



Applied Data Science Program

TIME SERIES

Munther A. Dahleh

Learning Time-Series

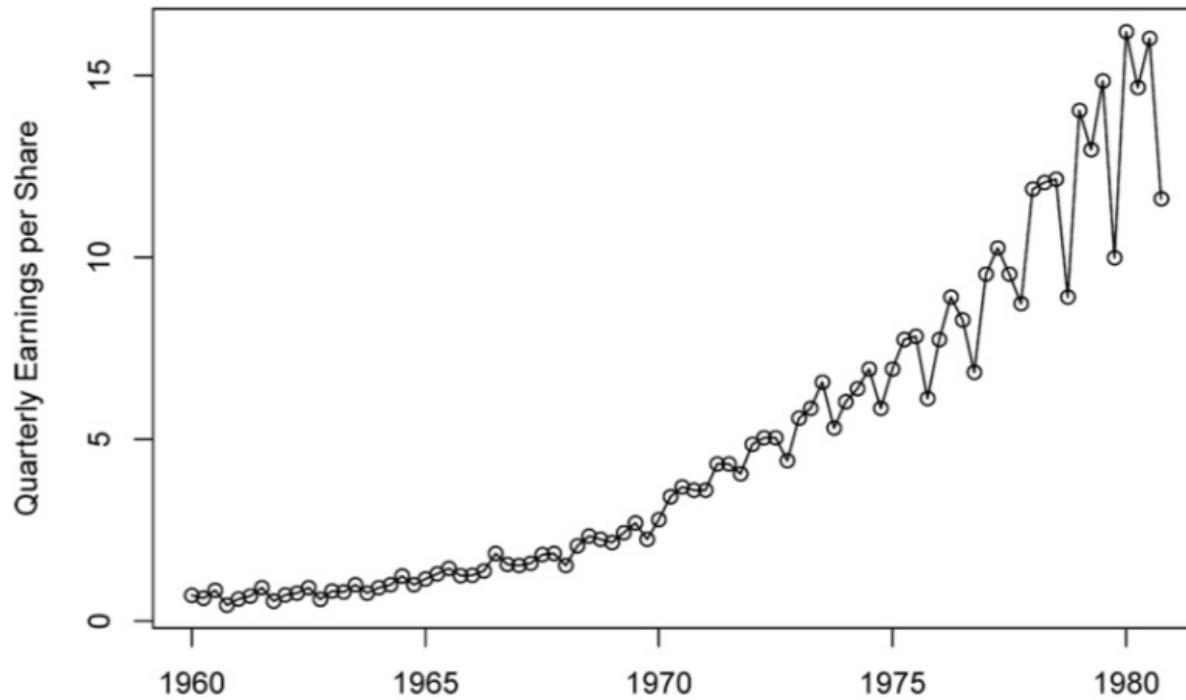
- Time Series are everywhere
 - Finance, weather, control systems
- Questions:
 - Modeling
 - Forecasting
 - Decisions and policy

Learning Time-Series: Outline

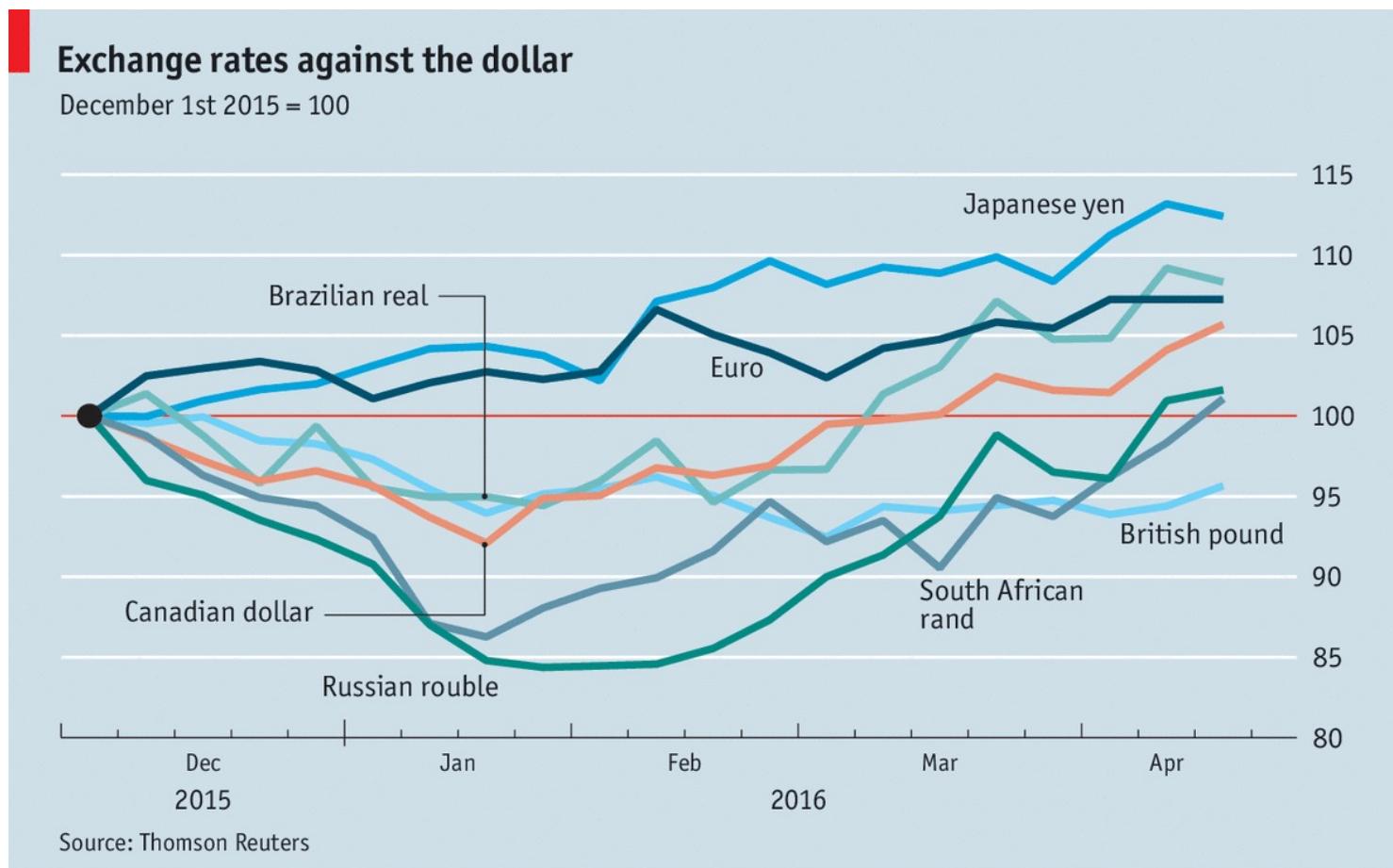
- Part I: Introduction to Time Series
 - Stationarity
 - Trends
- Part II: Models of Time Series
- Part 3: Learning Time Series

Introduction

Johnson & Johnson quarterly earnings per share

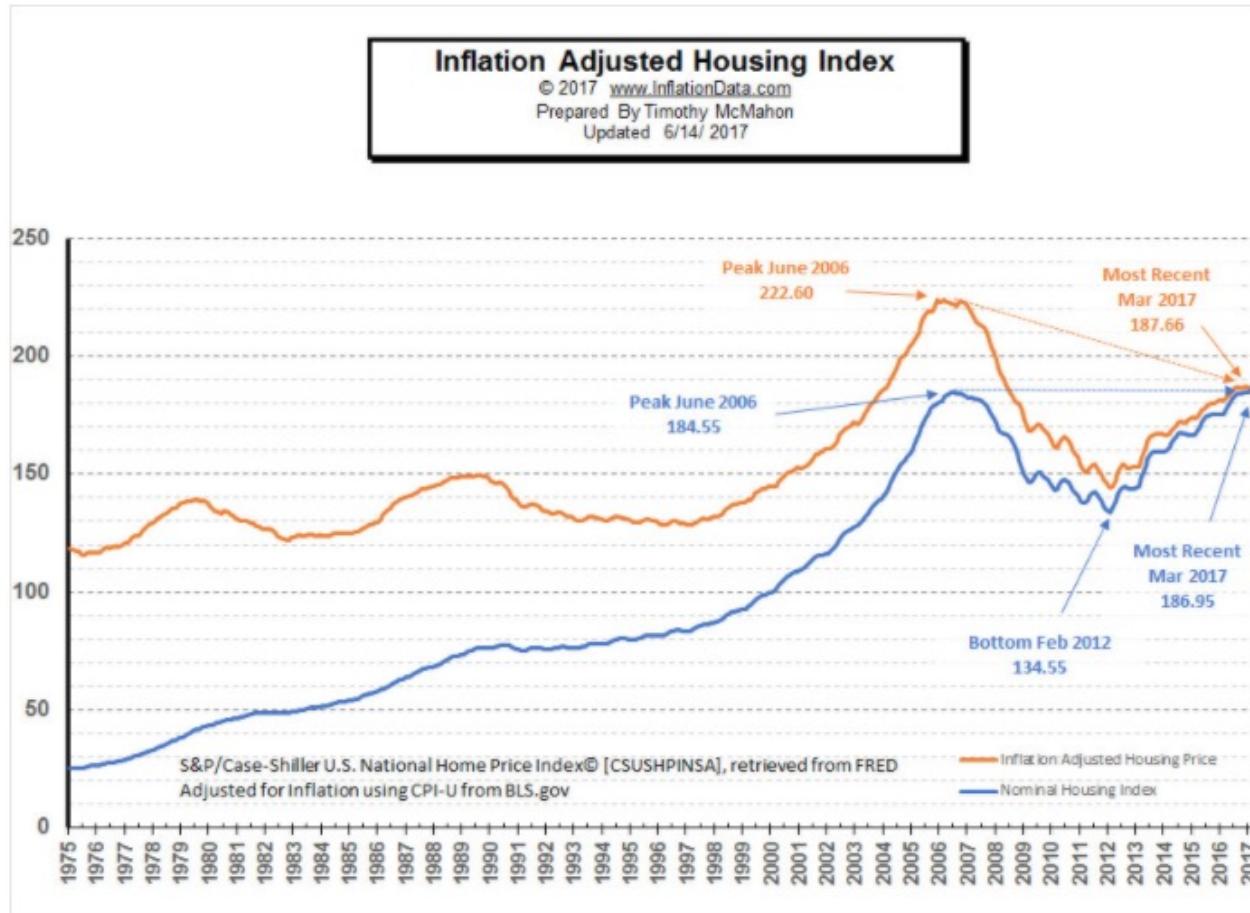


Exchange Rates Against the Dollar

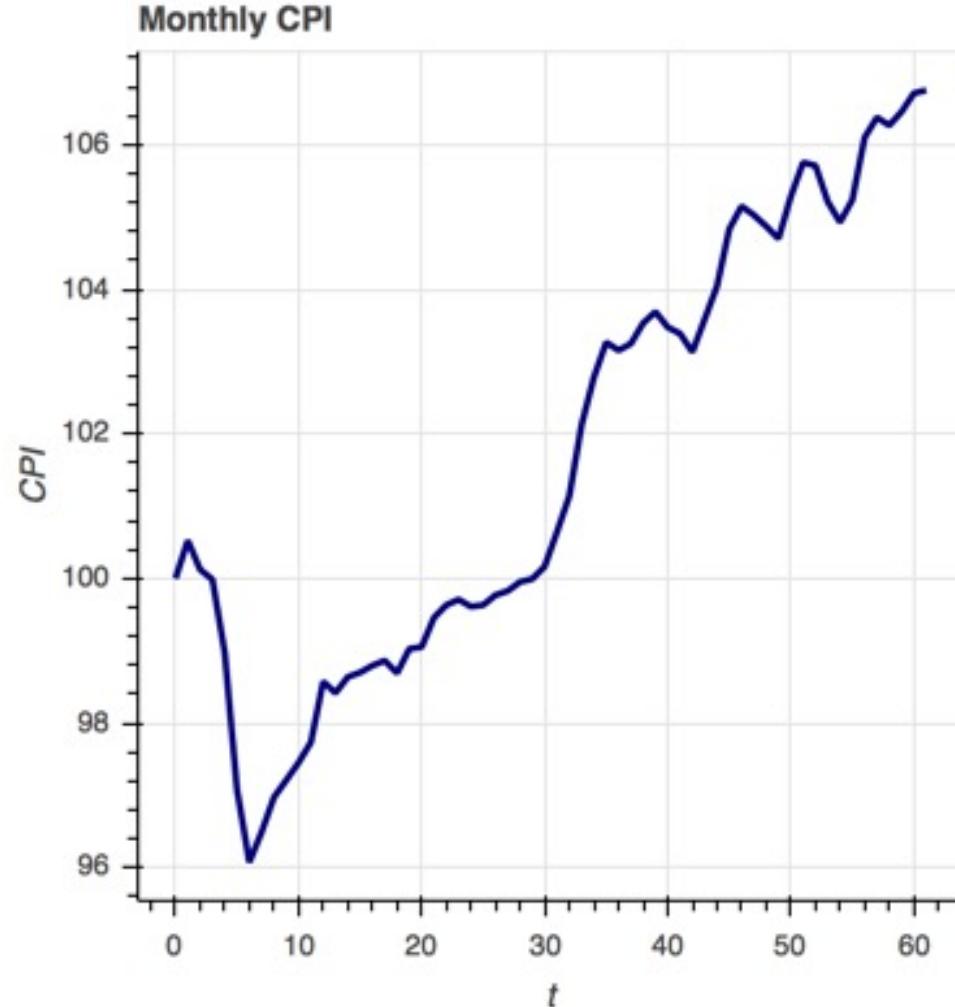


Economist.com

House Prices



Consumer Price Index (billion Prices)



...What is new here?

