

Assignment

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Exercise 1

1. Exploring the Dataset

```
load("Data ST523 813 E2025 Exam.rdata")  
dim(Data)
```

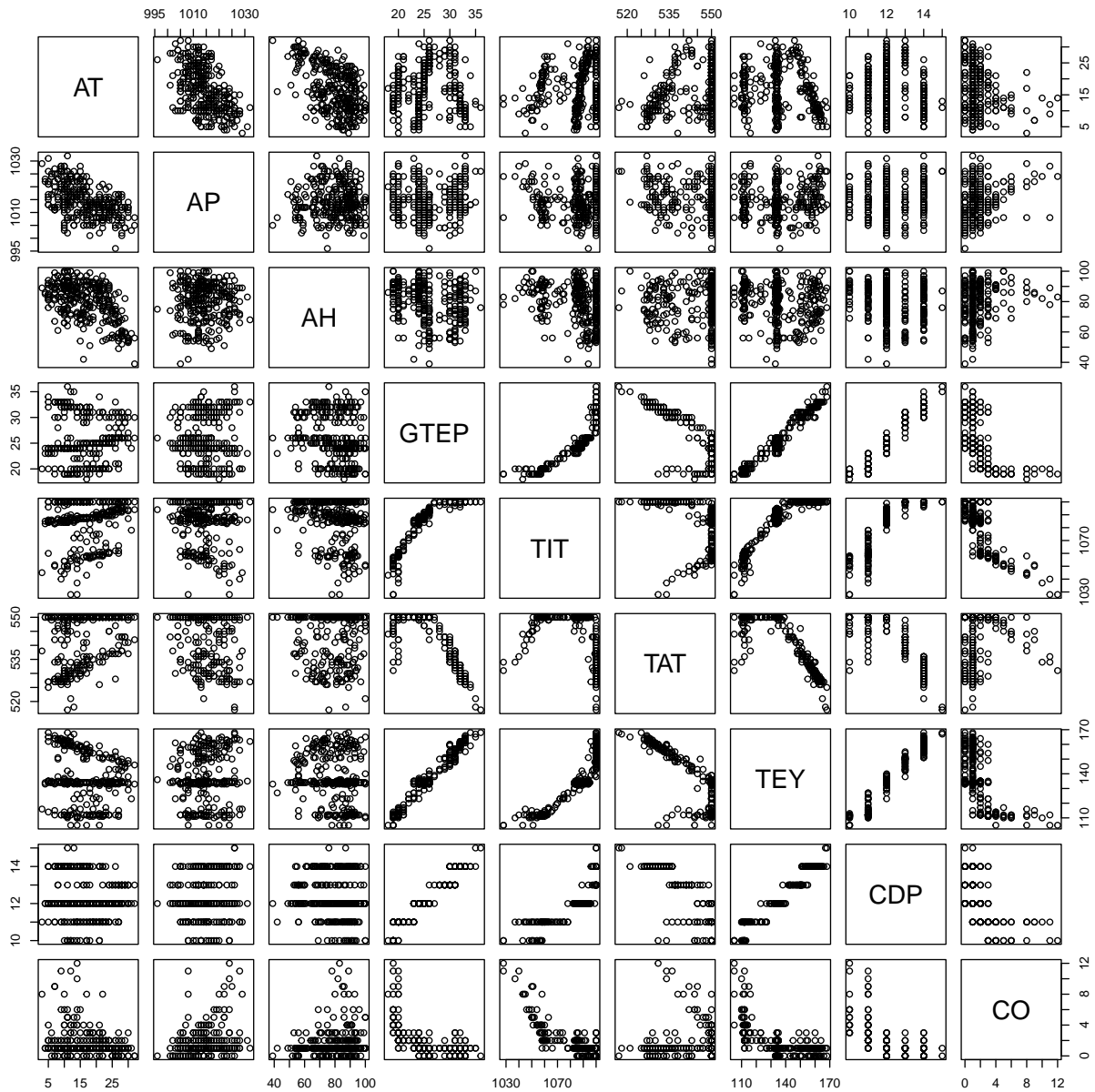
```
[1] 300  9
```

```
summary(Data)
```

