Time Series Analysis and Forecasting

Chapter 3: ARIMA Models

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

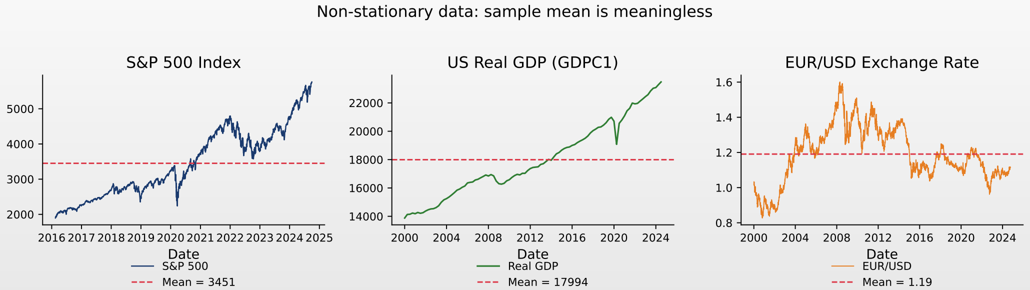
Learning Objectives

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

- Understand the concept and implications of non-stationarity
- Apply differencing to achieve stationarity in time series
- Use the Augmented Dickey-Fuller (ADF) test for unit root detection
- Build, estimate, and forecast with ARIMA models

Outline

Motivating Example: Non-Stationary Data Is Everywhere

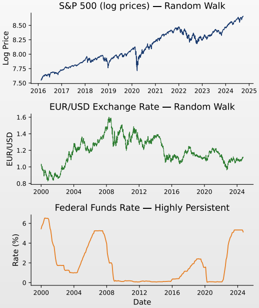


Key Observations

- Stock prices, GDP, exchange rates all exhibit **trends** or **wandering behavior**
- The sample mean (red line) is meaningless for a random walk
- Standard ARMA models **cannot** handle these series directly

TSA_ch3_motivation_nonstationary

Real-World Applications

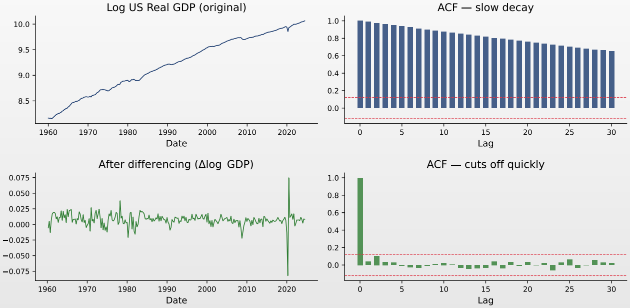


The Challenge

Financial/economic data are typically I(1): stock prices, exchange rates, interest rates.

TSA_ch3_motivation_realworld

The Solution: Differencing



Key Insight

Differencing transforms a non-stationary series into a stationary one: $\Delta Y_t = Y_t - Y_{t-1}$. The ACF changes from slow decay to quick decay!

TSA_ch3_motivation_differencing

What We'll Learn Today

Core Concepts

1. **Non-Stationarity**: Why it matters and how to detect it
2. **Unit Root Tests**: ADF, PP, KPSS tests
3. **Differencing**: The key transformation
4. **ARIMA Models**: Combining differencing with ARMA
5. **Box-Jenkins Methodology**: Identify $\rightarrow$ Estimate $\rightarrow$ Diagnose

By the End of This Lecture

You will be able to model and forecast non-stationary time series like stock prices, GDP, and exchange rates using ARIMA models.

Why Non-Stationarity Matters

The Problem

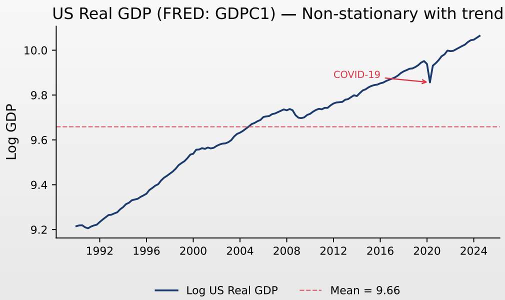
Many economic and financial time series are **non-stationary**:

- GDP, stock prices, exchange rates, inflation indices
- They exhibit trends, changing means, or growing variance

Consequences of Non-Stationarity

- Standard ARMA models assume stationarity
- OLS regression with non-stationary data leads to **spurious regression**
- Sample moments (mean, variance, ACF) are not consistent estimators
- Statistical inference becomes invalid

Example: US Real GDP



Key Observations

- Clear upward **trend** – mean is not constant
- This is a classic example of a **non-stationary** time series
- We cannot apply ARMA models directly to this data

TSA_ch3_gdp_levels

Types of Non-Stationarity

Deterministic Trend

$$Y_t = \alpha + \beta t + \varepsilon_t$$

- Trend is a deterministic function of time
- Can be removed by **detrending**
- Shocks have temporary effects

Stochastic Trend (Unit Root)

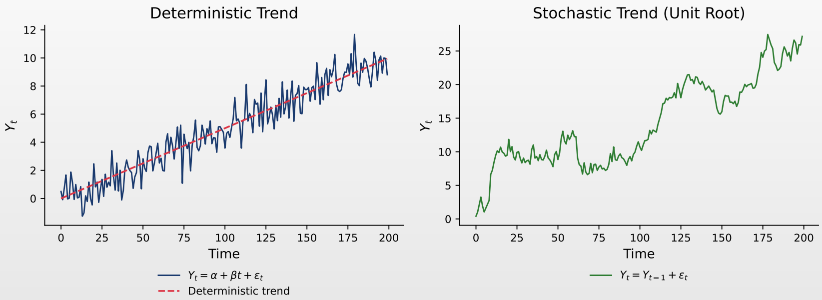
$$Y_t = Y_{t-1} + \varepsilon_t$$

- Random walk process
- Must be removed by **differencing**
- Shocks have permanent effects

Key Distinction

Correct identification is crucial: detrending a unit root $\rightarrow$ misspecification; differencing trend-stationary $\rightarrow$ misspecification.

Visualizing the Difference



Key Distinction

- **Left**: Deterministic trend – deviations from trend are temporary
- **Right**: Stochastic trend – shocks accumulate permanently
- Both look similar, but require **different** treatments!

TSA_ch3_trend_comparison

The Random Walk Process

Definition 1 (Random Walk)

A **random walk** is defined as:

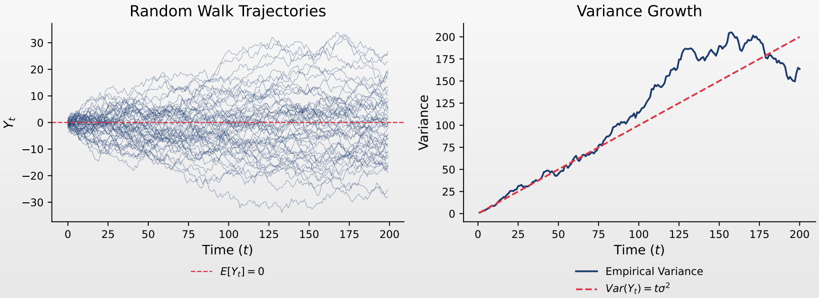
$$Y_t = Y_{t-1} + \varepsilon_t, \quad \varepsilon_t \sim WN(0, \sigma^2)$$

With initial condition $Y_0 = 0$, we have: $Y_t = \sum_{i=1}^{t} \varepsilon_i$

Properties of Random Walk

- $\mathbb{E}[Y_t] = 0$ (constant mean)
- $\text{Var}(Y_t) = t\sigma^2$ (variance grows with time!)
- $\text{Cov}(Y_t, Y_{t-k}) = (t-k)\sigma^2$ for $k \leq t$
- ACF: $\rho_k = \sqrt{\frac{t-k}{t}} \to 1$ as $t \to \infty$

Random Walk: Visual Illustration



Key Properties

Left: Paths wander unpredictably, no mean reversion. **Right**: $\text{Var}(Y_t) = t\sigma^2$ grows linearly $\Rightarrow$ non-stationary.