- What you measure today depends on yesterday
 - Could be simple or complicated dependence
 - Memory can be high
 - Memory is typically unknown
- The variation in the data can be due to a time-varying average: trends
 - Linear, quadratic (deterministic)
 - Periodic (seasonal)
- Transformation of the data may help

Stationarity

- Time series need to have some structure
- Stationarity: Some variables are ‘constant’ over time
 - Mean
 - Autocovariance
- What happens if such variables are changing
 - Transform to a stationary series
 - Assume slow variation

Mean and Autocovariance

- Mean of process

$$\mu_t = \mathbf{E}(X_t)$$

- Autocovariance

$$R_X(t_1, t_2) = \mathbf{E}((X_{t_1} - \mu_{t_1})(X_{t_2} - \mu_{t_2}))$$

Stationarity

- Mean of process is constant over time
- Sample Mean (constant over λ)

$$\mathbf{E}(X_t) = \mu$$

$$\hat{\mu} = \frac{1}{N - \lambda} \sum_{i=\lambda}^{N-1} X_i$$

Testing Stationarity: Should not see large variations over λ

Mean and Autocovariance: Stationarity

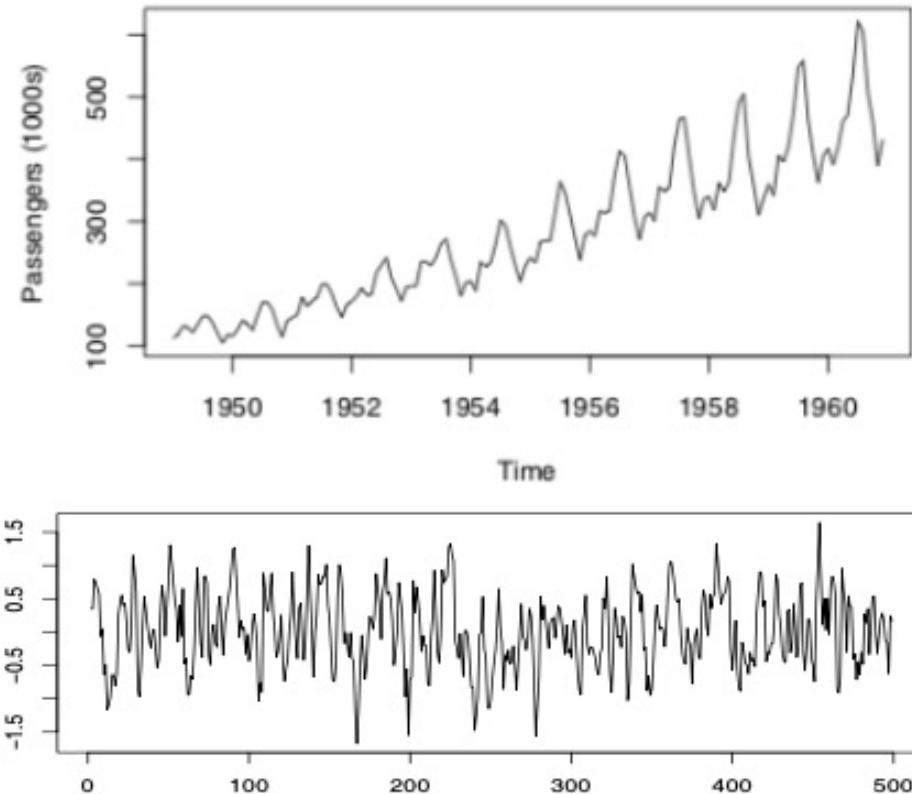
- Autocovariance is a function of the time difference
- Sample Autocovariance

$$R_X(t, t + \tau) = R_X(\tau)$$

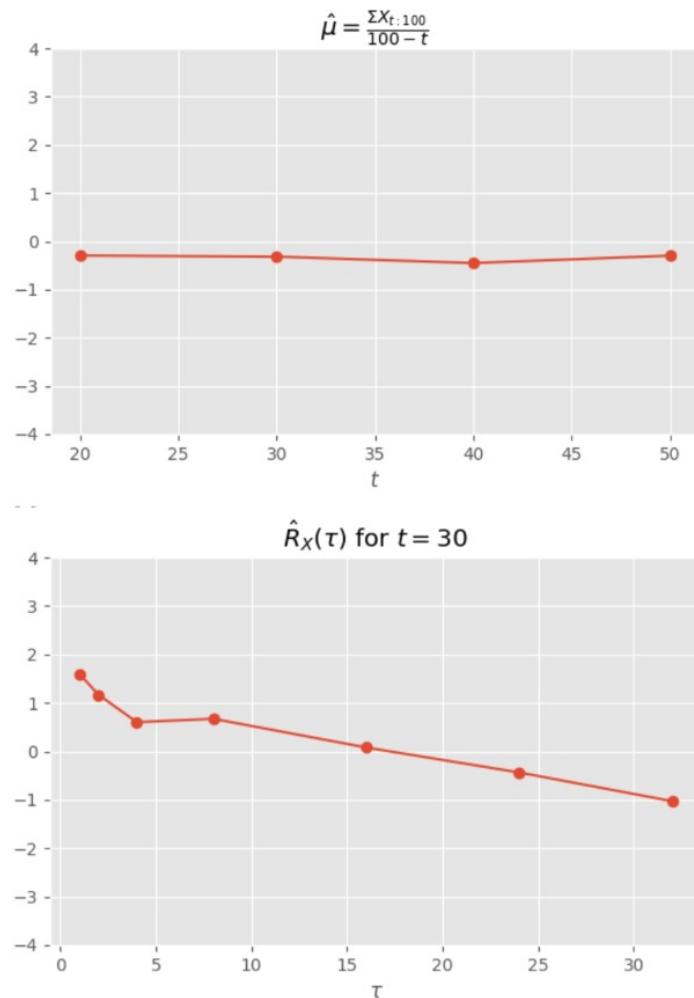
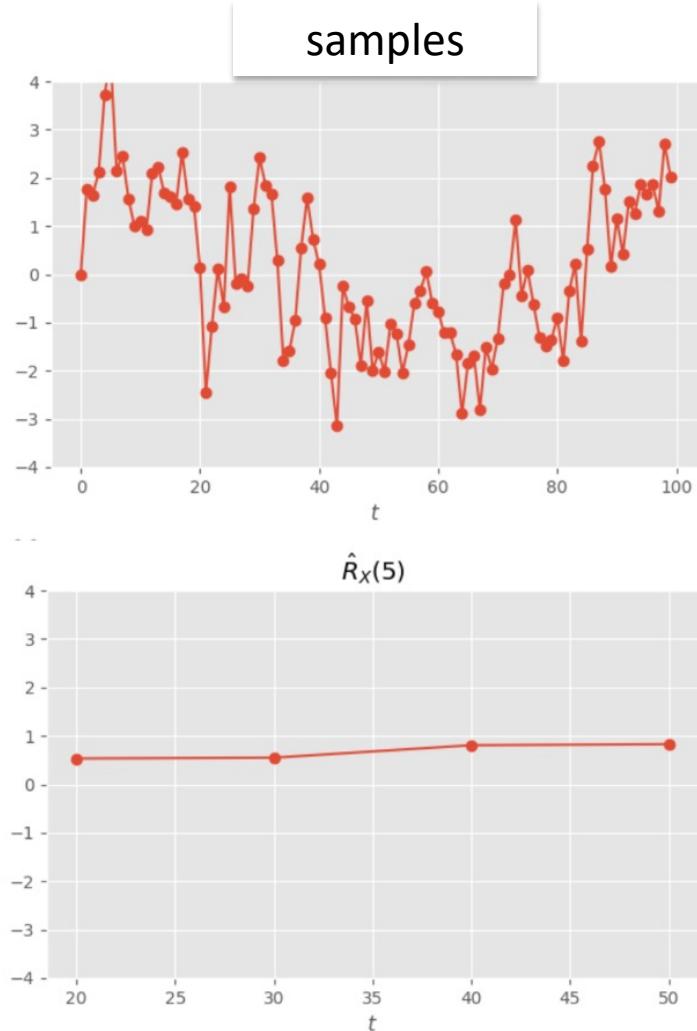
$$\hat{R}_X(\tau) = \frac{1}{N - \lambda} \sum_{i=\lambda}^{N-1} (X_i - \hat{\mu})(X_{i+\tau} - \hat{\mu})$$

Testing Stationarity: Should not see large variations over λ

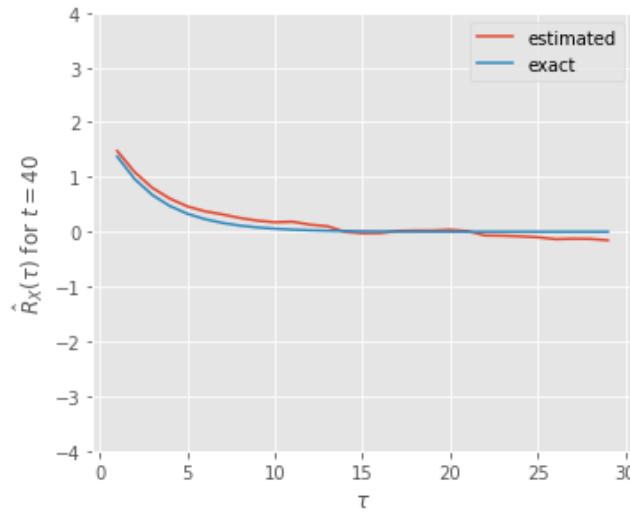
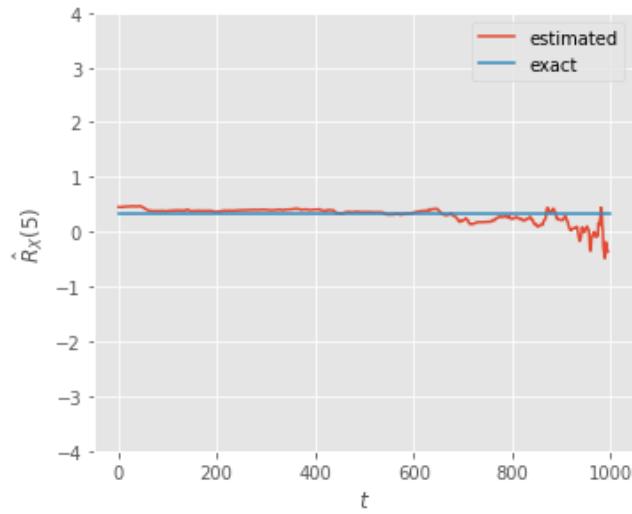
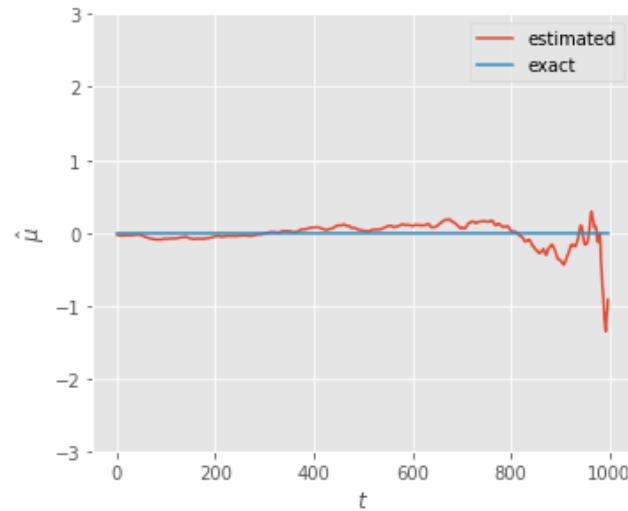
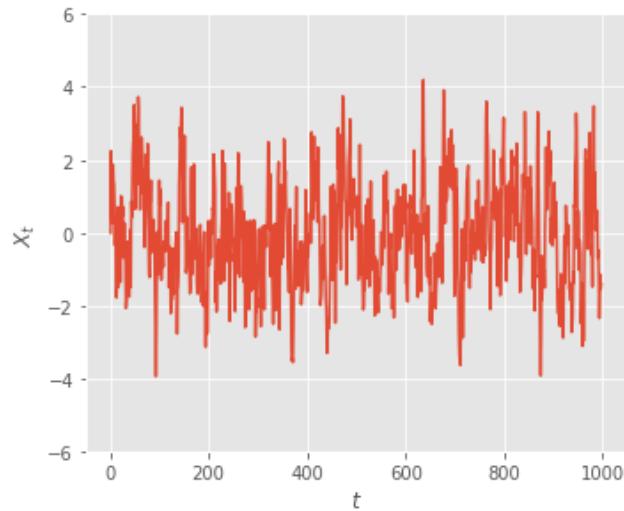
Testing Stationarity