| AT | AP | AH | GTEP | TIT |
|---------------|--------------|----------------|---------------|--------------|
| Min. : 3.00 | Min. : 996 | Min. : 39.00 | Min. :18.00 | Min. :1028 |
| 1st Qu.:11.00 | 1st Qu.:1010 | 1st Qu.: 72.00 | 1st Qu.:23.00 | 1st Qu.:1083 |
| Median :16.00 | Median :1014 | Median : 82.00 | Median :25.00 | Median :1089 |
| Mean :16.74 | Mean :1015 | Mean : 79.82 | Mean :25.85 | Mean :1085 |
| 3rd Qu.:22.25 | 3rd Qu.:1019 | 3rd Qu.: 90.00 | 3rd Qu.:30.00 | 3rd Qu.:1100 |
| Max. :32.00 | Max. :1032 | Max. :100.00 | Max. :36.00 | Max. :1100 |

| TAT | TEY | CDP | CO |
|---------------|---------------|---------------|--------------|
| Min. :517.0 | Min. :105.0 | Min. :10.00 | Min. : 0.0 |
| 1st Qu.:536.0 | 1st Qu.:130.0 | 1st Qu.:12.00 | 1st Qu.: 1.0 |
| Median :550.0 | Median :134.0 | Median :12.00 | Median : 1.0 |
| Mean :543.8 | Mean :136.5 | Mean :12.29 | Mean : 1.7 |
| 3rd Qu.:550.0 | 3rd Qu.:151.0 | 3rd Qu.:13.00 | 3rd Qu.: 2.0 |
| Max. :550.0 | Max. :168.0 | Max. :15.00 | Max. :12.0 |

```
pairs(Data)
```



So we have 9 non-categorical variables and a total of 300 observations.

2. Linear Model

```
fit = lm(CO ~ AT + AP + AH + GTEP + TIT + TAT + TEY + CDP, data = Data)
summary(fit)
```

```
Call:
lm(formula = CO ~ AT + AP + AH + GTEP + TIT + TAT + TEY + CDP,
    data = Data)
```

Residuals:

| | Min | 1Q | Median | 3Q | Max |
|--|---------|---------|---------|--------|--------|
| | -2.8724 | -0.5804 | -0.0571 | 0.4270 | 4.3507 |

Coefficients:

| | Estimate | Std. Error | t value | Pr(> t) |
|-------------|------------|------------|---------|--------------|
| (Intercept) | 124.201441 | 17.933449 | 6.926 | 2.78e-11 *** |
| AT | -0.021611 | 0.028025 | -0.771 | 0.441242 |
| AP | 0.009737 | 0.012831 | 0.759 | 0.448558 |
| AH | -0.009622 | 0.005824 | -1.652 | 0.099605 . |
| GTEP | -0.370650 | 0.158512 | -2.338 | 0.020048 * |
| TIT | 0.029652 | 0.058304 | 0.509 | 0.611437 |
| TAT | -0.255241 | 0.072992 | -3.497 | 0.000544 *** |
| TEY | -0.068439 | 0.071399 | -0.959 | 0.338581 |
| CDP | -0.463762 | 0.221422 | -2.094 | 0.037083 * |

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

Residual standard error: 0.9744 on 291 degrees of freedom

Multiple R-squared: 0.7386, Adjusted R-squared: 0.7314

F-statistic: 102.8 on 8 and 291 DF, p-value: < 2.2e-16

$$n = 300 \quad p = 9$$

We can see the estimated intercept and other 8 parameters in the “Estimate” column above. We have $300 - 9 = 291$ degrees of freedom.

Judging by the coefficient of Ambient Temperature predictor we can expect a 0.021611 decrease in CO-level for every 1°C increase in Ambient Temperature.

