

ETC3550/ETC5550

Applied forecasting

Ch7. Regression models

OTexts.org/fpp3/



Outline

- 1 The linear model with time series
- 2 Some useful predictors for linear models
- 3 Residual diagnostics
- 4 Selecting predictors and forecast evaluation
- 5 Forecasting with regression
- 6 Matrix formulation
- 7 Correlation, causation and forecasting

Multiple regression and forecasting

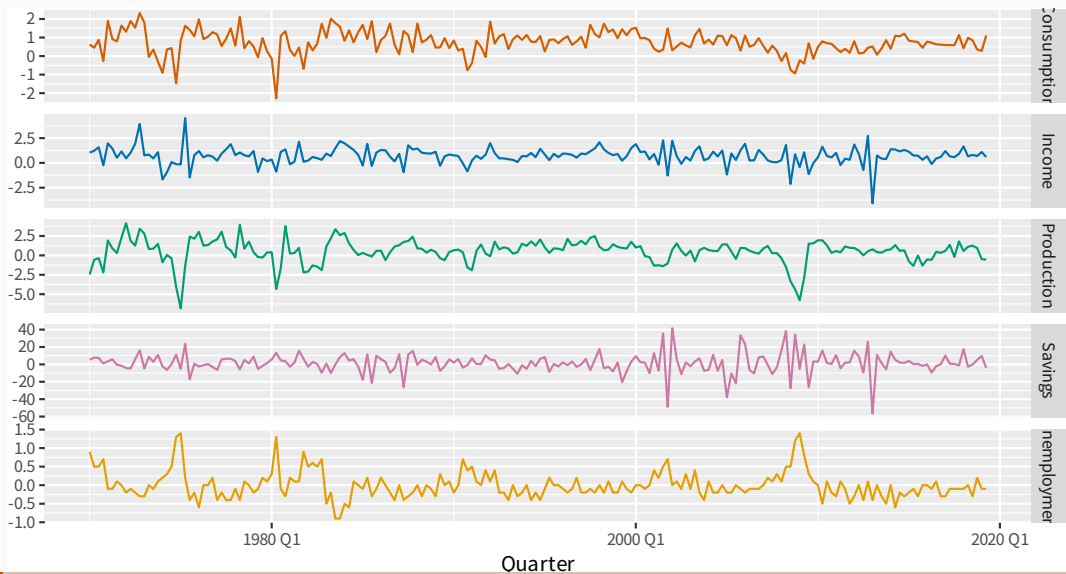
$$y_t = \beta_0 + \beta_1 x_{1,t} + \beta_2 x_{2,t} + \cdots + \beta_k x_{k,t} + \varepsilon_t.$$

- y_t is the variable we want to predict: the “response” variable
- Each $x_{j,t}$ is numerical and is called a “predictor”. They are usually assumed to be known for all past and future times.
- The coefficients β_1, \dots, β_k measure the effect of each predictor after taking account of the effect of all other predictors in the model.

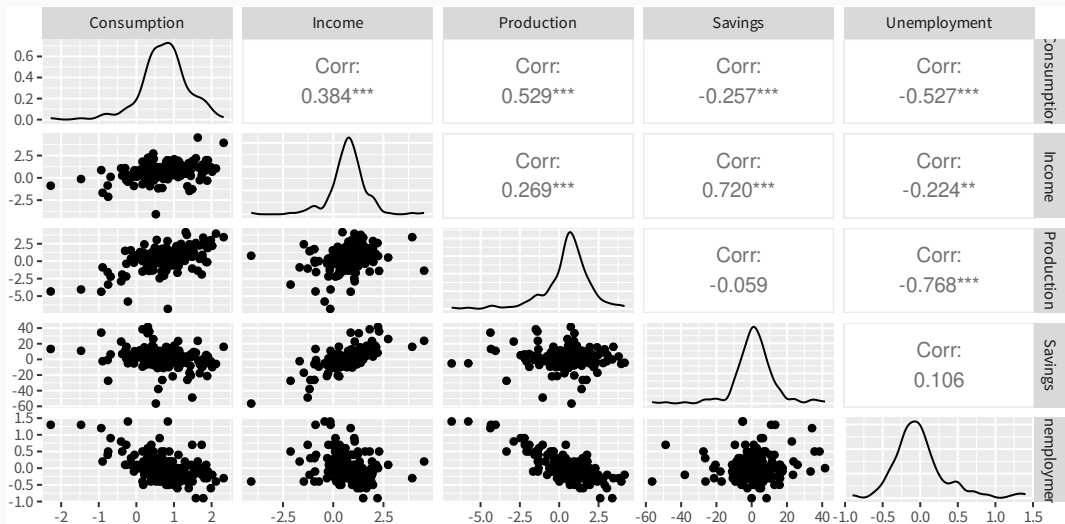
That is, the coefficients measure the **marginal effects**.

- ε_t is a white noise error term

Example: US consumption expenditure



Example: US consumption expenditure



Example: US consumption expenditure

```
fit_consMR <- us_change |>  
  model(lm = TSLM(Consumption ~ Income + Production + Unemployment + Savings))  
report(fit_consMR)
```

Series: Consumption

Model: TSLM

Residuals:

Min	1Q	Median	3Q	Max
-0.906	-0.158	-0.036	0.136	1.155

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	0.25311	0.03447	7.34	5.7e-12 ***
Income	0.74058	0.04012	18.46	< 2e-16 ***
Production	0.04717	0.02314	2.04	0.043 *
Unemployment	-0.17469	0.09551	-1.83	0.069 .
Savings	-0.05289	0.00292	-18.09	< 2e-16 ***

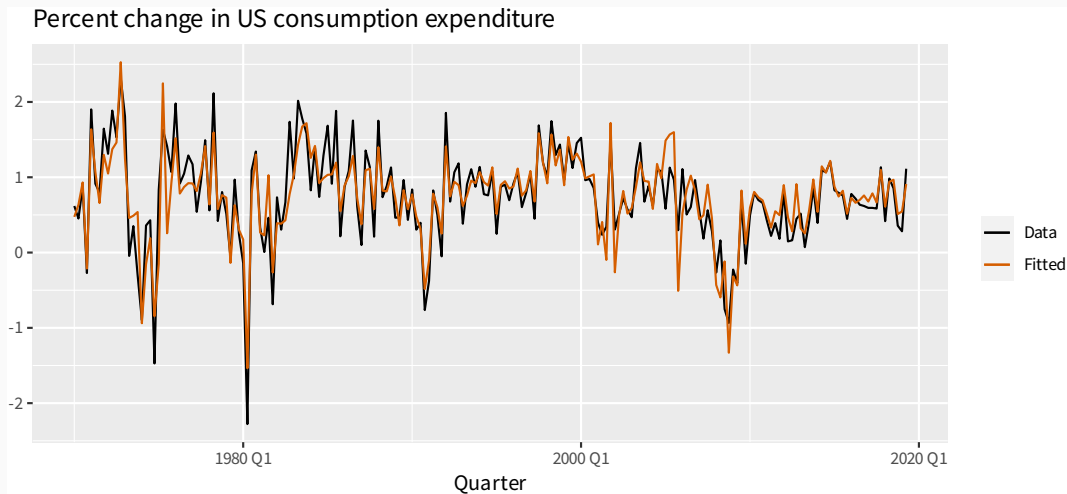
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.31 on 193 degrees of freedom