Demonstrate: 100 samples

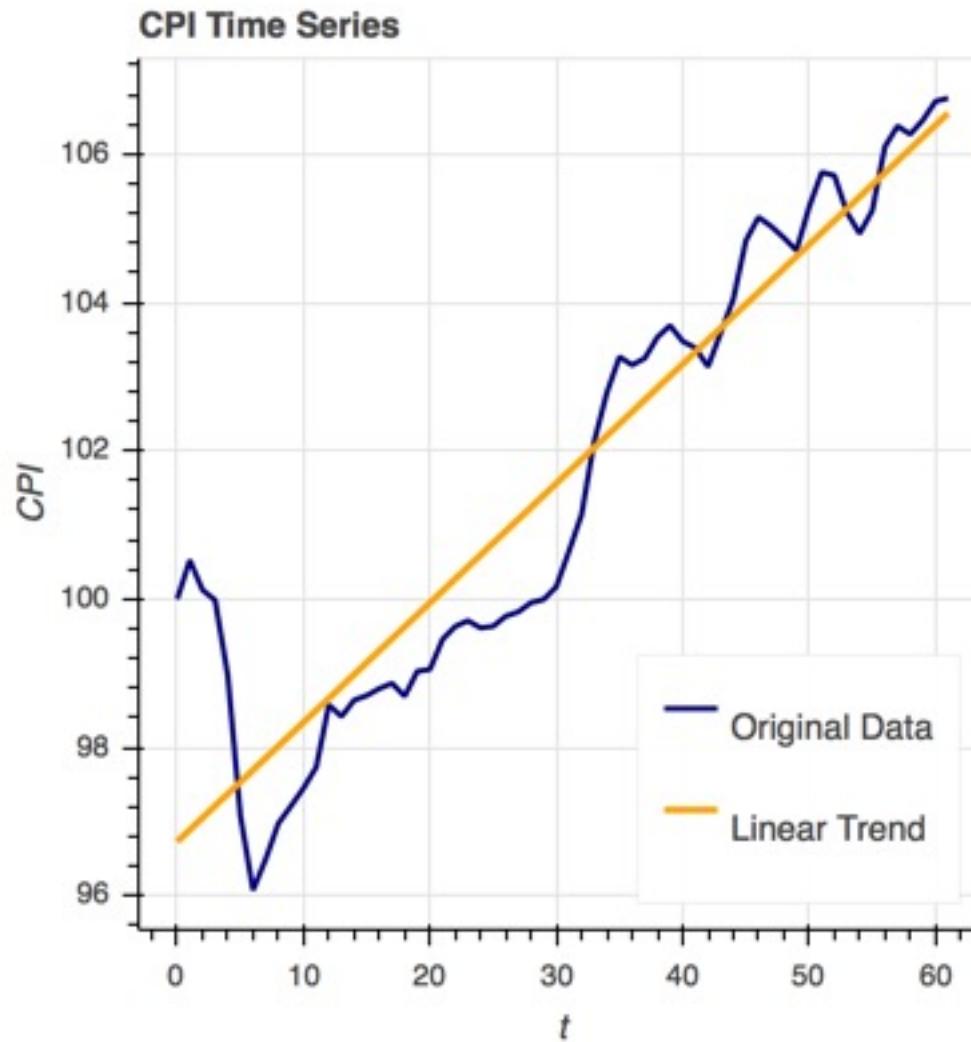


Demonstrate: 1000 samples

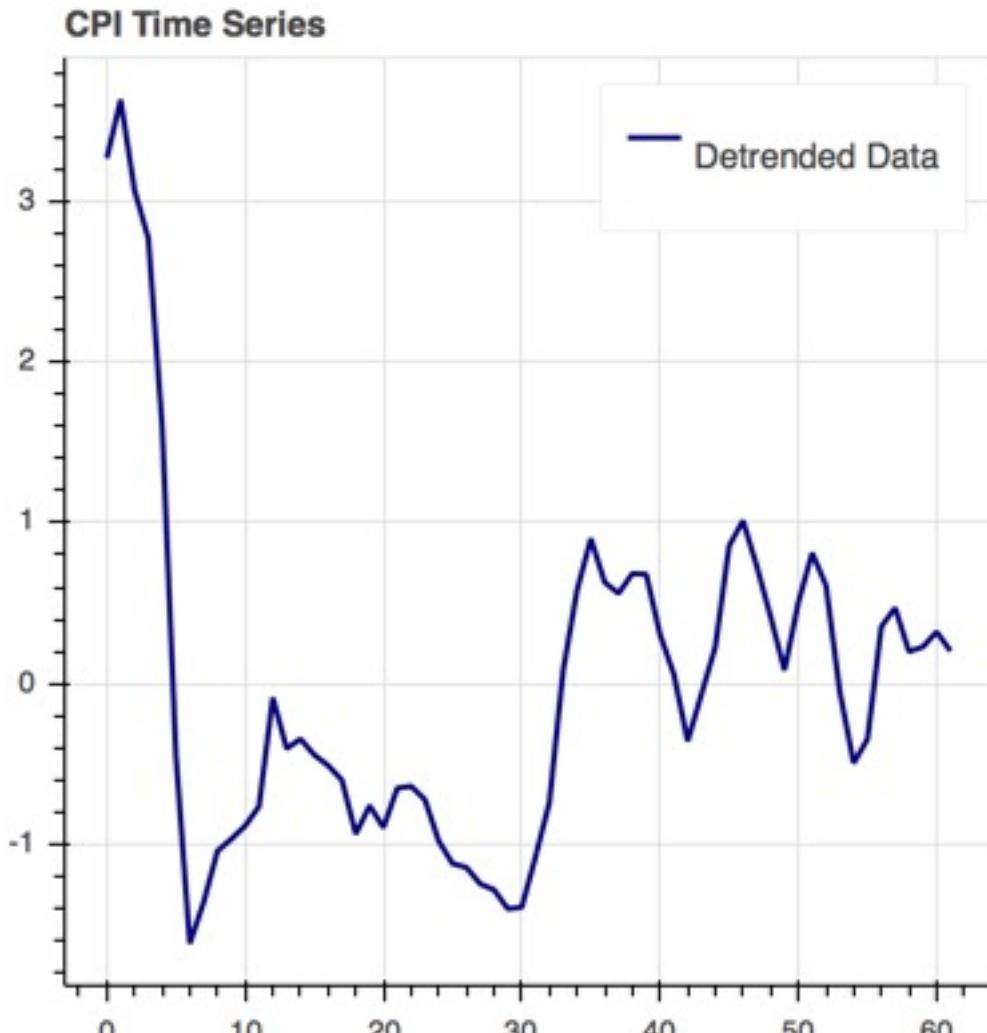


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Trends in the Consumer Price Index (CPI) data

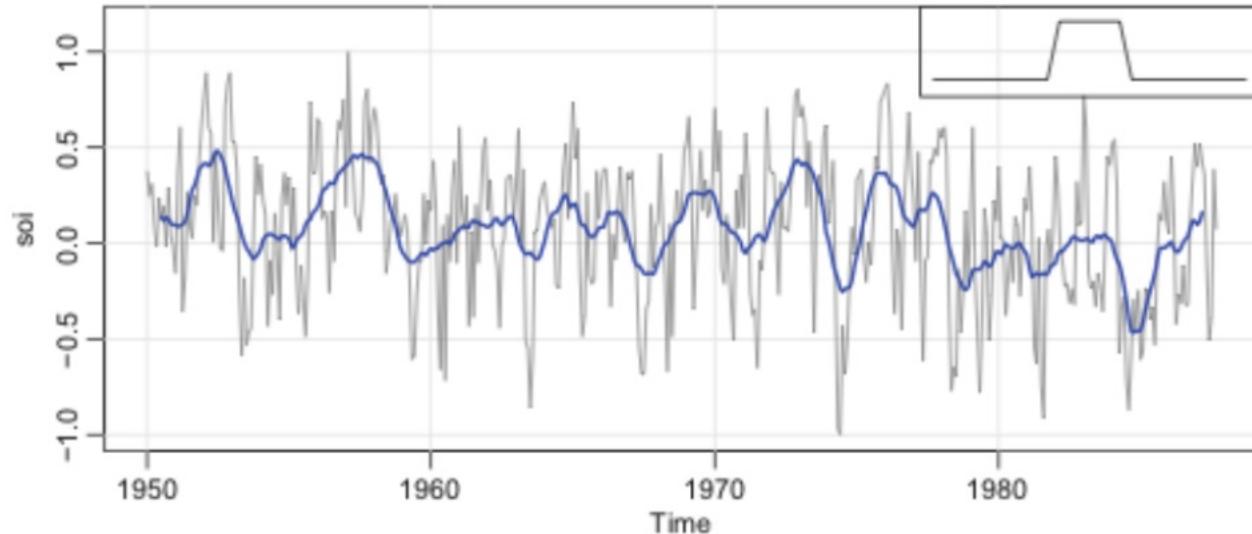


De-trended



Removing Seasonality

- $X_t = S_t + Y_t$
- Estimate S_t using a periodic regression
- Model the difference $X_t - X_{t-h} = Y_t - Y_{t-h}$



End

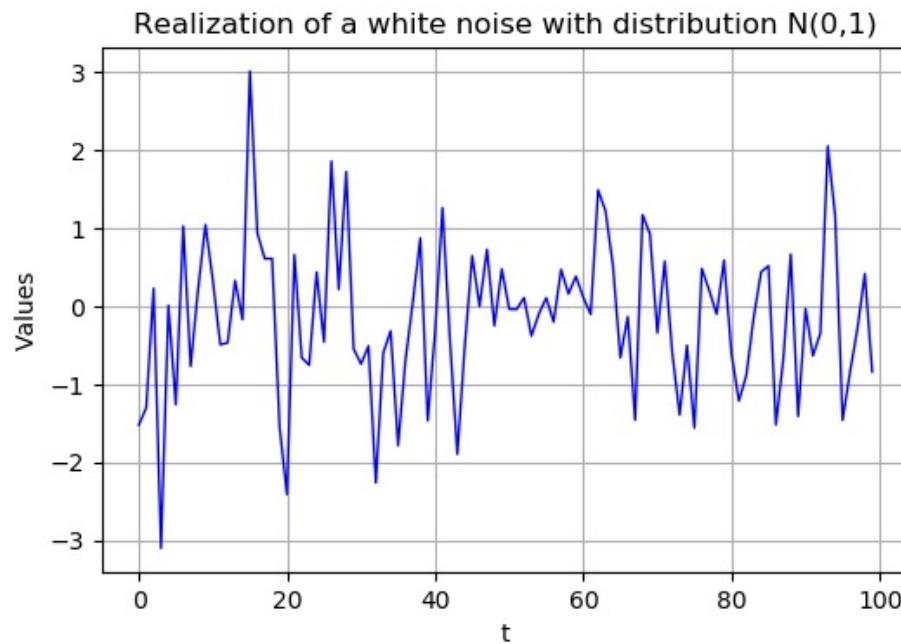
Models of time series

Models of Time-Series

- White noise
- Auto-regressive (AR)
- Moving Average (MA)
- Auto-regressive moving average (ARMA)
- Autocovariance of these examples

