



# Time Series Analysis and Forecasting

## Chapter 8: Modern Extensions



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## Learning Objectives

By the end of this chapter, you will be able to:

1. Understand long memory and fractional integration
2. Distinguish between short and long memory processes
3. Estimate the fractional parameter  $d$  using GPH, Local Whittle, and MLE
4. Apply Random Forest for time series forecasting
5. Build LSTM networks for sequential data
6. Compare classical vs ML model performance
7. Choose the appropriate method based on data characteristics
8. Implement ARFIMA, Random Forest, and LSTM in Python



## Outline

- Motivation
- ARFIMA: Long Memory Models
- Random Forest for Time Series
- LSTM: Deep Learning for Time Series
- Comparison and Model Selection
- Practical Applications
- Complete Case Study: EUR/RON Exchange Rate
- Final Comparison: All Methods
- Case Study 2: Energy Consumption
- Additional Examples with Real Data
- AI Use Case
- Summary
- Quiz



## From Classical Models to Machine Learning

### The Evolution of Time Series Methods

- **Classical ARIMA** (Box & Jenkins, 1970) — revolutionized forecasting but has limitations:
  - ▶ Assumes **short memory**: autocorrelations decay exponentially
  - ▶ **Linear** relationships only — cannot capture complex dynamics
  - ▶ Requires **stationarity** through integer differencing

### Three Paradigm Shifts

- **ARFIMA** (Granger & Joyeux, 1980)
  - ▶ Fractional integration for long memory processes
- **Random Forest** (Breiman, 2001)
  - ▶ Ensemble learning for nonlinear relationships
- **LSTM** (Hochreiter & Schmidhuber, 1997)
  - ▶ Deep learning for complex sequential patterns



## When to Use Each Method?

Feature	ARIMA	ARFIMA	RF	LSTM
Long memory	✗	✓	✓	✓
Nonlinear relationships	✗	✗	✓	✓
Interpretability	✓	✓	~	✗
Small data	✓	✓	✗	✗
Exogenous variables	✓	✓	✓	✓
Uncertainty quantification	✓	✓	~	✗

### Principle of Parsimony (Occam's Razor)

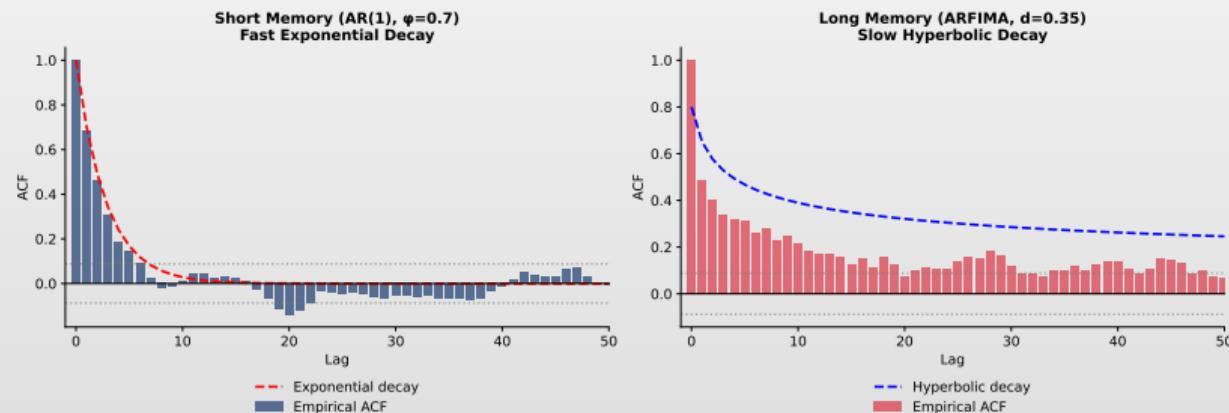
Start **simple** (ARIMA), then increase complexity only if justified by **out-of-sample** performance gains. Makridakis et al. (2018) M4 Competition: simple methods often outperform complex ML models.



## ACF Comparison: Short Memory vs Long Memory

### Interpretation

- **Data:** Simulated AR(1) with  $\phi = 0.8$  and ARFIMA( $0,d,0$ ) with  $d = 0.35$  ( $n = 1000$ )
- **Left:** AR(1) — autocorrelations decay exponentially (short memory)
- **Right:** ARFIMA with  $d = 0.35$  — autocorrelations decay hyperbolically (long memory)



## What is Long Memory?

### Short Memory (ARMA)

- **ACF Behavior:**
  - ▶ Autocorrelations  $\rho_k$  decay **exponentially**:  $|\rho_k| \leq C \cdot r^k$ ,  $r < 1$
  - ▶ Finite sum:  $\sum_{k=0}^{\infty} |\rho_k| < \infty$
- **Implication:** Shock effects disappear quickly

### Long Memory (ARFIMA)

- **ACF Behavior:**
  - ▶ Autocorrelations decay **hyperbolically**:  $\rho_k \sim C \cdot k^{2d-1}$
  - ▶ Infinite sum:  $\sum_{k=0}^{\infty} |\rho_k| = \infty$
- **Implication:** Shock effects persist for a long time

### Examples

Financial volatility, river flows, network traffic, inflation, climate data



## The ARFIMA(p,d,q) Model

Definition 1 (ARFIMA — Granger & Joyeux (1980), Hosking (1981))

A process  $\{Y_t\}$  follows an **ARFIMA(p,d,q)** model if:  $\phi(L)(1 - L)^d Y_t = \theta(L)\varepsilon_t$  where  $d \in (-0.5, 0.5)$  is the **fractional differencing parameter**.

### Fractional Differencing Operator

$$(1 - L)^d = \sum_{k=0}^{\infty} \binom{d}{k} (-L)^k = 1 - dL - \frac{d(1-d)}{2!} L^2 - \frac{d(1-d)(2-d)}{3!} L^3 - \dots$$

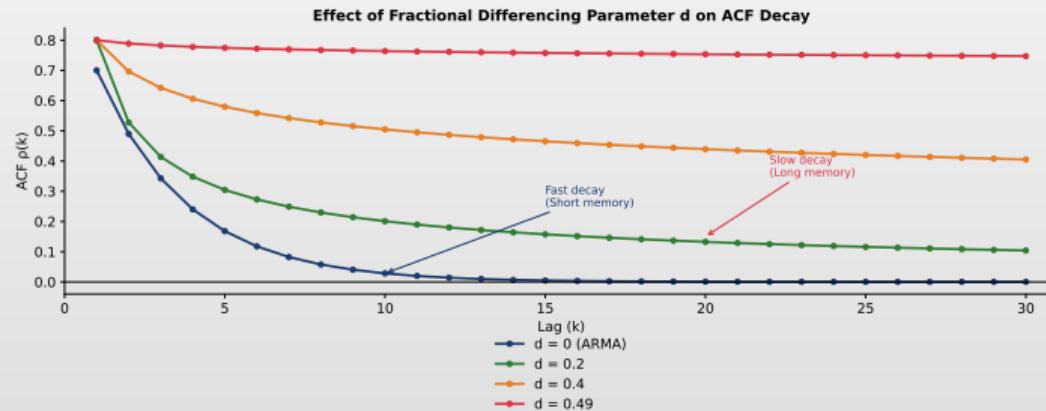
- $d = 0$ : Standard ARMA (short memory)
- $0 < d < 0.5$ : Long memory, stationary
- $d = 0.5$ : Stationarity boundary
- $0.5 \leq d < 1$ : Non-stationary, mean-reverting
- $d = 1$ : Random walk (standard ARIMA)



## Effect of Parameter $d$ on ACF

### Interpretation

- **Data:** Simulated ARFIMA( $0,d,0$ ) for  $d \in \{0.1, 0.2, 0.3, 0.4\}$  ( $n = 1000$ )
- The higher  $d$ , the slower autocorrelations decay
- As  $d \rightarrow 0.5$ , autocorrelations remain significant even at very large lags



## Interpreting the Parameter $d$

Value of $d$	ACF Behavior	Interpretation
$d = 0$	Exponential decay	Short memory
$0 < d < 0.5$	Hyperbolic decay	Long memory, stationary
$d = 0.5$	Non-summable ACF	At the boundary
$0.5 < d < 1$	Very slow decay	Long memory, non-stationary
$d = 1$	ACF = 1 (constant)	Random walk

## Hurst Parameter $H$

Relationship with Hurst exponent:  $d = H - 0.5$

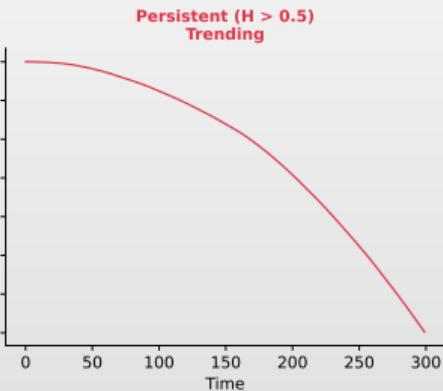
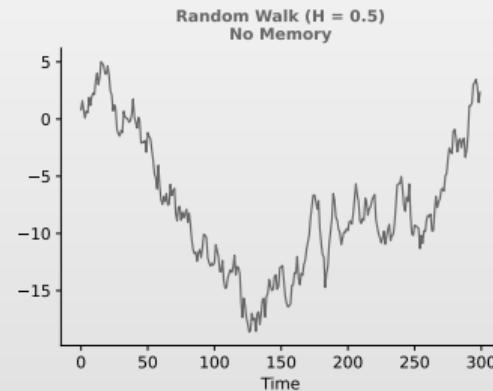
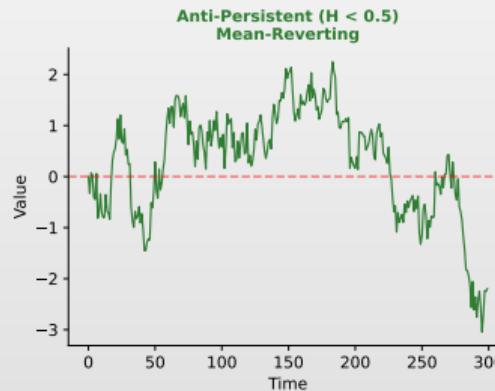
- $H = 0.5$ : Random walk (no memory)
- $H > 0.5$ : Persistence (trend-following)
- $H < 0.5$ : Anti-persistence (mean-reverting)