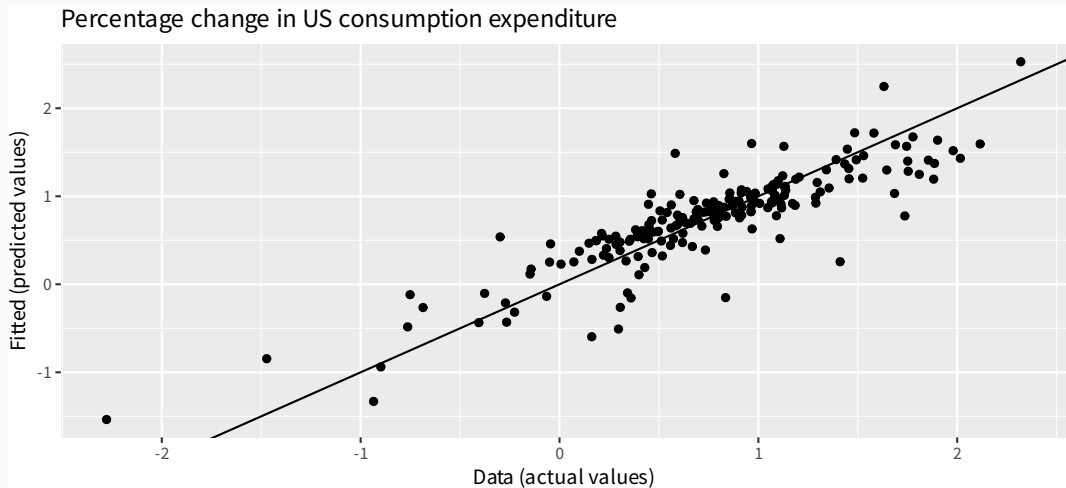
Multiple R-squared: 0.768, Adjusted R-squared: 0.763

F-statistic: 160 on 4 and 193 DF, p-value: <2e-16

Example: US consumption expenditure

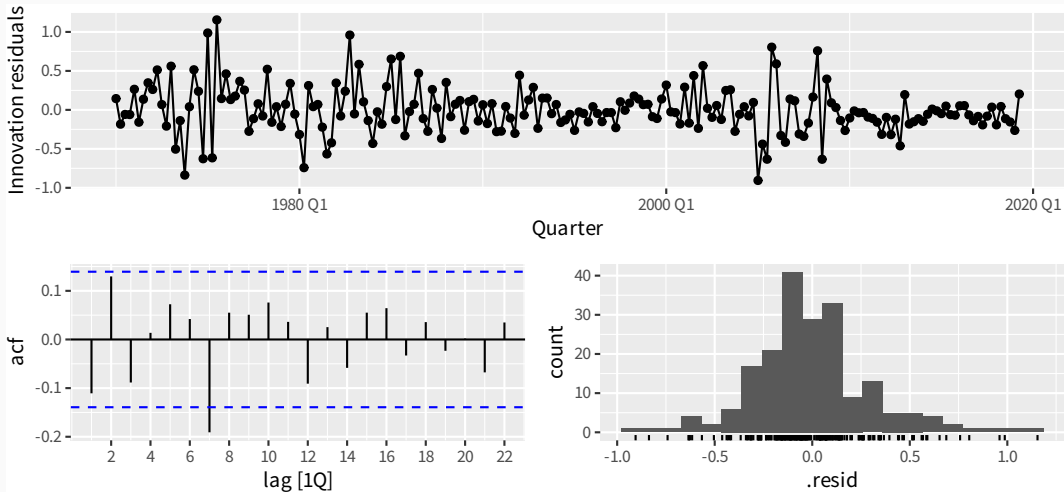


Example: US consumption expenditure



Example: US consumption expenditure

```
fit_consMR |> gg_tsresiduals()
```



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Linear trend

$$x_t = t$$

- $t = 1, 2, \dots, T$
- Strong assumption that trend will continue.

Nonlinear trend

Piecewise linear trend with bend at τ

$$x_{1,t} = t$$

$$x_{2,t} = \begin{cases} 0 & t < \tau \\ (t - \tau) & t \geq \tau \end{cases}$$

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Quadratic or higher order trend

$$x_{1,t} = t \quad x_{2,t} = t^2$$

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Dummy variables

If a categorical variable takes only two values (e.g., 'Yes' or 'No'), then an equivalent numerical variable can be constructed taking value 1 if yes and 0 if no. This is called a **dummy variable**.

	A	B
1	Yes	1
2	Yes	1
3	No	0
4	Yes	1
5	No	0
6	No	0
7	Yes	1
8	Yes	1
9	No	0
10	No	0
11	No	0
12	No	0
13	Yes	1
14	No	0

Dummy variables

If there are more than two categories, then the variable can be coded using several dummy variables (one fewer than the total number of categories).

	A	B	C	D	E
1	Monday	1	0	0	0
2	Tuesday	0	1	0	0
3	Wednesday	0	0	1	0
4	Thursday	0	0	0	1
5	Friday	0	0	0	0
6	Monday	1	0	0	0
7	Tuesday	0	1	0	0
8	Wednesday	0	0	1	0
9	Thursday	0	0	0	1
10	Friday	0	0	0	0
11	Monday	1	0	0	0
12	Tuesday	0	1	0	0
13	Wednesday	0	0	1	0
14	Thursday	0	0	0	1
15	Friday	0	0	0	0

Beware of the dummy variable trap!

- Using one dummy for each category gives too many dummy variables!
- The regression will then be singular and inestimable.
- Either omit the constant, or omit the dummy for one category.
- The coefficients of the dummies are relative to the omitted category.

Uses of dummy variables

Seasonal dummies

- For quarterly data: use 3 dummies
- For monthly data: use 11 dummies
- For daily data: use 6 dummies
- What to do with weekly data?

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- For daily data: use 6 dummies
- What to do with weekly data?

Outliers

- If there is an outlier, you can use a dummy variable to remove its effect.

Uses of dummy variables

Seasonal dummies

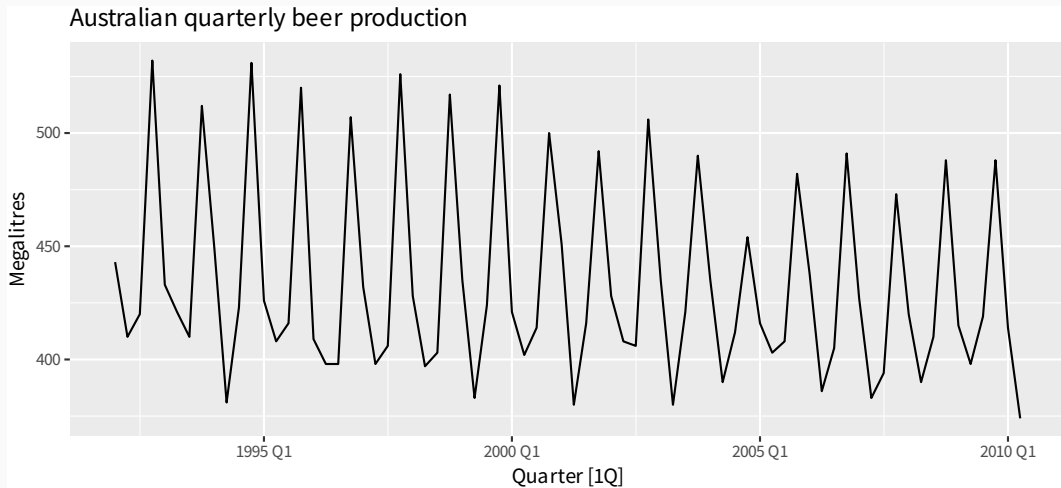
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- For daily data: use 6 dummies
- What to do with weekly data?