White noise

- Process $X_t = w$ $\mathbf{E}(w_t) = 0$

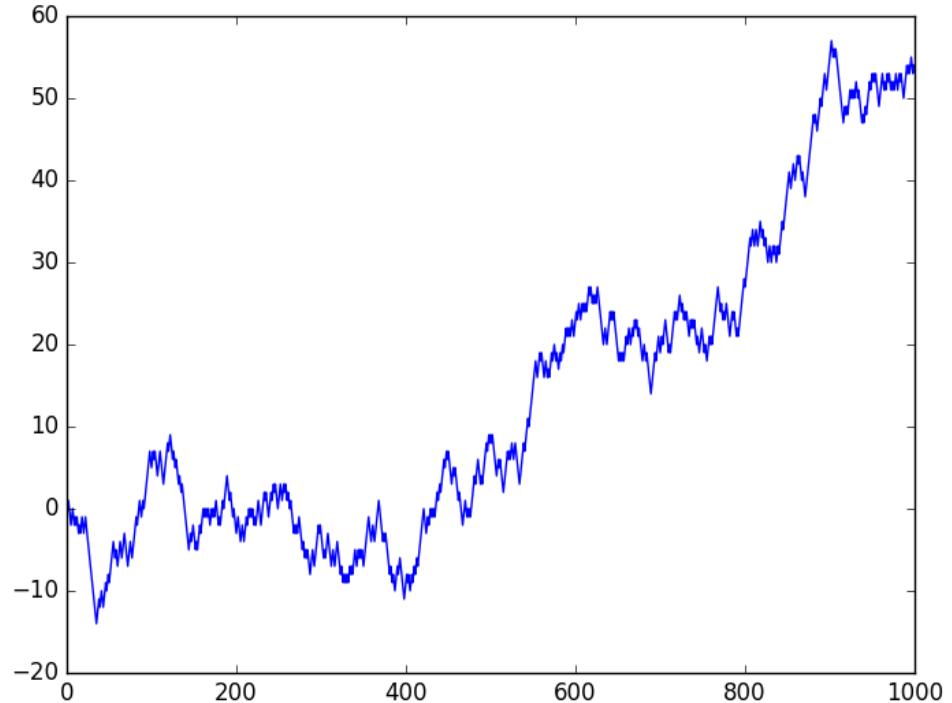


- Autocovariance =

$$\mathbf{E}(w_{t_1} w_{t_2}) = \sigma^2 \delta(t_1 - t_2)$$

Random Walk

$$X_t = X_{t-1} + w_t$$



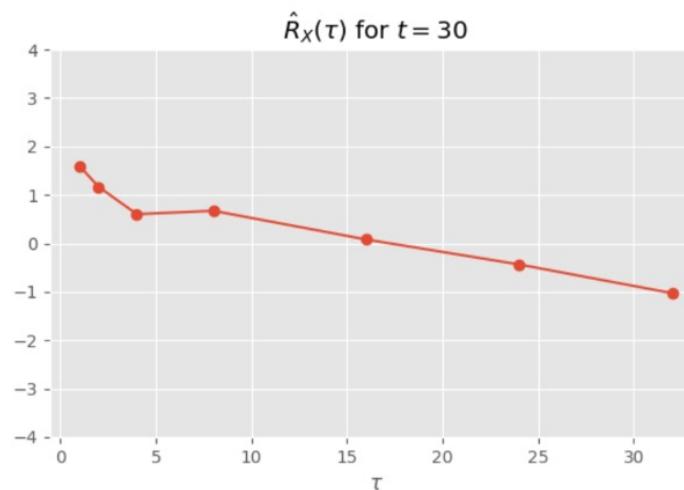
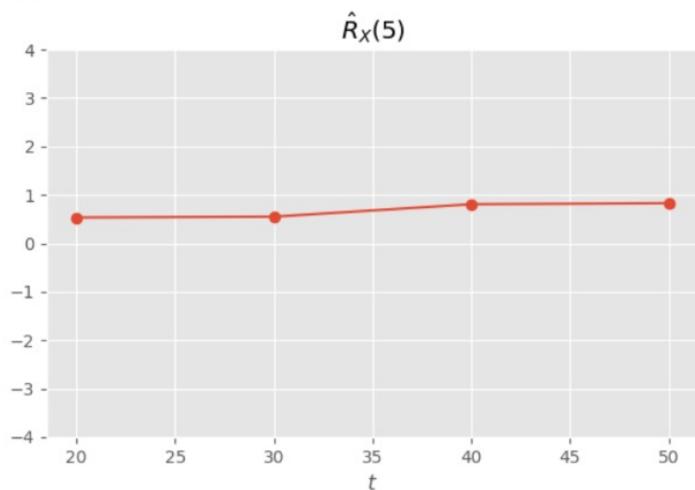
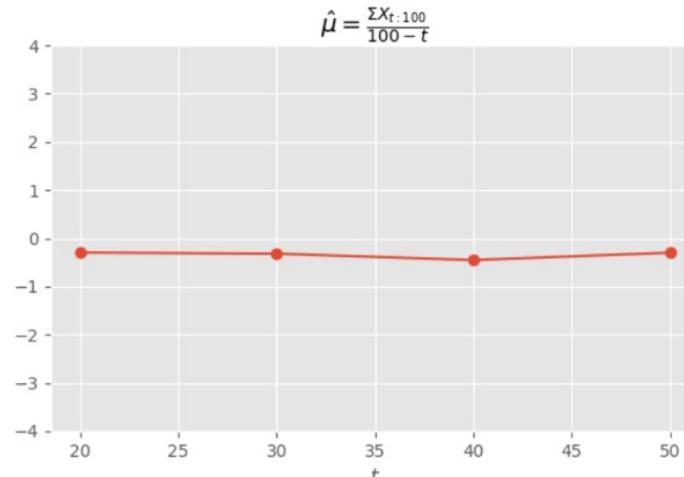
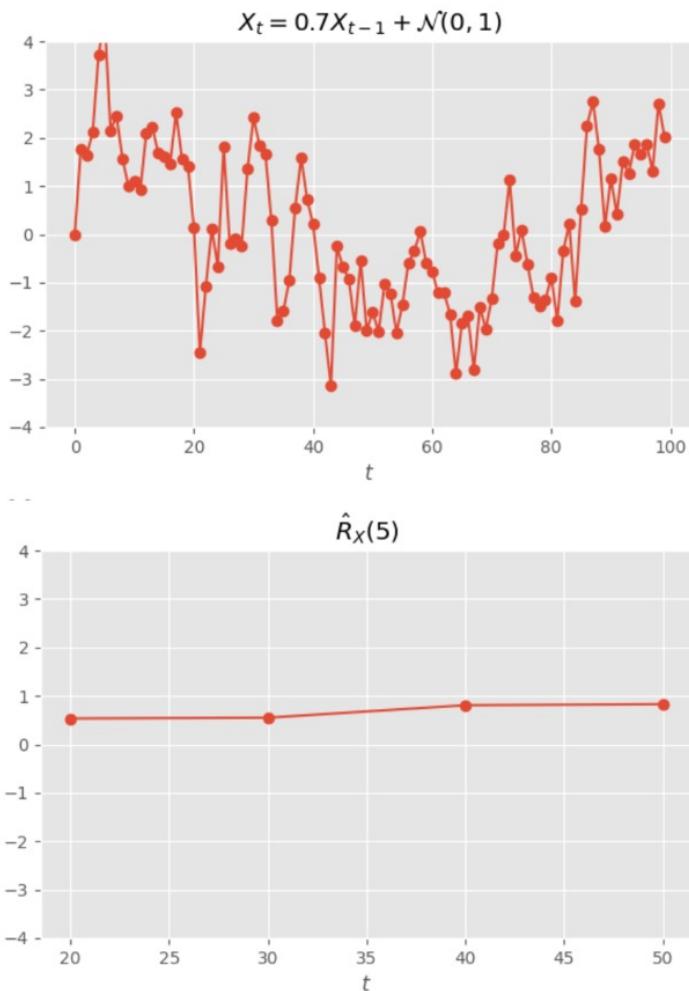
Autoregressive Process AR(p)

- Process

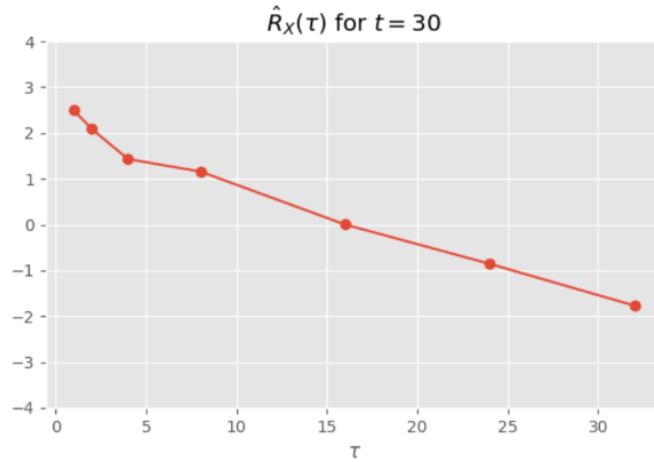
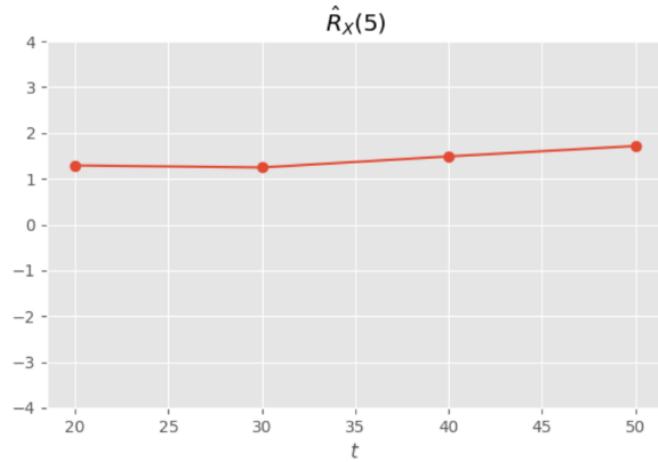
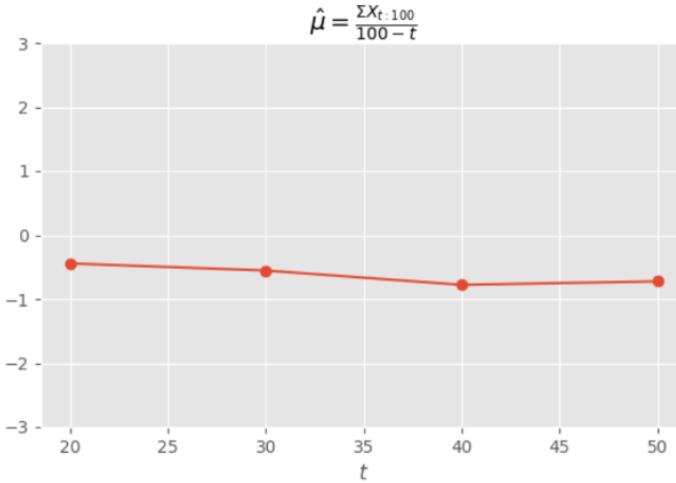
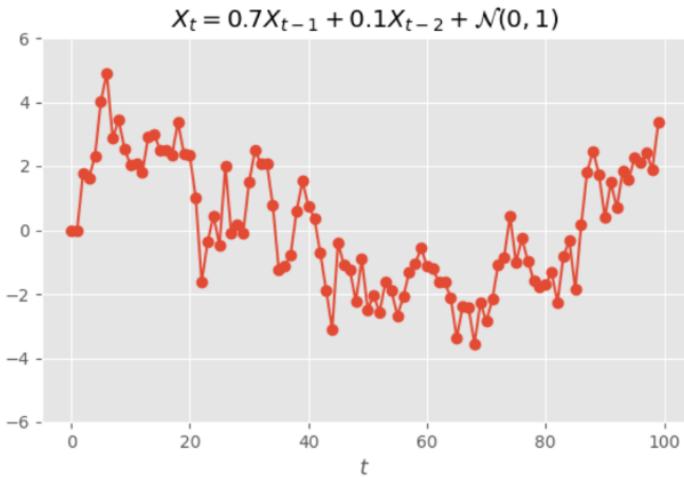
$$X_t = \sum_{i=1}^p a_i X_{t-i} + w_t$$

- w_t is white
- Interpretation

Example AR(1)

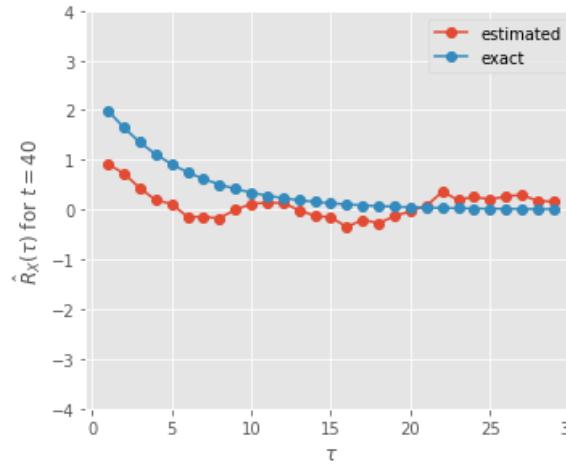
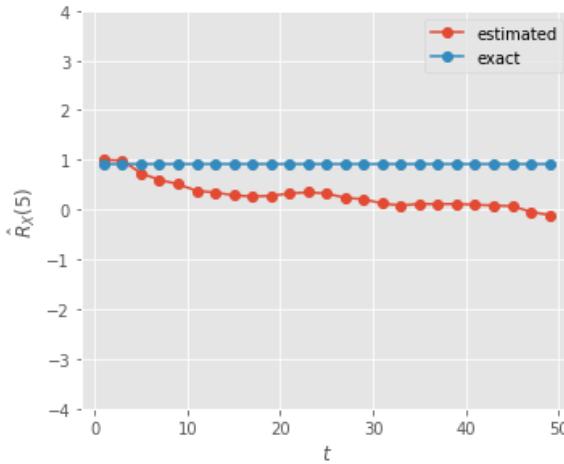
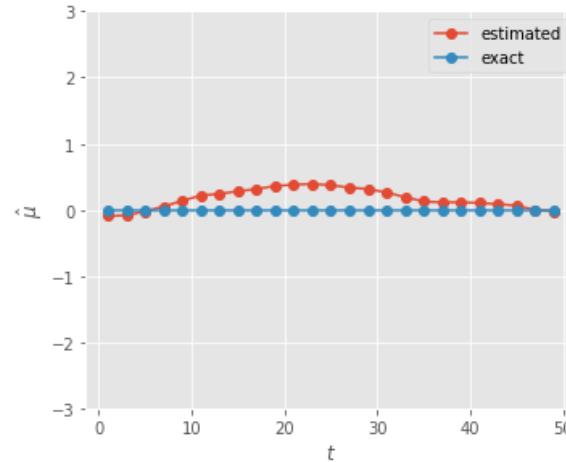
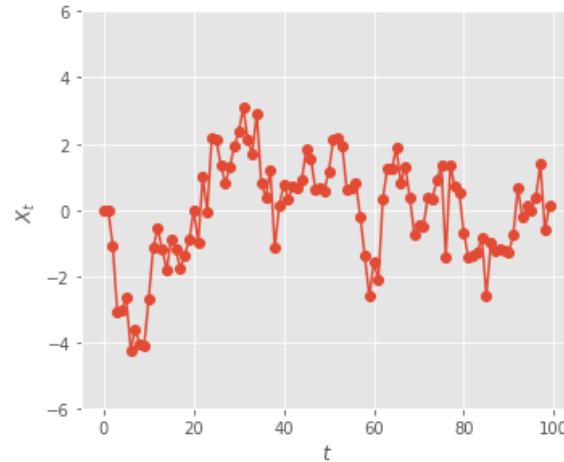


AR(2)



Example: AR(2)

$$X_t = 0.7X_{t-1} + 0.1X_{t-2} + w_t$$



Autocovariance of AR(p)

- How do you compute the exact Autocovariance of

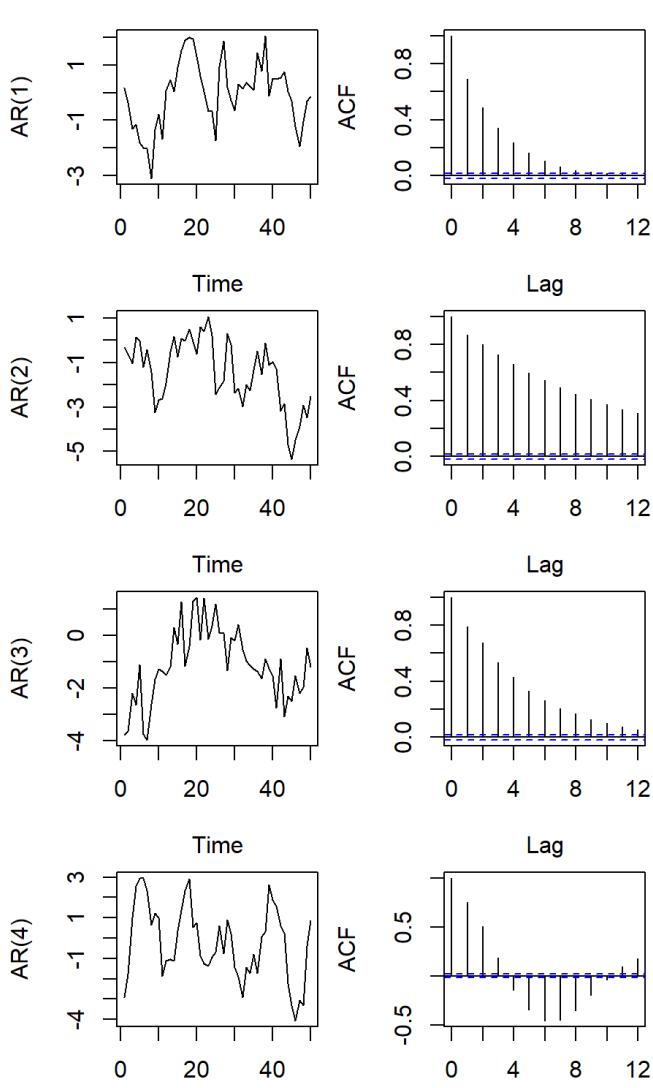
$$X_t = \sum_{i=1}^p a_i X_{t-i} + w_t$$

- Autocovariance

$$R_X(\tau) = \sum_{i=1}^p a_i R_X(\tau - i) + \sigma^2 \delta(\tau)$$

- Sum of decaying exponentials!

