



# Time Series Analysis and Forecasting

## Chapter 7: Cointegration and VECM



Daniel Traian PELE

Bucharest University of Economic Studies

IDA Institute Digital Assets

Blockchain Research Center

AI4EFin Artificial Intelligence for Energy Finance

Romanian Academy, Institute for Economic Forecasting

MSCA Digital Finance

## Learning Objectives

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

- Understand the problem of spurious regression with non-stationary data
- Test for cointegration using Engle-Granger and Johansen methods
- Estimate Vector Error Correction Models (VECM)
- Interpret error correction mechanisms and adjustment speeds



## Outline

- Motivation
- Spurious Regression
- Cointegration Concept
- Engle-Granger Method
- Johansen Method
- VECM Estimation
- Practical Considerations
- Real-World Examples
- Case Study: Interest Rates
- AI Use Case
- Summary
- Quiz



## Why Cointegration Matters

### The Challenge

- Many economic/financial time series are **non-stationary ( $I(1)$ )**
- GDP, stock prices, exchange rates, interest rates all have unit roots
- Standard regression with  $I(1)$  variables  $\Rightarrow$  **spurious results**
- Differencing removes non-stationarity but loses **long-run information**

### The Solution: Cointegration

Some non-stationary series share a **common stochastic trend**—they move together in the long run.

### Nobel Prize 2003

Granger & Engle received the Nobel Prize for “methods for analyzing economic time series with common trends.”



## Real-World Applications

### Finance

- Pairs Trading:** Cointegrated stocks
- Term Structure:** Interest rates
- Spot-Futures:** Arbitrage

### Policy Analysis

- Fiscal:** Spending & taxes
- Monetary:** Rate pass-through
- Labor:** Wages & productivity

### Macroeconomics

- Consumption & Income**
- Money & Prices**
- PPP:** Exchange rates



## The Spurious Regression Problem

Granger & Newbold (1974)

Regressing one random walk on another **independent** random walk:  $Y_t = \alpha + \beta X_t + u_t$  where  $Y_t$  and  $X_t$  are independent I(1) processes.

### Symptoms of Spurious Regression

- High  $R^2$  (often  $> 0.9$ ) even though variables are **unrelated**
- Highly significant  $t$ -statistics (reject  $H_0 : \beta = 0$ )
- Very low Durbin-Watson statistic ( $DW \approx 0$ )
- Residuals are non-stationary (have unit root)

### Rule of Thumb

If  $R^2 > DW$ , suspect spurious regression!



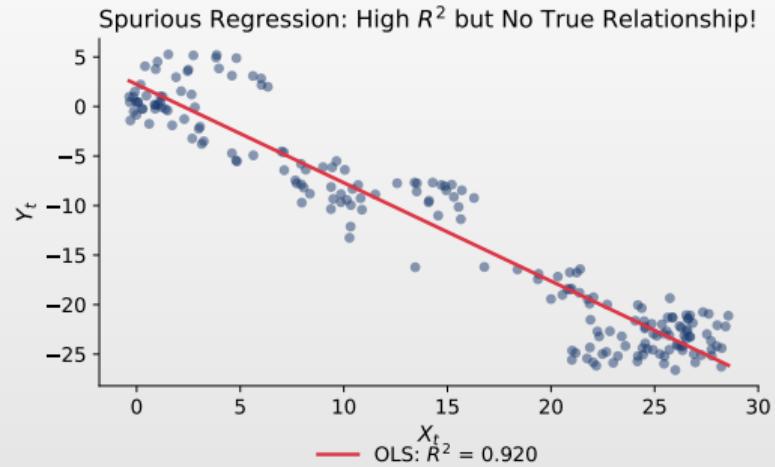
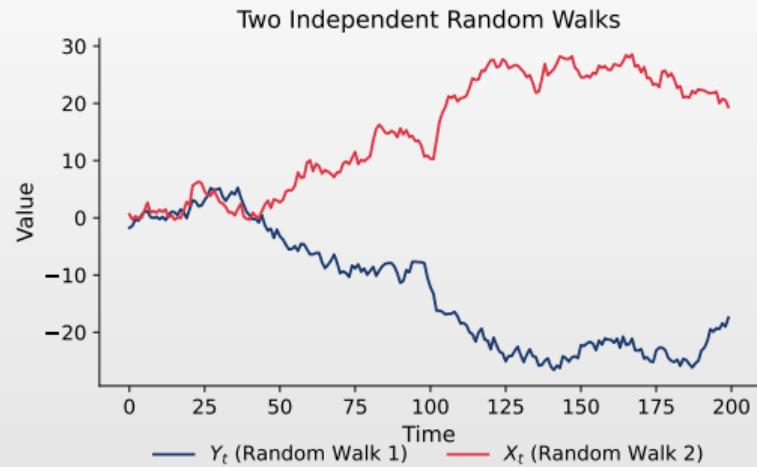
## Spurious Regression: Visual Example

### Warning

- Result: Two completely independent random walks show high correlation ( $R^2 > 0.8$ ) purely by chance!  
This is why we need cointegration analysis



## Spurious Regression: Visual Example



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## Spurious Correlations in the Real World

### Data Mining Can Produce Meaningless Correlations

With enough variables and long time series, purely coincidental patterns emerge:

- Distance between Neptune and Uranus ↔ SAP SE stock price (2002–2023)
- GMO corn use in South Dakota ↔ Google searches for “i cant even” (2004–2023)
- *Two and a Half Men* season ratings ↔ Jet fuel used in Serbia (2006–2015)
- “It's Wednesday my dudes” meme popularity ↔ Boeing stock price (2006–2023)

### Lesson

High correlation  $\neq$  causation. Non-stationary series with common trends produce high  $R^2$  by construction. Always test for stationarity and cointegration before interpreting regression results!

🌐 Explore more examples: [tylervigen.com/spurious-correlations](http://tylervigen.com/spurious-correlations)



## Definition of Cointegration

### Definition 1 (Cointegration (Engle & Granger, 1987))

Variables  $Y_{1t}, Y_{2t}, \dots, Y_{kt}$  are **cointegrated of order  $(d, b)$** , written  $CI(d, b)$ , if:

1. All variables are integrated of order  $d$ :  $Y_{it} \sim I(d)$
2. There exists a linear combination  $\beta' Y_t = \beta_1 Y_{1t} + \dots + \beta_k Y_{kt}$  that is integrated of order  $(d - b)$ , where  $b > 0$

### Most Common Case: $CI(1, 1)$

- ◻ Variables are  $I(1)$  (have unit roots)
- ◻ Linear combination is  $I(0)$  (stationary)
- ◻ Vector  $\beta = (\beta_1, \dots, \beta_k)'$  is the **cointegrating vector**

The cointegrating vector is unique only up to scalar multiplication. Usually normalized:  $\beta_1 = 1$ .



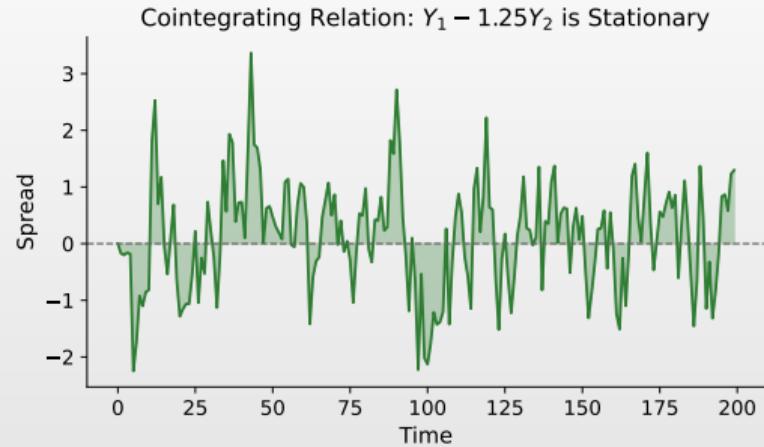
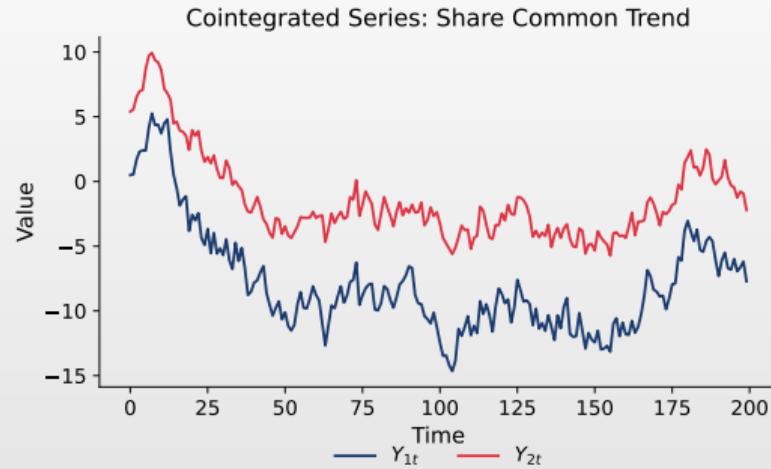
## Cointegration: Visual Example

### Key Insight

- **Cointegration:** Both series are  $I(1)$  and trend together, but their linear combination (spread) is stationary — this is cointegration!