## Hurst Exponent: Visual Interpretation

### Interpretation

- **Data:** Simulated fractional Brownian motion with  $H \in \{0.3, 0.5, 0.7\}$
- $H < 0.5$ : Mean-reverting     $H = 0.5$ : Random walk     $H > 0.5$ : Persistent



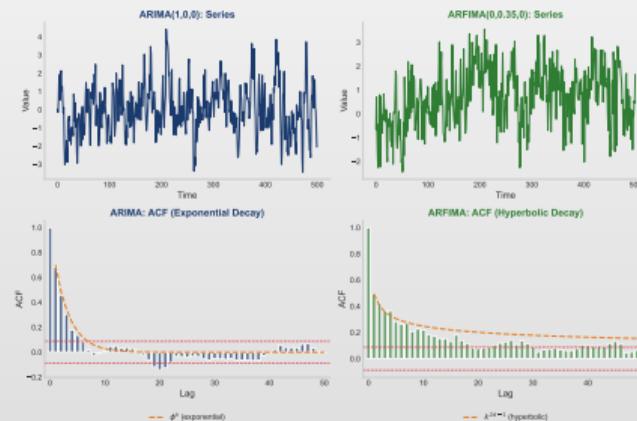
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## ARIMA vs ARFIMA: Memory Decay Patterns

### Interpretation

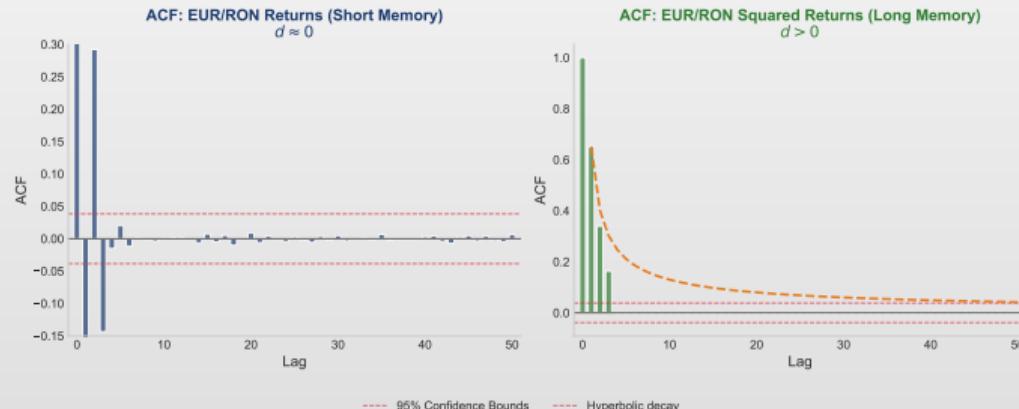
- **Data:** Simulated ARIMA(1,1,1) vs ARFIMA(1, $d$ ,1) with  $d = 0.35$
- **ARIMA** (left): ACF decays **exponentially** – shocks are quickly “forgotten”
- **ARFIMA** (right,  $d = 0.35$ ): ACF decays **hyperbolically** – shocks persist for long periods



## EUR/RON Long Memory Analysis

### Interpretation

- **Data:** EUR/RON daily exchange rate (Yahoo Finance, 2015–2025)
- **Returns:**  $H \approx 0.50$ ,  $d \approx 0$  – short memory
- **Squared returns:**  $H \approx 0.65$ ,  $d \approx 0.15$  – long memory in volatility



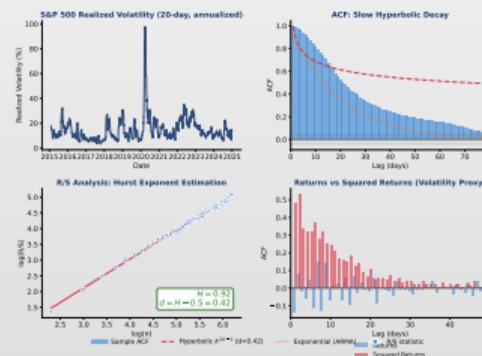
## ARFIMA Example: S&P 500 Realized Volatility

### Estimation Results

- **Data:** S&P 500 daily returns (Yahoo Finance, 2015–2024)
- **Hurst:**  $H = 0.92$ ,  $d = H - 0.5 = 0.42$  – strong long memory in realized volatility

### Key Insight

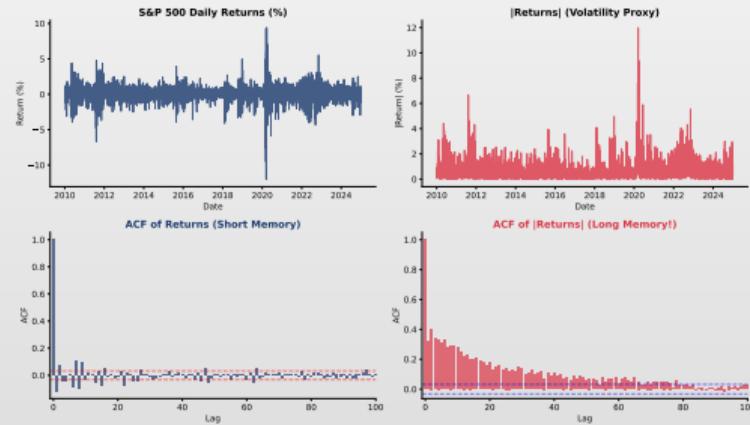
Volatility has **long memory** – shocks persist longer than ARMA; use ARFIMA or FIGARCH!



## Real Example: Long Memory in Volatility

### Interpretation

- **Data:** S&P 500 daily returns (Yahoo Finance, 2010–2025)
- **Stylized Fact:** Financial returns have short memory, but volatility ( $|r_t|$ ) has long memory
- This is the basis for FIGARCH models



## Estimating the Parameter $d$

### Estimation Methods

- **GPH (Geweke-Porter-Hudak)**: Frequency-domain regression
  - ▶  $\ln I(\omega_j) = c - d \cdot \ln\left(4 \sin^2 \frac{\omega_j}{2}\right) + \varepsilon_j$
- **R/S (Rescaled Range)**: Hurst's method
  - ▶  $\frac{R}{S}(n) \sim c \cdot n^H$
- **MLE (Maximum Likelihood)**: Full ARFIMA estimation
- **Whittle**: Efficient frequency-domain approximation

### Implementation

- In Python: `arch package, statsmodels.tsa.arima.model.ARIMA` with `order=(p,d,q)` where  $d$  can be fractional



## Random Forest: Basic Concepts

### What is Random Forest? (Breiman, 2001)

- **Ensemble** of decision trees
- Each tree trained on a **bootstrap subset** of the data
- At each node, a **random** subset of features is selected
- Final prediction = **average** of all tree predictions

### Advantages for Time Series

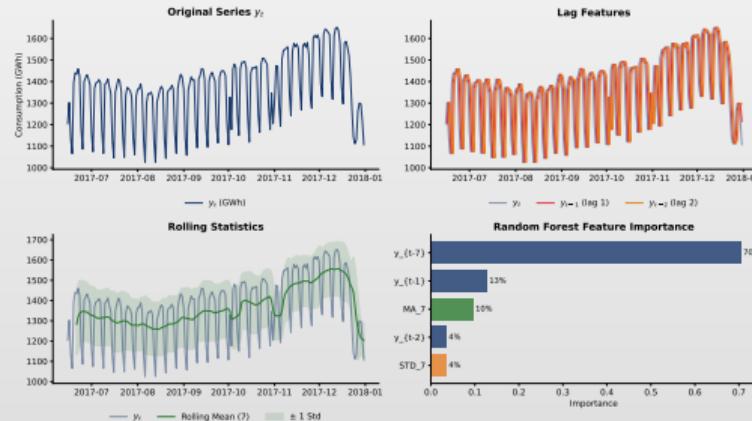
- Captures **nonlinear relationships**
- **Robust** to outliers and noise
- Does not require **stationarity**
- Provides **feature importance** (interpretability)
- Works well with **many variables**



## Feature Engineering: Illustration

### Interpretation

- Data: Germany daily electricity consumption (OPSD, 2012–2017)
- We transform the time series into features: lags, rolling statistics
- The RF model learns relationships between these and future values



## Data Preparation for Random Forest

### Feature Engineering for Time Series

1. **Lag features:**  $Y_{t-1}, Y_{t-2}, \dots, Y_{t-p}$
2. **Rolling statistics:** moving average, standard deviation
3. **Calendar features:** day of week, month, season
4. **Trend features:** time, quadratic trend
5. **Exogenous variables:** economic indicators, events