Geometric Shape of ACF for AR(p)



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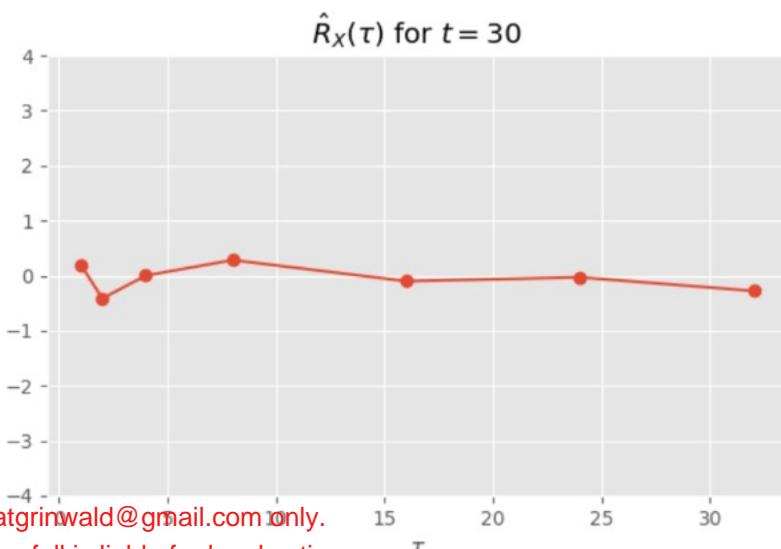
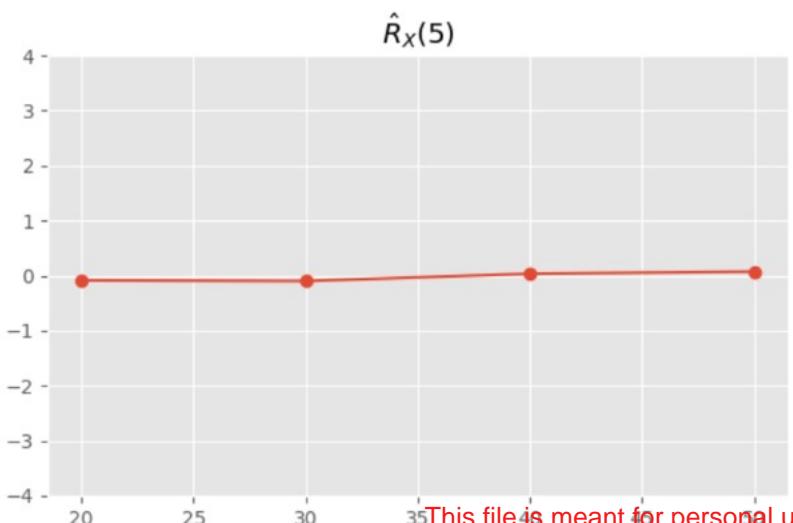
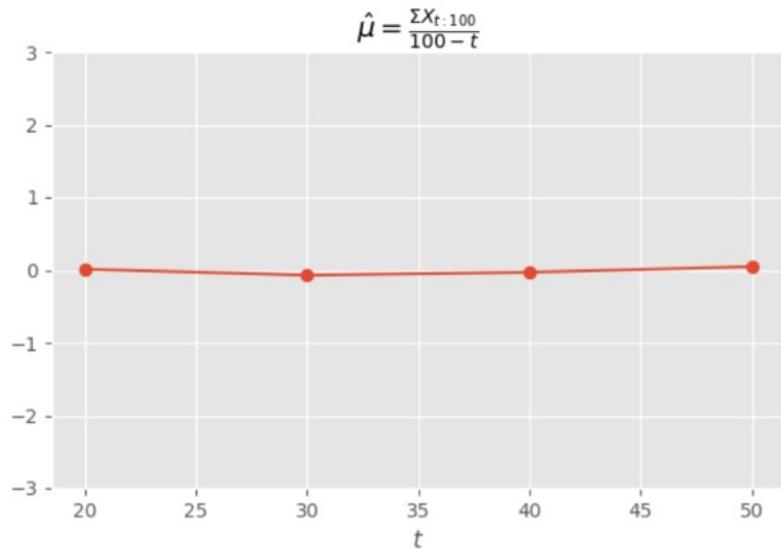
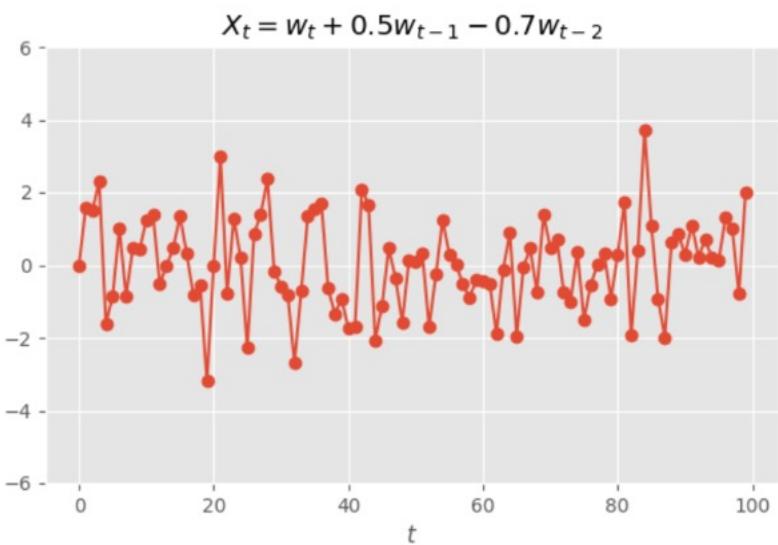
Moving Average MA(q)

- Process

$$X_t = \sum_{i=0}^q b_i w_{t-i}$$

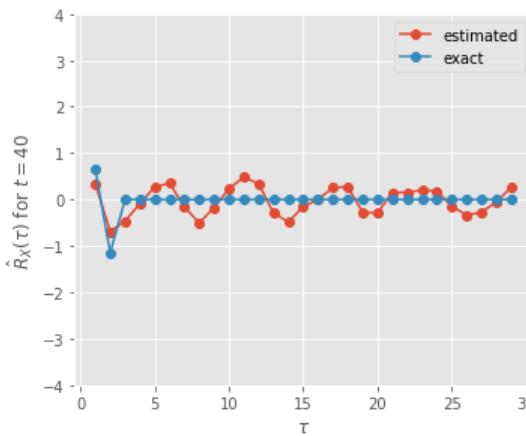
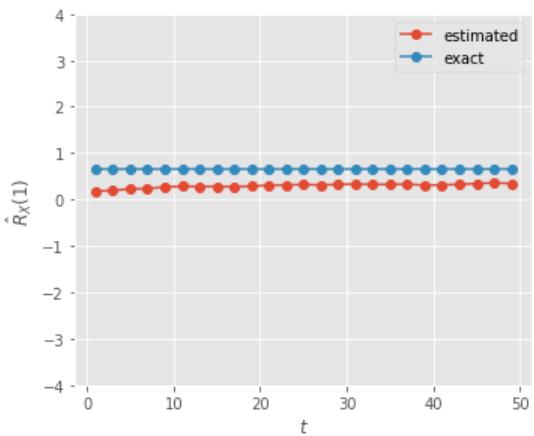
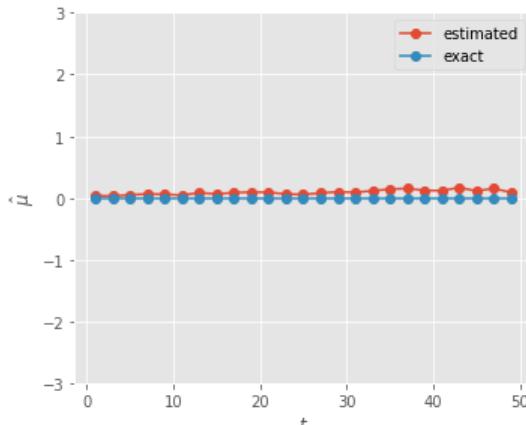
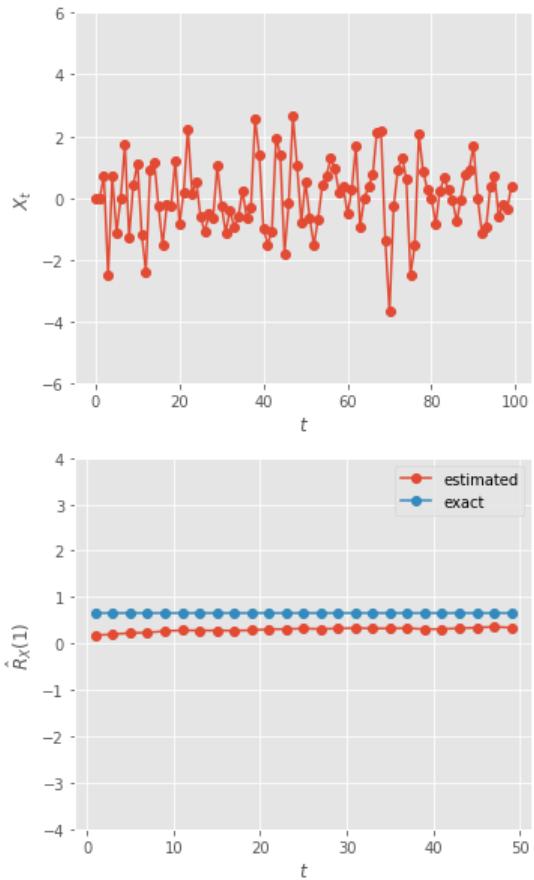
- w_t is white
- Interpretation

Example MA(2)



Sample vs Actual

$$X_t = w_t + 0.5w_{t-1} - 0.7w_{t-2}$$



Autocovariance of MA

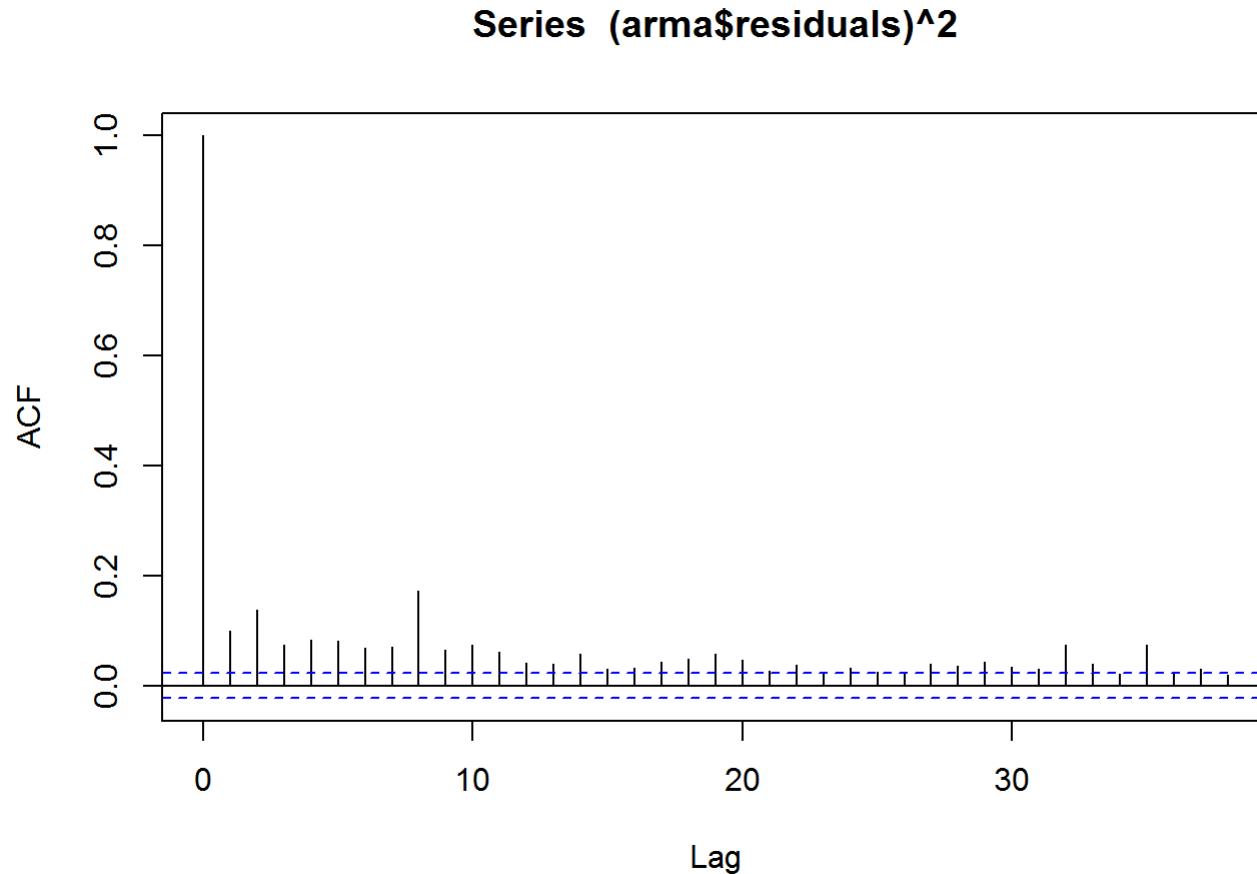
- How do you compute the exact Autocovariance of