## Cointegration: Visual Example



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## Intuition: Common Stochastic Trends

### Why Does Cointegration Occur?

Cointegrated variables share **common stochastic trends**:  $Y_{1t} = \gamma_1 \tau_t + S_{1t}$ ,  $Y_{2t} = \gamma_2 \tau_t + S_{2t}$  where  $\tau_t$  is a common random walk and  $S_{it}$  are stationary.

### Linear Combination Eliminates the Trend

$$\gamma_2 Y_{1t} - \gamma_1 Y_{2t} = \gamma_2 S_{1t} - \gamma_1 S_{2t} \sim I(0)$$

### Economic Interpretation

- Cointegration = **long-run equilibrium relationship**
- Variables may deviate in the short run, but are “pulled back”
- The cointegrating vector defines the equilibrium



## Cointegrating Rank

### How Many Cointegrating Relationships?

For  $k$  variables that are  $I(1)$ :

- Maximum possible cointegrating relationships:  $r = k - 1$
- If  $r = 0$ : No cointegration (variables drift apart)
- If  $r = k$ : All variables are  $I(0)$  (contradiction)

### Example: 3 Variables

- $r = 0$ : No cointegration
- $r = 1$ : One cointegrating relationship
- $r = 2$ : Two cointegrating relationships (only 1 common trend)

The number of common stochastic trends =  $k - r$



## Engle-Granger Two-Step Method

### Step 1: Estimate Cointegrating Regression

Run OLS:  $Y_t = \alpha + \beta X_t + e_t$ . Save residuals:  $\hat{e}_t = Y_t - \hat{\alpha} - \hat{\beta} X_t$

### Step 2: Test Residuals for Stationarity

Test if  $\hat{e}_t$  is  $I(0)$  using ADF:  $\Delta \hat{e}_t = \rho \hat{e}_{t-1} + \sum_{j=1}^p \gamma_j \Delta \hat{e}_{t-j} + v_t$

- $H_0: \rho = 0$  (unit root  $\Rightarrow$  no cointegration)
- $H_1: \rho < 0$  (stationary  $\Rightarrow$  cointegration)

### Important

Use Engle-Granger critical values, not standard ADF! (More negative because residuals are estimated)



## Engle-Granger Critical Values

### Critical Values for Cointegration Test

Variables	1%	5%	10%
2	-3.90	-3.34	-3.04
3	-4.29	-3.74	-3.45
4	-4.64	-4.10	-3.81
5	-4.96	-4.42	-4.13

MacKinnon (1991),  $T = 100$

### Limitations of Engle-Granger

- Only tests for **one** cointegrating relationship
- Results depend on choice of dependent variable
- Small sample bias; cannot test hypotheses on cointegrating vector



## Researcher Spotlight: Søren Johansen



\*1939

W Wikipedia

### Biography

- Danish statistician and econometrician, Professor Emeritus at University of Copenhagen
- Known for his rigorous mathematical approach to econometrics
- Fellow of the Econometric Society; recipient of numerous honors in statistical science

### Key Contributions

- **Johansen cointegration test** (1988, 1991) — maximum likelihood approach to testing for multiple cointegrating vectors
- **Trace and maximum eigenvalue** statistics for determining cointegration rank
- **VECM estimation** — linking cointegration with error correction models
- Standard framework for multivariate cointegration analysis in economics and finance



## Johansen Cointegration Test

### Advantages over Engle-Granger

- Tests for **multiple** cointegrating relationships
- Maximum likelihood estimation (more efficient)
- Can test restrictions on cointegrating vectors
- Does not require choosing a dependent variable

### Starting Point: VAR in Levels

$$Y_t = c + A_1 Y_{t-1} + A_2 Y_{t-2} + \cdots + A_p Y_{t-p} + \varepsilon_t$$

Rewrite in **Vector Error Correction** form...



## VECM Representation

### Vector Error Correction Model

$$\Delta \mathbf{Y}_t = \mathbf{c} + \boldsymbol{\Pi} \mathbf{Y}_{t-1} + \sum_{j=1}^{p-1} \boldsymbol{\Gamma}_j \Delta \mathbf{Y}_{t-j} + \boldsymbol{\varepsilon}_t$$

- $\boldsymbol{\Pi} = \sum_i \mathbf{A}_i - \mathbf{I}$  (long-run impact);  $\boldsymbol{\Gamma}_j$  (short-run dynamics)

### Key Insight: Rank of $\boldsymbol{\Pi}$

The **rank of  $\boldsymbol{\Pi}$**  determines cointegration:

- $\text{rank}(\boldsymbol{\Pi}) = 0$ : No cointegration (VAR in differences)
- $\text{rank}(\boldsymbol{\Pi}) = k$ : All variables are  $I(0)$  (VAR in levels)
- $0 < \text{rank}(\boldsymbol{\Pi}) = r < k$ :  $r$  cointegrating vectors



## Derivation: From VAR to VECM

Starting Point: VAR( $p$ ) in Levels

$$\mathbf{Y}_t = \mathbf{A}_1 \mathbf{Y}_{t-1} + \mathbf{A}_2 \mathbf{Y}_{t-2} + \cdots + \mathbf{A}_p \mathbf{Y}_{t-p} + \boldsymbol{\varepsilon}_t$$

Step 1: Subtract  $\mathbf{Y}_{t-1}$  from Both Sides

$$\mathbf{Y}_t - \mathbf{Y}_{t-1} = \mathbf{A}_1 \mathbf{Y}_{t-1} + \mathbf{A}_2 \mathbf{Y}_{t-2} + \cdots + \mathbf{A}_p \mathbf{Y}_{t-p} - \mathbf{Y}_{t-1} + \boldsymbol{\varepsilon}_t$$

$$\Delta \mathbf{Y}_t = (\mathbf{A}_1 - \mathbf{I}) \mathbf{Y}_{t-1} + \mathbf{A}_2 \mathbf{Y}_{t-2} + \cdots + \mathbf{A}_p \mathbf{Y}_{t-p} + \boldsymbol{\varepsilon}_t$$

### Goal

Rewrite so that all terms are either in levels ( $\mathbf{Y}_{t-1}$ ) or differences ( $\Delta \mathbf{Y}_{t-j}$ ).



## Derivation: From VAR to VECM (cont.)

### Step 2: Add and Subtract Terms Strategically

Add  $A_2 Y_{t-1}$  and subtract  $A_2 Y_{t-1}$ :  $\Delta Y_t = (A_1 + A_2 - I)Y_{t-1} - A_2(Y_{t-1} - Y_{t-2}) + A_3 Y_{t-3} + \dots + \epsilon_t$

Continue adding  $A_3 Y_{t-1}$ , etc., until all lagged levels are collected in one term.