### Warning: Data Leakage!

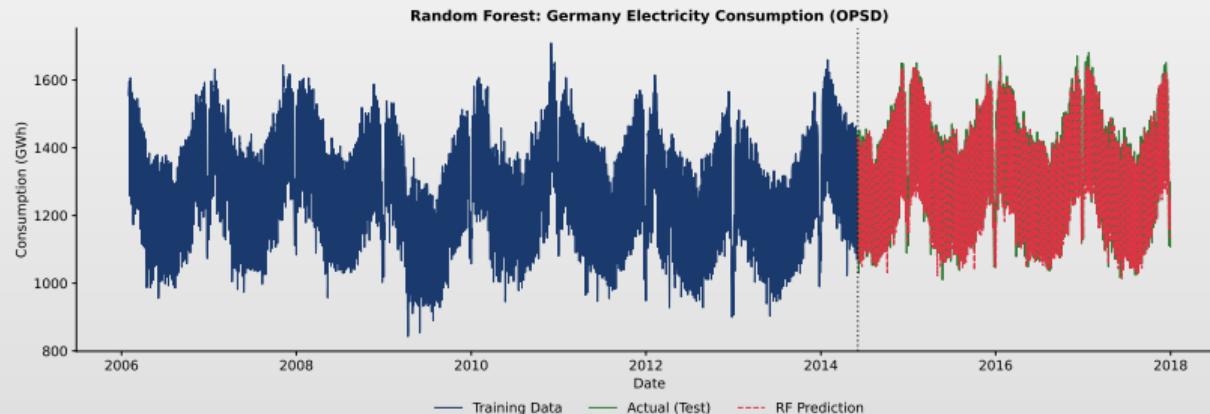
- Do not use future information in features
- Train/test split: **temporal**, not random!
- Rolling statistics: compute only on **past** data



## Random Forest: Forecast Example

### Interpretation

- Data: Germany daily electricity consumption (OPSD, 2012–2017)
- RF trained on historical data (blue) produces forecasts (red dashed) that closely track actual values (green)



## Feature Importance and Interpretation

### Feature Importance

- ☐ **Mean Decrease Impurity (MDI)**: Impurity reduction at each split
- ☐ **Permutation Importance**: How much performance drops when a feature is randomly permuted

### Typical Interpretation for Time Series

- ☐ lag\_1 very important ⇒ Strong autocorrelation
- ☐ rolling\_mean important ⇒ Local trend matters
- ☐ month important ⇒ Seasonality present

### Code

- ☐ `rf.feature_importances_ or permutation_importance(rf, X_test, y_test)`



## Researcher Spotlight: Hochreiter & Schmidhuber



Sepp Hochreiter (\*1967)

[W Wikipedia](#)



Jürgen Schmidhuber (\*1963)

[W Wikipedia](#)

### Biography

- **Sepp Hochreiter:** Austrian computer scientist, Professor at Johannes Kepler University Linz and head of ELLIS Unit Linz
- **Jürgen Schmidhuber:** German-Swiss computer scientist, Scientific Director of IDSIA
- Together they solved the vanishing gradient problem

### Key Contributions

- **Long Short-Term Memory (LSTM, 1997)** — gated recurrent architecture solving the vanishing gradient problem
- **Vanishing gradient analysis** (Hochreiter, 1991) — identified the fundamental training problem in deep networks
- **Forget gate** extension (Gers et al., 2000) — crucial addition enabling practical LSTM use
- Foundation for modern sequence modeling in NLP, speech, and time series



## From Biological to Artificial Neurons

### The Analogy

- Dendrites → Inputs  $x_i$
- Synapses → Weights  $w_i$
- Soma → Sum + Activation
- Axon → Output  $y$



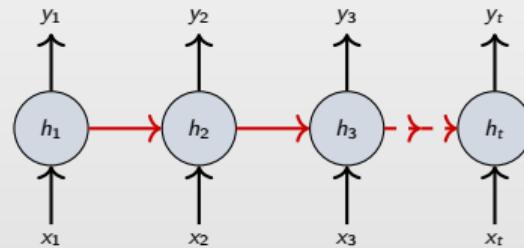
Dendrites → Inputs with weights | Soma → Weighted sum + activation | Axon → Output

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## Recurrent Neural Networks (RNN)

### Basic Idea

- Networks that process **sequences** of data
- Have **internal memory** (hidden state)
- Current state depends on input + previous state



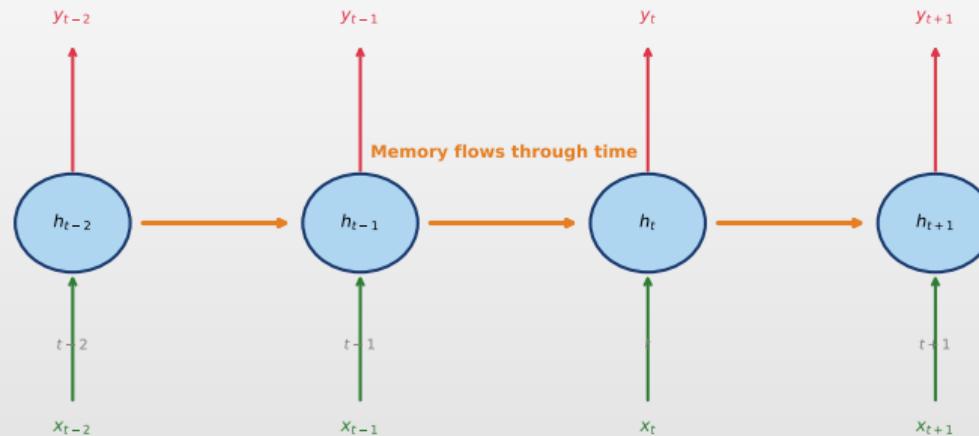
### Problem: Vanishing Gradient

- Simple RNNs “forget” information from the distant past.



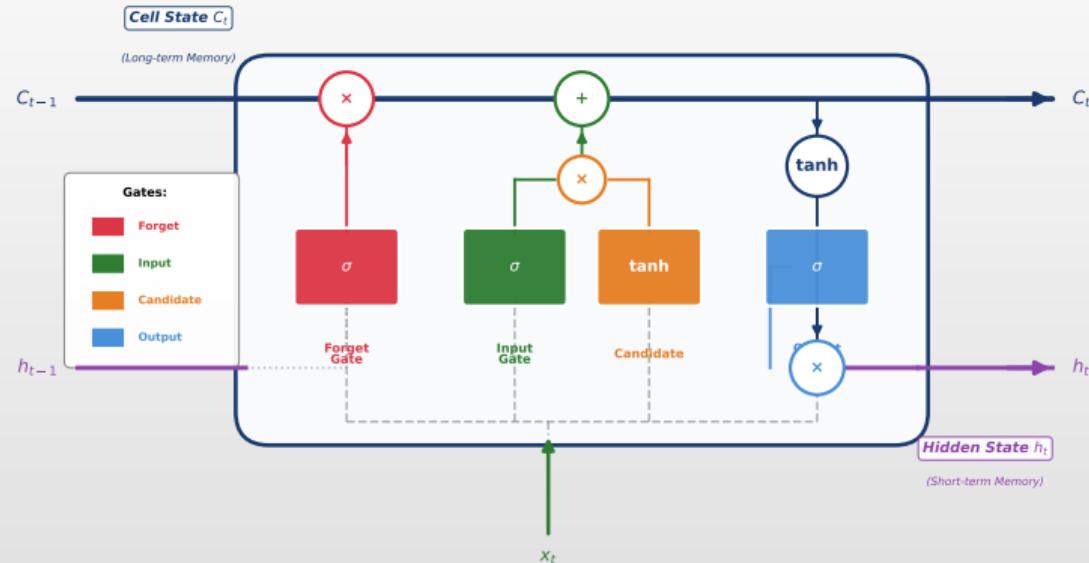
## RNN Unfolded in Time

Recurrent Neural Network (Unfolded Through Time)



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## LSTM Cell: Detailed Diagram



**Forget Gate  $f_t$**   
 $\sigma(W_f[h_{t-1}, x_t] + b_f)$   
 What to forget?

**Input Gate  $i_t$**   
 $\sigma(W_i[h_{t-1}, x_t] + b_i)$   
 What to store?

**Output Gate  $o_t$**   
 $\sigma(W_o[h_{t-1}, x_t] + b_o)$   
 What to transmit?

## LSTM: Long Short-Term Memory

### The LSTM Solution

- **Concept:** Special cells with 3 gates that control information flow
- **Forget Gate ( $f_t$ ):** What to forget from previous memory
- **Input Gate ( $i_t$ ):** What new information to add
- **Output Gate ( $o_t$ ):** What to send to output

### LSTM Equations

▪

$$f_t = \sigma(W_f \cdot [h_{t-1}, x_t] + b_f) \quad (\text{Forget})$$

$$i_t = \sigma(W_i \cdot [h_{t-1}, x_t] + b_i) \quad (\text{Input})$$

$$\tilde{C}_t = \tanh(W_C \cdot [h_{t-1}, x_t] + b_C) \quad (\text{Candidate})$$

$$C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \quad (\text{Cell state})$$

$$o_t = \sigma(W_o \cdot [h_{t-1}, x_t] + b_o) \quad (\text{Output})$$

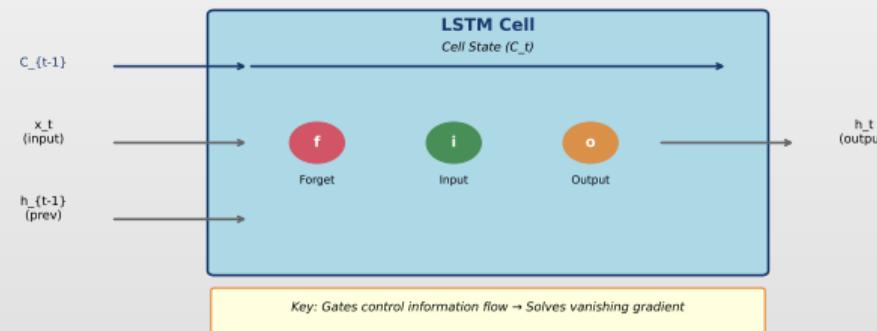
$$h_t = o_t \odot \tanh(C_t) \quad (\text{Hidden state})$$