TSA_ch3_def_random_walk

Proof: Random Walk Variance

Claim: For $Y_t = Y_{t-1} + \varepsilon_t$ with $Y_0 = 0$: $\text{Var}(Y_t) = t\sigma^2$

Proof: By recursive substitution: $Y_t = \sum_{i=1}^t \varepsilon_i$
Taking variance:

$$\text{Var}(Y_t) = \text{Var}\left(\sum_{i=1}^t \varepsilon_i\right) = \sum_{i=1}^t \text{Var}(\varepsilon_i) + 2\sum_{i<j} \text{Cov}(\varepsilon_i, \varepsilon_j)$$

Since ε_t independent (white noise): $\text{Var}(Y_t) = \sum_{i=1}^t \sigma^2 = \boxed{t\sigma^2}$

Variance depends on $t \Rightarrow$ non-stationary

Proof: Random Walk Autocovariance

Claim: $\text{Cov}(Y_t, Y_{t-k}) = (t-k)\sigma^2$ for $k \leq t$

Proof: Using $Y_t = \sum_{i=1}^{t} \varepsilon_i$ and $Y_{t-k} = \sum_{i=1}^{t-k} \varepsilon_i$:

$$\text{Cov}(Y_t, Y_{t-k}) = \text{Cov}\left(\sum_{i=1}^{t} \varepsilon_i, \sum_{j=1}^{t-k} \varepsilon_j\right)$$

$$= \sum_{i=1}^{t} \sum_{j=1}^{t-k} \text{Cov}(\varepsilon_i, \varepsilon_j) = \sum_{i=1}^{t-k} \text{Var}(\varepsilon_i) = \boxed{(t-k)\sigma^2}$$

Only terms with $i = j$ survive (when $i \leq t-k$).

ACF:

$$\rho(k) = \frac{\text{Cov}(Y_t, Y_{t-k})}{\sqrt{\text{Var}(Y_t)\text{Var}(Y_{t-k})}} = \frac{(t-k)\sigma^2}{\sqrt{t\sigma^2 \cdot (t-k)\sigma^2}} = \sqrt{\frac{t-k}{t}}$$

Random Walk with Drift

Definition 2 (Random Walk with Drift)

A random walk with drift includes a constant term:

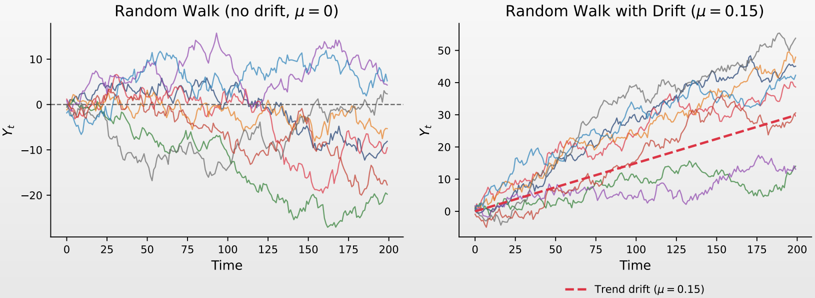
$$Y_t = \mu + Y_{t-1} + \varepsilon_t$$

Equivalently: $Y_t = Y_0 + \mu t + \sum_{i=1}^{t} \varepsilon_i$

Properties

- $\mathbb{E}[Y_t] = Y_0 + \mu t$ (mean grows linearly)
- $\text{Var}(Y_t) = t\sigma^2$ (variance still grows)
- The drift μ creates an upward or downward trend
- Still non-stationary despite having a "trend"

Random Walk with Drift: Visual Illustration

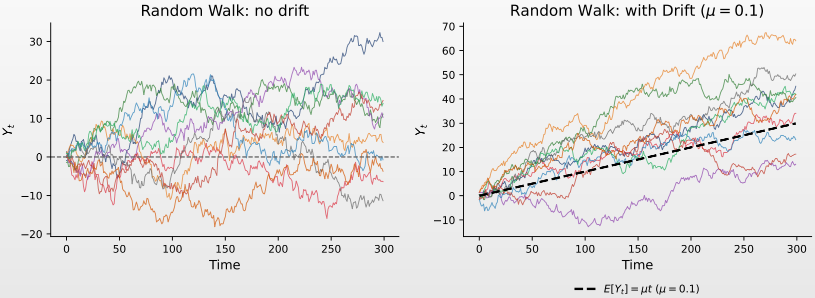


Comparison

Without drift (blue): wanders around zero with no direction. With drift $\mu > 0$ (red): systematic upward trend. Both are non-stationary — drift adds deterministic trend to stochastic wandering.

TSA_ch3_def_random_walk_drift

Simulating Random Walks

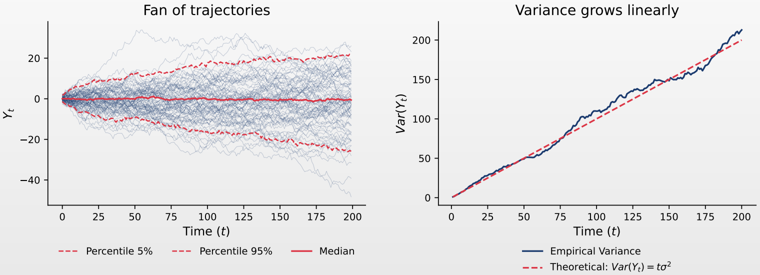


Random Walk Types

- **Left**: Pure random walks – no drift, wander unpredictably
- **Right**: Random walks with drift – upward trend on average
- Each path is unique; uncertainty grows over time

TSA_ch3_random_walk

Variance Growth: Why Random Walks Are Non-Stationary



Key Observations

- **Left**: Fan of paths shows uncertainty growing over time
- **Right**: Variance grows linearly: $\text{Var}(Y_t) = t\sigma^2$
- This violates stationarity (variance should be constant)

TSA_ch3_variance_growth

Integrated Processes

Definition 3 (Integrated Process of Order d)

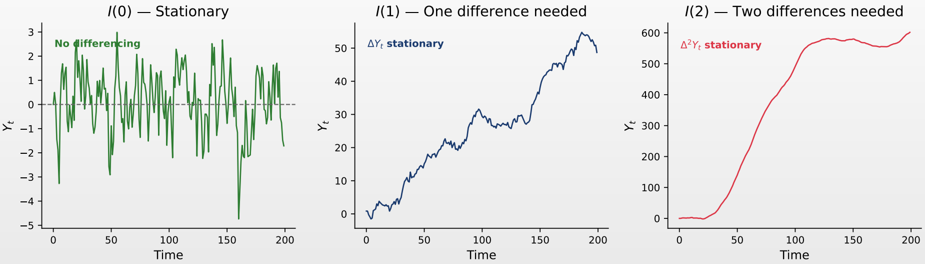
A time series $\{Y_t\}$ is **integrated of order** d, written $Y_t \sim I(d)$, if:

- Y_t is non-stationary
- $(1-L)^d Y_t = \Delta^d Y_t$ is stationary
- $(1-L)^{d-1} Y_t$ is still non-stationary

Common Cases

- $I(0)$: Stationary process (e.g., ARMA)
- $I(1)$: First difference is stationary (most common for economic data)
- $I(2)$:
  - Second difference is stationary (less common)

Integrated Process: Visual Illustration



Order of Integration

- $I(0)$: Stationary $\Rightarrow$ no differencing needed
- $I(1)$: One difference needed (random walk)
- $I(2)$: Two differences needed
- Most economic series are $I(0)$ or $I(1)$

TSA_ch3_def_integrated

The Difference Operator

Definition 4 (First Difference)

The **first difference operator** Δ is defined as: $\Delta Y_t = Y_t - Y_{t-1} = (1 - L)Y_t$, where L is the lag operator ($LY_t = Y_{t-1}$).