### Step 3: General Pattern

After algebraic manipulation:  $\Delta Y_t = \Pi Y_{t-1} + \sum_{j=1}^{p-1} \Gamma_j \Delta Y_{t-j} + \epsilon_t$

### The Key Matrices

$$\Pi = \sum_{i=1}^p A_i - I = -(I - A_1 - A_2 - \dots - A_p)$$

$$\Gamma_j = - \sum_{i=j+1}^p A_i \text{ for } j = 1, \dots, p-1$$



## Derivation: Verifying the $\Gamma_j$ Formula

### Example: VAR(2)

Starting from:  $Y_t = A_1 Y_{t-1} + A_2 Y_{t-2} + \varepsilon_t$

Subtract  $Y_{t-1}$ :

$$\Delta Y_t = (A_1 - I)Y_{t-1} + A_2 Y_{t-2} + \varepsilon_t$$

Add and subtract  $A_2 Y_{t-1}$ :

$$\Delta Y_t = (A_1 + A_2 - I)Y_{t-1} + A_2(Y_{t-2} - Y_{t-1}) + \varepsilon_t$$

$$\Delta Y_t = \underbrace{(A_1 + A_2 - I)}_{\Pi} Y_{t-1} - \underbrace{A_2}_{\Gamma_1} \Delta Y_{t-1} + \varepsilon_t$$

### Verification

For VAR(2):  $\Pi = A_1 + A_2 - I$  and  $\Gamma_1 = -A_2$

Using our formula:  $\Gamma_1 = -\sum_{i=2}^2 A_i = -A_2 \quad \checkmark$



## Economic Interpretation of Error Correction

### The VECM with Cointegration

When  $\text{rank}(\Pi) = r$ , we write  $\Pi = \alpha\beta'$ :  $\Delta Y_t = \alpha \underbrace{(\beta' Y_{t-1})}_{\text{equilibrium error}} + \sum_{j=1}^{p-1} \Gamma_j \Delta Y_{t-j} + \varepsilon_t$

### Economic Interpretation

- $\beta' Y_{t-1}$  = **equilibrium error**: deviation from long-run relationship
- $\alpha$  = **adjustment speeds**: how fast variables correct deviations
- $\Gamma_j$  = **short-run dynamics**: transitory effects

### Error Correction Mechanism

If  $\beta' Y_{t-1} > 0$  (above equilibrium) and  $\alpha_i < 0$ , then  $\Delta Y_{it}$  decreases. **The system self-corrects toward equilibrium!**



## Decomposition of $\Pi$

When  $\text{rank}(\Pi) = r < k$

$\Pi = \alpha\beta'$  where  $\beta$  ( $k \times r$ ) = cointegrating vectors,  $\alpha$  ( $k \times r$ ) = adjustment coefficients

### Interpretation

- ◻  $\beta'Y_{t-1}$  = deviations from equilibrium (error correction terms)
- ◻  $\alpha$  = speed of adjustment; rows show each variable's response

$$\text{VECM: } \Delta Y_t = c + \alpha(\beta' Y_{t-1}) + \sum_{j=1}^{p-1} \Gamma_j \Delta Y_{t-j} + \epsilon_t$$



## Johansen Test Statistics

### Two Test Statistics

Based on eigenvalues  $\hat{\lambda}_1 > \hat{\lambda}_2 > \dots > \hat{\lambda}_k$  of a certain matrix:

Trace Test:

$$\lambda_{\text{trace}}(r) = -T \sum_{i=r+1}^k \ln(1 - \hat{\lambda}_i)$$

Tests  $H_0$ : rank  $\leq r$  vs  $H_1$ : rank  $> r$

Maximum Eigenvalue Test:

$$\lambda_{\max}(r, r+1) = -T \ln(1 - \hat{\lambda}_{r+1})$$

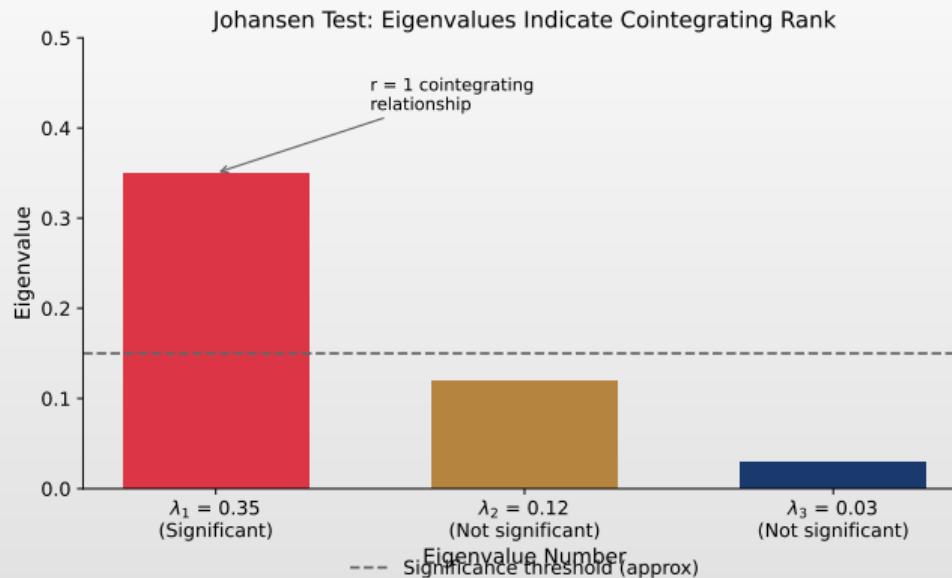
Tests  $H_0$ : rank  $= r$  vs  $H_1$ : rank  $= r + 1$

Critical values from Johansen & Juselius (1990), depend on:

- Number of variables  $k$
- Deterministic components (constant, trend)



## Johansen Test: Visual Interpretation



Significant eigenvalues (above threshold) indicate cointegrating relationships. First eigenvalue significant  $\Rightarrow r = 1$ .

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## Testing Procedure

### Sequential Testing (Trace Test)

1. Test  $H_0: r = 0$ . If rejected  $\Rightarrow$  continue
2. Test  $H_0: r \leq 1$ . If not rejected  $\Rightarrow r = 1$
3. Continue until  $H_0$  is not rejected

### Deterministic Components

- No constant, no trend (rarely used)
- Constant in cointegrating relation only
- Constant in both** (most common)
- Constant + trend in cointegrating relation



## VECM Structure

### Full VECM Specification

For  $k = 2$  variables with  $r = 1$  cointegrating relation:

$$\Delta Y_{1t} = c_1 + \alpha_1(Y_{1,t-1} - \beta Y_{2,t-1}) + \gamma_{11}\Delta Y_{1,t-1} + \gamma_{12}\Delta Y_{2,t-1} + \varepsilon_{1t}$$

$$\Delta Y_{2t} = c_2 + \alpha_2(Y_{1,t-1} - \beta Y_{2,t-1}) + \gamma_{21}\Delta Y_{1,t-1} + \gamma_{22}\Delta Y_{2,t-1} + \varepsilon_{2t}$$

### Components

- $(Y_{1,t-1} - \beta Y_{2,t-1})$  = error correction term (deviation from equilibrium)
- $\alpha_1, \alpha_2$  = adjustment speeds (should have opposite signs)
- $\gamma_{ij}$  = short-run dynamics
- $\varepsilon_{it}$  = innovations