## LSTM Cell Architecture

### Interpretation

- The gates (forget, input, output) control what information is discarded, added, and transmitted
- **Cell state** allows gradients to “flow” without degradation



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## LSTM Advantages for Time Series

### Why LSTM?

- Captures **long-term dependencies** (unlike simple RNN)
- Learns **complex patterns** and nonlinear relationships
- Handles **variable-length sequences**
- Works well with **multivariate data**

### Disadvantages

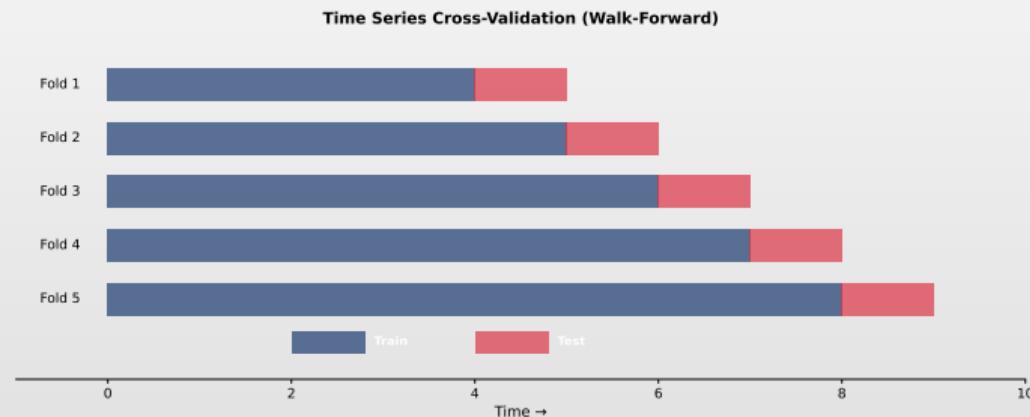
- Requires **large datasets** for training
- Computationally intensive**
- “**Black box**” – difficult to interpret
- Sensitive to **hyperparameters**
- Can **overfit** easily



## Time Series Cross-Validation

### Interpretation

- Illustration: Schematic of expanding-window walk-forward validation (5 folds)
- Training set grows progressively; test is always in the future  $\Rightarrow$  avoids data leakage



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## Evaluation Metrics

**Notation:**  $y_i$  = actual value,  $\hat{y}_i$  = predicted value,  $n$  = number of observations

### Common Metrics

#### □ Scale-Dependent:

- ▶ RMSE:  $\sqrt{\frac{1}{n} \sum (y_i - \hat{y}_i)^2}$  — penalizes large errors
- ▶ MAE:  $\frac{1}{n} \sum |y_i - \hat{y}_i|$  — robust to outliers

#### □ Scale-Free:

- ▶ MAPE:  $\frac{100}{n} \sum \left| \frac{y_i - \hat{y}_i}{y_i} \right|$  — percentage error
- ▶ MASE:  $\frac{\text{MAE}}{\frac{1}{n-1} \sum_{i=2}^n |y_i - y_{i-1}|}$  — relative to naive (random walk)

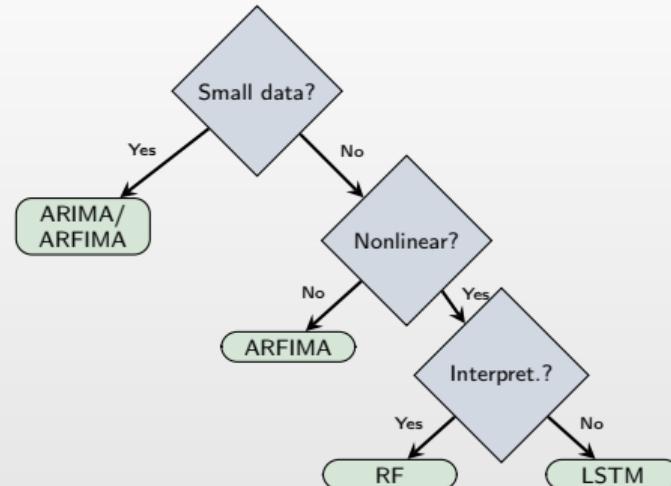
### Validation for Time Series

#### □ Critical: Do NOT use standard k-fold cross-validation!

- ▶ Use Time Series CV (walk-forward validation)
- ▶ Or temporal train/validation/test split



## Model Selection Guide



### Trade-off

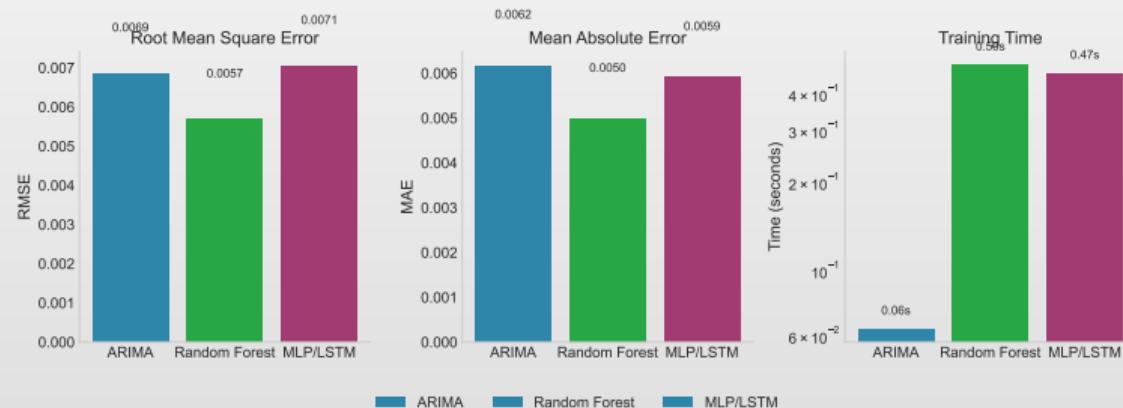
ML models offer better accuracy but higher computational cost. For small data or interpretability, ARIMA/ARFIMA remain excellent choices.



## Model Comparison: Accuracy vs Computational Cost

### Interpretation

- **Data:** EUR/RON daily exchange rate (Yahoo Finance, 2019–2025)
- **Trade-off:** ML models may achieve better accuracy, but computational cost increases significantly
- For small data or interpretability, ARIMA/ARFIMA remain excellent choices



## Bitcoin: Price Evolution and Returns

### Key Observations

- Exponential price growth → strongly **leptokurtic** distribution
- Daily returns: mean  $\approx 0.15\%$ , volatility  $\approx 3.5\%$
- Volatility clustering evident → crisis periods (2018, 2020, 2022)
- Kurtosis  $\approx 10\text{--}15$  (well above the normal's 3)



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## Case Study: Bitcoin Price Forecasting

### Why Bitcoin?

- Extreme** volatility and complex patterns
- Potential **long memory** in volatility
- Nonlinear** relationships with exogenous variables
- Data available at **high frequency**

### Comparative Approach

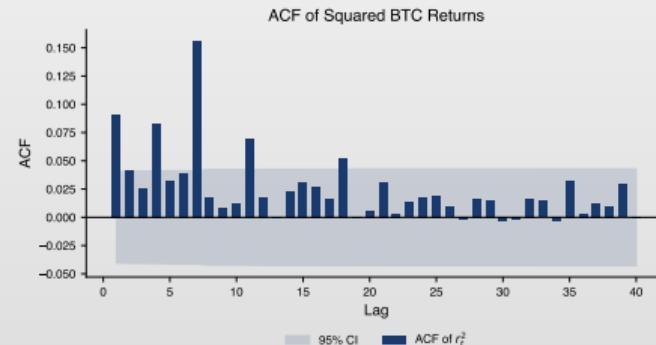
1. ARIMA on returns
2. ARFIMA for long memory
3. Random Forest with technical features
4. LSTM on price sequences



## Bitcoin: ACF and Evidence for Long Memory

### ACF Analysis

- ACF of returns: rapid decay → short memory in the mean
- ACF of squared returns: **slow, hyperbolic** decay
  - ▶ Indicates **long memory in volatility**
  - ▶ Hurst  $H \approx 0.65\text{--}0.70$  ( $d \approx 0.15\text{--}0.20$ )
- ARFIMA on volatility > ARMA → captures shock persistence



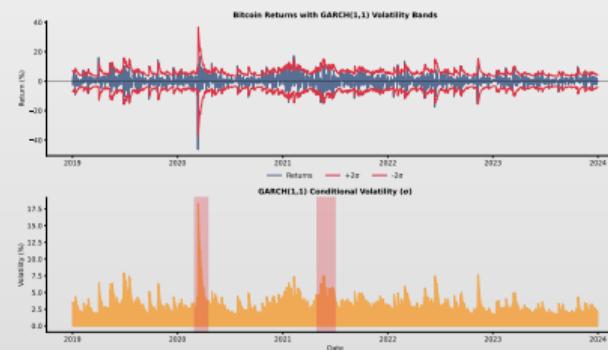
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## Bitcoin: GARCH and Risk Management

