Unit 7: Multiple linear regression

1. Introduction to multiple linear regression

GOVT 3990 - Spring 2018

Cornell University

Outline

1. Housekeeping

2. Main ideas

    1. In MLR everything is conditional on all other variables in the model

    2. Categorical predictors and slopes for (almost) each level

    3. Inference for MLR: model as a whole + individual slopes

    4. Adjusted R^2 applies a penalty for additional variables

    5. Avoid collinearity in MLR

    6. Model selection criterion depends on goal: significance vs. prediction

    7. Conditions for MLR are (almost) the same as conditions for SLR

3. Summary

Announcements

- Project questions?

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3. Summary

(1) In MLR everything is conditional on all other variables in the model

- All estimates in a MLR for a given variable are conditional on all other variables being in the model.
- Slope:
  - Numerical x: *All else held constant*, for one unit increase in x_i, y is expected to be higher / lower on average by b_i units.
  - Categorical x: *All else held constant*, the predicted difference in y for the baseline and given levels of x_i is b_i.

A random sample of 783 observations from the 2012 ACS.

1. `income`: Yearly income (wages and salaries)
2. `employment`: Employment status, not in labor force, unemployed, or employed
3. `hrs_work`: Weekly hours worked
4. `race`: Race, White, Black, Asian, or other
5. `age`: Age
6. `gender`: gender, male or female
7. `citizens`: Whether respondent is a US citizen or not
8. `time_to_work`: Travel time to work
9. `lang`: Language spoken at home, English or other
10. `married`: Whether respondent is married or not
11. `edu`: Education level, hs or lower, college, or grad
12. `disability`: Whether respondent is disabled or not
13. `birth_qrtr`: Quarter in which respondent is born, jan thru mar, apr thru jun, jul thru sep, or oct thru dec

Activity: MLR interpretations

1. Interpret the intercept.
2. Interpret the slope for hrs_work.
3. Interpret the slope for gender.

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-15342.76	11716.57	-1.31	0.19
hrs_work	1048.96	149.25	7.03	0.00
raceblack	-7998.99	6191.83	-1.29	0.20
raceasian	29909.80	9154.92	3.27	0.00
raceother	-6756.32	7240.08	-0.93	0.35
age	565.07	133.77	4.22	0.00
genderfemale	-17135.05	3705.35	-4.62	0.00
citizenyes	-12907.34	8231.66	-1.57	0.12
time_to_work	90.04	79.83	1.13	0.26
langother	-10510.44	5447.45	-1.93	0.05
marriedyes	5409.24	3900.76	1.39	0.17
educollege	15993.85	4098.99	3.90	0.00
edugrad	59658.52	5660.26	10.54	0.00
disabilityyes	-14142.79	6639.40	-2.13	0.03
birth_qrtrapr thru jun	-2043.42	4978.12	-0.41	0.68
birth_qrtrjul thru sep	3036.02	4853.19	0.63	0.53
birth_qrtroct thru dec	2674.11	5038.45	0.53	0.60

Outline

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    1. In MLR everything is conditional on all other variables in the model

    2. Categorical predictors and slopes for (almost) each level

    3. Inference for MLR: model as a whole + individual slopes

    4. Adjusted R^2 applies a penalty for additional variables

    5. Avoid collinearity in MLR

    6. Model selection criterion depends on goal: significance vs. prediction

    7. Conditions for MLR are (almost) the same as conditions for SLR

3. Summary

(2) Categorical predictors and slopes for (almost) each level

- Each categorical variable, with k levels, added to the model results in $k-1$ parameters being estimated.
- It only takes $k-1$ columns to code a categorical variable with k levels as 0/1s.

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Citizen: yes / no ($k=2$)

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Citizen: yes / no ($k=2$)

Baseline: no

(2) Categorical predictors and slopes for (almost) each level

- Each categorical variable, with k levels, added to the model results in $k - 1$ parameters being estimated.
- It only takes $k - 1$ columns to code a categorical variable with k levels as 0/1s.

Citizen: yes / no ($k = 2$)
Baseline: no

Respondent	citizen:yes

- Each categorical variable, with k levels, added to the model results in $k-1$ parameters being estimated.
- It only takes $k-1$ columns to code a categorical variable with k levels as 0/1s.