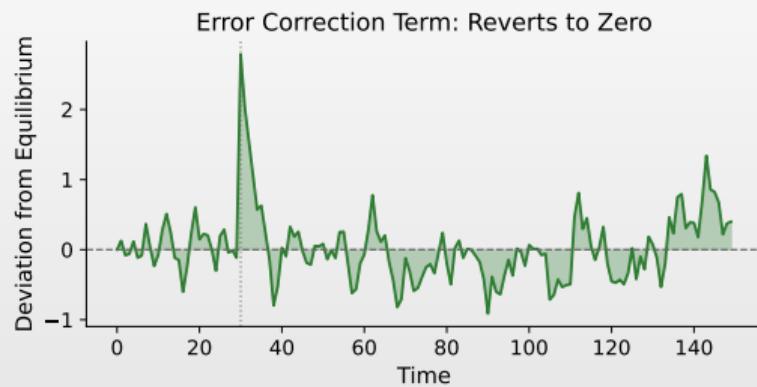
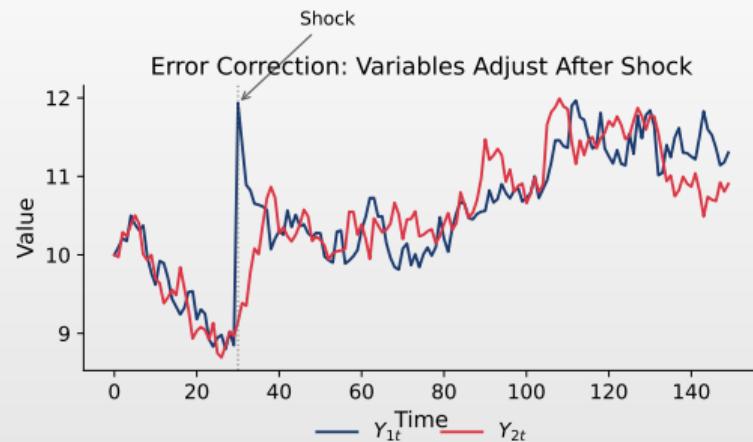
## Error Correction Mechanism: Visual

### Interpretation

- **Error correction:** When series deviate from equilibrium (shaded regions), the adjustment mechanism pulls them back. Positive deviations lead to downward adjustment, negative deviations lead to upward adjustment



## Error Correction Mechanism: Visual



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## Interpreting Adjustment Coefficients

### The $\alpha$ Coefficients

If the cointegrating relation is  $Y_1 - \beta Y_2 = 0$  (equilibrium):

- $\alpha_1 < 0$ :  $Y_1$  adjusts downward when above equilibrium
- $\alpha_2 > 0$ :  $Y_2$  adjusts upward when  $Y_1$  is above equilibrium

### Weak Exogeneity

If  $\alpha_i = 0$ , variable  $Y_i$  does **not** respond to disequilibrium.

- $Y_i$  is **weakly exogenous** for the long-run parameters
- The other variable does all the adjusting
- Can simplify estimation (single-equation approach)

Test weak exogeneity:  $H_0 : \alpha_i = 0$  using likelihood ratio test.



## VECM vs VAR in Differences

### When Variables are Cointegrated

	VAR in Differences	VECM
Long-run info	Lost	Preserved
Short-run dynamics	Yes	Yes
Error correction	No	Yes
Forecasting	Poor (long-run)	Better
IRF interpretation	Short-run only	Both

### Granger Representation Theorem

If variables are cointegrated, there **must** exist an error correction representation. Ignoring cointegration = model misspecification!



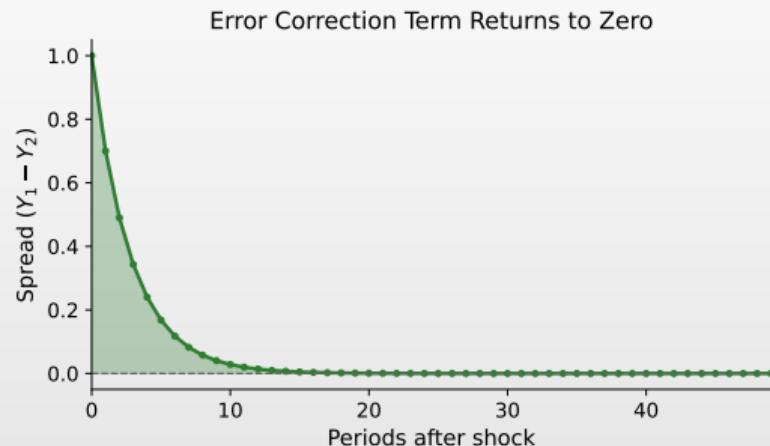
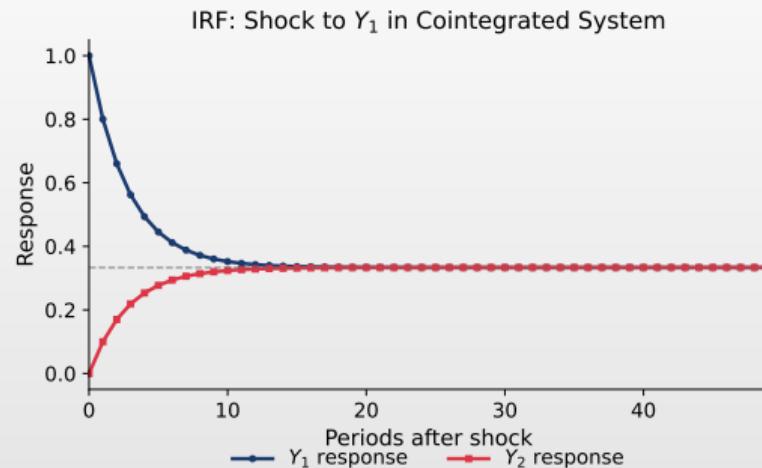
## VECM Impulse Response Functions

### IRF Interpretation

- ◻ **Permanent effects:** In a cointegrated system, shocks have permanent effects on levels, but the system returns to equilibrium — they converge to a new long-run value



## VECM Impulse Response Functions



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## Practical Workflow

### Step-by-Step Procedure

1. **Unit Root Tests:** Verify all variables are  $I(1)$ 
  - ▶ ADF, KPSS on levels and first differences
2. **Lag Length Selection:** Choose  $p$  for VAR in levels
  - ▶ Use AIC, BIC, or sequential LR tests
3. **Cointegration Test:** Johansen trace/max-eigenvalue tests
  - ▶ Determine cointegrating rank  $r$
4. **Estimate VECM:** If  $0 < r < k$ 
  - ▶ Estimate  $\alpha, \beta, \Gamma_j$
5. **Diagnostics:** Check residuals for autocorrelation, normality
6. **Analysis:** IRF, FEVD, hypothesis tests



## Common Pitfalls

### Things to Watch Out For

- Structural breaks:** Cause spurious unit roots or cointegration
- Near-unit-root:** Tests have low power
- Lag selection:** Too many/few lags bias results
- Small samples:** Johansen test oversized

### Recommendation

Always check: residual diagnostics, stability of cointegrating relationship, sensitivity to specification



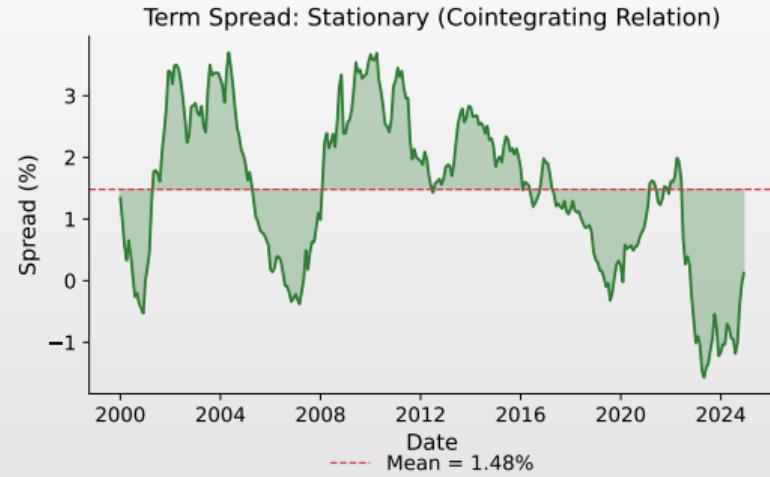
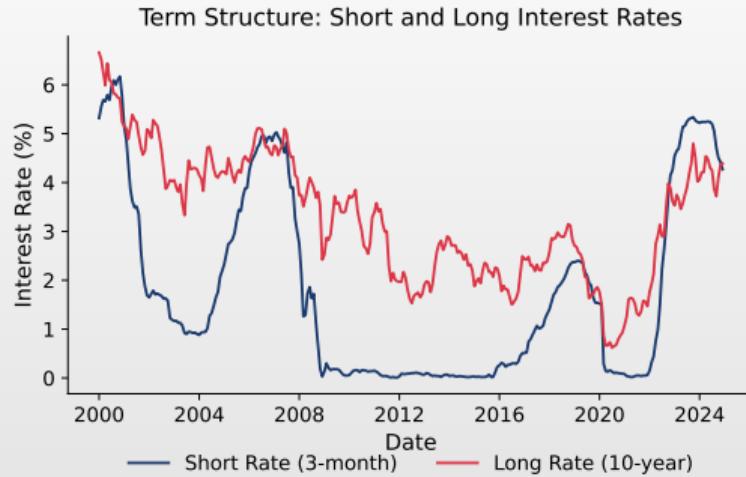
## Example 1: Term Structure of Interest Rates

### Expectations Hypothesis

- **Conclusion:** Short and long rates share a common trend. The spread (term premium) is stationary — evidence of cointegration!