Outliers

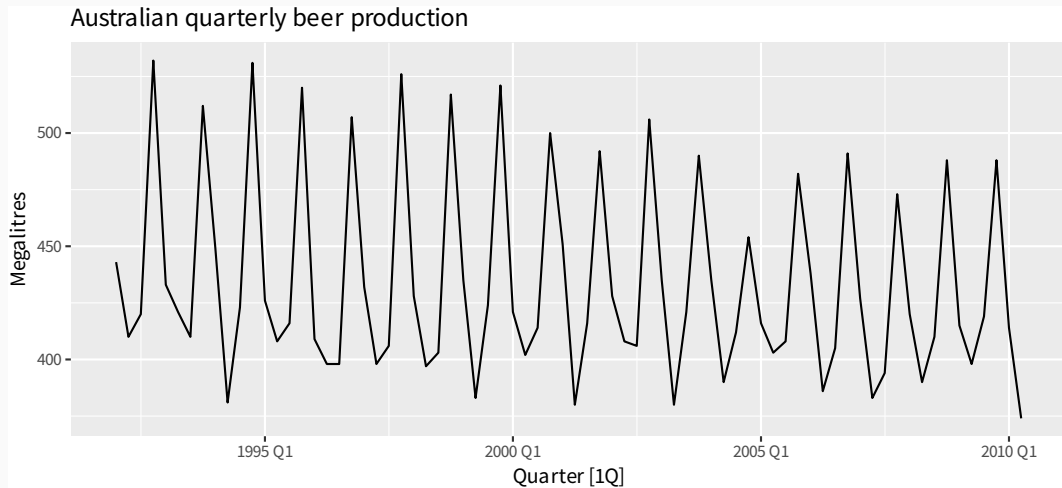
- If there is an outlier, you can use a dummy variable to remove its effect.

Public holidays

Beer production revisited



Beer production revisited



Regression model

Beer production revisited

```
fit_beer <- recent_production |> model(TSLM(Beer ~ trend() + season()))  
report(fit_beer)
```

Series: Beer

Model: TSLM

Residuals:

Min	1Q	Median	3Q	Max
-42.9	-7.6	-0.5	8.0	21.8

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)	
(Intercept)	441.8004	3.7335	118.33	< 2e-16	***
trend()	-0.3403	0.0666	-5.11	2.7e-06	***
season()year2	-34.6597	3.9683	-8.73	9.1e-13	***
season()year3	-17.8216	4.0225	-4.43	3.4e-05	***
season()year4	72.7964	4.0230	18.09	< 2e-16	***

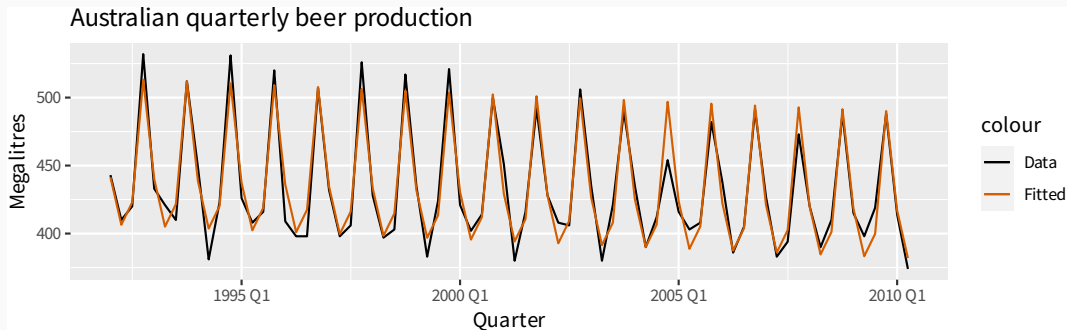
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 12.2 on 69 degrees of freedom

Multiple R-squared: 0.924, Adjusted R-squared: 0.92

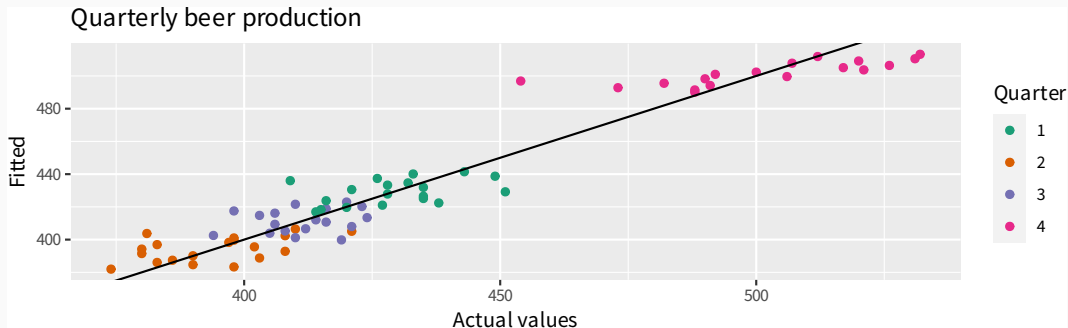
Beer production revisited

```
augment(fit_beer) |>
  ggplot(aes(x = Quarter)) +
  geom_line(aes(y = Beer, colour = "Data")) +
  geom_line(aes(y = .fitted, colour = "Fitted")) +
  labs(y = "Megalitres", title = "Australian quarterly beer production") +
  scale_colour_manual(values = c(Data = "black", Fitted = "#D55E00"))
```



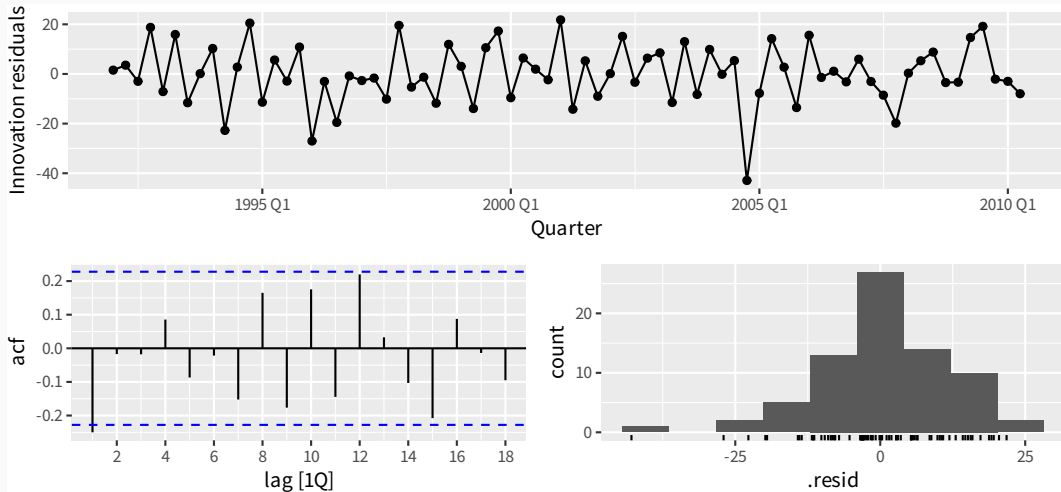
Beer production revisited

```
augment(fit_beer) |>
  ggplot(aes(x = Beer, y = .fitted, colour = factor(quarter(Quarter)))) +
  geom_point() +
  labs(y = "Fitted", x = "Actual values", title = "Quarterly beer production") +
  scale_colour_brewer(palette = "Dark2", name = "Quarter") +
  geom_abline(intercept = 0, slope = 1)
```