$$X_t = \sum_{i=0}^q b_i w_{t-i}$$

- Finite support

$$R_X(\tau) = \sigma^2 \sum_{j=0}^q b_j b_{j-\tau}$$

Finite lag Shape of ACF for MA



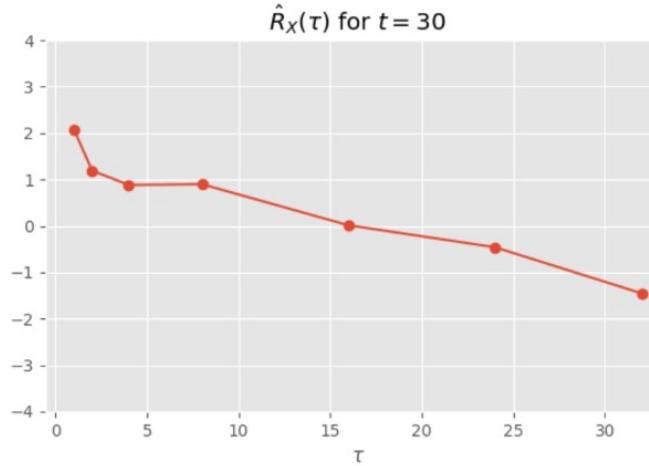
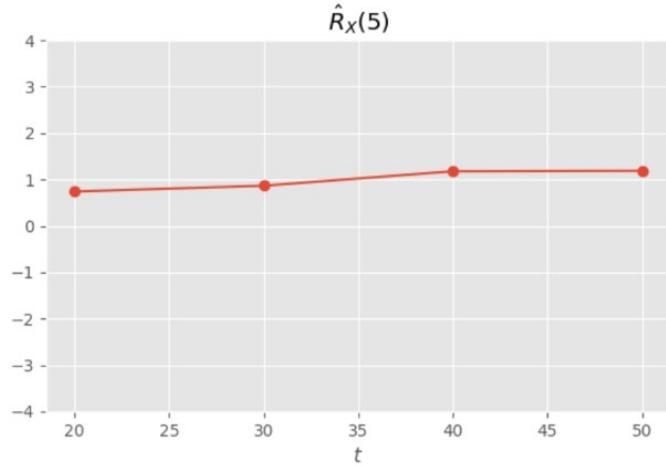
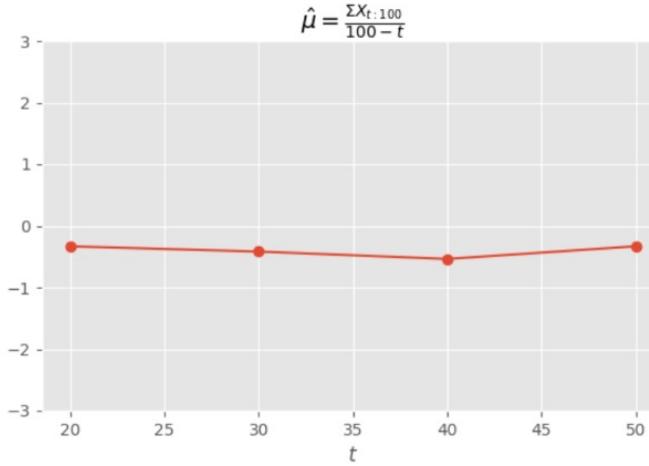
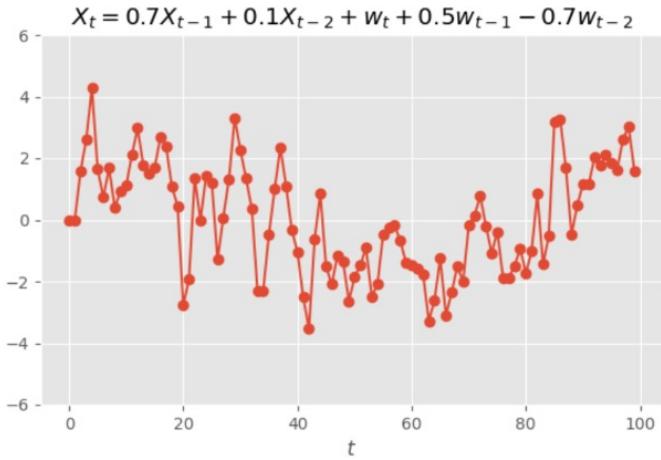
Autoregressive Moving Average Process (ARMA)

- We can combine the two processes

$$X_t = \sum_{i=1}^p a_i X_{t-i} + \sum_{j=0}^q b_j w_{t-j}$$

- Superposition of different processes

Example: ARMA



End

Learning Time Series

Learning a Time Series Model

- Data to Models
 - Autoregressive (AR) models
 - Moving Average (MA)
- AR learning Looks like a standard Least Squares
 - What's the catch?
 - What can we learn?
- How about other models
- Example: Consumer Price Data

Learning AR(p)

- Data

$$X_0, X_1, X_2, \dots X_N$$

- Model (known p)

$$X_t = \sum_{i=1}^p a_i X_{t-i} + w_t$$

- Least squares to estimate

$$(a_1, a_2, \dots a_p)$$

Example

- Generate 100 data points according to

$$x_t = .7 x_{t-1} + .1 x_{t-2} + w_t$$

- Fit an AR(1) model
 - Answer: $a = .8704$
- Fit an AR(2) model
 - Answer $a_1 = 0.7448$ and $a_2 = .1742$
- Observations?

Order Estimation

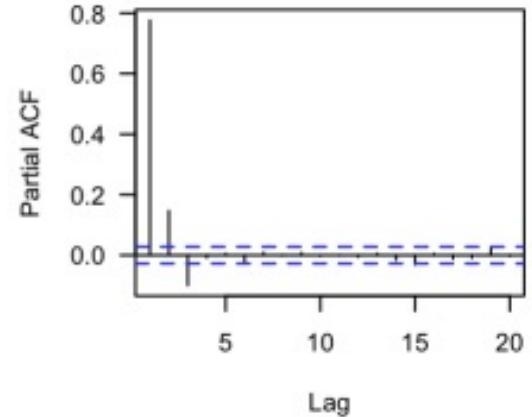
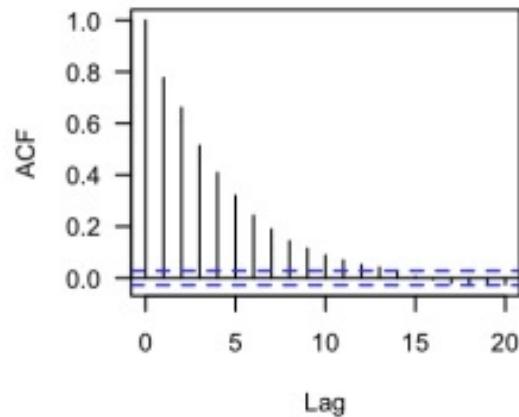
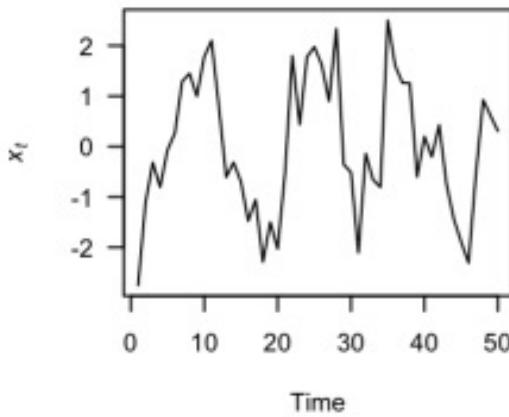
- Example highlights the importance of order estimation
- Derive multiple estimates and choose based on error on cross validation data
- Add penalty to model complexity (MDL, AIC)
- Use the Autocovariance function (ACF) as a guidance!
 - Can we do better than ACF?

Partial Autocovariance Function (PACF)

- $X_t \mid X_{t+1}, X_{t+2}, \dots, X_{t+k-1} \mid X_{t+k}$
- Project X_{t+1} and X_{t+k} on the variables in between:
 P_t and P_{t+k}
- In the case of ARX, the new PACF is zero outside p
- *Use to estimate order!*

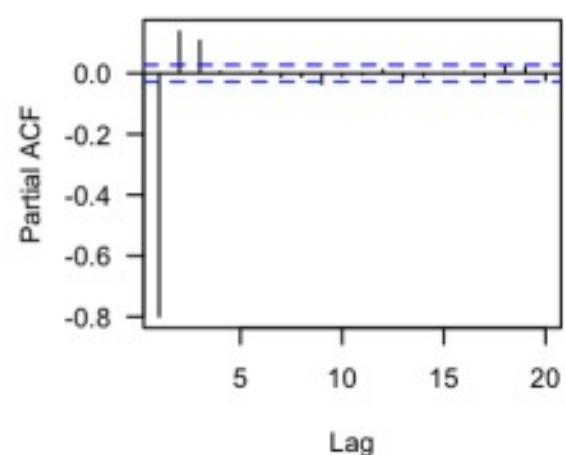
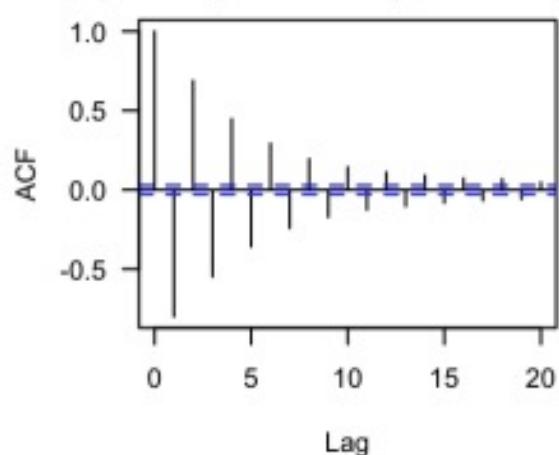
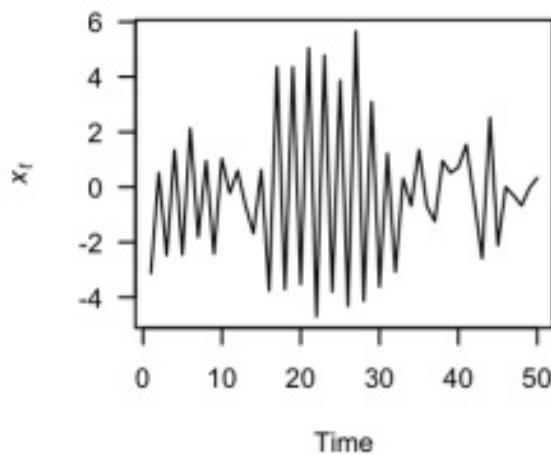
Example: AR(3)

$$X_t = .7 X_{t-1} + .2 X_{t-2} - .1 X_{t-3}$$

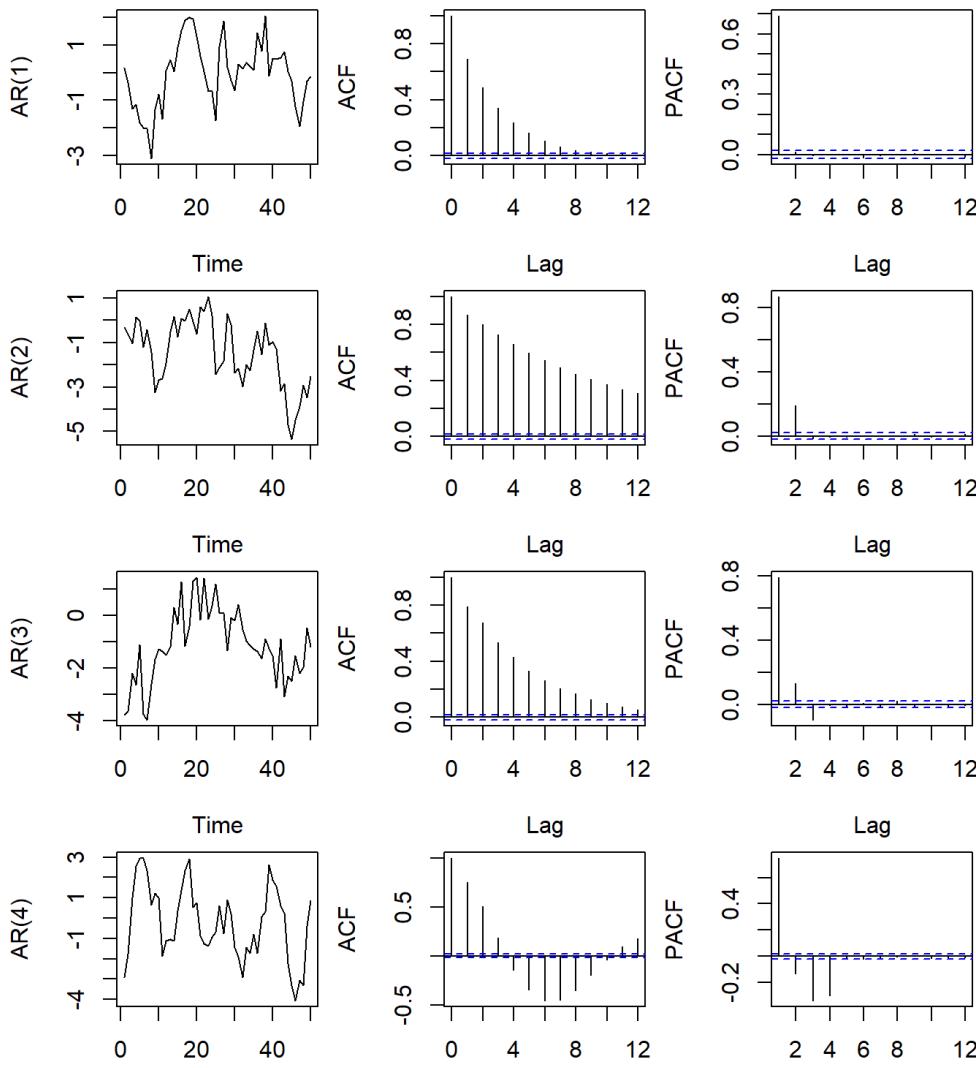


Example: AR(3)

$$X_t = -.7 X_{t-1} + .2 X_{t-2} + .1 X_{t-3}$$



Geometric Shape of ACF and PACF for AR(p)