3. F - test

- Hypothesis:

$$H_0 : \beta_2 = \beta_3 = \dots = \beta_p = 0 \quad H_1 : \exists_{j \in \{2 \dots p\}} \beta_j \neq 0$$

```
fit.0 = lm(CO ~ 1, data = Data)
anova(fit.0, fit)
```

Analysis of Variance Table

Model 1: CO ~ 1

Model 2: CO ~ AT + AP + AH + GTEP + TIT + TAT + TEY + CDP

| | Res.Df | RSS | Df | Sum of Sq | F | Pr(>F) |
|---|--------|---------|----|-----------|--------|---------------|
| 1 | 299 | 1057.00 | | | | |
| 2 | 291 | 276.31 | 8 | 780.69 | 102.77 | < 2.2e-16 *** |

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

As we can see the RSS drastically dropped in the wider model, compared to the null, which already gives us an indication that it might explain the data much better.

- The observed test statistic can be read from the table: $F = 102.77$
- The probability of getting such a high value is very small: $p_{val} < 2.2 \cdot 10^{-16}$
- Under the Null Hypothesis F should follow the $F_{8,291}$ distribution.

(Because the difference in parameters / degrees of freedom is 8, and the wider model has 291 degrees of freedom, which we've shown before)

The p-value is much smaller than the significance level therefore we can definitely reject the null hypothesis - we know that our test statistic must be much higher than the 0.95th quantile of the null distribution.

4. Reduced Models

Model A

Similarly as before, we state the hypothesis:

$$H_0 : \beta_5 = \beta_6 = \dots = \beta_p = 0 \quad H_1 : \exists_{j \in \{5 \dots p\}} \beta_j \neq 0$$

```
fit.A = lm(CO ~ AT + AP + AH, data = Data)
anova(fit.A, fit)
```

Analysis of Variance Table

Model 1: CO ~ AT + AP + AH

Model 2: CO ~ AT + AP + AH + GTEP + TIT + TAT + TEY + CDP

| | Res.Df | RSS | Df | Sum of Sq | F | Pr(>F) |
|---|--------|--------|----|-----------|-------|---------------|
| 1 | 296 | 971.35 | | | | |
| 2 | 291 | 276.31 | 5 | 695.04 | 146.4 | < 2.2e-16 *** |

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

And similarly as before we can see that the test statistic is very high (146.4), while the p-value is very low (close to 0) - which strongly speaks against the null hypothesis.

The conclusion is - we cannot reduce the full model to Model A.

Model B

$$H_0 : \beta_2 = \beta_3 = \beta_4 = \beta_9 = 0 \quad H_1 : \exists_{j \in \{2,3,4,9\}} \beta_j \neq 0$$

```
fit.B = lm(CO ~ GTEP + TIT + TAT + TEY, data = Data)
anova(fit.B, fit)
```

Analysis of Variance Table

Model 1: CO ~ GTEP + TIT + TAT + TEY

Model 2: CO ~ AT + AP + AH + GTEP + TIT + TAT + TEY + CDP

| | Res.Df | RSS | Df | Sum of Sq | F | Pr(>F) |
|---|--------|--------|----|-----------|--------|----------|
| 1 | 295 | 286.13 | | | | |
| 2 | 291 | 276.31 | 4 | 9.8158 | 2.5844 | 0.0373 * |

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

Here the situation is slightly different. The test statistic is much lower (2.5844), and the p-value is much higher than with the previous 2 models (0.0373) - but it's still quite low. Depending on our significance level we might reject the null hypothesis or not. For signif. level $\alpha = 0.05$ we would reject the null and say that the model can't be reduced. For signif. level $\alpha = 0.01$ however we would be able to say that the full model can be reduced to Model B.

5. Explained Variation

Since I'm choosing to work with significance level of 0.05 and therefore rejecting the hypothesis that the full model can be reduced to either of the above - I must assume that my "final model" is the full one.