### Conclusions – Bitcoin Case Study

- Differences between models are **small** for mean returns
- Major added value: **volatility modeling** (GARCH, EGARCH)
- ARFIMA captures volatility persistence (long memory)
- Random Forest: useful for **nonlinear features** (volume, sentiment)
- Optimal combination: ARFIMA-GARCH + exogenous features via RF

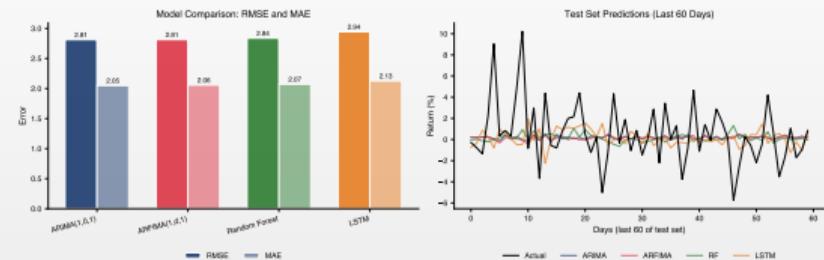


## Bitcoin: ARFIMA Estimation and Model Comparison

BTC-USD Returns (2019–2024, test: 2024-02 – 2024-12)

Model	RMSE	MAE	Interpr.?
ARIMA(1,0,1)	2.81	2.05	Yes
ARFIMA(1,d,1)	2.81	2.06	Yes
Random Forest	2.84	2.07	Partial
LSTM	2.94	2.13	No

Hurst  $\hat{d} = 0.13$ ; 70/15/15 temporal split



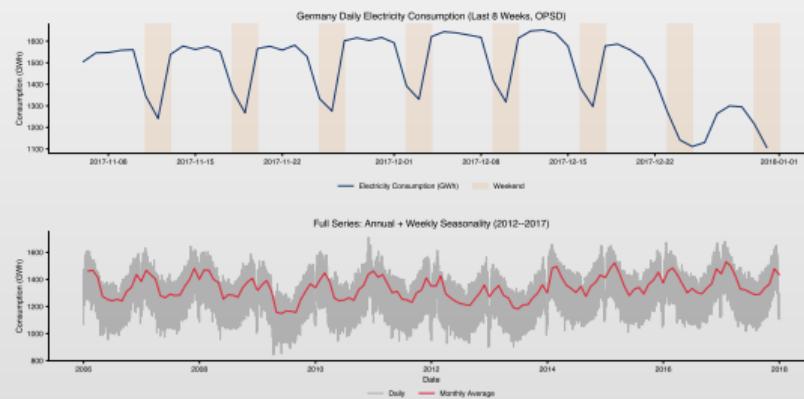
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## Energy: Demand Visualization and Multiple Seasonality

### Identified Patterns

- Daily (24h): peak morning (8–10) and evening (18–21), minimum at night
- Weekly (168h): reduced consumption on weekends (~15–20% less)
- Annual (8766h): peak in summer (AC) and winter (heating)
- SARIMA cannot simultaneously model these 3 periods!



## Case Study: Energy Consumption Forecasting

### Characteristics

- **Multiple seasonality:** daily, weekly, annual
- **Long-term trend of growth**
- **Exogenous variables:** temperature, holidays, price
- **Anomalies:** special events, outages

### Challenges

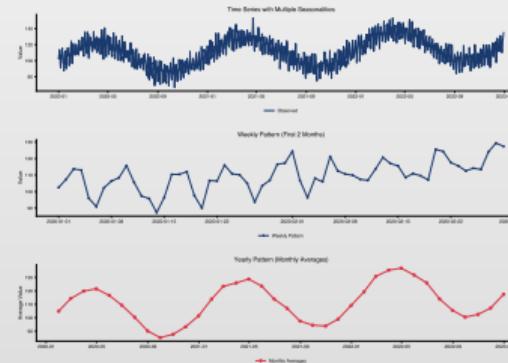
- Patterns at different temporal scales
- Complex interactions between variables
- Need for forecasts at different horizons



## Energy: Why Prophet and TBATS?

### Solution: Models with Multiple Seasonality

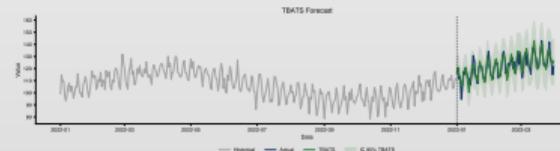
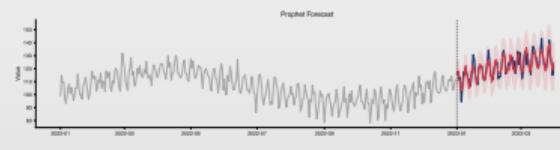
- **TBATS:** periods [24, 168, 8766] → Fourier for each season
  - ▶ Automatic, no manual tuning, good for production
- **Prophet:** additive/multiplicative seasonality + regressors
  - ▶ Add temperature, holidays, special events
- **Classical ARIMA:** can handle only 1 season → MAPE  $\approx$  8–10%



## Energy: Prophet Decomposition and Results

### Comparison Results on Energy Data (MAPE)

Model	MAPE	RMSE (MW)	95% Coverage
SARIMA (1 season)	8.5%	450	75%
TBATS	4.2%	220	82%
Prophet	4.8%	250	85%
Prophet + regressors	3.9%	200	88%



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## Energy: Conclusions and Practical Recommendations

### Lessons Learned

- Models with **multiple seasonality** reduce MAPE by ~50% compared to SARIMA
- **Exogenous variables** (temperature) bring an additional 10–15% gain
- Prophet excels at **interpretability**: trend + season + holiday decomposition
- TBATS: best **out-of-the-box** → no hyperparameter tuning needed

### When to Choose Each Model?

- **Prophet**: when you have external regressors + interpretation for management
- **TBATS**: automation, production, no human intervention
- **LSTM/RF**: if you have >100,000 observations and complex nonlinear patterns

Full details on Prophet and TBATS → Chapter 9



## Key Formulas – Summary

### ARFIMA(p,d,q)

$$\phi(L)(1 - L)^d Y_t = \theta(L)\varepsilon_t \quad d \in (-0.5, 0.5): \text{long memory}$$

### Long Memory

ACF:  $\rho_k \sim C \cdot k^{2d-1}$     Hurst:  $d = H - 0.5$      $H > 0.5$ : persistence

### Random Forest

$$\hat{y} = \frac{1}{B} \sum_{b=1}^B T_b(x) \quad B \text{ trees, random features}$$

### LSTM Cell

$$f_t = \sigma(W_f[h_{t-1}, x_t] + b_f) \quad C_t = f_t \odot C_{t-1} + i_t \odot \tilde{C}_t \quad \text{Forget, Input, Output gates}$$

### Evaluation Metrics

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum (y_i - \hat{y}_i)^2} \quad \text{MAPE} = \frac{100}{n} \sum \left| \frac{y_i - \hat{y}_i}{y_i} \right|$$

### Time Series CV

Walk-forward validation — Train → Test (temporal split)



## Case Study: EUR/RON Exchange Rate Forecasting

### Why EUR/RON?

- Relevance for the Romanian economy
- Potential **long memory** (shock persistence)
- Patterns influenced by **macroeconomic factors**
- Easily accessible data (BNR, Yahoo Finance)

### Objective

- We compare ARIMA, ARFIMA, Random Forest, and LSTM on the same data to understand the strengths of each method



## EUR/RON Exchange Rate Visualization

### Interpretation

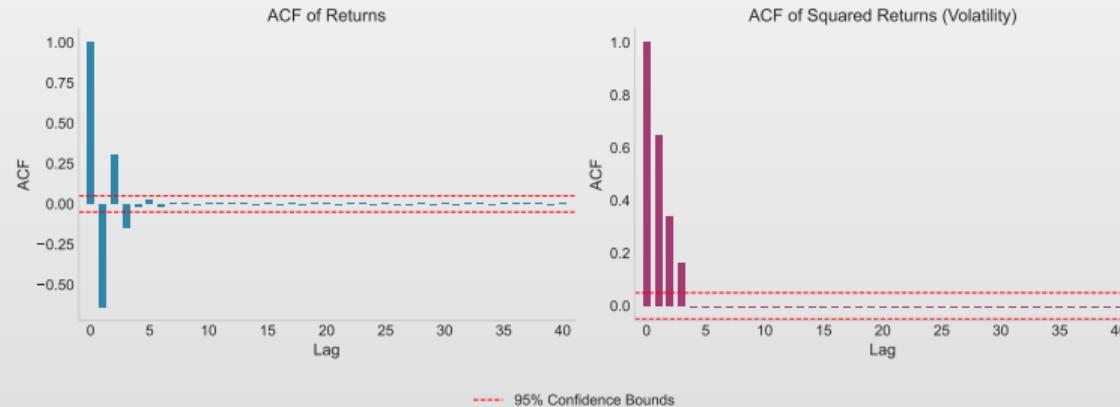
- **Data:** EUR/RON daily exchange rate (Yahoo Finance, 2019–2025)
- **Top:** EUR/RON rate — depreciation trend and periods of high volatility
- **Bottom:** Daily returns — volatility clustering (periods of high volatility are followed by similar periods)



## ACF Analysis: Returns vs Squared Returns

### Interpretation

- **Data:** EUR/RON daily returns and squared returns (Yahoo Finance, 2019–2025)
- **Left:** ACF of returns — rapid decay, no significant autocorrelation after lag 1
- **Right:** ACF of squared returns — slow decay indicates **volatility clustering** (ARCH effects)