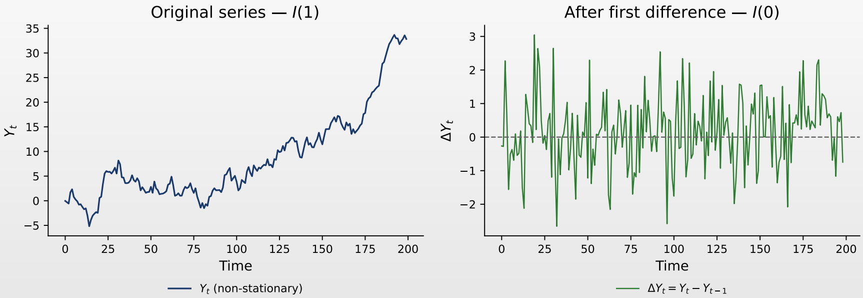
Higher-Order Differences

- Second difference: $\Delta^2 Y_t = \Delta(\Delta Y_t) = (1 - L)^2 Y_t$
- $\Delta^2 Y_t = Y_t - 2Y_{t-1} + Y_{t-2}$
- d-th difference: $\Delta^d Y_t = (1 - L)^d Y_t$

Key Result

If $Y_t \sim I(d)$, then $\Delta^d Y_t \sim I(0)$ (stationary).

First Difference: Visual Illustration



Observation

- **Left**: non-stationary series
- **Right**: after first difference, the series becomes stationary

TSA_ch3_def_difference

Example: Differencing a Random Walk

Random Walk to White Noise

Let $Y_t = Y_{t-1} + \varepsilon_t$ (random walk). Taking the first difference:

$$\Delta Y_t = Y_t - Y_{t-1} = \varepsilon_t$$

The first difference is white noise – a stationary process!

Interpretation

- A random walk is $I(1)$
- One difference transforms it to $I(0)$
- The “changes” in a random walk are stationary

Proof: Differencing Induces Stationarity

Claim: If $Y_t \sim I(1)$, then $\Delta Y_t = Y_t - Y_{t-1}$ is stationary.

Proof for Random Walk with Drift: $Y_t = \mu + Y_{t-1} + \varepsilon_t$
The first difference is:

$$\Delta Y_t = Y_t - Y_{t-1} = \mu + \varepsilon_t$$

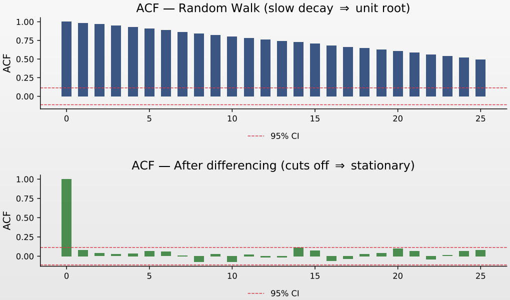
Check stationarity conditions:

1. **Mean:** $\mathbb{E}[\Delta Y_t] = \mu$ (constant, does not depend on t) ✓
2. **Variance:** $\text{Var}(\Delta Y_t) = \text{Var}(\varepsilon_t) = \sigma^2$ (constant) ✓
3. **Autocovariance:** $\text{Cov}(\Delta Y_t, \Delta Y_{t-k}) = \text{Cov}(\varepsilon_t, \varepsilon_{t-k}) = 0$ for $k \neq 0$ ✓

General Principle

- Differencing removes the "memory" that causes variance to accumulate
- For $I(d)$ processes, d differences are needed

ACF Diagnostic: Detecting Non-Stationarity

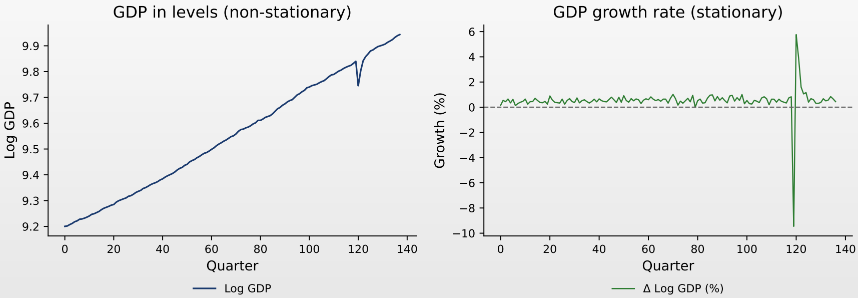


ACF Patterns

- **Top**: Random walk ACF decays very slowly $\Rightarrow$ unit root
- **Bottom**: After differencing, ACF cuts off $\Rightarrow$ stationary

TSA_ch3_acf_nonstationary

Differencing in Practice: GDP Example



Transformation

Left: GDP in levels with clear upward trend (non-stationary). **Right**: GDP growth rate $\Delta \log(GDP_t)$ fluctuates around constant mean (stationary). One difference removes the stochastic trend.

TSA_ch3_differencing

Overdifferencing

Warning: Overdifferencing

Differencing more than necessary introduces problems:

- Creates artificial negative autocorrelation
  - ACF shows spurious patterns
- Inflates variance
  - Reduces forecast accuracy
- Loses information
  - Cannot recover original level

Example

If $Y_t \sim I(1)$, then $\Delta Y_t \sim I(0)$. But if we difference again:

$$\Delta^2 Y_t = \Delta Y_t - \Delta Y_{t-1} = \varepsilon_t - \varepsilon_{t-1}$$

This is an MA(1) with $\theta = 1$ (non-invertible boundary)!

Definition of ARIMA

Definition 5 (ARIMA(p,d,q))

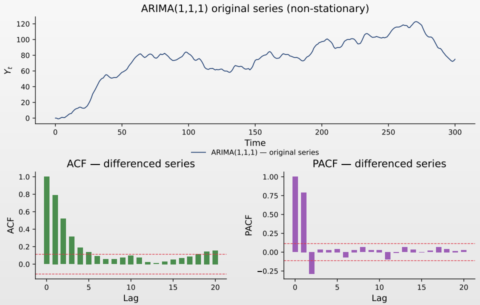
A time series $\{Y_t\}$ follows an **ARIMA(p,d,q)** process if:

$$\phi(L)(1-L)^d Y_t = c + \theta(L)\varepsilon_t$$

where:

- $\phi(L) = 1 - \phi_1 L - \phi_2 L^2 - \cdots - \phi_p L^p$ (AR polynomial)
- $\theta(L) = 1 + \theta_1 L + \theta_2 L^2 + \cdots + \theta_q L^q$ (MA polynomial)
- d is the order of integration (number of differences)
- $\varepsilon_t \sim WN(0, \sigma^2)$

ARIMA: Visual Illustration



Interpretation

Top: original ARIMA series (non-stationary). Bottom: after differencing d times, ACF/PACF reveal the AR and MA orders for the stationary component.