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Learning a MA model

- Data

$$X_0, X_1, X_2, \dots X_N$$

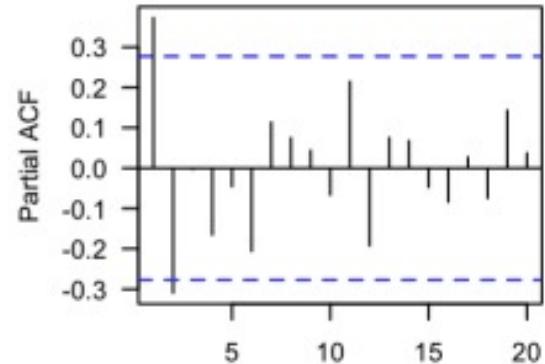
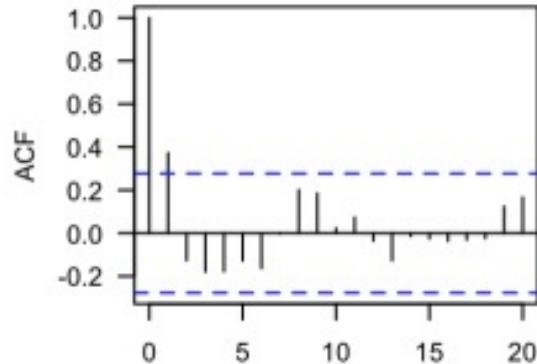
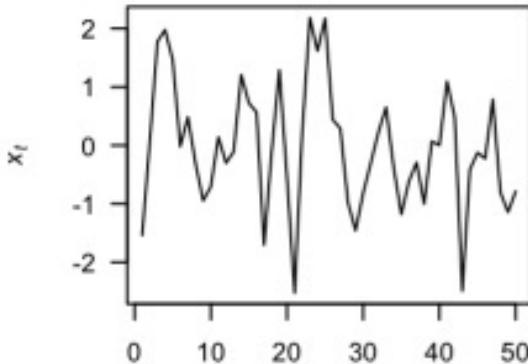
- Model (known p)

$$X_t = \sum_{i=0}^p b_i w_{t-i}$$

- Recall ACF has finite support

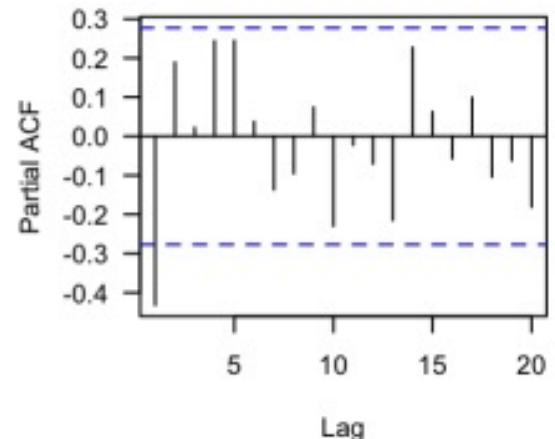
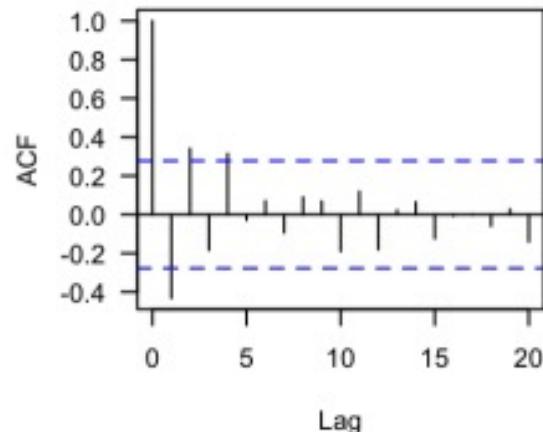
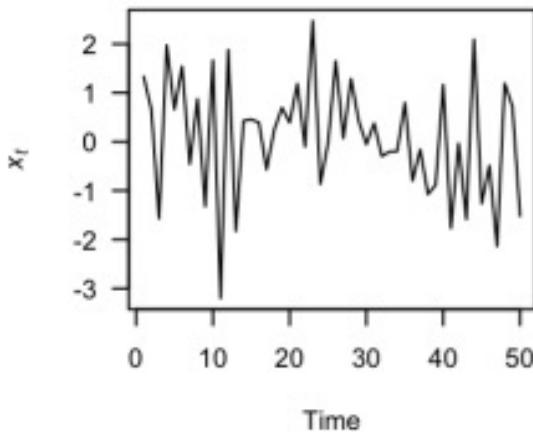
Example: MA(2)

$$X_t = .7 W_{t-1} + W_t$$



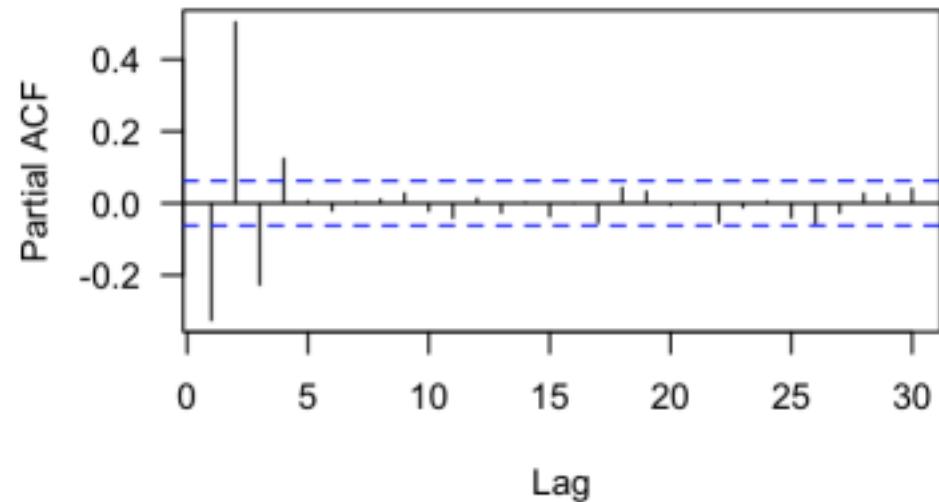
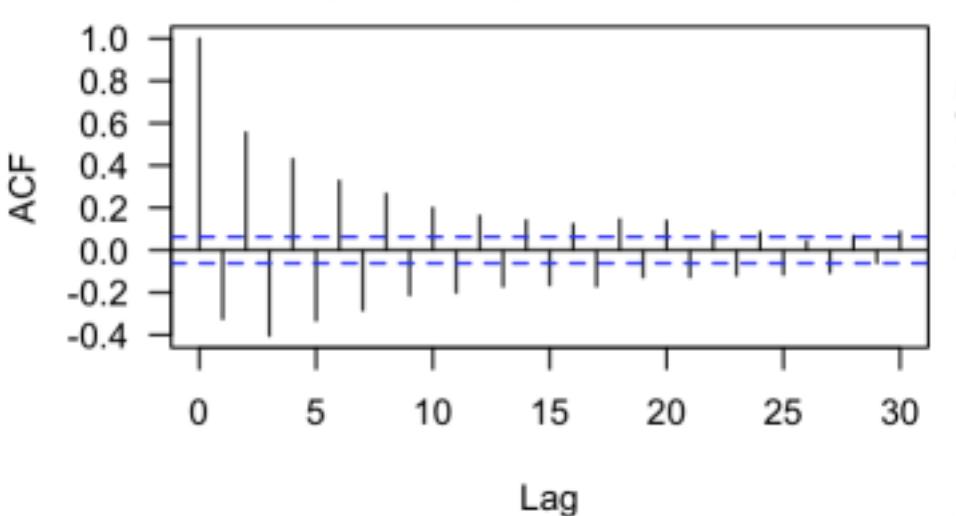
Example: MA(3)

$$X_t = W_t - .7 W_{t-1} + .2 W_{t-2} + .1 W_{t-3}$$



What about ARMA Models?

$$X_t = .7 X_{t-1} + .2 X_{t-2} + .7 W_t + .2 W_{t-1}$$



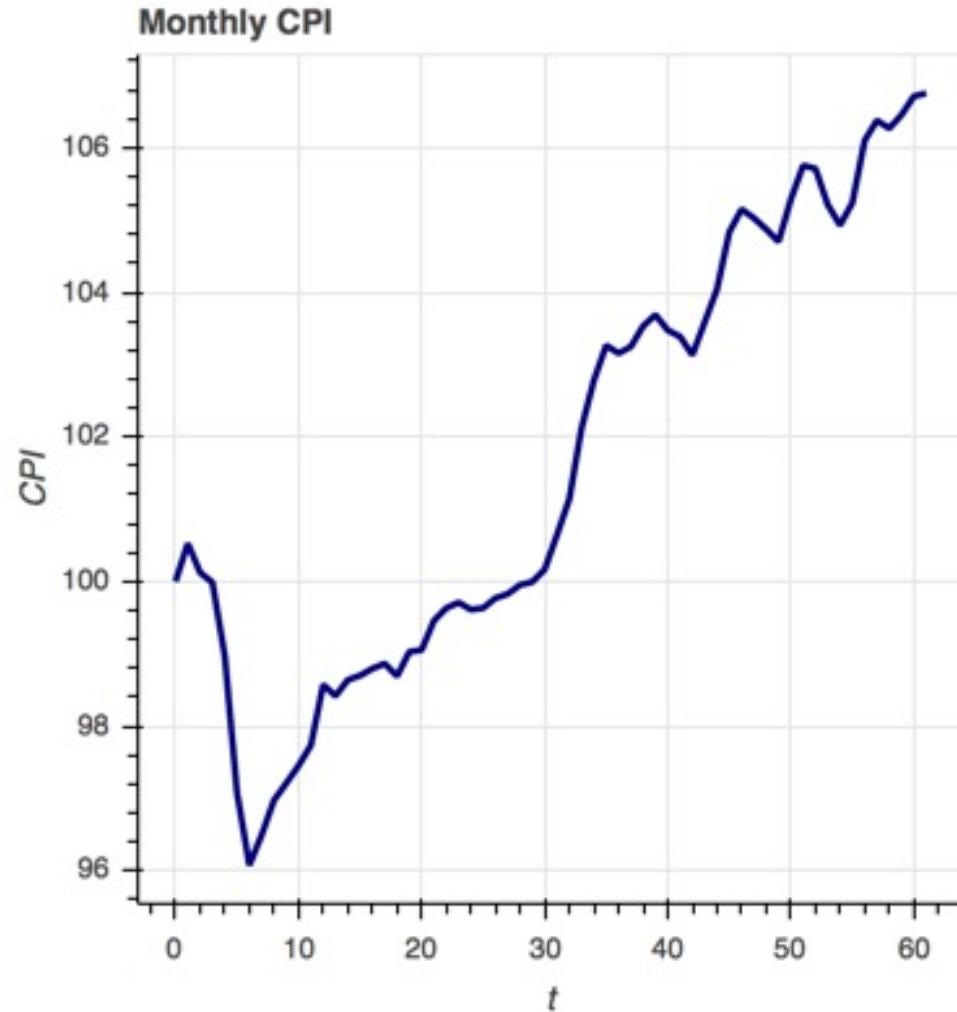
ACF vs PACF

	ACF	PACF
AR(p)	decays	zero for $h > p$
MA(q)	zero for $h > q$	decays
ARMA(p,q)	decays	decays

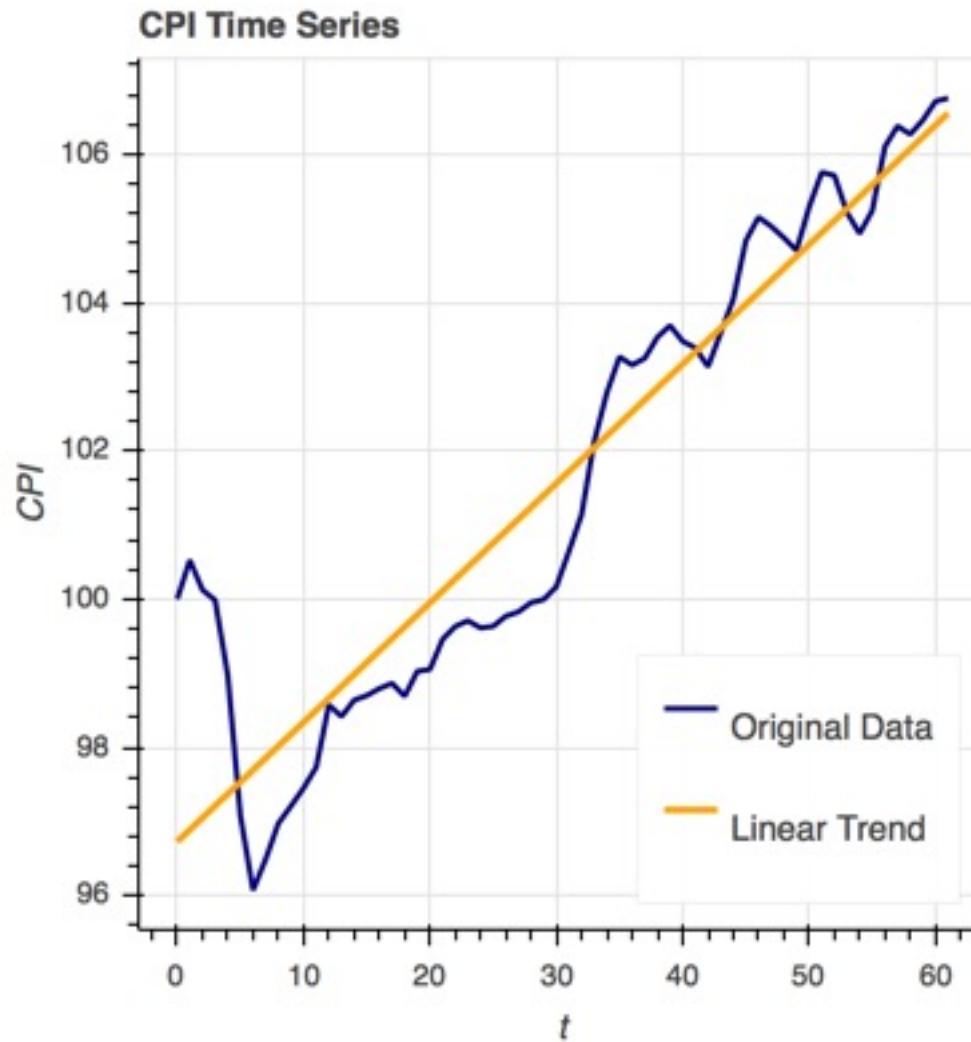
Billion Price Data

- The goal of this problem is to analyze the PriceStats data from the MIT Billion Prices Project, provided by Professor Rigobon.
- Consumer Price Index Data: (consumer price index, the price of a "market basket of consumer goods and services" - a proxy for inflation)