## Long Memory Test Results – EUR/RON

### Typical Output

- Phillips-Perron p-value: 0.0001 (returns are stationary)
- Hurst Exponent ( $H$ ): 0.47
- Estimated parameter  $d$ : -0.03
- Slightly ANTI-PERSISTENT series (mean-reverting)

### Interpretation

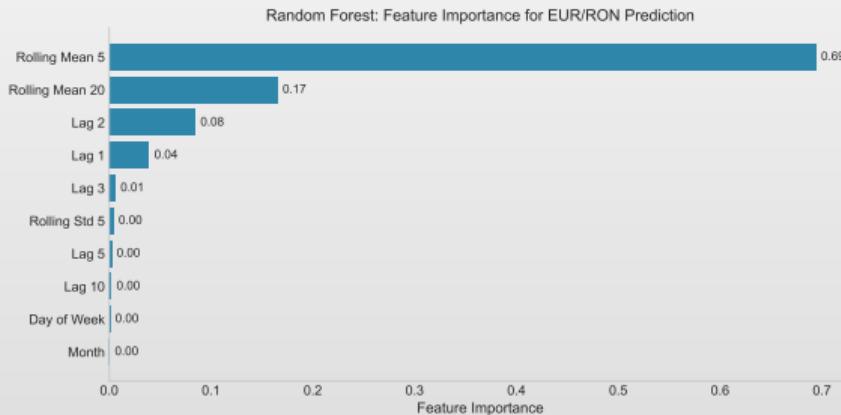
- EUR/RON returns are **stationary** ( $p\text{-value} < 0.05$ )
- $H \approx 0.47 < 0.5$ : slight mean-reversion tendency
- $d \approx 0$ : **short memory** – ARMA may be sufficient
- However, **volatility** may have long memory!



## Random Forest: Feature Importance

### Interpretation

- **Data:** EUR/RON exchange rate (Yahoo Finance, 2019–2025) — RF with 10 engineered features
- Recent lags (lag\_1, lag\_2) and rolling volatility are the most important features
- Calendar features have minor impact for daily return prediction



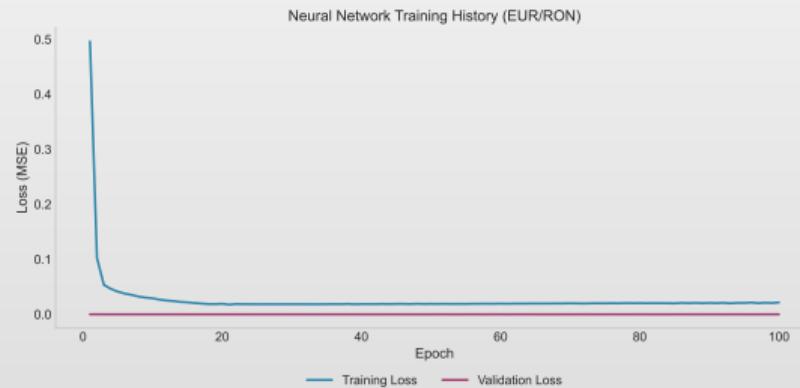
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## LSTM: Learning Curve

### Interpretation

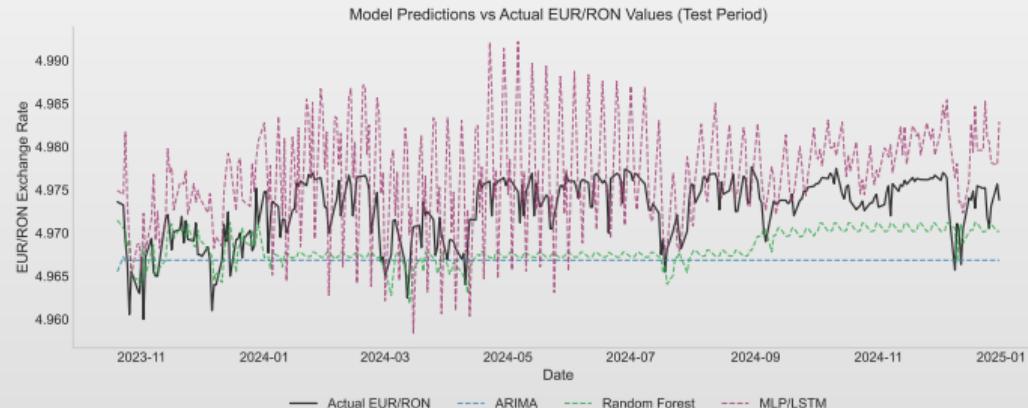
- **Data:** EUR/RON exchange rate (Yahoo Finance, 2019–2025) — Neural Network (100 epochs, MSE loss)
- **Training Loss:** Decreases rapidly in early epochs, then stabilizes
- **Validation Loss:** Tracks training loss — no severe overfitting



## Visualization: Predictions vs Actual Values

### Interpretation

- **Data:** EUR/RON test period — ARIMA, Random Forest, MLP/LSTM predictions vs actual values
- All models capture the general pattern, but none perfectly predicts volatility spikes
- This reflects **market efficiency** and **prediction limits** for financial series



## Comparison: Results on EUR/RON

Model	RMSE	MAE	Time (s)	Interpretable?
ARIMA(1,1,1)	0.0069	0.0062	0.08	Yes
Random Forest	0.0057	0.0050	0.51	Yes (features)
MLP/LSTM	0.0071	0.0059	0.47	No

### Conclusions

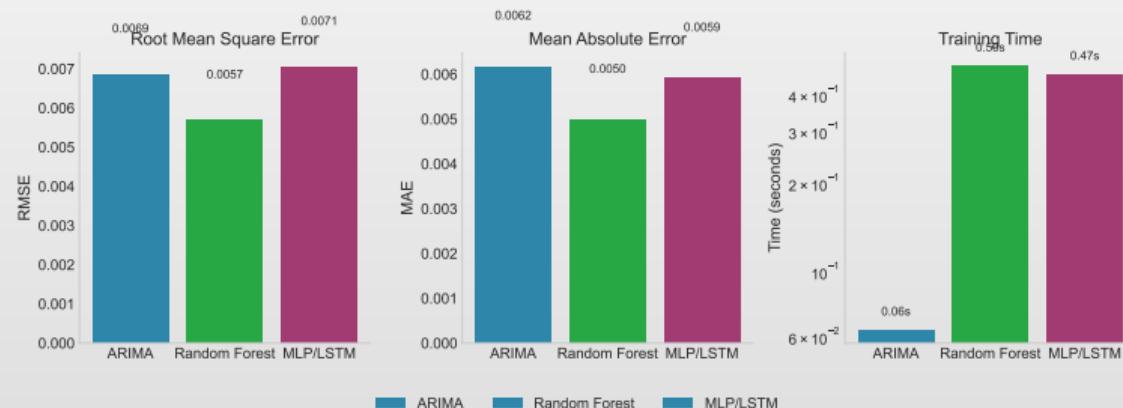
- For EUR/RON, the differences are **small** – the market is efficient
- Random Forest offers the best **accuracy/interpretability** trade-off
- LSTM has high computational cost for marginal gain
- ARIMA remains a solid choice for **baseline**



## Model Comparison: Performance Metrics

### Interpretation

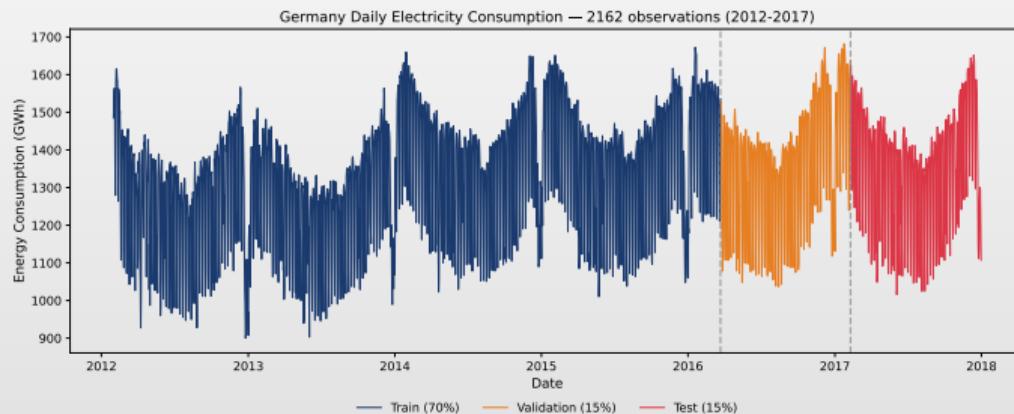
- **Data:** EUR/RON exchange rate (Yahoo Finance, 2019–2025) — ARIMA vs RF vs MLP/LSTM
- **Left:** Error metrics (lower = better) — RF achieves the lowest RMSE and MAE
- **Right:** Training time (log scale) — ML models require more computational resources



## Case Study: Data Overview

### Interpretation

- Train:** 1513 obs (70%)    **Validation:** 324 obs (15%)    **Test:** 325 obs (15%)