Citizen: yes / no ($k=2$)
Baseline: no

Respondent	citizen:yes
1, Citizen	1

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Citizen: yes / no ($k=2$)
Baseline: no

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

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- It only takes $k-1$ columns to code a categorical variable with k levels as 0/1s.

Citizen: yes / no $(k=2)$
Baseline: no

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

Race: $(k=4)$

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Citizen: yes / no ($k=2$)
Baseline: no

Race: ($k=4$)
Baseline: White

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

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- It only takes $k-1$ columns to code a categorical variable with k levels as 0/1s.

Citizen: yes / no ($k=2$)
Baseline: no

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

Race: ($k=4$)
Baseline: White

Respondent	race:black	race:asian	race:other

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Citizen: yes / no ($k=2$)
Baseline: no

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1, Citizen	1
2, Not-citizen	0

Race: ($k=4$)
Baseline: White

Respondent	race:black	race:asian	race:other
1, White	0	0	0

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Citizen: yes / no ($k=2$)
Baseline: no

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1, Citizen	1
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Race: ($k=4$)
Baseline: White

Respondent	race:black	race:asian	race:other
1, White	0	0	0
2, Black	1	0	0

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Citizen: yes / no ($k = 2$)
Baseline: no

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

Race: ($k = 4$)
Baseline: White

Respondent	race:black	race:asian	race:other
1, White	0	0	0
2, Black	1	0	0
3, Asian	0	1	0

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Citizen: yes / no $(k=2)$
Baseline: no

Respondent	citizen:yes
1, Citizen	1
2, Not-citizen	0

Race: $(k=4)$
Baseline: White

Respondent	race:black	race:asian	race:other
1, White	0	0	0
2, Black	1	0	0
3, Asian	0	1	0
4, Other	0	0	1

Your turn

All else held constant, how do incomes of those born January thru March compare to those born April thru June?

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-15342.76	11716.57	-1.31	0.19
hrs_work	1048.96	149.25	7.03	0.00
raceblack	-7998.99	6191.83	-1.29	0.20
raceasian	29909.80	9154.92	3.27	0.00
raceother	-6756.32	7240.08	-0.93	0.35
age	565.07	133.77	4.22	0.00
genderfemale	-17135.05	3705.35	-4.62	0.00
citizenyes	-12907.34	8231.66	-1.57	0.12
time_to_work	90.04	79.83	1.13	0.26
langother	-10510.44	5447.45	-1.93	0.05
marriedyes	5409.24	3900.76	1.39	0.17
educollege	15993.85	4098.99	3.90	0.00
edugrad	59658.52	5660.26	10.54	0.00
disabilityyes	-14142.79	6639.40	-2.13	0.03
birth_qrtrapr thru jun	-2043.42	4978.12	-0.41	0.68
birth_qrtrjul thru sep	3036.02	4853.19	0.63	0.53
birth_qrtroct thru dec	2674.11	5038.45	0.53	0.60

All else held constant, those born Jan thru Mar make, on average,

(a) $2,043.42 less

(b) $2,043.42 more

(c) $4978.12 less

(d) $4978.12 more

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(a) \$2,043.42 less

(b) ***\$2,043.42 more***

(c) \$4978.12 less

(d) \$4978.12 more

Outline

(3) Inference for MLR: model as a whole + individual slopes

- Inference for the model as a whole: F-test, $df_1 = p$, $df_2 = n - k - 1$

  H_0 : $\beta_1 = \beta_2 = \cdots = \beta_k = 0$

  H_A : At least one of the $\beta_i \neq 0$

(3) Inference for MLR: model as a whole + individual slopes

- Inference for the model as a whole: F-test, $df_1 = p$, $df_2 = n - k - 1$

  H_0 : $\beta_1 = \beta_2 = \cdots = \beta_k = 0$

  H_A : At least one of the $\beta_i \neq 0$

- Inference for each slope: T-test, $df = n - k - 1$
  - HT:

    H_0 : $\beta_1 = 0$, when all other variables are included in the model

    H_A : $\beta_1 \neq 0$, when all other variables are included in the model
  - CI: $b_1 \pm T^\star_{df} SE_{b_1}$