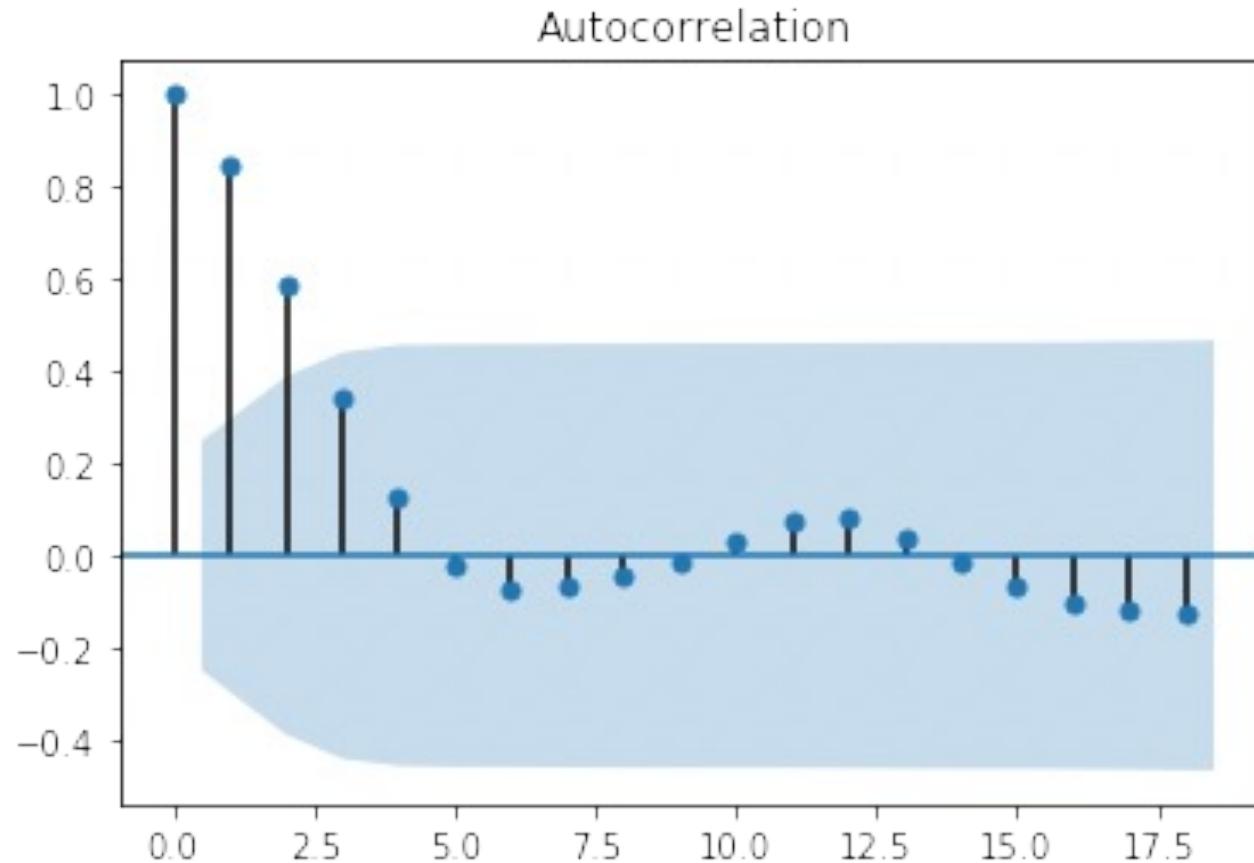
Consumer Price Index



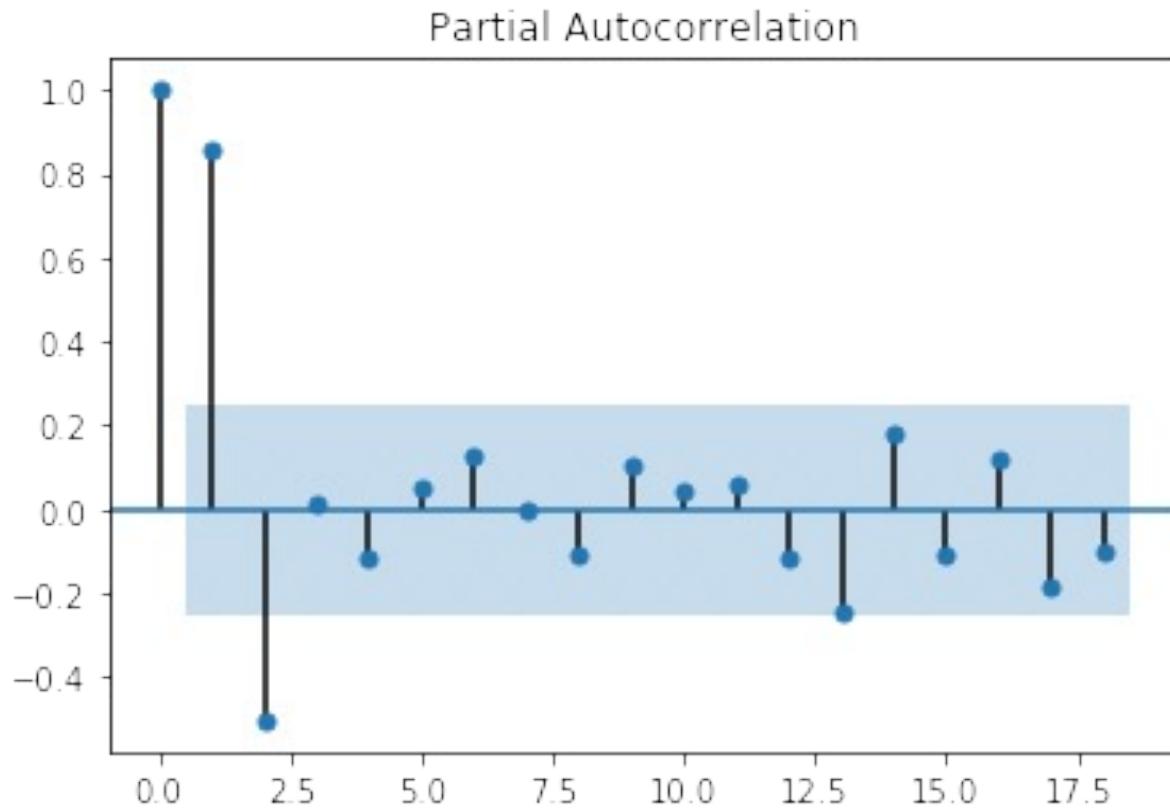
Identify Trends in the CPI data



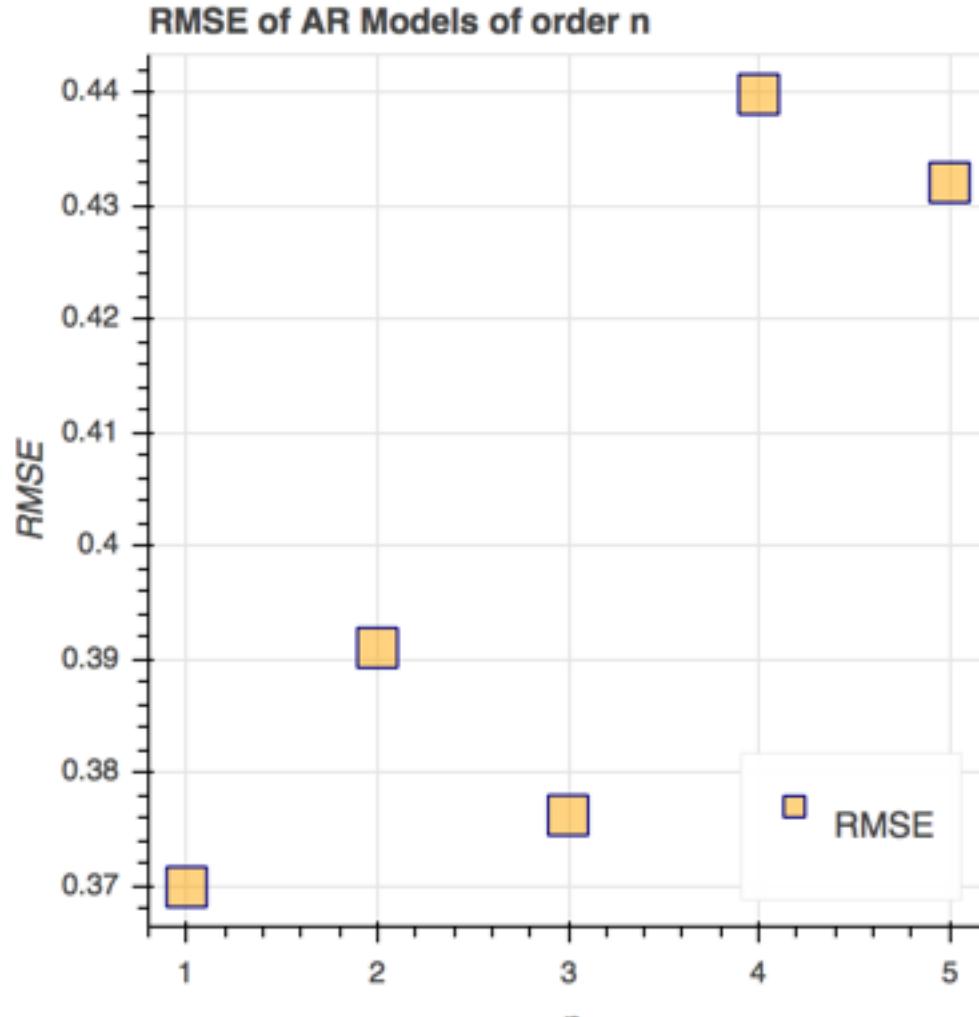
Empirical Autocovariance



Empirical Partial Autocovariance

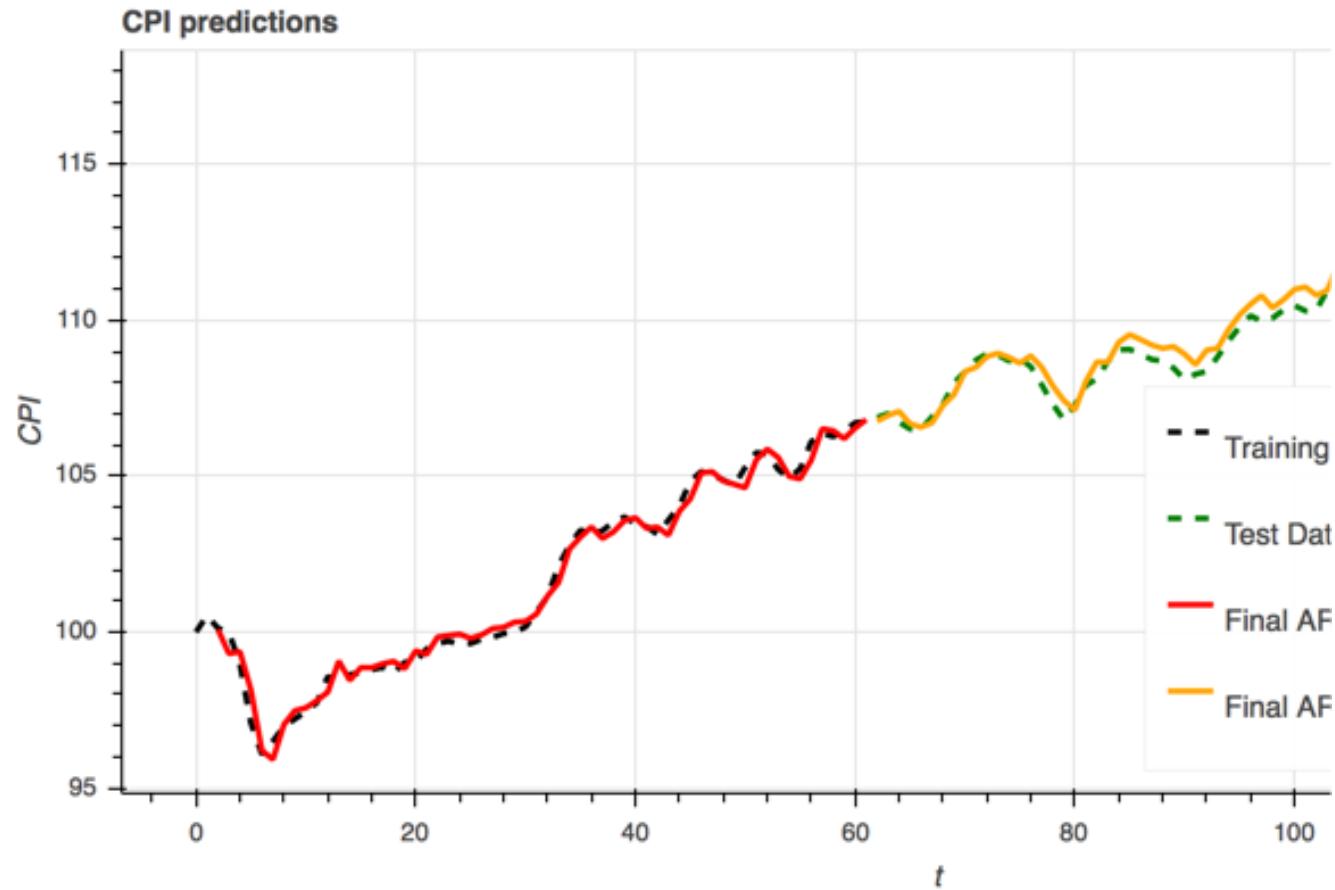


AR(1) or AR(2)



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Prediction of AR(2)



Conclusions

- Time Series are everywhere
- Stationarity is important for modeling
- AR, MA, and ARMA are powerful models
 - Estimate the order
 - Compare across models
- Trends

End

Thank You