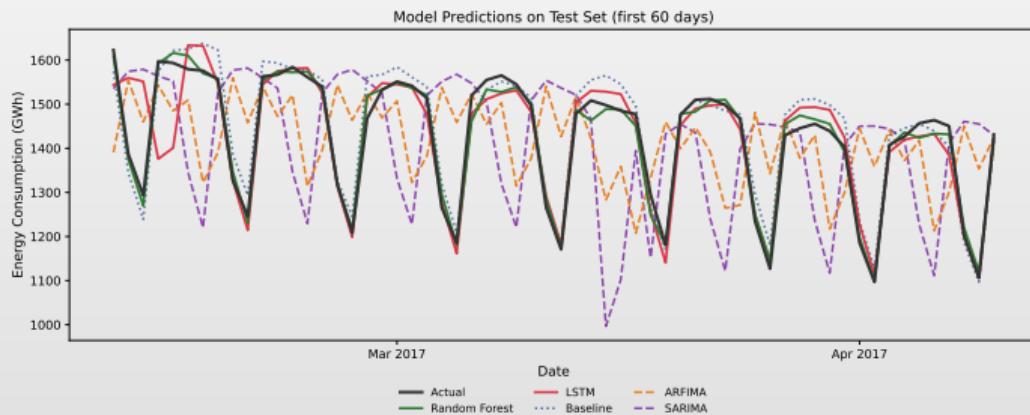


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## Case Study: Model Predictions

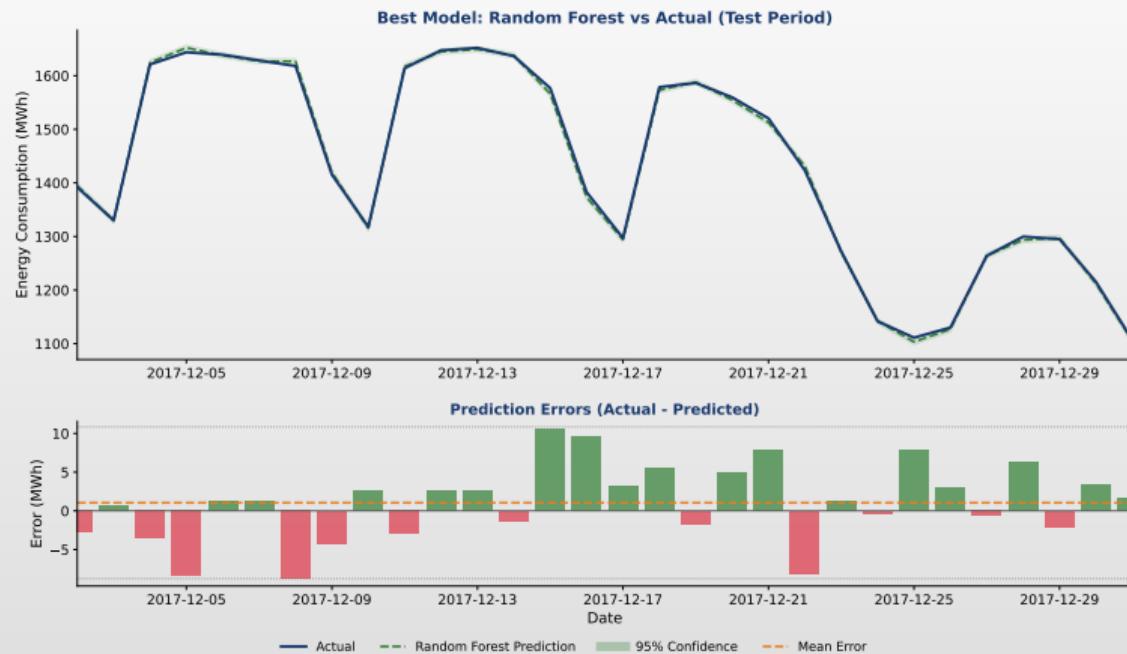
Rank	Model	MAPE	Interpretation
1	Random Forest	2.2%	Best: captures nonlinear patterns
2	LSTM	3.3%	Good, needs more data
3	Baseline	3.9%	Simple but competitive
4	ARFIMA	12.3%	Long memory not sufficient
5	SARIMA	14.6%	Struggles with patterns



Q TSA\_ch8\_model\_predictions



## Case Study: Best Model Performance



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## When to Choose Each Model?

### ARIMA/ARFIMA

- Few data (< 500 obs.), interpretation important, suspected long memory, quick baseline

### Random Forest

- Many exogenous variables, nonlinear relationships, feature importance, moderate data

### LSTM/Deep Learning

- Very large data (> 10,000), complex sequences, computational resources, hidden patterns

### Golden Rule

- Start simple (ARIMA), add complexity only if performance increases significantly!



## Example 2: BET Index (Bucharest Stock Exchange)

### Characteristics

- Strong **volatility clustering**
- Influenced by international markets
- Lower liquidity than developed markets
- Potential for long memory in volatility

### Typical Results (RMSE on returns)

- GARCH(1,1): 1.45 – best for volatility
- ARFIMA for volatility: 1.52
- Random Forest: 1.48
- LSTM: 1.51



## Example 3: Romania Inflation Rate

### Characteristics

- Monthly series (low frequency)
- **High persistence** – shocks last long
- Influenced by monetary policy
- Strong potential for **long memory**

### Typical Results

- ARFIMA with  $d \approx 0.35$  – captures persistence
- ARIMA underestimates shock persistence
- ML does not work well (few data, 300 obs.)

- 
- **Lesson:** For monthly series with few data, classical models (ARFIMA) are superior!



## Practical Summary: Model Selection

Criterion	ARIMA	ARFIMA	RF	LSTM
Data needed	Few	Few	Medium	Many
Long memory	No	Yes	Partial	Partial
Nonlinearity	No	No	Yes	Yes
Interpretability	Yes	Yes	Partial	No
Computation time	Fast	Fast	Medium	Slow
Exog. variables	Limited	Limited	Yes	Yes

### Recommended Workflow

1. Start with **ARIMA** as baseline
2. Test for **long memory** → ARFIMA if  $d$  is significant
3. Add **features** → Random Forest
4. Only with lots of data and resources → LSTM



## AI Exercise: Critical Thinking

Prompt to test in ChatGPT / Claude / Copilot

"Using yfinance, download daily Bitcoin prices (BTC-USD) from 2019-01-01 to 2024-12-31 (approx. 2,200 observations). Compute daily percentage returns. Compare ARIMA, Random Forest, and LSTM for 7-day-ahead forecasting using a 70/15/15 temporal split. Which model is best? Give me complete Python code with comparison charts."

**Exercise:**

1. Run the prompt in an LLM of your choice and critically analyze the response.
2. How are features engineered for Random Forest? Lags, calendar variables, Fourier terms?
3. Is the LSTM properly structured? Input shape, scaling, train/test split without leakage?
4. Does it use walk-forward validation or just a single train/test split?
5. Does it mention interpretability and computational cost trade-offs?

**Warning:** AI-generated code may run without errors and look professional. *That does not mean it is correct.*



## Summary

### What We Learned

- **ARFIMA:** Extends ARIMA for long memory (fractional  $d$ )
- **Random Forest:** Ensemble of trees, nonlinear relationships, interpretable
- **LSTM:** Deep learning for sequences, complex dependencies
- **Trade-offs:** Complexity vs interpretability vs data requirements

### Practical Recommendations

- Start with **simple models** (ARIMA) as baseline
- Use **Time Series CV** for proper evaluation
- ML requires careful **feature engineering**
- LSTM: only with **lots of data** and computational resources



## Question 1

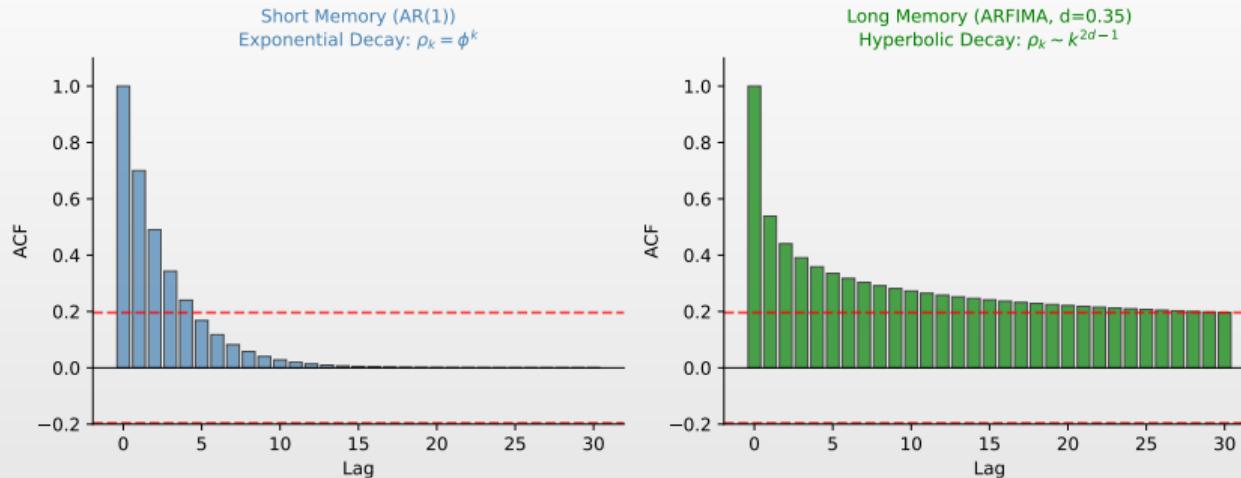
### Question

- What does  $d = 0.3$  mean in an ARFIMA model?

### Answer Choices

- (A)** The series needs 0.3 differences to become stationary
- (B)** Long memory: stationary but ACF decays hyperbolically (slowly)
- (C)** The series is non-stationary with a unit root
- (D)** Short memory: ACF decays exponentially (fast)

## Question 1: Answer



Answer: (B)

- For  $0 < d < 0.5$ : stationary but  $ACF \sim k^{2d-1}$  decays much slower than exponential. This “long memory” means distant observations still matter.