## Example 1: Term Structure of Interest Rates



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## Interest Rates: Economic Theory

### Expectations Hypothesis of the Term Structure

- **Formula:** Long-term rate as average of expected future rates
  - ▶  $R_t^{(n)} = \frac{1}{n} \sum_{i=0}^{n-1} E_t[r_{t+i}] + \text{term premium}$
- **Implication:** If the term premium is constant,  $r_t$  and  $R_t$  are cointegrated
  - ▶ Cointegrating vector:  $(1, -1)$

### Empirical Results

- **Unit root tests:** Both rates are  $I(1)$ 
  - ▶ One cointegrating relationship (Johansen test)
- **Cointegrating vector:**  $\approx (1, -1)$ , the spread is stationary
  - ▶ The short rate adjusts to disequilibrium (the long rate is weakly exogenous)



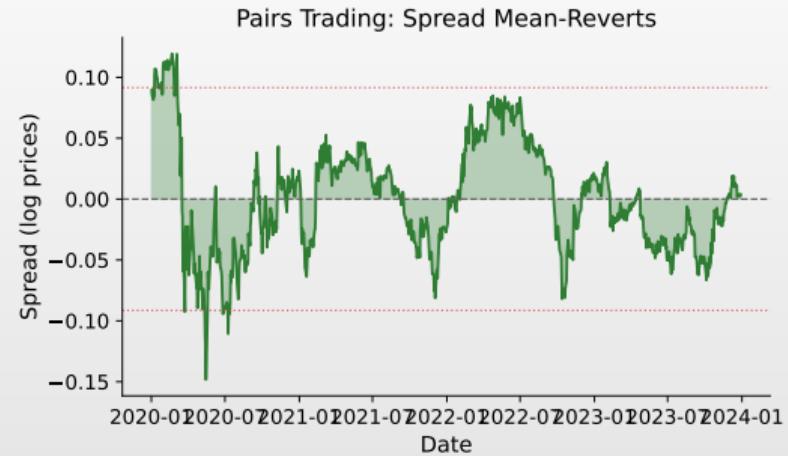
## Example 2: Pairs Trading in Finance

### Strategy

- ❑ **Pairs trading:** Find cointegrated stock pairs (e.g., Coca-Cola & Pepsi). When the spread deviates from the mean, trade expecting mean reversion



## Example 2: Pairs Trading in Finance



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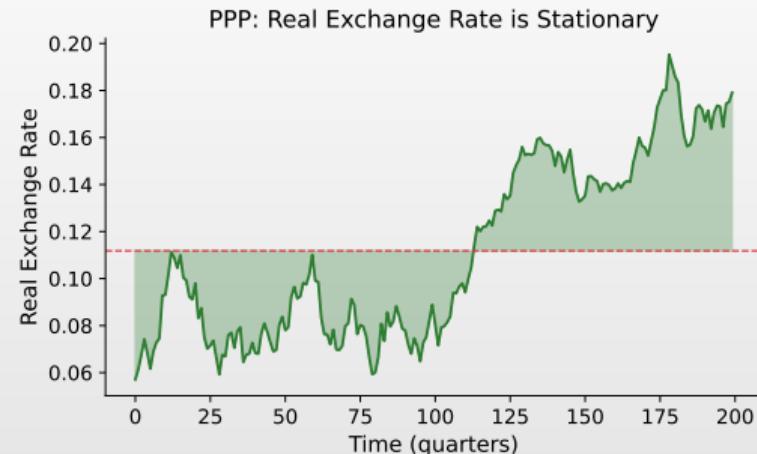
## Example 3: Purchasing Power Parity (PPP)

### PPP Theory

- ☐ **Formula:**  $e_t = p_t - p_t^*$  (log exchange rate equals price differential). The real exchange rate should be stationary in the long run



### Example 3: Purchasing Power Parity (PPP)



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## VECM Results for Interest Rates

### Typical Results

- **Integration:** Both rates are  $I(1)$ , one cointegrating relationship identified
  - ▶ Cointegrating vector close to  $(1, -1)$ : the spread is stationary
- **Adjustment:** The short rate adjusts to the long rate
  - ▶ The long rate does not adjust (weakly exogenous)

### VECM Equations (Stylized)

- **Estimated system:**
  - ▶  $\Delta r_t = 0.02 - 0.15(r_{t-1} - R_{t-1}) + \text{lags} + \varepsilon_{1t}$
  - ▶  $\Delta R_t = 0.01 - 0.02(r_{t-1} - R_{t-1}) + \text{lags} + \varepsilon_{2t}$
- **Interpretation:** The short rate adjusts faster ( $\alpha_1 = -0.15$ )
  - ▶ The long rate is nearly weakly exogenous ( $\alpha_2 \approx 0$ )



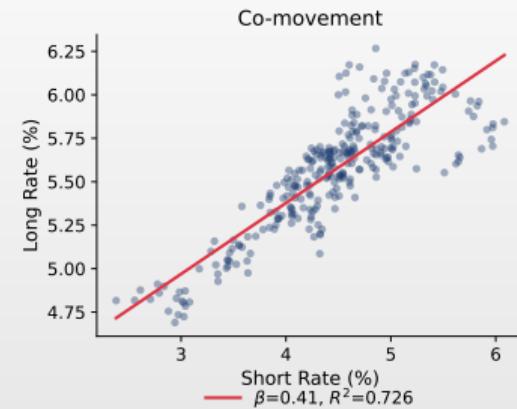
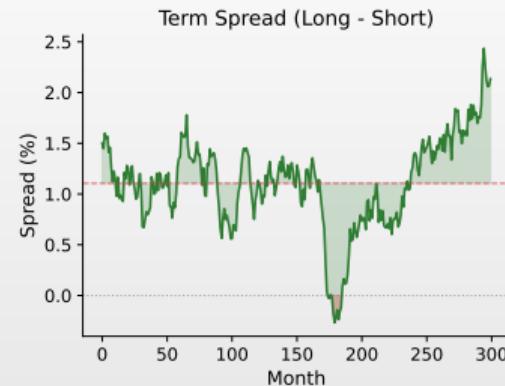
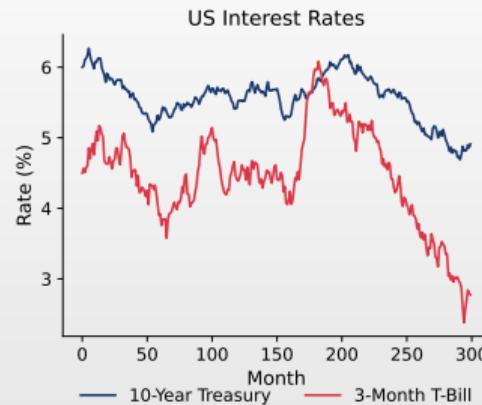
## Case Study: Cointegration of Interest Rates

### Data

- US Interest Rates:** Long-term (10 years) and short-term (3 months)
- Observation:** Both series are  $I(1)$ , but the spread appears stationary