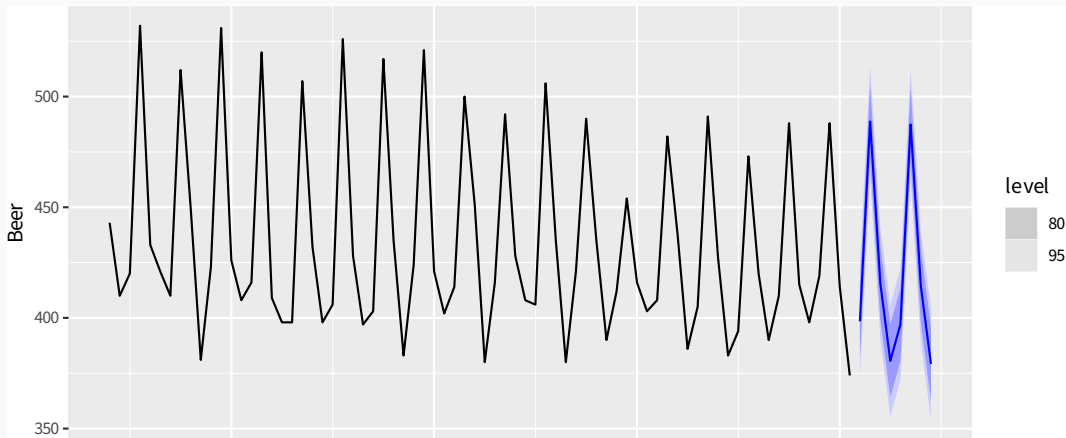
Beer production revisited

```
fit_beer |> gg_tsresiduals()
```



Beer production revisited

```
fit_beer |>  
  forecast() |>  
  autoplot(recent_production)
```



Fourier series

Periodic seasonality can be handled using pairs of Fourier terms:

$$s_k(t) = \sin\left(\frac{2\pi kt}{m}\right) \quad c_k(t) = \cos\left(\frac{2\pi kt}{m}\right)$$

$$y_t = a + bt + \sum_{k=1}^K [\alpha_k s_k(t) + \beta_k c_k(t)] + \varepsilon_t$$

- Every periodic function can be approximated by sums of sin and cos terms for large enough K .
- Choose K by minimizing AICc.
- Called “harmonic regression”

Harmonic regression: beer production

```
fourier_beer <- recent_production |> model(TSLM(Beer ~ trend() + fourier(K = 2)))  
report(fourier_beer)
```

Series: Beer

Model: TSLM

Residuals:

Min	1Q	Median	3Q	Max
-42.9	-7.6	-0.5	8.0	21.8

Coefficients:

	Estimate	Std. Error	t value	Pr(> t)
(Intercept)	446.8792	2.8732	155.53	< 2e-16 ***
trend()	-0.3403	0.0666	-5.11	2.7e-06 ***
fourier(K = 2)C1_4	8.9108	2.0112	4.43	3.4e-05 ***
fourier(K = 2)S1_4	-53.7281	2.0112	-26.71	< 2e-16 ***
fourier(K = 2)C2_4	-13.9896	1.4226	-9.83	9.3e-15 ***

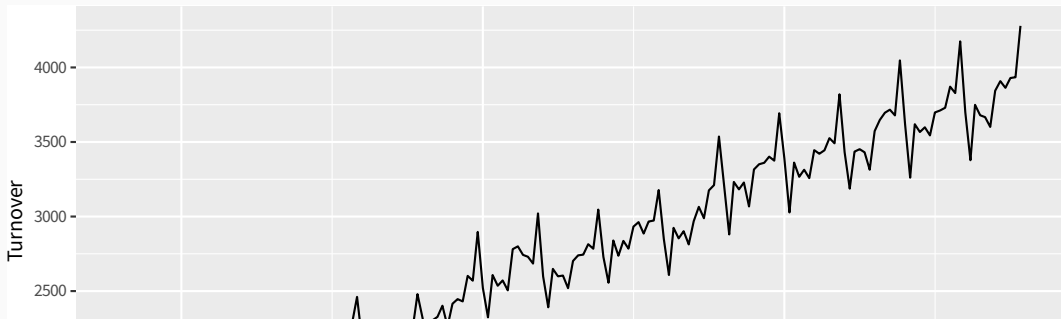
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 12.2 on 69 degrees of freedom

Multiple R-squared: 0.924, Adjusted R-squared: 0.92

Harmonic regression: eating-out expenditure

```
aus_cafe <- aus_retail |>  
  filter(  
    Industry == "Cafes, restaurants and takeaway food services",  
    year(Month) %in% 2004:2018  
  ) |>  
  summarise(Turnover = sum(Turnover))  
aus_cafe |> autoplot(Turnover)
```



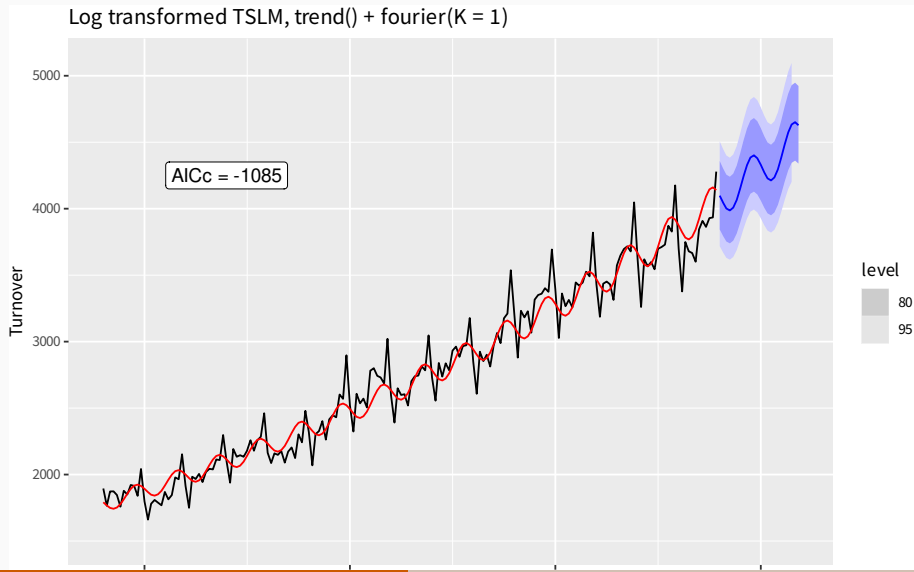
Harmonic regression: eating-out expenditure

```
fit <- aus_cafe |>
  model(
    K1 = TSLM(log(Turnover) ~ trend() + fourier(K = 1)),
    K2 = TSLM(log(Turnover) ~ trend() + fourier(K = 2)),
    K3 = TSLM(log(Turnover) ~ trend() + fourier(K = 3)),
    K4 = TSLM(log(Turnover) ~ trend() + fourier(K = 4)),
    K5 = TSLM(log(Turnover) ~ trend() + fourier(K = 5)),
    K6 = TSLM(log(Turnover) ~ trend() + fourier(K = 6))
  )
glance(fit) |> select(.model, r_squared, adj_r_squared, AICc)
```

