlinear, Chaotic
Lorenz	Classic chaotic system describing atmospheric convection (Lorenz, 2017)	Nonlinear, Chaotic
Rossler	Simplified 3D chaotic attractor system (Rössler, 1976)	Nonlinear, Chaotic
Thomas	Chaotic attractor with simple structure and rich dynamics (Thomas, 1999)	Nonlinear, Chaotic
Damped Oscillator	Harmonic oscillator with damping and noise (Classical linear model)	Linear, Stochastic
SIS	Epidemiological model (Susceptible-Infected-Susceptible) (Prasse & Van Mieghem, 2022)	Nonlinear, Stochastic
VARMA Dynamics	Vector AutoRegressive Moving Average for time series modeling (Hamilton, 2020)	Linear, Stochastic
Wilson Cowan	Neural mass model for neuronal population dynamics (Wilson & Cowan, 1972)	Nonlinear
Geometric Brownian Motion	Stochastic model widely used in financial mathematics (Black & Scholes, 1973)	Nonlinear, Stochastic
Planted Tank Nitrogen Cycle	Biochemical cycle modeling nitrogen transformation in aquatic systems (Fazio & Jannelli, 2006)	Nonlinear
Generative Forecaster	Predictive forecasting models trained on simulation, then used to generate data (Written for Interfere)	Stochastic
Standard Normal Noise	IID noise from standard normal distribution (Cliff et al., 2023)	Stochastic
Standard Cauchy Noise	IID noise from standard Cauchy distribution (Cliff et al., 2023)	Stochastic
Standard Exponential Noise	IID noise from standard exponential distribution (Cliff et al., 2023)	Stochastic
Standard Gamma Noise	IID noise from standard gamma distribution (Cliff et al., 2023)	Stochastic
Standard T Noise	IID noise from Student's t-distribution (Cliff et al., 2023)	Stochastic

Acknowledgements

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