## Case Study: Cointegration of Interest Rates



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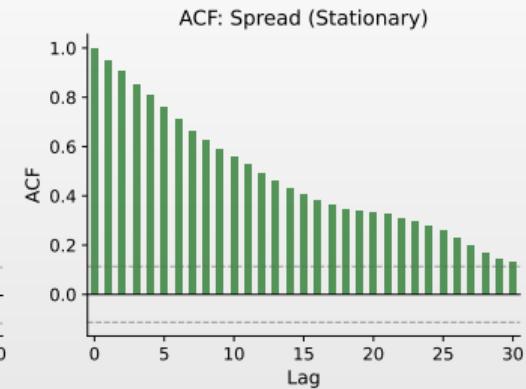
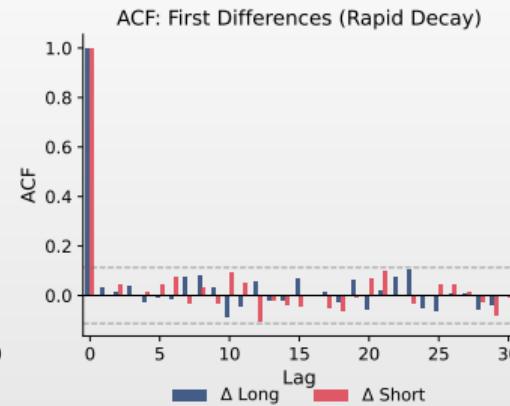
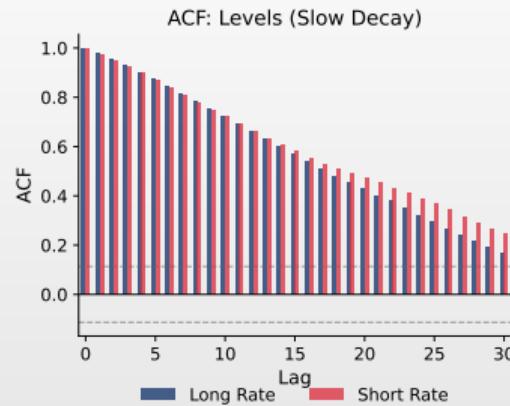
## Step 1: Unit Root Tests

### Results

- ACF levels:** Slow decay — non-stationarity; after differencing: rapid decay — I(1)
- ACF spread:** Stationary — possible cointegration!



## Step 1: Unit Root Tests



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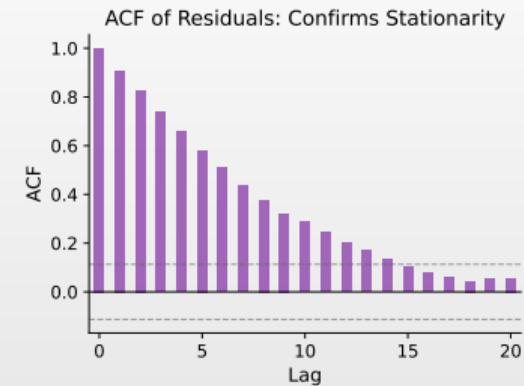
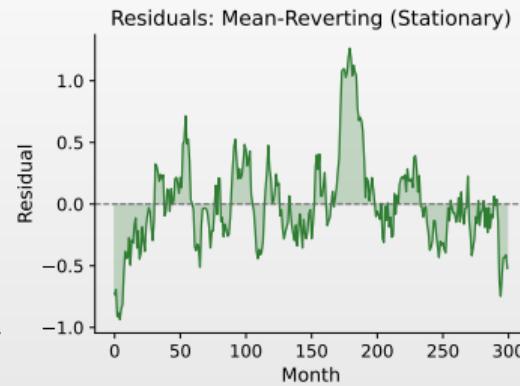
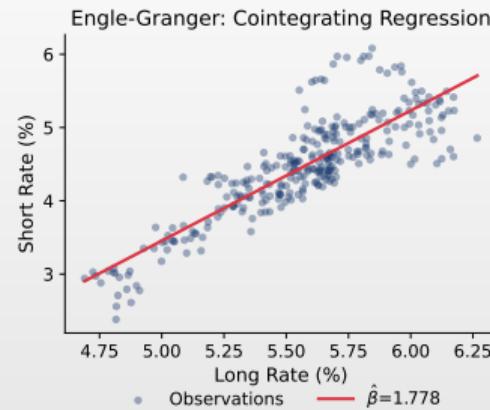
## Step 2: Engle-Granger Cointegration Test

### Results

- Engle-Granger regression:** Short rate =  $\alpha + \beta \times$  Long rate +  $\varepsilon_t$
- Conclusion:** The series are cointegrated — a long-run equilibrium relationship exists



## Step 2: Engle-Granger Cointegration Test



Q TSA\_ch7\_case\_cointegration



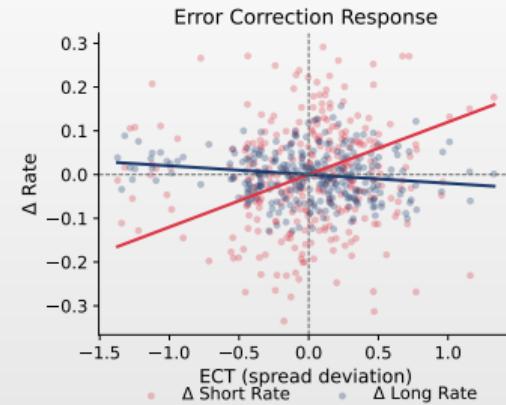
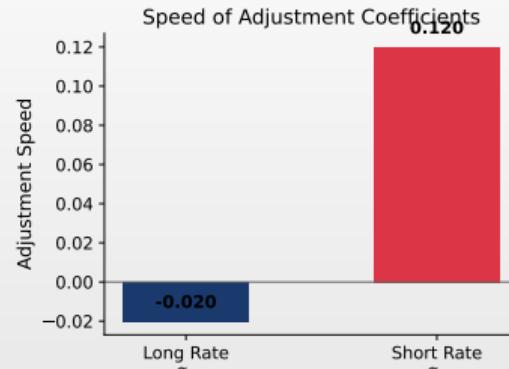
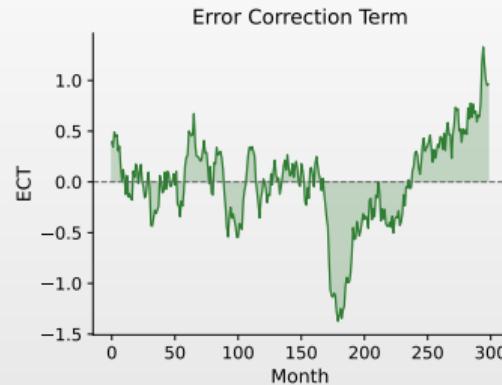
## Step 3: VECM Estimation

### Model

- VECM(2)**: Cointegration rank = 1
- Adjustment**: The  $\alpha$  coefficients indicate the speed of return to equilibrium



## Step 3: VECM Estimation



Q TSA\_ch7\_case\_vecm



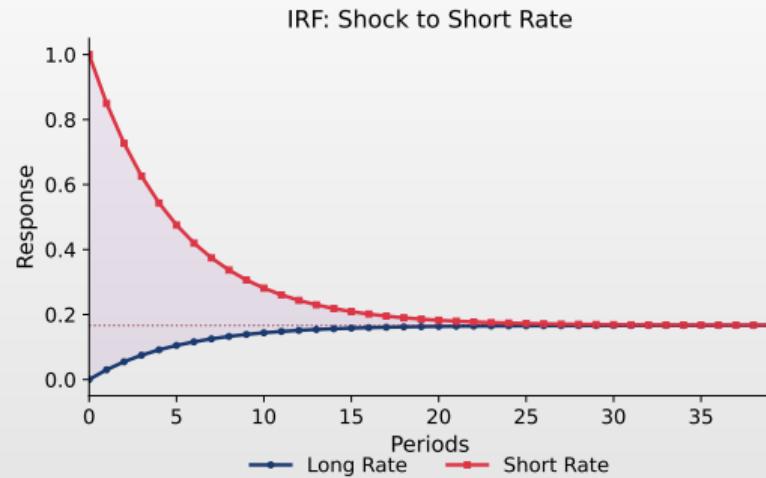
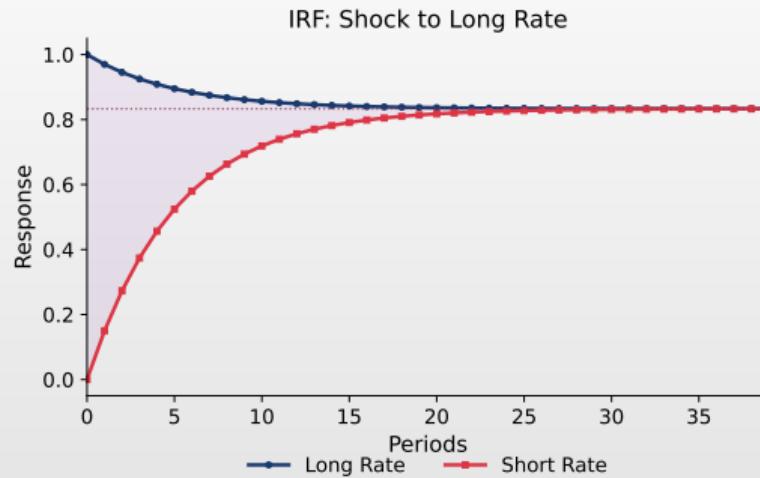
## Step 4: Impulse Response Functions

