Lecture 04
Applications and Intro to Multivariate Regression

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Notes

1. Problem set 1 due start of next class
2. TA session tomorrow night
3. One typo; 4(b) has hypothesis test for the intercept not the slope
4. Try to get a fresh copy of notes!

Goals for today

1. Galton’s heights data
2. Multivariate regression; normal equations
3. Model frames in R

Galton Heights Application

Multivariate Regression Models

The multivariate linear regression model is, on the surface, only a slight generalization of the simple linear regression model:

$$y_i = x_{1,i}\beta_1 + x_{2,i}\beta_2 + \cdots + x_{1,p}\beta_p + \epsilon$$

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The statistical estimation problem now becomes one of estimating the p components of the multivariate vector β.

A sample can be re-written in terms of the vector x_i (the vector of covariates for a single observation):

$$y_i = x_i^t \beta + \epsilon$$

In matrix notation, we can write the linear model simultaneously for all observations:

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \begin{pmatrix} x_{1,1} & x_{2,1} & \cdots & x_{p,1} \\ x_{1,2} & \ddots & & x_{p,2} \\ \vdots & & \ddots & \vdots \\ x_{1,n} & x_{2,n} & \cdots & x_{p,n} \end{pmatrix} \begin{pmatrix} \beta_1 \\ \beta_2 \\ \vdots \\ \beta_p \end{pmatrix} + \begin{pmatrix} \epsilon_1 \\ \epsilon_1 \\ \vdots \\ \epsilon_n \end{pmatrix}$$

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Which can be compactly written as:

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Note: we use the transpose for $x_i^t\beta$ but not for $X\beta$!

For reference, note the following equation

$$Y = X\beta + \epsilon$$

Yields these dimensions:

$$\begin{aligned} Y &\in \mathbb{R}^{n} \\ X &\in \mathbb{R}^{n \times p} \\ \beta &\in \mathbb{R}^{p} \\ \epsilon &\in \mathbb{R}^{n} \end{aligned}$$

Vector Norms

When working with vectors and matricies, it will be helpful to represent certain quantities by norms. The p-norm of a vector is given by:

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In particular, the squared 2-norm yields the sum of squares of a vector.

Vector Norm Properties

The following properties are true of all vector norms, for a scalar α and vectors v_1 and v_2.

$$||\alpha v_1|| = |\alpha| \cdot ||v_1||$$
$$||v_1 + v_2|| \leq ||v_1|| + ||v_2||$$

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Notice that the 2-norm is dual to itself.

p-Norm Properties, cont.

Hölder's inequality then yields

$$|v_1^t v_2| \leq ||v_1||_p ||v_2||_q$$

p-Norm Properties, cont.

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As a special case, the Cauchy–Schwarz inequality gives that:

$$|v_1^t v_2|^2 \leq ||v_1||_2^2 ||v_2||_2^2$$

p-Norm Properties, cont.

Finally, and of most importance for us today, note that the squared 2-norm is exactly equal to the self inner product:

$$||v_1||_2^2 = v_1^t v_1$$

Least squares (again)

To estimate the least squares solution, which is again the MLE for independent normal errors, we see that:

$$\widehat{\beta} \in \operatorname*{arg\,min}_{b \in \mathbb{R}^p} \left\{ ||Y - X\beta||_2^2 \right\}$$

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Now using vector norms to denote the sum of squares.

It will be helpful to re-write the sum of squares as:

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Normal Equations

In order to find the minimum of the sum of squares, we take the gradient with respect to β and set it equal to zero.

Recall that, for a vector a and symmetric matrix A :

$$\begin{aligned} \nabla_\beta a^t \beta &= a \\ \nabla_\beta \beta^t A \beta &= 2A\beta \end{aligned}$$

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$$\nabla_\beta \beta^t A\beta = 2A\beta$$

This gives the gradient of the sum of squares as:

$$\begin{aligned}\nabla_\beta ||Y - X\beta||_2^2 &= \nabla_\beta \left(Y^tY - 2Y^tX\beta + \beta^tX^tX\beta\right)\\ &= 2X^tX\beta - 2X^ty\end{aligned}$$

Setting this equal to zero gives a set of p equations called the normal equations:

$$X^t X\widehat{\beta} = X^t y$$

Maximum or Minimum?

To determine whether the normal equations give a local minimum, maximum, or saddle point, we can calculate the Hessian matrix.

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To determine whether the normal equations give a local minimum, maximum, or saddle point, we can calculate the Hessian matrix. This is a $p \times p$ matrix giving every combination of the second partial derivatives:

$$Hf(\beta) = \begin{pmatrix} \frac{\partial^2 f}{\partial \beta_1 \partial \beta_1} & \frac{\partial^2 f}{\partial \beta_1 \partial \beta_2} & \cdots & \frac{\partial^2 f}{\partial \beta_1 \partial \beta_p} \\ \frac{\partial^2 f}{\partial \beta_2 \partial \beta_1} & \ddots & & \frac{\partial^2 f}{\partial \beta_2 \partial \beta_p} \\ \vdots & & \ddots & \vdots \\ \frac{\partial^2 f}{\partial \beta_n \partial \beta_1} & \frac{\partial^2 f}{\partial \beta_n \partial \beta_2} & \cdots & \frac{\partial^2 f}{\partial \beta_n \partial \beta_p} \end{pmatrix}$$

If the Hessian is positive definite ($x^t H x \geq 0$) at a critical point, then the critical point is a local minimum.

Looking at the gradiant of the sum of squares:

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Why is this positive definite?

$$\begin{aligned} v^t\left(2X^tX\right)v &= 2\left(v^tX^tXv\right) \\ &= 2||Xv||_2^2 \\ &\geq 0 \end{aligned}$$

Back to the normal equations themselves, notice that if the matrix X^tX is invertable, we can 'solve' the normal equations as:

$$\begin{aligned} X^tX\widehat{\beta} &= X^ty \\ \widehat{\beta} &= (X^tX)^{-1}X^ty \end{aligned}$$

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This is not a good way to solve the normal equations numerically, but for deriving theoretical results about the least squares estimator this form will be very useful.

Matricies and Model Frames in R