Model output

```
Coefficients:
                        Estimate Std. Error t value Pr(>|t|)
(Intercept)            -15342.76   11716.57  -1.309 0.190760
hrs_work                 1048.96     149.25   7.028 4.63e-12 ***
raceblack               -7998.99    6191.83  -1.292 0.196795
raceasian               29909.80    9154.92   3.267 0.001135 **
raceother               -6756.32    7240.08  -0.933 0.351019
age                       565.07     133.77   4.224 2.69e-05 ***
genderfemale           -17135.05    3705.35  -4.624 4.41e-06 ***
citizenyes             -12907.34    8231.66  -1.568 0.117291
time_to_work               90.04      79.83   1.128 0.259716
langother              -10510.44    5447.45  -1.929 0.054047 .
marriedyes               5409.24    3900.76   1.387 0.165932
educollege              15993.85    4098.99   3.902 0.000104 ***
edugrad                 59658.52    5660.26  10.540  < 2e-16 ***
disabilityyes          -14142.79    6639.40  -2.130 0.033479 *
birth_qrtrapr thru jun  -2043.42    4978.12  -0.410 0.681569
birth_qrtrjul thru sep   3036.02    4853.19   0.626 0.531782
birth_qrtroct thru dec   2674.11    5038.45   0.531 0.595752

Residual standard error: 48670 on 766 degrees of freedom
  (60 observations deleted due to missingness)
Multiple R-squared:  0.3126,^^IAdjusted R-squared:  0.2982
F-statistic: 21.77 on 16 and 766 DF,  p-value: < 2.2e-16
```

Your turn

True / False: The F test yielding a significant result means the model fits the data well.

(a) True
(b) False

Your turn

True / False: The F test yielding a significant result means the model fits the data well.

(a) True

(b) *False*

The F test yielding a significant result doesn't mean the model fits the data well, it just means at least one of the βs is non-zero. Whether or not the model fit the data well is evaluated based on model diagnostics.

Your turn

True / False: The F test not yielding a significant result means individual variables included in the model are not good predictors of y.

(a) True

(b) False

Your turn

True / False: The F test not yielding a significant result means individual variables included in the model are not good predictors of y.

(a) True

(b) *False*

The F test not yielding a significant result doesn't mean individuals variables included in the model are not good predictors of y, it just means that the combination of these variables doesn't yield a good model.

Significance also depends on what else is in the model

```
Model 1:                  Estimate Std. Error t value Pr(>|t|)
(Intercept)              -15342.76   11716.57  -1.309 0.190760
hrs_work                   1048.96     149.25   7.028 4.63e-12
raceblack                 -7998.99    6191.83  -1.292 0.196795
raceasian                 29909.80    9154.92   3.267 0.001135
raceother                 -6756.32    7240.08  -0.933 0.351019
age                         565.07     133.77   4.224 2.69e-05
genderfemale             -17135.05    3705.35  -4.624 4.41e-06
citizenyes               -12907.34    8231.66  -1.568 0.117291
time_to_work                 90.04      79.83   1.128 0.259716
langother                -10510.44    5447.45  -1.929 0.054047
marriedyes                 5409.24    3900.76   1.387 0.165932 <----
educollege                15993.85    4098.99   3.902 0.000104
edugrad                   59658.52    5660.26  10.540  < 2e-16
disabilityyes            -14142.79    6639.40  -2.130 0.033479
birth_qrtrapr thru jun    -2043.42    4978.12  -0.410 0.681569
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birth_qrtroct thru dec    2674.11    5038.45   0.531 0.595752
```

```
Model 2:     Estimate Std. Error t value Pr(>|t|)
(Intercept)  -22498.2     8216.2  -2.738  0.00631
hrs_work       1149.7      145.2   7.919 7.60e-15
raceblack     -7677.5     6350.8  -1.209  0.22704
raceasian     38600.2     8566.4   4.506 7.55e-06
raceother     -7907.1     7116.2  -1.111  0.26683
age             533.1      131.2   4.064 5.27e-05
genderfemale -15178.9     3767.4  -4.029 6.11e-05
marriedyes     8731.0     3956.8   2.207  0.02762 <----
```

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    4. Adjusted R^2 applies a penalty for additional variables
    5. Avoid collinearity in MLR
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3. Summary

(4) Adjusted R^2 applies a penalty for additional variables

- When <u>any</u> variable is added to the model R^2 increases.

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- When any variable is added to the model R^2 increases.
- But if the added variable doesn't really provide any new information, or is completely unrelated, adjusted R^2 does not increase.