### Interpretation

- Permanent effects:** Shocks to the long rate persistently affect both rates
- Cointegration:** Effects do not converge to zero — characteristic of cointegrated series



## Step 4: Impulse Response Functions



Q TSA\_ch7\_case\_irf



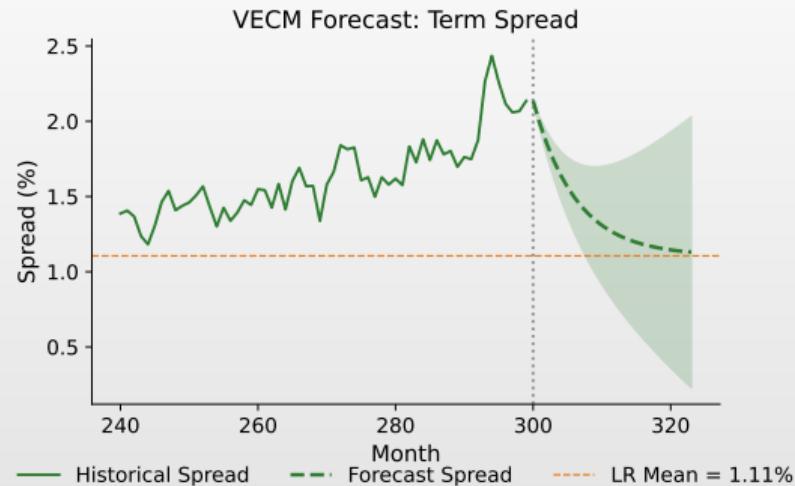
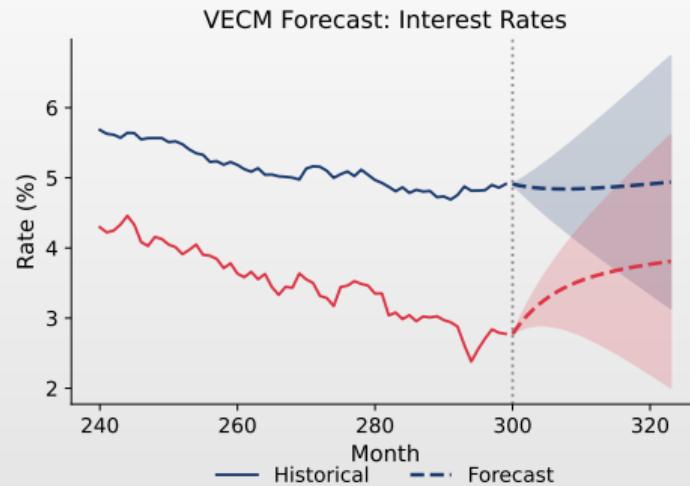
## Step 5: VECM Forecast

### Forecast

- Horizon:** 24 months for both rates simultaneously
- Advantage:** VECM maintains the cointegrating relationship in the forecast



## Step 5: VECM Forecast



Q TSA\_ch7\_case\_forecast



## AI Exercise: Critical Thinking

Prompt to test in ChatGPT / Claude / Copilot

"Download daily prices for gold and silver using yfinance. Test for cointegration and estimate a VECM model. Analyze the speed of adjustment parameters. Give me complete Python code."

**Exercise:**

1. Run the prompt in an LLM of your choice and critically analyze the response.
2. Does it verify that each series is I(1) before testing for cointegration?
3. Does it use both Engle-Granger and Johansen tests? What are the trade-offs?
4. How does it determine the cointegration rank? Trace vs max-eigenvalue statistics?
5. Does it correctly interpret the  $\alpha$  (adjustment) coefficients?

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



## Key Takeaways

### Main Concepts

- Cointegration:**  $I(1)$  variables with stationary linear combination
- Spurious regression:** High  $R^2$  with unrelated  $I(1)$  variables
- VECM:** VAR with error correction for cointegrated systems

### Testing Methods

- Engle-Granger:** Simple, one vector only
- Johansen:** Multiple vectors, MLE-based

### Remember

Tests have low power in small samples. Theory should guide specification.



## What's Next?

### Extensions and Related Topics

- Structural VECM:** Identifying structural shocks
- Threshold cointegration:** Nonlinear adjustment
- Panel cointegration:** Multiple cross-sections
- Fractional cointegration:** Long memory
- Time-varying cointegration:** Regime changes

- Questions?**



## Key Formulas – Summary

### Cointegration

- **Definition:**  $Y_t - \beta X_t = u_t \sim I(0)$
- **Interpretation:** Long-run equilibrium

### Engle-Granger Test

- **Step 1:**  $Y_t = \alpha + \beta X_t + u_t$
- **Step 2:** ADF test on  $\hat{u}_t$
- **Note:** Special critical values

### Cointegration Rank

- **Rank  $r$ :**  $0 \leq r \leq K - 1$  relationships

### VECM Model

- **Equation:**  $\Delta Y_t = \Pi Y_{t-1} + \sum_{i=1}^{p-1} \Gamma_i \Delta Y_{t-i} + \varepsilon_t$
- **Factorization:**  $\Pi = \alpha \beta'$

### Interpretation of $\alpha$ and $\beta$

- $\beta$ : Cointegrating vectors
- $\alpha$ : Speed of adjustment

### Johansen Test

- **Trace:**  $\lambda_{trace} = -T \sum_{i=r+1}^K \ln(1 - \hat{\lambda}_i)$
- **Max-Eigen:**  $\lambda_{max} = -T \ln(1 - \hat{\lambda}_{r+1})$



## Question 1

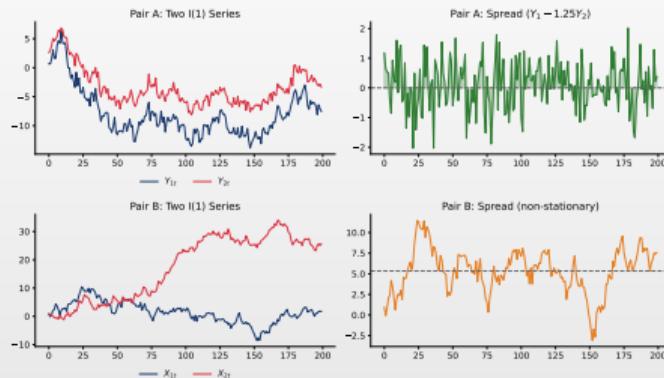
### Question

- Analyze the two pairs of I(1) series below. Which pair is cointegrated?