TSA_ch3_def_arima

ARIMA Components

AR(p)	I(d)	MA(q)
Autoregressive Memory	Integration Differencing	Moving Average Shocks

Special Cases

- ARIMA(p,0,q) = ARMA(p,q) – stationary
- ARIMA(0,1,0) = Random walk
- ARIMA(0,1,1) = IMA(1,1) – exponential smoothing
- ARIMA(1,1,0) = ARI(1,1) – differenced AR(1)

ARIMA(1,1,0) Example

ARI(1,1) Model

$$\Delta Y_t = c + \phi_1 \Delta Y_{t-1} + \varepsilon_t$$

Equivalently: $(1 - \phi_1 L)(1 - L) Y_t = c + \varepsilon_t$

Interpretation

- The **changes** in Y_t follow an AR(1) process
- If $|\phi_1| < 1$, the changes are stationary
- Y_t itself has a stochastic trend
- Common model for many economic time series

ARIMA(0,1,1) Example

IMA(1,1) Model

$$\Delta Y_t = c + \varepsilon_t + \theta_1 \varepsilon_{t-1}$$

Equivalently: $(1 - L)Y_t = c + (1 + \theta_1 L)\varepsilon_t$

Connection to Exponential Smoothing

The IMA(1,1) model is equivalent to **simple exponential smoothing**:

$$\hat{Y}_{t+1} = \alpha Y_t + (1 - \alpha)\hat{Y}_t$$

where $\alpha = 1 + \theta_1$ (for $-1 < \theta_1 < 0$).

The Role of the Constant in ARIMA

Constant Term in ARIMA(p,d,q)

When $d > 0$, the constant c has a different interpretation: $\phi(L)(1-L)^d Y_t = c + \theta(L)\varepsilon_t$

Important Implications

- For $d = 1$: c represents the **drift**
  - Average change: $\mathbb{E}[\Delta Y_t] = \frac{c}{1-\phi_1-\cdots-\phi_p}$
  - Linear trend in levels
- For $d = 2$: c affects the **curvature**
  - Quadratic trend in levels
- Often $c = 0$ is assumed when $d \geq 1$
  - No deterministic trend component

Testing for Unit Roots

Why Test?

Before fitting an ARIMA model, we need to determine:

1. Is the series stationary? (Is $d = 0$?)
2. If not, how many differences are needed? (What is d?)

Common Unit Root Tests

- **Dickey-Fuller (DF)** and **Augmented Dickey-Fuller (ADF)**
- **Phillips-Perron (PP)**
- **KPSS** (stationarity test – reversed null hypothesis)

Researcher Spotlight: Dickey & Fuller

David Dickey (*1945)

W Wikipedia

Wayne Fuller (1931–2022)

W Wikipedia

Biography

- **David Dickey**: American statistician at NC State University. PhD student of Wayne Fuller at Iowa State
- **Wayne Fuller**: American statistician, professor at Iowa State University
- Together they developed the foundational test for unit roots in time series

Key Contributions

- **Dickey-Fuller test** (1979) — the fundamental unit root test
- **Augmented Dickey-Fuller (ADF)** — extension with lagged differences
- **Critical value tables** — non-standard distributions under the null
- Enabled rigorous testing of integration order for ARIMA modeling

The Dickey-Fuller Test

Setup

Consider the AR(1) model: $Y_t = \phi Y_{t-1} + \varepsilon_t$. Subtract Y_{t-1}: $\Delta Y_t = (\phi - 1)Y_{t-1} + \varepsilon_t = \gamma Y_{t-1} + \varepsilon_t$, where $\gamma = \phi - 1$.

Hypotheses

- H_0: $\gamma = 0$ (unit root, $\phi = 1$, non-stationary)
- H_1: $\gamma < 0$ (stationary, $|\phi| < 1$)

Key Issue

Under H_0, the t-statistic does **not** follow a standard t-distribution! Must use Dickey-Fuller critical values.

Dickey-Fuller Test Variants

Three Specifications

1. **No constant, no trend**: $\Delta Y_t = \gamma Y_{t-1} + \varepsilon_t$
2. **With constant (drift)**: $\Delta Y_t = \alpha + \gamma Y_{t-1} + \varepsilon_t$
3. **With constant and trend**: $\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \varepsilon_t$

Choosing the Right Specification

- Examine the data: does it have a visible trend?
- Including unnecessary terms reduces power
- Excluding necessary terms leads to incorrect inference

Augmented Dickey-Fuller (ADF) Test

The Problem with Simple DF

If AR dynamics beyond AR(1) exist, DF residuals will be autocorrelated.

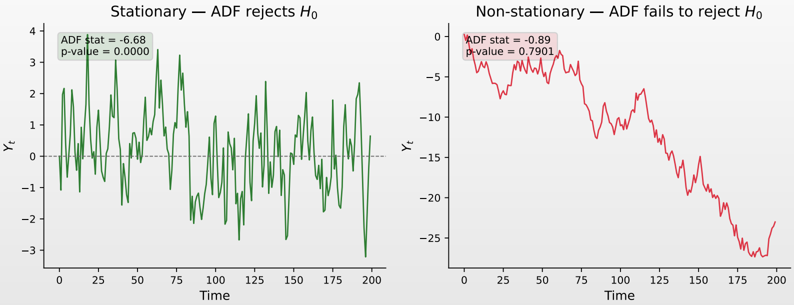
Definition 6 (ADF Test)

Add lagged differences: $\Delta Y_t = \alpha + \beta t + \gamma Y_{t-1} + \sum_{j=1}^{k} \delta_j \Delta Y_{t-j} + \varepsilon_t$
Test $H_0 : \gamma = 0$ using ADF critical values.

Choosing Lag Length k

- Use information criteria (AIC, BIC)
- Start with k_{max}, reduce until last lag significant

ADF Test: Visual Illustration



Observation

- **Left**: stationary series $\Rightarrow$ ADF rejects unit root
- **Right**: non-stationary $\Rightarrow$ ADF fails to reject

TSA_ch3_def_adf

ADF Test Critical Values

Model	**1%**	**5%**	**10%**
No constant, no trend	-2.58	-1.95	-1.62
With constant	-3.43	-2.86	-2.57
With constant and trend	-3.96	-3.41	-3.13

Decision Rule

- Test statistic $<$ critical value $\Rightarrow$ Reject H_0 (stationary)
- Test statistic $\geq$ critical value $\Rightarrow$ Fail to reject (unit root)

The Phillips-Perron (PP) Test

Motivation

Like ADF, tests H_0: Unit root vs H_1: Stationary, but uses a **non-parametric correction** for serial correlation instead of adding lagged differences.

Test Statistic

The PP test modifies the DF t-statistic:

$$Z_t = t_{\hat{\gamma}} \cdot \sqrt{\frac{\hat{\sigma}^2}{\hat{\lambda}^2}} - \frac{T(\hat{\lambda}^2 - \hat{\sigma}^2)(se(\hat{\gamma}))}{2\hat{\lambda}^2 \cdot s}$$

where $\hat{\lambda}^2$ is a consistent estimate of the long-run variance using Newey-West.

Advantages over ADF

- Robust to heteroskedasticity and serial correlation
- No need to select lag length (uses bandwidth instead)

The KPSS Test

Reversed Hypotheses

Unlike ADF: H_0: Stationary vs H_1: Unit root

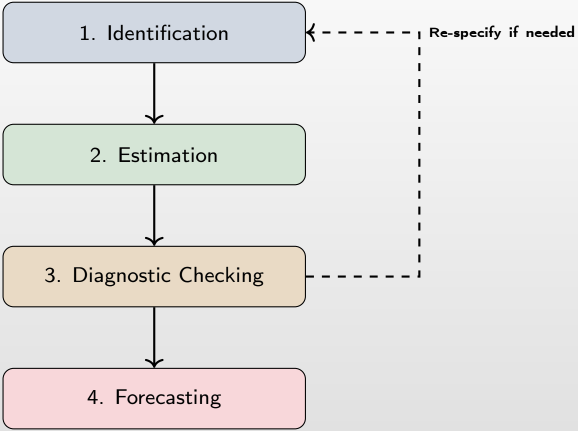
KPSS Procedure

Decompose: $Y_t = \xi t + r_t + \varepsilon_t$ where $r_t = r_{t-1} + u_t$. Test whether $\text{Var}(u_t) = 0$.