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Adjusted R^2

$$R^2_{adj} = 1 - \left(\frac{SS_{Error}}{SS_{Total}} \times \frac{n-1}{n-k-1} \right)$$

where n is the number of cases and k is the number of sloped estimated in the model.

```
Analysis of Variance Table

Response: income
              Df     Sum Sq    Mean Sq  F value    Pr(>F)    
hrs_work       1 3.0633e+11 3.0633e+11 129.3025 < 2.2e-16 ***
race           3 7.1656e+10 2.3885e+10  10.0821 1.608e-06 ***
age            1 7.6008e+10 7.6008e+10  32.0836 2.090e-08 ***
gender         1 4.8665e+10 4.8665e+10  20.5418 6.767e-06 ***
citizen        1 1.1135e+09 1.1135e+09   0.4700   0.49319    
time_to_work   1 3.5371e+09 3.5371e+09   1.4930   0.22213    
lang           1 1.2815e+10 1.2815e+10   5.4094   0.02029 *  
married        1 1.2190e+10 1.2190e+10   5.1453   0.02359 *  
edu            2 2.7867e+11 1.3933e+11  58.8131 < 2.2e-16 ***
disability     1 1.0852e+10 1.0852e+10   4.5808   0.03265 *  
birth_qrtr     3 3.3060e+09 1.1020e+09   0.4652   0.70667    
Residuals    766 1.8147e+12 2.3691e+09                       
Total        782 2.6399e+12
```

$$R^2_{adj} = 1 - \left(\frac{1.8147e+12}{2.6399e+12} \times \frac{783-1}{783-16-1} \right) \approx 1 - 0.7018 = 0.2982$$

Your turn

True / False: For a model with at least one predictor, R^2_{adj} will always be smaller than R^2.

(a) True

(b) False

Your turn

True / False: For a model with at least one predictor, R^2_{adj} will always be smaller than R^2.

(a) *True*

(b) False

Because k is never negative, R^2_{adj} will always be smaller than R^2.

$$R^2_{adj} = 1 - \left(\frac{SS_{Error}}{SS_{Total}} \times \frac{n-1}{n-k-1}\right)$$

Your turn

True / False: Adjusted R^2 tells us the percentage of variability in the response variable explained by the model.

(a) True

(b) False

Your turn

True / False: Adjusted R^2 tells us the percentage of variability in the response variable explained by the model.

(a) True

(b) *False*

R^2 tells us the percentage of variability in the response variable explained by the model, adjusted R^2 is only useful for model selection.

Outline

(5) Avoid collinearity in MLR

- Two predictor variables are said to be collinear when they are correlated, and this *collinearity* (also called *multicollinearity*) complicates model estimation.

  Remember: Predictors are also called explanatory or independent variables, so they should be independent of each other.

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- Two predictor variables are said to be collinear when they are correlated, and this *collinearity* (also called *multicollinearity*) complicates model estimation.

  Remember: Predictors are also called explanatory or independent variables, so they should be independent of each other.
- We don't like adding predictors that are associated with each other to the model, because often times the addition of such variable brings nothing to the table. Instead, we prefer the simplest best model, i.e. *parsimonious* model.

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- In addition, addition of collinear variables can result in unreliable estimates of the slope parameters.

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- Two predictor variables are said to be collinear when they are correlated, and this *collinearity* (also called *multicollinearity*) complicates model estimation.

  Remember: Predictors are also called explanatory or <u>independent</u> variables, so they should be independent of each other.

- We don't like adding predictors that are associated with each other to the model, because often times the addition of such variable brings nothing to the table. Instead, we prefer the simplest best model, i.e. *parsimonious* model.
- In addition, addition of collinear variables can result in unreliable estimates of the slope parameters.
- While it's impossible to avoid collinearity from arising in observational data, experiments are usually designed to control for correlated predictors.

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(6) Model selection criterion depends on goal: significance vs. prediction

- If the goal is to find the set of statistically predictors of y
  $\rightarrow$ use p-value selection.

(6) Model selection criterion depends on goal: significance vs. prediction

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- Either way, can use *backward elimination* or *forward selection*.
- Expert opinion and focus of research might also demand that a particular variable be included in the model.

Your turn

Using the p-value approach, which variable would you remove from the model first?