- The amount of variation explained is $\frac{SS_{tot}-RSS}{SS_{tot}} = \frac{RSS_0-RSS}{RSS_0}$ which is the R^2 value.

We can see it already in the full model summary at the beginning - it's around 0.74, but we can make a quick sanity check:

```
RSS = sum(residuals(fit) ^ 2)
RSS.0 = sum(residuals(fit.0) ^ 2)
R.2 = (RSS.0 - RSS) / RSS.0

c(RSS, RSS.0, R.2)
```

```
[1] 276.3108503 1057.0000000 0.7385895
```

Now we can clearly see:

- Variation explained by the model: ~ 0.74
- Residual Sum of Squares: ~ 276
- Total Sum of Squares: 1057
- Absolute reduction: $1057 - 276 = 781$

which agrees with the output of our first `anova` test, where we can also find all this information.

Exercise 2

Model:

$$Y_i = \mu + \alpha_{j(i)} + \beta' \cdot X_i + \epsilon_i$$

$i \in \{1 \dots n\}$
 $n = 45$

Model Matrix and Coefficients

$$\mathbf{X} = \begin{bmatrix} 1 & 0 & 0 & 0 & X_1 \\ \vdots & 1 & 0 & 0 & \vdots \\ \vdots & 0 & 1 & 0 & \vdots \\ 1 & 0 & 0 & 1 & X_n \end{bmatrix} \quad \beta = \begin{bmatrix} \mu \\ \alpha_{TempResearch} \\ \alpha_{TempPrivate} \\ \alpha_{Freelance} \\ \beta' \end{bmatrix}$$

$p = 5$

1. Confidence Interval

$$c^T = [0 \quad 1 \quad -1 \quad 0 \quad 0]$$

$$c^T \beta = \alpha_{TempResearch} - \alpha_{TempPrivate}$$

$$\Rightarrow CI = c^T \hat{\beta} \pm \widehat{SE}_{c^T \hat{\beta}} \cdot t_{n-p; 1-\frac{\alpha}{2}}$$

The only thing in the above formula that we don't have is the $\widehat{SE}_{c^T \hat{\beta}}$. We usually used RSS to get it, but since we don't have access neither to the predictors nor responses we can use the output of the statistical software to calculate it differently:

$$\begin{aligned} \widehat{SE}_{c^T \hat{\beta}} &= \sqrt{Var(c^T \hat{\beta})} \\ Var(c^T \hat{\beta}) &= Var(\hat{\alpha}_{TempResearch} - \hat{\alpha}_{TempPrivate}) = \\ &= Var(\hat{\alpha}_{TempResearch}) + Var(\hat{\alpha}_{TempPrivate}) - 2Cov(\hat{\alpha}_{TempResearch}, \hat{\alpha}_{TempPrivate}) = \\ &= \widehat{SE}_{\hat{\alpha}_{TempResearch}}^2 + \widehat{SE}_{\hat{\alpha}_{TempPrivate}}^2 - 2Cov(\hat{\alpha}_{TempResearch}, \hat{\alpha}_{TempPrivate}) \end{aligned}$$

Now we have everything we need to calculate the confidence interval.

```
n = 45
p = 5

a.re = -40000
a.pr = -10000

psi = a.re - a.pr

SE.re = 24000
SE.pr = 23000
COV.re.pr = 22000000

SE = sqrt(SE.re ^ 2 + SE.pr ^ 2 - 2 * COV.re.pr)
```

```
CI.lower = psi - SE * qt(0.95, n - p)
CI.upper = psi + SE * qt(0.95, n - p)

c(CI.lower, CI.upper)
```

```
[1] -84848.07 24848.07
```

So the confidence interval for $\alpha_{TempResearch} - \alpha_{TempPrivate}$ is $[-84848.07, 24848.07]$.