Complementary Use with ADF

- ADF rejects, KPSS doesn't $\Rightarrow$ Stationary
- ADF doesn't reject, KPSS rejects $\Rightarrow$ Unit root
- Both reject or neither $\Rightarrow$ Inconclusive

The Box-Jenkins Methodology



Step 1: Determining d

Procedure

1. Plot the time series – look for trends, changing variance
2. Examine ACF – slow decay suggests non-stationarity
3. Apply unit root tests (ADF, KPSS)
4. If non-stationary, difference and repeat

Practical Guidelines

- Most economic series: $d = 1$ is sufficient
- Rarely need $d > 2$
- If ACF of ΔY_t still decays slowly, try $d = 2$
- Watch for overdifferencing (ACF with $\rho_1 \approx -0.5$)

Step 2: Determining p and q

After Differencing

Once $W_t = \Delta^d Y_t$ is stationary, use ACF/PACF to identify ARMA(p,q):

Model	**ACF**	**PACF**
AR(p)	Decays exponentially	Cuts off after lag p
MA(q)	Cuts off after lag q	Decays exponentially
ARMA(p,q)	Decays	Decays

Information Criteria

When patterns are unclear, compare models using:

- $\text{AIC} = -2\ln(L) + 2k; \quad \text{BIC} = -2\ln(L) + k\ln(n)$

Lower is better. BIC penalizes complexity more.

Auto-ARIMA Algorithms

Automated Model Selection

Modern software can automatically select (p, d, q):

- Python: `pmdarima.auto_arima()`
- R: `forecast::auto.arima()`

How Auto-ARIMA Works

1. Use unit root tests to determine d
2. Fit models for various (p, q) combinations
3. Select model with lowest AIC/BIC
4. Optionally use stepwise search for efficiency

Caution

Automated selection is helpful but not infallible. Always check diagnostics!

Estimation Methods

Maximum Likelihood Estimation (MLE)

The standard approach for ARIMA:

- Assumes $\varepsilon_t \sim N(0, \sigma^2)$
- Maximizes the likelihood function
- Provides consistent, efficient estimators
- Yields standard errors for inference

Conditional vs Exact MLE

- **Conditional MLE**: Conditions on initial values
- **Exact MLE**: Treats initial values as unknown
- Difference diminishes as sample size grows

Conditional Log-Likelihood

Gaussian Log-Likelihood Function

- $\ell(\boldsymbol{\theta}, \sigma^2) = -\frac{T}{2}\ln(2\pi) - \frac{T}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}\sum_{t=1}^{T} e_t^2(\boldsymbol{\theta})$
- $e_t(\boldsymbol{\theta}) = X_t - \hat{X}_{t|t-1}$ are the **one-step prediction errors**
- $\boldsymbol{\theta} = (\phi_1, \ldots, \phi_p, \theta_1, \ldots, \theta_q, c)$

Example: ARIMA(1,1,1)

- Prediction errors: $e_t = \Delta X_t - \phi_1 \Delta X_{t-1} - \theta_1 e_{t-1} - c$
- Conditional MLE: set $e_0 = 0$, compute $e_1, \ldots, e_T$, maximize ℓ

Estimating σ^2

- At optimal parameters $\hat{\boldsymbol{\theta}}$: $\hat{\sigma}^2 = \frac{1}{T}\sum_{t=1}^{T} e_t^2(\hat{\boldsymbol{\theta}})$

Parameter Constraints

Stationarity and Invertibility

The estimated ARIMA model should satisfy:

- **AR stationarity**: Roots of $\phi(z) = 0$ outside unit circle
- **MA invertibility**: Roots of $\theta(z) = 0$ outside unit circle

Checking in Practice

Most software reports:

- Estimated coefficients with standard errors
- Roots of AR and MA polynomials
- Warning if near-unit-root detected

Residual Analysis

What to Check

If the model is correct, residuals $\hat{\varepsilon}_t$ should be white noise:

1. Zero mean
2. Constant variance
3. No autocorrelation
4. (Optional) Normality

Diagnostic Tools

- **Residual ACF/PACF**: Should show no significant spikes
- **Ljung-Box test**: Tests for autocorrelation at multiple lags
- **Q-Q plot**: Checks normality assumption
- **Residual vs fitted**:
  - Checks for heteroskedasticity

The Ljung-Box Test

Definition 7 (Ljung-Box Q Statistic)

$Q(m) = n(n+2)\sum_{k=1}^{m} \frac{\hat{\rho}_k^2}{n-k}$. Under H_0 (no autocorrelation): $Q(m) \sim \chi^2(m-p-q)$

Usage

- Choose $m \approx \ln(n)$ or $m = 10$ for quarterly, $m = 20$ for monthly
- Degrees of freedom adjusted for estimated parameters
- Reject if $Q(m)$ exceeds critical value

If Test Fails

Consider adding AR or MA terms, or check for structural breaks.

Point Forecasts

Minimum MSE Forecast

The optimal h-step ahead forecast is the conditional expectation: $\hat{Y}_{T+h|T} = \mathbb{E}[Y_{T+h}|Y_T, Y_{T-1}, \ldots]$

ARIMA(1,1,1) Forecasting

Model: $(1-\phi_1 L)(1-L)Y_t = c + (1+\theta_1 L)\varepsilon_t$
One-step forecast: $\hat{Y}_{T+1|T} = c + Y_T + \phi_1(Y_T - Y_{T-1}) + \theta_1\hat{\varepsilon}_T$
For $h > 1$: replace unknown ε_{T+j} with 0, unknown Y_{T+j} with $\hat{Y}_{T+j|T}$

Forecast Intervals

Forecast Uncertainty

The h-step forecast error variance: $\text{Var}(e_{T+h}) = \sigma^2 \sum_{j=0}^{h-1} \psi_j^2$, where ψ_j are MA(∞) coefficients.

Confidence Intervals

Under normality, $(1-\alpha)$% interval: $\hat{Y}_{T+h|T} \pm z_{\alpha/2}\sqrt{\text{Var}(e_{T+h})}$

Key Property for I(1) Series

For integrated processes, forecast variance grows without bound as $h \to \infty$. Intervals widen over time!

Long-Run Forecasts for ARIMA

Behavior as $h \to \infty$

For ARIMA(p,1,q) with drift c:

- Point forecasts: Linear trend with slope = drift
- Forecast intervals: Width grows with $\sqrt{h}$

For ARIMA(p,1,q) without drift:

- Point forecasts: Converge to last level
- Forecast intervals: Still grow unboundedly

Practical Implication

- ARIMA forecasts are most reliable for short horizons
- Long-term forecasts have very wide uncertainty bands

Rolling Forecasting: Concept

What is Rolling Forecasting?

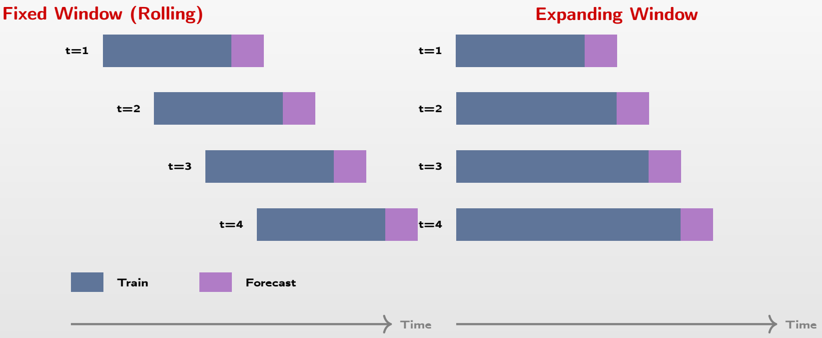
A technique to evaluate forecast accuracy out-of-sample:

1. Fix a **training window** of size w
2. Estimate model on observations $t = 1, \ldots, w$
3. Forecast h steps ahead: $\hat{Y}_{w+h|w}$
4. **Roll** the window forward by one period
5. Repeat until end of sample

Why Rolling Forecasts?