### Answer choices

- (A) Pair A, because the series have the same trend
- (B) Pair B, because the series are uncorrelated
- (C) Pair A, because their spread is stationary
- (D) Both pairs are cointegrated

## Question 1: Answer



Correct answer: (C) Pair A – stationary spread

- Cointegration = stationary linear combination, not just correlation
- Pair B's spread is non-stationary → not cointegrated

Q TSA\_ch7\_quiz1\_cointegration\_concept



## Question 2

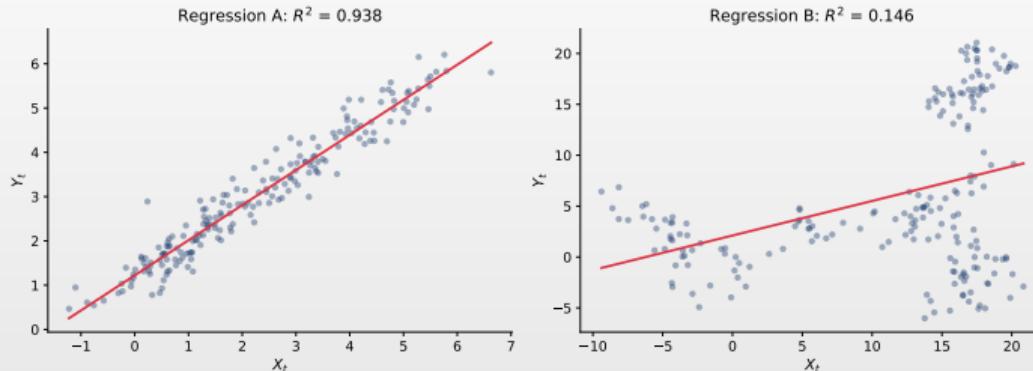
### Question

- Both regressions below have high  $R^2$ . How can you distinguish a spurious regression from a genuine one?

### Answer choices

- (A) Cannot distinguish – both have high  $R^2$
- (B) Test the residuals: stationary residuals = genuine cointegration
- (C) Check the significance of the  $\beta$  coefficient
- (D) Compare  $R^2$  values: higher = more real relationship

## Question 2: Answer



Correct answer: (B) Test the stationarity of residuals

- Engle-Granger test: if OLS residuals are stationary (ADF), the relationship is genuine
- High  $R^2$  does NOT imply a real relationship between  $I(1)$  variables!



## Question 3

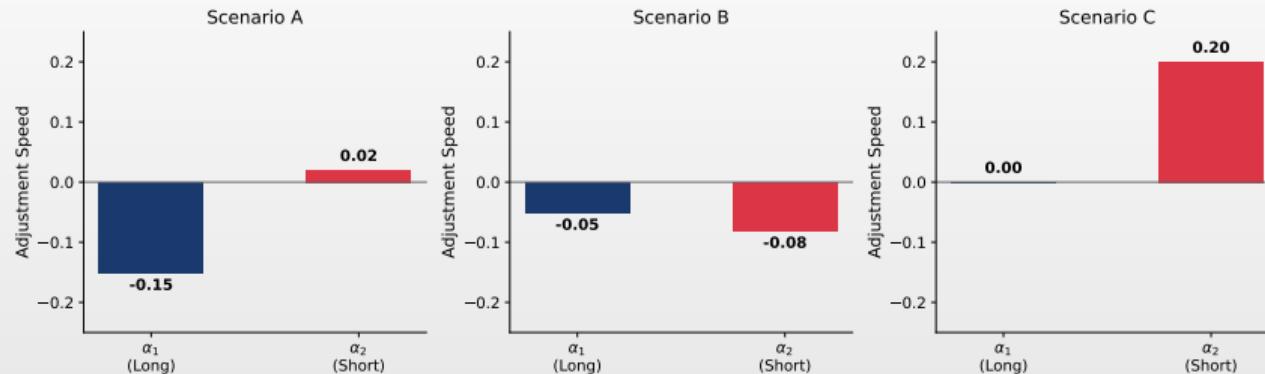
### Question

- In which scenario is the long rate weakly exogenous (does not adjust to disequilibrium)?

### Answer choices

- (A) Scenario A:  $\alpha_1 = -0.15, \alpha_2 = 0.02$
- (B) Scenario B:  $\alpha_1 = -0.05, \alpha_2 = -0.08$
- (C) Scenario C:  $\alpha_1 = 0.00, \alpha_2 = 0.20$
- (D) No scenario – both variables must adjust

### Question 3: Answer



Correct answer: (C) Scenario C –  $\alpha_1 = 0$

- $\alpha_1 = 0$ : the long rate does not respond to disequilibrium (weakly exogenous)
- All adjustment is done by the short rate ( $\alpha_2 = 0.20$ )



## Question 4

### Question

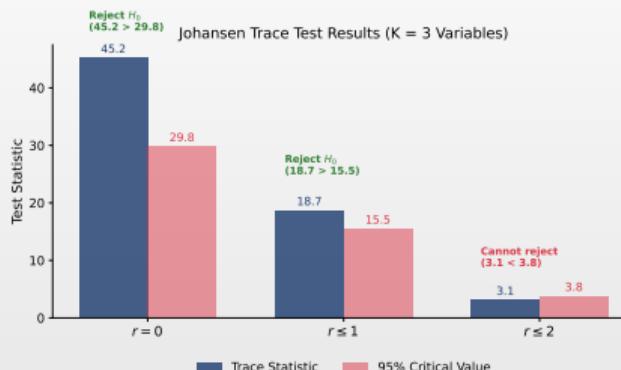
- Given the Johansen Trace test results for  $K = 3$  variables, what is the cointegrating rank?

### Answer choices

- (A)  $r = 0$  (no cointegrating relationships)
- (B)  $r = 1$  (one cointegrating relationship)
- (C)  $r = 2$  (two cointegrating relationships)
- (D)  $r = 3$  (fully stationary system)



## Question 4: Answer



Correct answer: (C)  $r = 2$  cointegrating relationships

- Reject  $H_0 : r = 0$  ( $45.2 > 29.8$ ) and  $H_0 : r \leq 1$  ( $18.7 > 15.5$ )
- Cannot reject  $H_0 : r \leq 2$  ( $3.1 < 3.8$ ) → rank is  $r = 2$



## Question 5

### Question

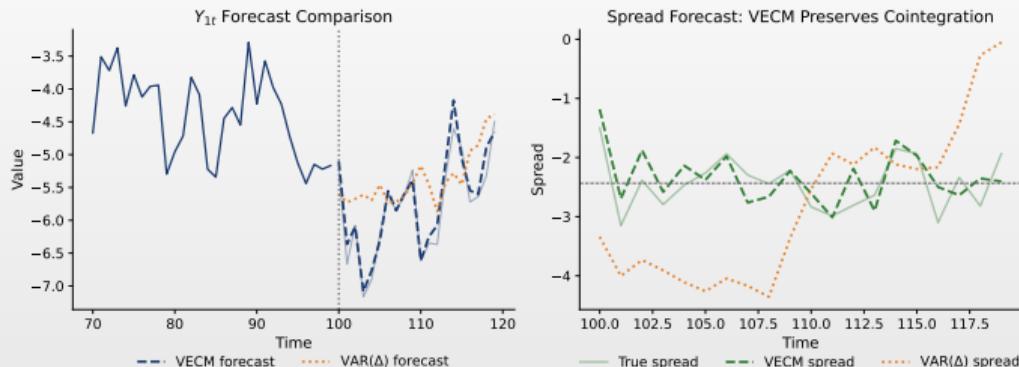
- What is the main advantage of VECM over VAR in differences for forecasting?

### Answer choices

- (A) VECM has fewer parameters to estimate
- (B) VECM preserves the cointegrating relationship in long-run forecasts
- (C) VAR in differences cannot produce forecasts
- (D) No advantage – both are equivalent



## Question 5: Answer



Correct answer: (B) VECM preserves cointegration

- VAR( $\Delta$ ) loses the level relationship → spread diverges
- VECM incorporates long-run equilibrium → forecast stays coherent



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- Johansen, S. (1991). Estimation and Hypothesis Testing of Cointegration Vectors in Gaussian Vector Autoregressive Models, *Econometrica*, 59(6), 1551–1580.

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- Lütkepohl, H. (2005). *New Introduction to Multiple Time Series Analysis*, Springer.



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- Hamilton, J.D. (1994). *Time Series Analysis*, Princeton University Press.
- Banerjee, A., Dolado, J.J., Galbraith, J.W., & Hendry, D.F. (1993). *Co-Integration, Error-Correction, and the Econometric Analysis of Non-Stationary Data*, Oxford University Press.

### 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> → Python code for this course



# Thank You!

Questions?

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