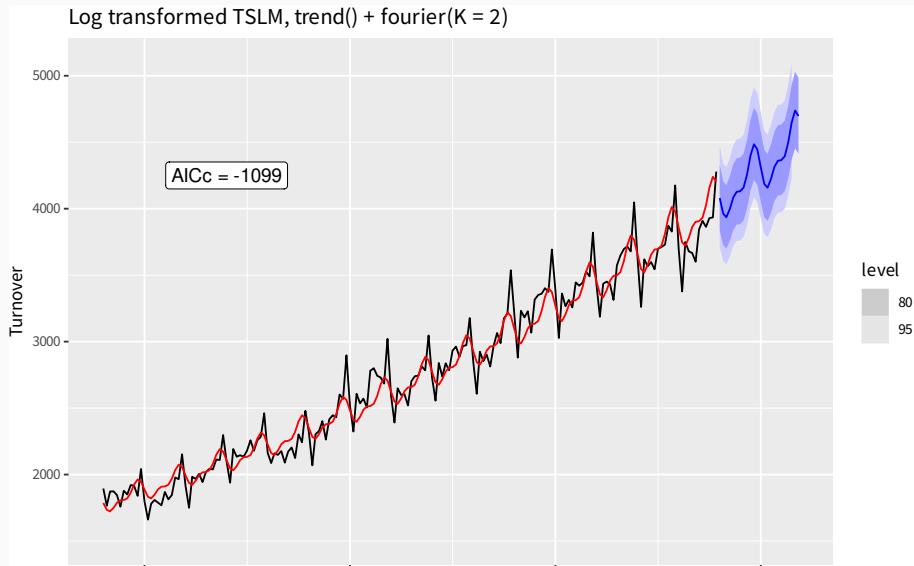
A tibble: 6 x 4

	.model	r_squared	adj_r_squared	AICc
	<chr>	<dbl>	<dbl>	<dbl>
1	K1	0.962	0.962	-1085.
2	K2	0.966	0.965	-1099.
3	K3	0.976	0.975	-1160.
4	K4	0.980	0.979	-1183.
5	K5	0.985	0.984	-1234.

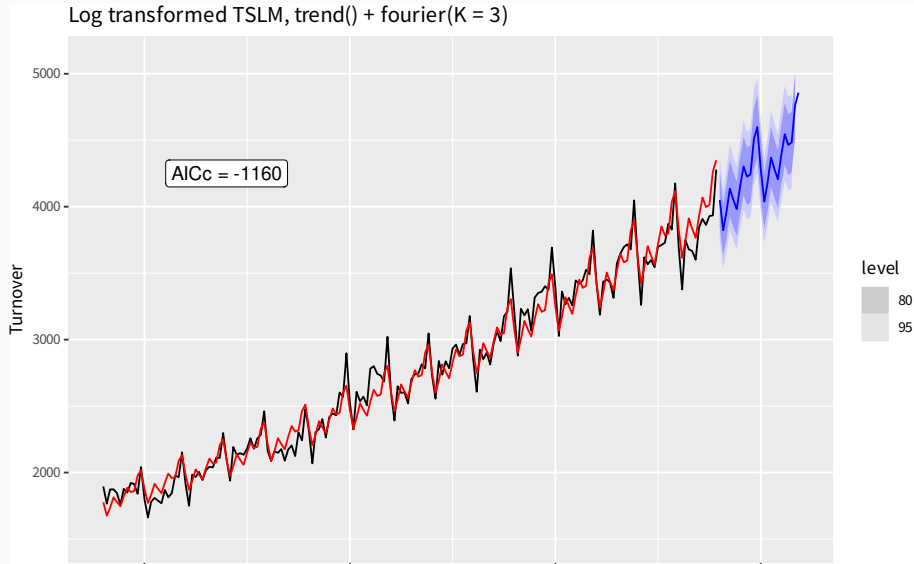
Harmonic regression: eating-out expenditure



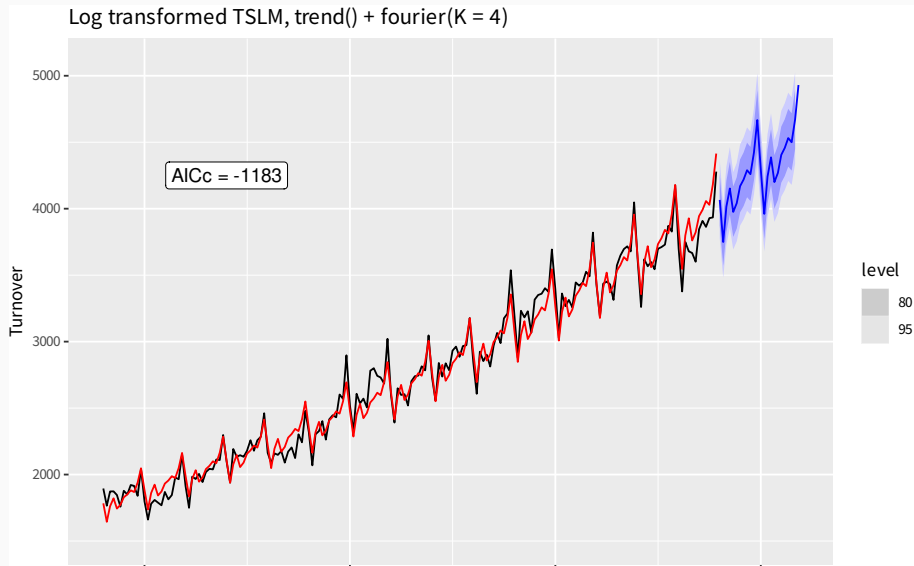
Harmonic regression: eating-out expenditure



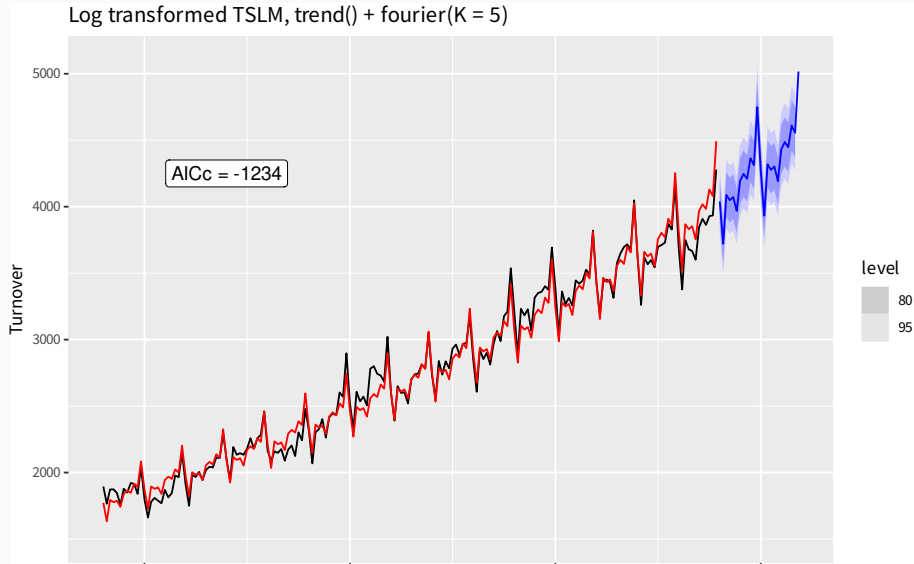
Harmonic regression: eating-out expenditure