- Mimics real-time forecasting scenario
- Provides multiple forecast errors for evaluation
- Avoids overfitting to full sample

Fixed vs Expanding Window



Comparison

- **Fixed**: Window slides forward, constant size — adapts to regime changes
- **Expanding**: Window grows over time — uses all historical data

1-Step vs Multi-Step Forecasting

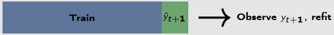
1-Step Ahead (Recursive)

- Forecast only next period
  - Refit model after each step
  - Use actual value once revealed
- Most accurate for short horizons

Multi-Step (Direct)

- Forecast multiple periods ahead
  - No refit between steps
  - Uses forecasted values as inputs
- Uncertainty compounds over horizon

1-Step Ahead



Multi-Step (h=3)

Rolling Forecast: Step-by-Step Example

Setup: ARIMA(1,1,0) with $\phi_1 = 0.6$

Model: $\Delta Y_t = \phi_1 \Delta Y_{t-1} + \varepsilon_t$ where $\Delta Y_t = Y_t - Y_{t-1}$

Given Data at Time T

$Y_{T-2} = 100, \quad Y_{T-1} = 103, \quad Y_T = 108 \quad \Rightarrow \quad \Delta Y_{T-1} = 3, \quad \Delta Y_T = 5$

1-Step Ahead Point Forecast

$$\begin{aligned} \hat{\Delta Y}_{T+1|T} &= \phi_1 \cdot \Delta Y_T = 0.6 \times 5 = 3 \\ \hat{Y}_{T+1|T} &= Y_T + \hat{\Delta Y}_{T+1|T} = 108 + 3 = \boxed{111} \end{aligned}$$

Multi-Step Point Forecasts

2-Step Ahead Forecast

$$\begin{aligned} \Delta\hat{Y}_{T+2|T} &= \phi_1 \cdot \Delta\hat{Y}_{T+1|T} = 0.6 \times 3 = 1.8 \\ \hat{Y}_{T+2|T} &= \hat{Y}_{T+1|T} + \Delta\hat{Y}_{T+2|T} = 111 + 1.8 = \boxed{112.8} \end{aligned}$$

General Formula for *h*-Step Forecast (ARIMA(1,1,0))

$$\begin{aligned} \Delta\hat{Y}_{T+h|T} &= \phi_1^h \cdot \Delta Y_T \\ \hat{Y}_{T+h|T} &= Y_T + \Delta Y_T \cdot \frac{\phi_1(1-\phi_1^h)}{1-\phi_1} \end{aligned}$$

Numerical: 3-Step Forecast

$\hat{Y}_{T+3|T} = 108 + 5 \times \frac{0.6(1-0.6^3)}{1-0.6} = 108 + 5 \times 1.092 = \boxed{113.46}$

Confidence Intervals: Formulas

Forecast Error Variance

For ARIMA(1,1,0), the h-step forecast error variance:

$$\text{Var}(e_{T+h|T}) = \sigma^2 \left(1 + \sum_{j=1}^{h-1} \psi_j^2\right)$$

where $\psi_j = \phi_1^{j-1}(1 + \phi_1 + \cdots + \phi_1^{j-1}) = \phi_1^{j-1} \cdot \frac{1-\phi_1^j}{1-\phi_1}$

$(1-\alpha)\%$ Confidence Interval

$$\hat{Y}_{T+h|T} \pm z_{\alpha/2} \cdot \sqrt{\text{Var}(e_{T+h|T})}$$

For 95% CI: $z_{0.025} = 1.96$

Confidence Interval: Numerical Example

Given: $\sigma^2 = 4$, $\phi_1 = 0.6$, $\hat{Y}_{T+1|T} = 111$

1-Step Ahead CI

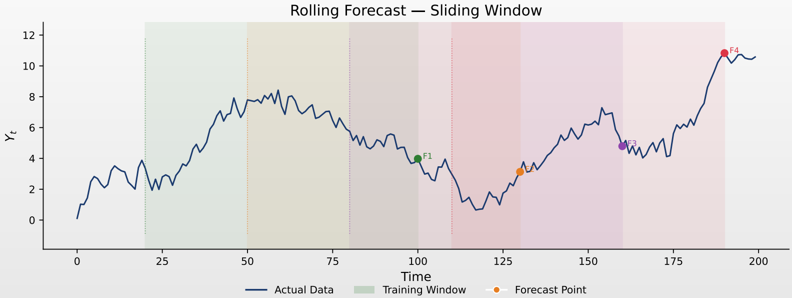
$$\mathrm{Var}(e_{T+1|T}) = \sigma^2 = 4$$
$$95\%\ \mathrm{CI} = 111 \pm 1.96 \times \sqrt{4} = 111 \pm 3.92 = \boxed{[107.08,\ 114.92]}$$

2-Step Ahead CI (for $\hat{Y}_{T+2|T} = 112.8$)

$$\psi_1 = 1 + \phi_1 = 1.6, \quad \mathrm{Var}(e_{T+2|T}) = 4(1 + 1.6^2) = 14.24$$
$$95\%\ \mathrm{CI} = 112.8 \pm 1.96 \times \sqrt{14.24} = 112.8 \pm 7.40 = \boxed{[105.40,\ 120.20]}$$

Note: CI widens as horizon increases!

Rolling Window Illustration



Rolling Procedure

- Each window produces a 1-step ahead forecast
- Compare forecasts to actuals to compute RMSE, MAE
- Rolling window keeps model estimation up-to-date

TSA_ch3_rolling_forecast

Case Study: Complete ARIMA Analysis

Objective

- Forecast US Real GDP using the Box-Jenkins methodology

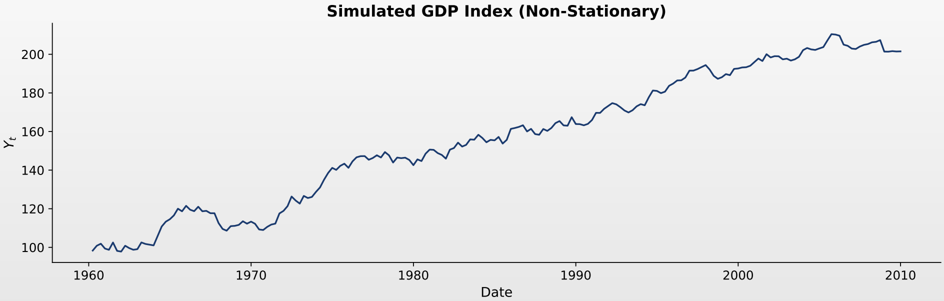
Steps

1. **Step 1**: Visualize data and check stationarity
2. **Step 2**: Apply unit root tests (ADF, KPSS)
3. **Step 3**: Difference if needed, identify p and q
4. **Step 4**: Estimate the ARIMA model
5. **Step 5**: Model diagnostics
6. **Step 6**: Generate forecasts with confidence intervals
7. **Step 7**: Evaluate forecast accuracy

Data

- US Real GDP (FRED: GDPC1), Quarterly, 1990Q1–2024Q2, $n = 138$

Case Study: US Real GDP (FRED)

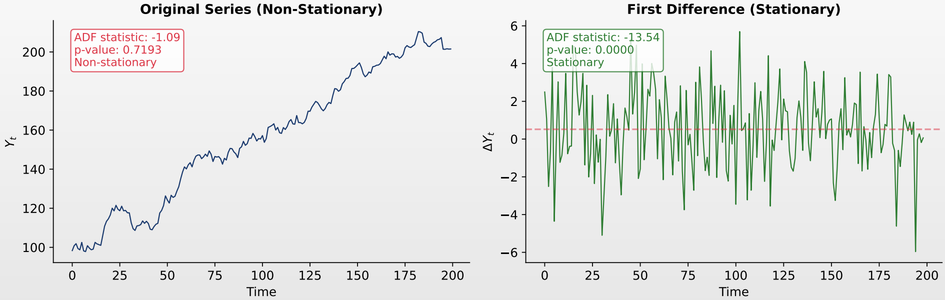


Data: FRED GDPC1 (1960Q1–2024Q3)

Quarterly Real GDP, seasonally adjusted, billions of chained 2017 dollars. Non-stationary series with upward trend ⇒ requires differencing.