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-15342.76	11716.57	-1.31	0.19
hrs_work	1048.96	149.25	7.03	0.00
raceblack	-7998.99	6191.83	-1.29	0.20
raceasian	29909.80	9154.92	3.27	0.00
raceother	-6756.32	7240.08	-0.93	0.35
age	565.07	133.77	4.22	0.00
genderfemale	-17135.05	3705.35	-4.62	0.00
citizenyes	-12907.34	8231.66	-1.57	0.12
time_to_work	90.04	79.83	1.13	0.26
langother	-10510.44	5447.45	-1.93	0.05
marriedyes	5409.24	3900.76	1.39	0.17
educollege	15993.85	4098.99	3.90	0.00
edugrad	59658.52	5660.26	10.54	0.00
disabilityyes	-14142.79	6639.40	-2.13	0.03
birth_qrtrapr thru jun	-2043.42	4978.12	-0.41	0.68
birth_qrtrjul thru sep	3036.02	4853.19	0.63	0.53
birth_qrtroct thru dec	2674.11	5038.45	0.53	0.60

(a) race:other

(b) race

(c) time_to_work

(d) birth_qrtr:apr thru jun

(e) birth_qrtr

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	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	-14022.48	11137.08	-1.26	0.21
hrs_work	1045.85	149.05	7.02	0.00
raceblack	-7636.32	6177.50	-1.24	0.22
raceasian	29944.35	9137.13	3.28	0.00
raceother	-7212.57	7212.25	-1.00	0.32
age	559.51	133.27	4.20	0.00
genderfemale	-17010.85	3699.19	-4.60	0.00
citizenyes	-13059.46	8219.99	-1.59	0.11
time_to_work	88.77	79.73	1.11	0.27
langother	-10150.41	5431.15	-1.87	0.06
marriedyes	5400.41	3896.12	1.39	0.17
educollege	16214.46	4089.17	3.97	0.00
edugrad	59572.20	5631.33	10.58	0.00
disabilityyes	-14201.11	6628.26	-2.14	0.03

(a) married

(b) race

(c) race:other

(d) race:black

(e) time_to_work

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(b) race

(c) race:other

(d) race:black

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Outline

(7) Conditions for MLR are (almost) the same as conditions for SLR

Important regardless of doing inference

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- Nearly normally distributed residuals $\rightarrow$ histogram or normal probability plot of residuals
- Constant variability of residuals (*homoscedasticity*) $\rightarrow$ no fan shape in the residuals plot
- Independence of residuals (and hence observations) $\rightarrow$ depends on data collection method, often violated for time-series data

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- Constant variability of residuals (*homoscedasticity*) $\rightarrow$ no fan shape in the residuals plot
- Independence of residuals (and hence observations) $\rightarrow$ depends on data collection method, often violated for time-series data
- Also important to make sure that your explanatory variables are not *collinear*

Your turn

Which of the following is the appropriate plot for checking the homoscedasticity condition in MLR?

(a) scatterplot of residuals vs. $\hat{y}$

(b) scatterplot of residuals vs. x

(c) histogram of residuals

(d) normal probability plot of residuals

(e) scatterplot of residuals vs. order of data collection

Your turn

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(a) *scatterplot of residuals vs.* $\hat{y}$

(b) scatterplot of residuals vs. x

(c) histogram of residuals

(d) normal probability plot of residuals

(e) scatterplot of residuals vs. order of data collection

Plotting residuals against $\hat{y}$ (predicted, or fitted, values of y) allows us to evaluate the whole model as a whole as opposed to homoscedasticity with regards to just one of the explanatory variables in the model.

Outline

1. Housekeeping

2. Main ideas

    1. In MLR everything is conditional on all other variables in the model

    2. Categorical predictors and slopes for (almost) each level

    3. Inference for MLR: model as a whole + individual slopes

    4. Adjusted R^2 applies a penalty for additional variables

    5. Avoid collinearity in MLR

    6. Model selection criterion depends on goal: significance vs. prediction

    7. Conditions for MLR are (almost) the same as conditions for SLR

3. Summary

Summary of main ideas

1. In MLR everything is conditional on all other variables in the model
2. Categorical predictors and slopes for (almost) each level
3. Inference for MLR: model as a whole + individual slopes
4. Adjusted R^2 applies a penalty for additional variables
5. Avoid collinearity in MLR
6. Model selection criterion depends on goal: significance vs. prediction
7. Conditions for MLR are (almost) the same as conditions for SLR