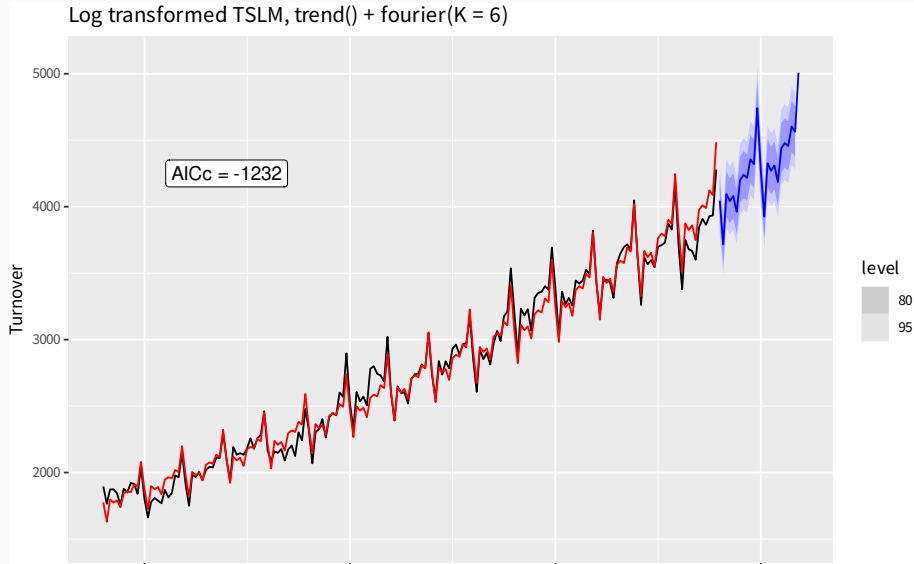
Harmonic regression: eating-out expenditure



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Intervention variables

Spikes

- Equivalent to a dummy variable for handling an outlier.

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Steps

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Change of slope

- Variables take values 0 before the intervention and values $\{1, 2, 3, \dots\}$ afterwards.

For monthly data

- Christmas: always in December so part of monthly seasonal effect
- Easter: use a dummy variable $v_t = 1$ if any part of Easter is in that month, $v_t = 0$ otherwise.
- Ramadan and Chinese new year similar.

Distributed lags

Lagged values of a predictor.

Example: x is advertising which has a delayed effect

x_1 = advertising for previous month;

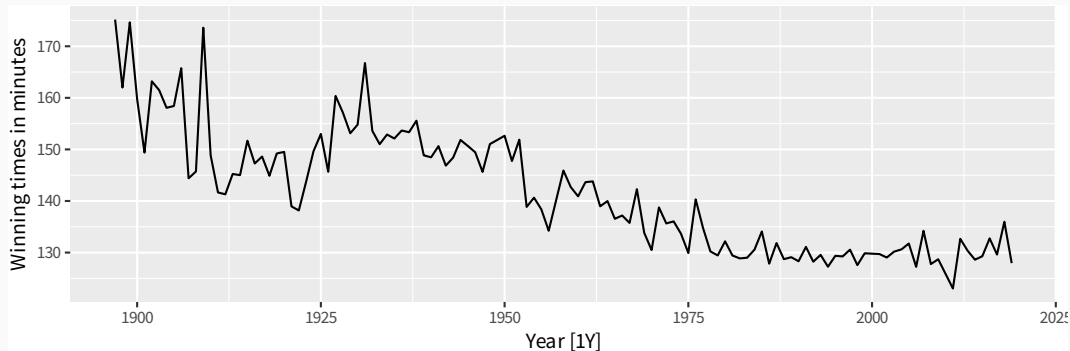
x_2 = advertising for two months previously;

\vdots

x_m = advertising for m months previously.

Example: Boston marathon winning times

```
marathon <- boston_marathon |>
  filter(Event == "Men's open division") |>
  select(-Event) |>
  mutate(Minutes = as.numeric(Time) / 60)
marathon |> autoplot(Minutes) + labs(y = "Winning times in minutes")
```



Example: Boston marathon winning times

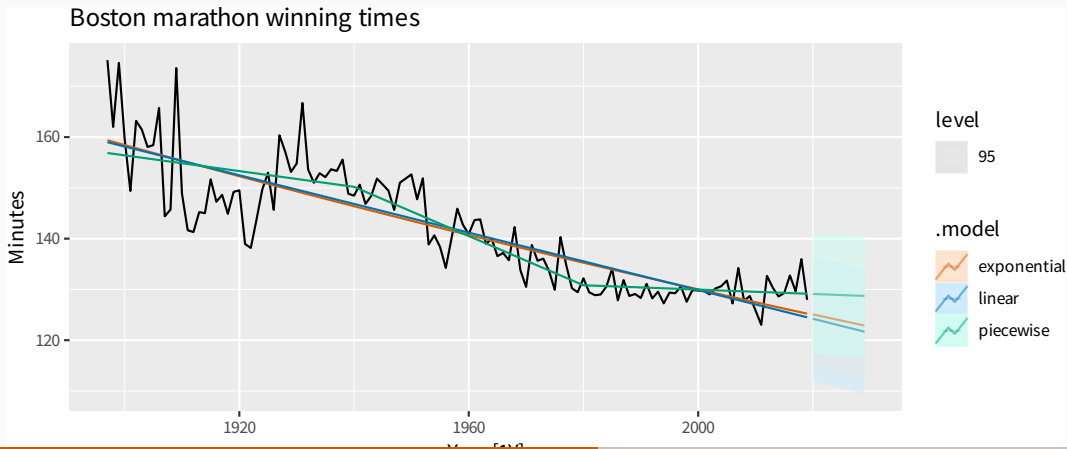
```
fit_trends <- marathon |>
  model(
    # Linear trend
    linear = TSLM(Minutes ~ trend()),
    # Exponential trend
    exponential = TSLM(log(Minutes) ~ trend()),
    # Piecewise linear trend
    piecewise = TSLM(Minutes ~ trend(knots = c(1940, 1980)))
  )
```

fit_trends

```
# A mable: 1 x 3
  linear exponential piecewise
  <model>      <model>      <model>
1  <TSLM>      <TSLM>      <TSLM>
```

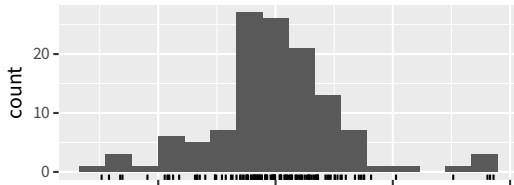
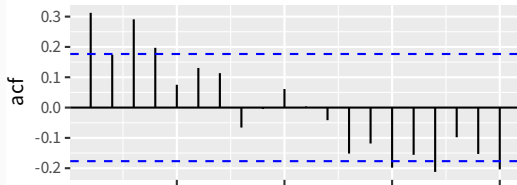
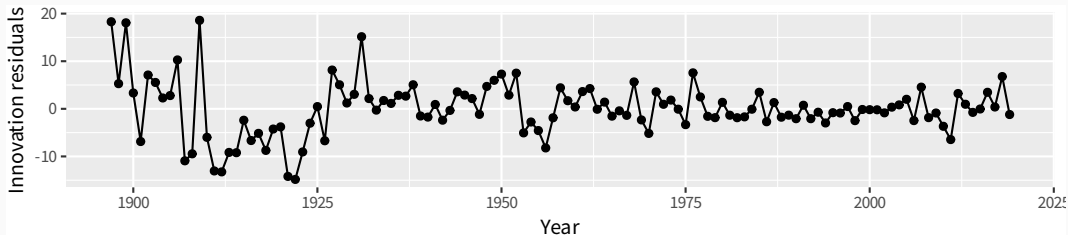
Example: Boston marathon winning times

```
fit_trends |>  
  forecast(h = 10) |>  
  autoplot(marathon)
```



Example: Boston marathon winning times

```
fit_trends |>  
  select(piecewise) |>  
  gg_tsresiduals()
```



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Multiple regression and forecasting

For forecasting purposes, we require the following assumptions:

- ε_t are uncorrelated and zero mean
- ε_t are uncorrelated with each $x_{j,t}$.