TSA_ch3_case_raw_data

Step 1: ADF Test for Stationarity

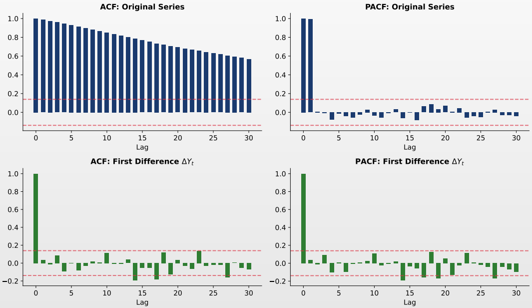


ADF Test Results

Original series: Large p-value $\Rightarrow$ fail to reject H_0 (unit root present). **First difference**: p-value $< 0.01 \Rightarrow$ reject $H_0 \Rightarrow d = 1$ is sufficient.

TSA_ch3_case_adf_test

Step 2: ACF/PACF Before and After Differencing

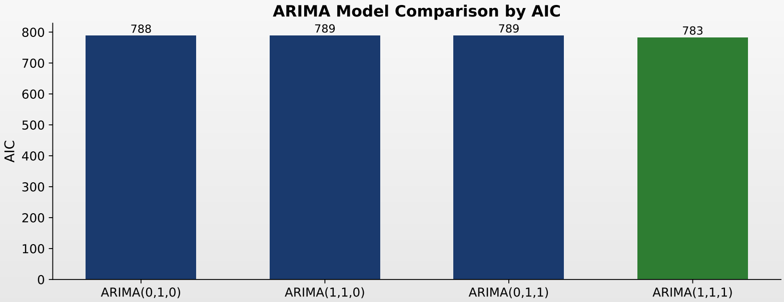


ACF/PACF Analysis

Top: Slow ACF decay (non-stationary) | Bottom: After differencing, low-order ARMA

TSA_ch3_case_acf_diff

Step 3: ARIMA Model Comparison

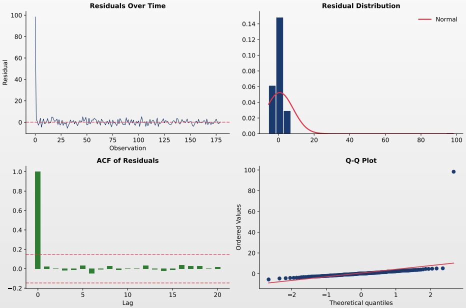


Model Selection

Compare ARIMA(0,1,0), ARIMA(1,1,0), ARIMA(0,1,1), ARIMA(1,1,1). The model with lowest AIC is selected.

TSA_ch3_case_model_comparison

Step 4: Diagnostic Checking

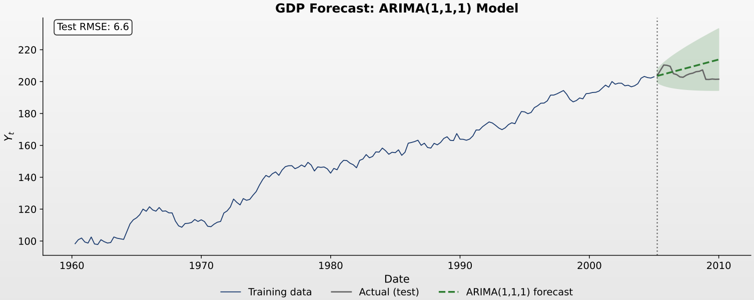


ARIMA(1,1,1) Diagnostics

ACF: no autocorrelation ✓ Q-Q: **non-normal** (COVID-19 outlier) JB test: $p < 0.001$

TSA_ch3_case_diagnostics

Step 5: Out-of-Sample Forecasting

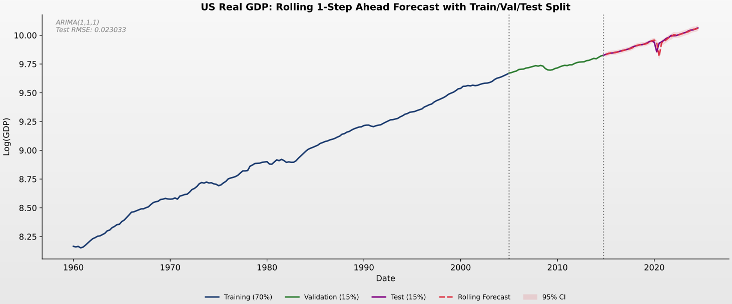


Train/Val/Test Split (70%/15%/15%)

Train 70% (blue): Estimation | **Val 15%** (green): Tuning | **Test 15%** (purple): Evaluation with 95% CI

TSA_ch3_case_forecast

Step 6: Rolling Forecast with Train/Val/Test



Rolling 1-Step Ahead Forecast (Expanding Window, 95% CI)

Train 70% → Val 15% → Test 15% | Expanding window refits model at each step

TSA_ch3_case_rolling_forecast

Summary

What we learned in this chapter

- Non-stationarity in time series
  - Deterministic vs stochastic trend; consequences for statistical inference
- Differencing and integrated processes
  - $\Delta Y_t = Y_t - Y_{t-1}$; if $Y_t \sim I(d)$, then $\Delta^d Y_t \sim I(0)$
- ARIMA(p, d, q) models and unit root tests
  - ADF, PP, KPSS; Box-Jenkins: identify $\rightarrow$ estimate $\rightarrow$ validate
- Forecasts with confidence intervals
  - For I(1): CIs widen without bound ($\propto \sqrt{h}$)

Key Insight

- **Difference carefully**: One difference is usually sufficient ($d = 1$). Over-differencing creates artificial autocorrelation.

AI Exercise: Critical Thinking

Prompt to test in ChatGPT / Claude / Copilot

"Download quarterly US Real GDP from FRED (series GDPC1) for 2000-Q1 to 2024-Q4 (100 observations). Test stationarity, difference if needed, estimate an ARIMA model, and forecast 8 quarters ahead. Give me complete Python code with plots."

Exercise:

1. Run the prompt in an LLM of your choice and critically analyze the response.
2. Does it test stationarity with ADF *before* estimating ARIMA? Does it also use KPSS?
3. How does it determine the differencing order d? Does it check for over-differencing?
4. How does it choose p and q? ACF/PACF or just auto_arima?
5. Do forecast confidence intervals widen with horizon? (key I(1) property)

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

What's Next?

Chapter 4: SARIMA Models for Seasonal Data

- **Seasonality**: repetitive patterns at regular intervals
- **Seasonal differencing**: the $(1 - L^s)$ operator
- **SARIMA$(p, d, q)(P, D, Q)_s$**: seasonal extension of ARIMA
- **Model identification**: seasonal ACF/PACF
- **Case study**: Airline passengers forecast

Questions?

Question 1

Question

- A time series Y_t follows a random walk: $Y_t = Y_{t-1} + \varepsilon_t$. What is $\text{Var}(Y_t)$?