## Question 2

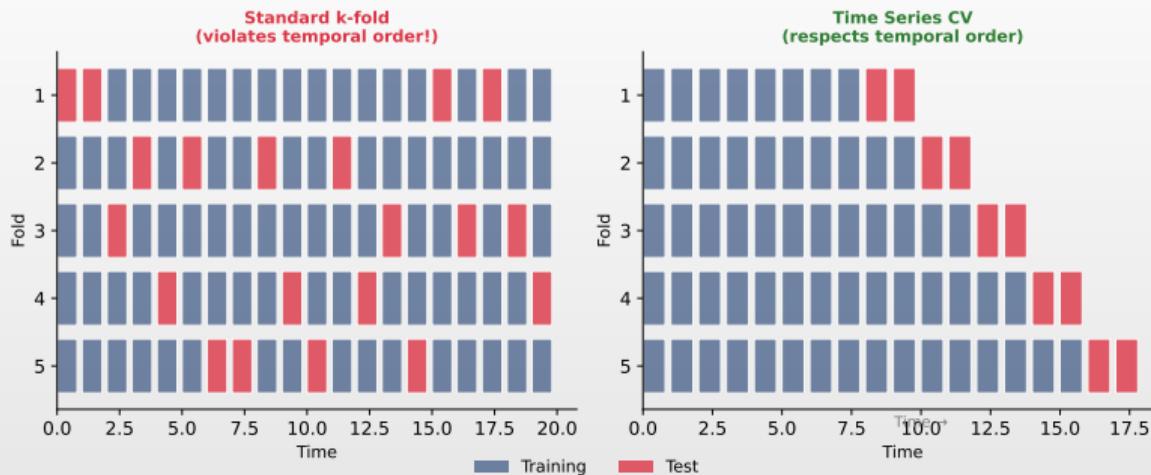
### Question

- Why should you use Time Series Cross-Validation instead of standard k-fold?

### Answer Choices

- (A)** k-fold is computationally more expensive
- (B)** Time Series CV uses more training data
- (C)** k-fold violates temporal order, causing data leakage
- (D)** There is no difference; both methods are equivalent

## Question 2: Answer



Answer: (C)

- Standard k-fold randomly shuffles data, using future observations to predict past ones. Time Series CV always trains on past and tests on future, respecting causality.



## Question 3

### Question

- What is the main advantage of LSTM over simple RNNs?

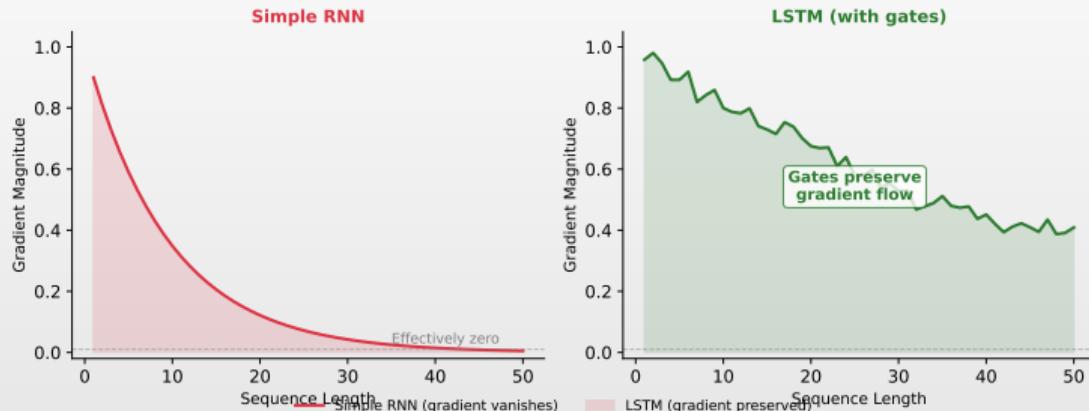
### Answer Choices

- (A)** LSTM uses fewer parameters
- (B)** LSTM solves the vanishing gradient problem via gating mechanisms
- (C)** LSTM is faster to train
- (D)** LSTM does not require sequential data



## Question 3: Answer

Vanishing Gradient Problem: RNN vs LSTM



Answer: (B)

- LSTM's forget, input, and output gates control information flow, preserving gradients across long sequences. Simple RNNs lose gradient signal after  $\sim 10\text{--}20$  steps.

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## Question 4

### Question

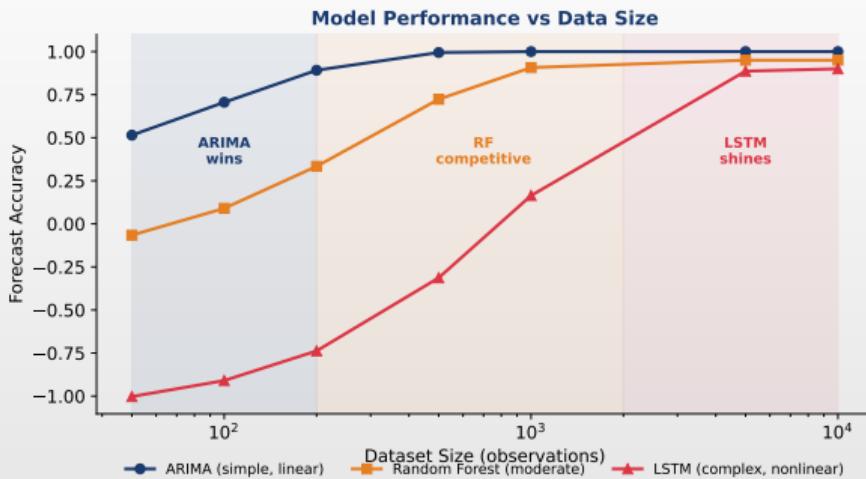
- You have a small dataset (100 observations) with linear relationships. Which model is most appropriate?

### Answer Choices

- (A)** LSTM — deep learning captures all patterns
- (B)** Random Forest — handles any relationship
- (C)** ARIMA/ARFIMA — parsimonious and effective with small data
- (D)** Ensemble of all models for best accuracy



## Question 4: Answer



Answer: (C)

- ML models (RF, LSTM) need large datasets to generalize. With 100 observations and linear dynamics, ARIMA's few parameters avoid overfitting and often outperform complex models.



## Question 5

### Question

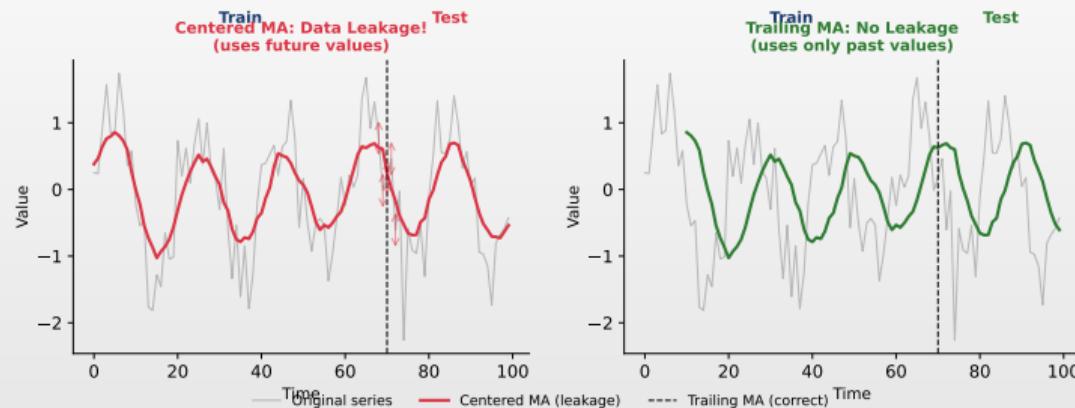
- What is “data leakage” in the context of ML for time series?

### Answer Choices

- (A)** Missing values in the dataset
- (B)** Using future information in features or during training
- (C)** Having too many features relative to observations
- (D)** The model memorizing the training data

## Question 5: Answer

Data Leakage in Time Series Feature Engineering



Answer: (B)

- Examples: centered moving averages (use future values), standard k-fold (mixes temporal order), computing statistics over the full dataset before splitting.

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## What Comes Next?

### Extensions and Advanced Topics

- Transformer** for time series (Temporal Fusion Transformer)
- Prophet** (Facebook/Meta) for seasonality
- Neural Prophet**: Prophet + neural networks
- Ensemble methods**: Combining multiple models
- Anomaly detection** with ML

Questions?



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- Bai, J., & Perron, P. (2003). Computation and Analysis of Multiple Structural Change Models, *Journal of Applied Econometrics*, 18(1), 1–22.



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- Hamilton, J.D. (1989). A New Approach to the Economic Analysis of Nonstationary Time Series and the Business Cycle, *Econometrica*, 57(2), 357–384.
- Petropoulos, F., et al. (2022). Forecasting: Theory and Practice, *International Journal of Forecasting*, 38(3), 845–1054.

### Online Resources and Code

- **Quantlet:** <https://quantlet.com> ↗ Code repository for statistics
- **Quantinar:** <https://quantinar.com> ↗ Learning platform for quantitative methods
- **GitHub TSA:** [https://github.com/QuantLet/TSA/tree/main/TSA\\_ch8](https://github.com/QuantLet/TSA/tree/main/TSA_ch8) ↗ Python code for this chapter



# Thank You!

Questions?

Course materials available at: <https://danpele.github.io/Time-Series-Analysis/>