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It is **useful** to also have $\varepsilon_t \sim N(0, \sigma^2)$ when producing prediction intervals or doing statistical tests.

Residual plots

Useful for spotting outliers and whether the linear model was appropriate.

- Scatterplot of residuals ε_t against each predictor $x_{j,t}$.
- Scatterplot residuals against the fitted values \hat{y}_t
- Expect to see scatterplots resembling a horizontal band with no values too far from the band and no patterns such as curvature or increasing spread.

Residual patterns

- If a plot of the residuals vs any predictor in the model shows a pattern, then the relationship is nonlinear.
- If a plot of the residuals vs any predictor **not** in the model shows a pattern, then the predictor should be added to the model.
- If a plot of the residuals vs fitted values shows a pattern, then there is heteroscedasticity in the errors. (Could try a transformation.)

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Comparing regression models

Computer output for regression will always give the R^2 value. This is a useful summary of the model.

- It is equal to the square of the correlation between y and \hat{y} .
- It is often called the “coefficient of determination”.
- It can also be calculated as follows:

$$R^2 = \frac{\sum(\hat{y}_t - \bar{y})^2}{\sum(y_t - \bar{y})^2}$$

- It is the proportion of variance accounted for (explained) by the predictors.

Comparing regression models

However ...

- R^2 does not allow for “degrees of freedom”.
- Adding *any* variable tends to increase the value of R^2 , even if that variable is irrelevant.

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To overcome this problem, we can use *adjusted* R^2 :

$$\bar{R}^2 = 1 - (1 - R^2) \frac{T - 1}{T - k - 1}$$

where k = no. predictors and T = no. observations.

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$$\bar{R}^2 = 1 - (1 - R^2) \frac{T - 1}{T - k - 1}$$

where k = no. predictors and T = no. observations.

Maximizing \bar{R}^2 is equivalent to minimizing $\hat{\sigma}^2$.

Akaike's Information Criterion

$$\text{AIC} = -2 \log(L) + 2(k + 2)$$

where L is the likelihood and k is the number of predictors in the model.

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where L is the likelihood and k is the number of predictors in the model.

- AIC penalizes terms more heavily than \bar{R}^2 .
- Minimizing the AIC is asymptotically equivalent to minimizing MSE via **leave-one-out cross-validation** (for any linear regression).

Corrected AIC

For small values of T , the AIC tends to select too many predictors, and so a bias-corrected version of the AIC has been developed.

$$\text{AIC}_C = \text{AIC} + \frac{2(k+2)(k+3)}{T-k-3}$$

As with the AIC, the AIC_C should be minimized.

Bayesian Information Criterion

$$\text{BIC} = -2 \log(L) + (k + 2) \log(T)$$

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where L is the likelihood and k is the number of predictors in the model.

- BIC penalizes terms more heavily than AIC
- Also called SBIC and SC.
- Minimizing BIC is asymptotically equivalent to leave- v -out cross-validation when $v = T[1 - 1/(\log(T) - 1)]$.

Leave-one-out cross-validation

For regression, leave-one-out cross-validation is faster and more efficient than time-series cross-validation.

- Select one observation for test set, and use *remaining* observations in training set. Compute error on test observation.
- Repeat using each possible observation as the test set.
- Compute accuracy measure over all errors.

Cross-validation

Traditional evaluation

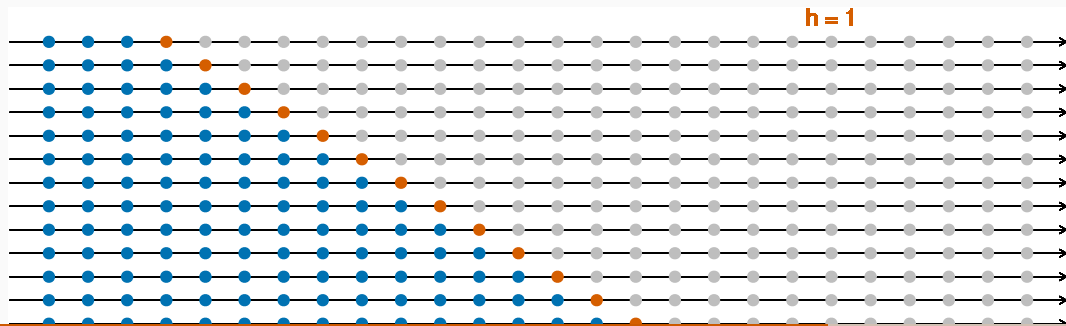


Cross-validation

Traditional evaluation



Time series cross-validation

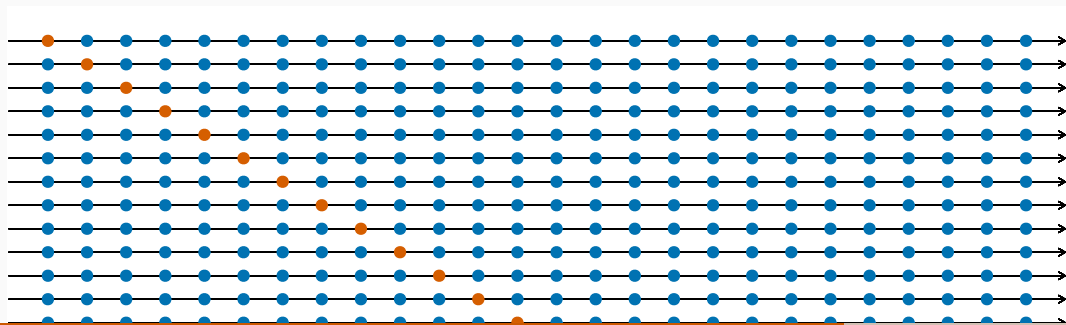


Cross-validation

Traditional evaluation



Leave-one-out cross-validation

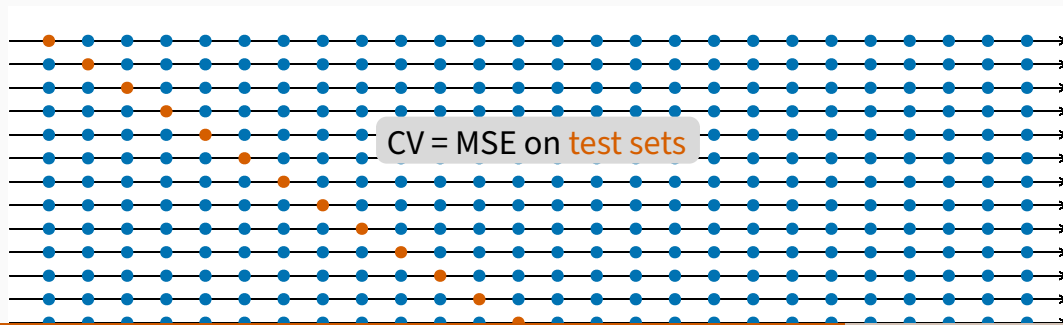


Cross-validation

Traditional evaluation



Leave-one-out cross-validation



Choosing regression variables

Best subsets regression

- Fit all possible regression models using one or more of the predictors.
- Choose the best model based on one of the measures of predictive ability (CV, AIC, AICc).

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Best subsets regression

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Warning!

- If there are a large number of predictors, this is not possible.
- For example, 44 predictors leads to 18 trillion possible models!