Answer Choices

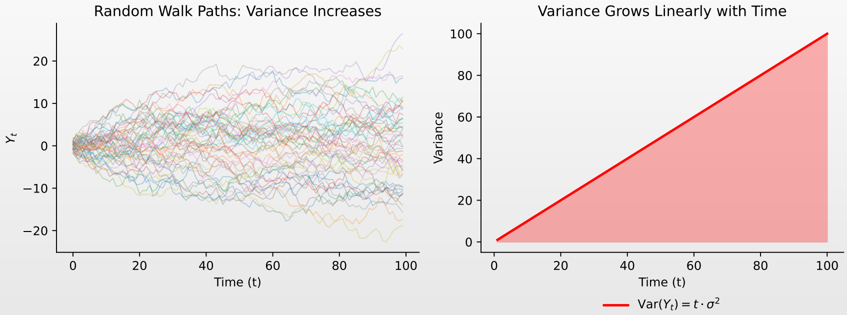
(A) σ^2 (constant)

(B) $t \cdot \sigma^2$ (grows linearly with time)

(C) σ^2/t (decreases with time)

(D) σ^{2t} (grows exponentially)

Question 1: Answer



Answer: (B)

- Random walk variance grows linearly with time — this is why random walks are non-stationary.

TSA_ch3_quiz1_rw_variance

Question 2

Question

If a series Y_t is I(2), how many times must you difference it to achieve stationarity?

Answer Choices

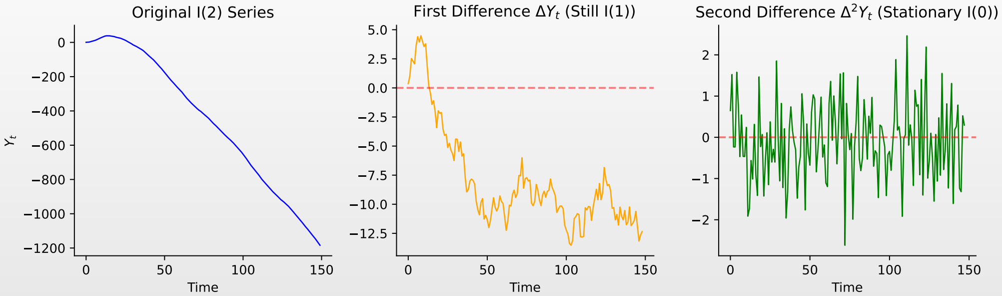
(A) 0 times (already stationary)

(B) 1 time

(C) 2 times

(D) Cannot be made stationary by differencing

Question 2: Answer



Answer: (C)

- I(d) means "integrated of order d" — requires d differences for stationarity.

TSA_ch3_quiz2_differencing

Question 3

Question

- You run an ADF test and get a test statistic of -2.1 with critical values: -3.43 (1%), -2.86 (5%), -2.57 (10%). What do you conclude?

Answer Choices

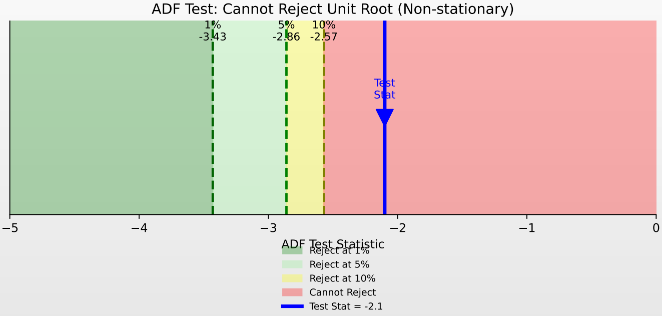
(A) Reject H_0: series is stationary at all levels

(B) Reject H_0: series is stationary at 10% level only

(C) Fail to reject H_0: series likely has a unit root

(D) The test is inconclusive

Question 3: Answer



Answer: (C)

- Test stat $-2.1 > -2.57$ (10% CV) $\Rightarrow$ Cannot reject at any level. Consider differencing.

TSA_ch3_quiz3_adf_test

Question 4

Question

- For an ARIMA(1,1,0) model, what is the ACF pattern of the **differenced** series ΔY_t?

Answer Choices

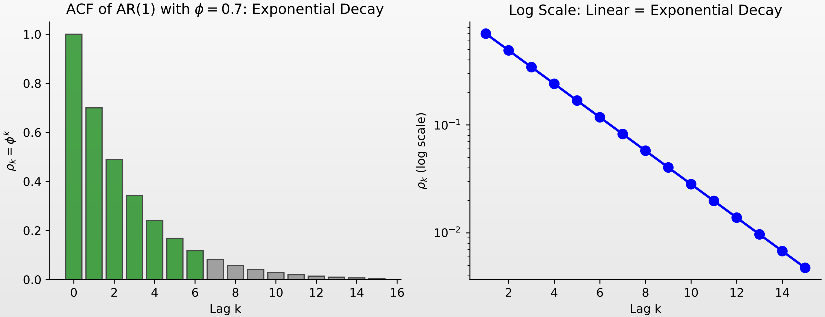
(A) Cuts off after lag 1

(B) Decays exponentially

(C) Alternates in sign

(D) Is zero at all lags

Question 4: Answer



Answer: (B)

- ARIMA(1,1,0) $\Rightarrow \Delta Y_t$ follows AR(1) with ACF $\rho_k = \phi_1^k$ (geometric decay).

TSA_ch3_quiz4_acf_decay

Question 5

Question

☐ What happens to ARIMA forecast confidence intervals as the horizon h increases for an I(1) series?

Answer Choices

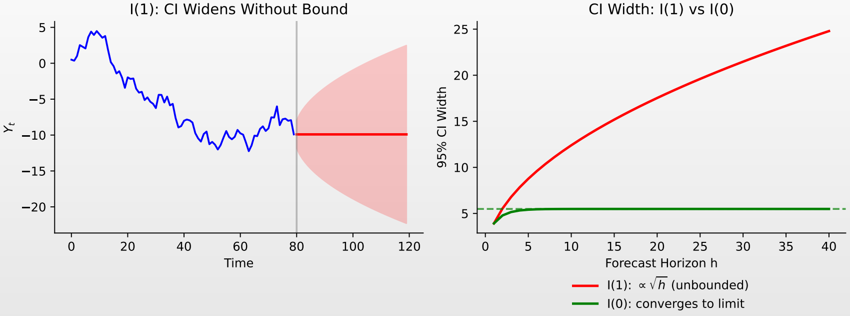
(A) They stay constant

(B) They narrow (more precision)

(C) They widen without bound

(D) They widen but converge to a limit

Question 5: Answer



Answer: (C)

- For I(1): CI width $\propto \sqrt{h}$ (unbounded). For I(0): CIs converge to a limit.

TSA_ch3_quiz5_forecast_ci

Bibliography I

Unit Root Tests

- Dickey, D.A., & Fuller, W.A. (1979). Distribution of the Estimators for Autoregressive Time Series with a Unit Root, *JASA*, 74(366), 427–431.
- Phillips, P.C.B., & Perron, P. (1988). Testing for a Unit Root in Time Series Regression, *Biometrika*, 75(2), 335–346.
- Kwiatkowski, D., Phillips, P.C.B., Schmidt, P., & Shin, Y. (1992). Testing the Null Hypothesis of Stationarity, *Journal of Econometrics*, 54(1-3), 159–178.

ARIMA Models and Automatic Selection

- Box, G.E.P., & Jenkins, G.M. (1970). *Time Series Analysis: Forecasting and Control*, Holden-Day.
- Hyndman, R.J., & Khandakar, Y. (2008). Automatic Time Series Forecasting: The `forecast` Package for R, *Journal of Statistical Software*, 27(3), 1–22.

Bibliography II

Textbooks and Additional References

- Hamilton, J.D. (1994). *Time Series Analysis*, Princeton University Press.
- Shumway, R.H., & Stoffer, D.S. (2017). *Time Series Analysis and Its Applications*, 4th ed., Springer.
- Hyndman, R.J., & Athanasopoulos, G. (2021). *Forecasting: Principles and Practice*, 3rd ed., OTexts.

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_ch3` ≻ Python code for this chapter

Thank You!

Questions?

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

Quantlet Quantinar