2. Hypothesis Testing

$$H_0 : \alpha_{TempResearch} \geq \alpha_{TempPrivate} \quad H_1 : -c^T \beta > 0 \\ \implies -c^T \beta \leq 0$$

We've shown on the lecture that if H_0 holds then:

$$T = \frac{-c^T \hat{\beta} - 0}{\widehat{SE}_{c^T \hat{\beta}}} \\ P(T > t_{n-p; 1-\alpha}) \leq \alpha$$

Which means we will have statistical evidence to reject H_0 if the test statistic is bigger than the 0.95 quantile of the given above t_{n-p} - distribution.

```
T = -psi / SE
t.95 = qt(0.95, n - p)

c(T, t.95)
```

```
[1] 0.9210083 1.6838510
```

As we can see, the test statistic - even though it's positive - is not bigger than the quantile, therefore we don't have sufficient statistical evidence to reject the null hypothesis and say that temporary researches are earning less than temporary private consultants.

Exercise 3

Model Matrix and Coefficients

For a simple linear relationship we have the model matrix and the parameter vector as so:

$$X = \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \\ 1 & x_n \end{bmatrix} \quad \beta = \begin{bmatrix} \beta_{intercept} \\ \beta_{slope} \end{bmatrix}$$

Since we want to estimate β_{slope} as precisely as possible, we would like to minimize $Var(\hat{\beta}_{slope}) = Var(\hat{\beta})_{22}$.

We know that for the Least Square Estimator $\hat{\beta} Var(\hat{\beta}) = \sigma^2(X^T X)^{-1}$

$$(X^T X)^{-1} = \left(\begin{bmatrix} 1 & 1 & \dots & 1 \\ x_1 & x_2 & \dots & x_n \end{bmatrix} \begin{bmatrix} 1 & x_1 \\ 1 & x_2 \\ \vdots & \vdots \\ 1 & x_n \end{bmatrix} \right)^{-1} = \begin{bmatrix} n & \sum x_i \\ \sum x_i & \sum x_i^2 \end{bmatrix}^{-1}$$

We can find it's reverse using any method.

$$\begin{aligned} & \left[\begin{array}{cc|cc} n & \sum x_i & 1 & 0 \\ \sum x_i & \sum x_i^2 & 0 & 1 \end{array} \right] \\ & \left[\begin{array}{cc|cc} 1 & \bar{x} & \frac{1}{n} & 0 \\ \sum x_i & \sum x_i^2 & 0 & 1 \end{array} \right] \\ & \left[\begin{array}{cc|cc} 1 & \bar{x} & \frac{1}{n} & 0 \\ 0 & \sum x_i^2 - \bar{x} \sum x_i & -\bar{x} & 1 \end{array} \right] \\ & \left[\begin{array}{cc|cc} 1 & \bar{x} & \frac{1}{n} & 0 \\ 0 & \sum (x_i^2 - \bar{x} x_i) & -\bar{x} & 1 \end{array} \right] \\ & \left[\begin{array}{cc|cc} 1 & \bar{x} & \frac{1}{n} & 0 \\ 0 & 1 & \frac{-\bar{x}}{\sum (x_i^2 - \bar{x} x_i)} & \frac{1}{\sum (x_i^2 - \bar{x} x_i)} \end{array} \right] \end{aligned}$$

At this point we don't even need to calculate further, because we only want $Var(\hat{\beta})_{22}$ which we can see is equal to

$$\frac{\sigma^2}{\sum (x_i^2 - \bar{x}x_i)} = \frac{\sigma^2}{\sum x_i^2 - \bar{x} \sum x_i} = \frac{\sigma^2}{\sum x_i^2 - n\bar{x}^2} = \frac{\sigma^2}{\sum (x_i^2 - \bar{x}^2)}$$

σ^2 is a constant, so to minimize this value we need to maximize $\sum (x_i^2 - \bar{x}^2)$. In order to do that we need to take half of the observations for $x = -2$ and the other half for $x = 2$.