Choosing regression variables

Backwards stepwise regression

- Start with a model containing all variables.
- Try subtracting one variable at a time. Keep the model if it has lower CV or AICc.
- Iterate until no further improvement.

Choosing regression variables

Backwards stepwise regression

- Start with a model containing all variables.
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Notes

- Stepwise regression is not guaranteed to lead to the best possible model.
- Inference on coefficients of final model will be wrong.

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Ex-ante versus ex-post forecasts

- *Ex ante forecasts* are made using only information available in advance.
 - ▶ require forecasts of predictors
- *Ex post forecasts* are made using later information on the predictors.
 - ▶ useful for studying behaviour of forecasting models.
- trend, seasonal and calendar variables are all known in advance, so these don't need to be forecast.

Scenario based forecasting

- Assumes possible scenarios for the predictor variables
- Prediction intervals for scenario based forecasts do not include the uncertainty associated with the future values of the predictor variables.

Building a predictive regression model

- If getting forecasts of predictors is difficult, you can use lagged predictors instead.

$$y_t = \beta_0 + \beta_1 x_{1,t-h} + \cdots + \beta_k x_{k,t-h} + \varepsilon_t$$

- A different model for each forecast horizon h .

US Consumption

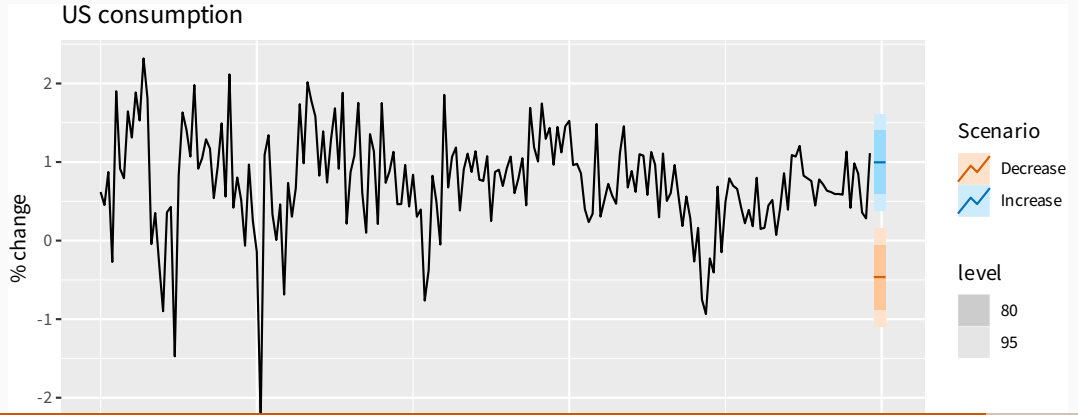
```
fit_consBest <- us_change |>
  model(
    TSLM(Consumption ~ Income + Savings + Unemployment)
  )

future_scenarios <- scenarios(
  Increase = new_data(us_change, 4) |>
    mutate(Income = 1, Savings = 0.5, Unemployment = 0),
  Decrease = new_data(us_change, 4) |>
    mutate(Income = -1, Savings = -0.5, Unemployment = 0),
  names_to = "Scenario"
)

fc <- forecast(fit_consBest, new_data = future_scenarios)
```

US Consumption

```
us_change |> autoplot(Consumption) +  
  labs(y = "% change in US consumption") +  
  autolayer(fc) +  
  labs(title = "US consumption", y = "% change")
```



Outline

- 1 The linear model with time series
- 2 Some useful predictors for linear models
- 3 Residual diagnostics
- 4 Selecting predictors and forecast evaluation
- 5 Forecasting with regression
- 6 Matrix formulation**
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Matrix formulation

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Let $\mathbf{y} = (y_1, \dots, y_T)'$, $\boldsymbol{\varepsilon} = (\varepsilon_1, \dots, \varepsilon_T)'$, $\boldsymbol{\beta} = (\beta_0, \beta_1, \dots, \beta_k)'$ and

$$\mathbf{X} = \begin{bmatrix} 1 & x_{1,1} & x_{2,1} & \cdots & x_{k,1} \\ 1 & x_{1,2} & x_{2,2} & \cdots & x_{k,2} \\ \vdots & \vdots & \vdots & & \vdots \\ 1 & x_{1,T} & x_{2,T} & \cdots & x_{k,T} \end{bmatrix}.$$

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Then

$$\mathbf{y} = \mathbf{X}\boldsymbol{\beta} + \boldsymbol{\varepsilon}.$$

Matrix formulation

Least squares estimation

Minimize: $(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})'(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})$

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Differentiate wrt $\boldsymbol{\beta}$ gives

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

Matrix formulation

Least squares estimation

Minimize: $(\mathbf{y} - \mathbf{X}\beta)'(\mathbf{y} - \mathbf{X}\beta)$

Differentiate wrt β gives

$$\hat{\beta} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

(The “normal equation”.)

Matrix formulation

Least squares estimation

Minimize: $(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})'(\mathbf{y} - \mathbf{X}\boldsymbol{\beta})$

Differentiate wrt $\boldsymbol{\beta}$ gives

$$\hat{\boldsymbol{\beta}} = (\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\mathbf{y}$$

(The “normal equation”.)

$$\hat{\sigma}^2 = \frac{1}{T - k - 1}(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})'(\mathbf{y} - \mathbf{X}\hat{\boldsymbol{\beta}})$$

Likelihood

If the errors are iid and normally distributed, then

$$\mathbf{y} \sim N(\mathbf{X}\boldsymbol{\beta}, \sigma^2 \mathbf{I}).$$

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So MLE = OLS.

Multiple regression forecasts

Optimal forecasts

$$\hat{y}^* = E(y^* | \mathbf{y}, \mathbf{X}, \mathbf{x}^*) = \mathbf{x}^* \hat{\boldsymbol{\beta}} = \mathbf{x}^* (\mathbf{X}'\mathbf{X})^{-1} \mathbf{X}'\mathbf{y}$$

where \mathbf{x}^* is a row vector containing the values of the predictors for the forecasts (in the same format as \mathbf{X}).

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Forecast variance

$$\text{Var}(y^* | \mathbf{X}, \mathbf{x}^*) = \sigma^2 \left[1 + \mathbf{x}^* (\mathbf{X}'\mathbf{X})^{-1} (\mathbf{x}^*)' \right]$$

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Forecast variance

$$\text{Var}(y^* | \mathbf{X}, \mathbf{x}^*) = \sigma^2 [1 + \mathbf{x}^* (\mathbf{X}'\mathbf{X})^{-1} (\mathbf{x}^*)']$$

- This ignores any errors in \mathbf{x}^* .
- 95% prediction intervals assuming normal errors:

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Correlation is not causation

- When x is useful for predicting y , it is not necessarily causing y .
- e.g., predict number of drownings y using number of ice-creams sold x .
- Correlations are useful for forecasting, even when there is no causality.
- Better models usually involve causal relationships (e.g., temperature x and people z to predict drownings y).

Multicollinearity

In regression analysis, multicollinearity occurs when:

- Two predictors are highly correlated (i.e., the correlation between them is close to ± 1).
- A linear combination of some of the predictors is highly correlated with another predictor.
- A linear combination of one subset of predictors is highly correlated with a linear combination of another subset of predictors.

Multicollinearity

If multicollinearity exists...

- the numerical estimates of coefficients may be wrong (worse in Excel than in a statistics package)
- don't rely on the p -values to determine significance.
- there is no problem with model *predictions* provided the predictors used for forecasting are within the range used for fitting.
- omitting variables can help.
- combining variables can help.