

# Lecture Notes in Financial Econometrics (MSc course)

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Warning: a few of the tables and figures are reused in later chapters. This can mess up the references, so that the text refers to a table/figure in another chapter. No worries: it is really the same table/figure. Still, I promise to fix this some day.

# Chapter 1

## Review of Statistics

Reference: Verbeek (2012) Appendix B

More advanced material is denoted by a star (\*). It is not required reading.

### 1.1 Random Variables and Distributions

#### 1.1.1 The Distribution of a Random Variable

A univariate distribution of a random variable  $x$  describes the probability of different values. If  $f(x)$  is the probability density function (pdf), then the probability that  $x$  is between  $A$  and  $B$  is calculated as the area under the density function from  $A$  to  $B$

$$\Pr(A < x \leq B) = \int_A^B f(x)dx. \quad (1.1)$$

See Figure 1.1 for illustrations of normal (gaussian) distributions.

**Remark 1.1** If  $x \sim N(\mu, \sigma^2)$ , then the probability density function is

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{1}{2}(\frac{x-\mu}{\sigma})^2}.$$

This is a bell-shaped curve centred on the mean  $\mu$  and where the standard deviation  $\sigma$  determines the “width” of the curve.

The probability that  $x \leq B$  (that is,  $-\infty < x \leq B$ ) is measured by the *cumulative distribution function*,  $\text{cdf}(B)$ . For instance, if  $x$  has a  $N(0, 1)$  distribution, then  $\Pr(x \leq -1.645) = 0.05$  and  $\Pr(x \leq 0) = 0.5$ . Once you have the cdf, you can calculate the probability of  $B < x$  as  $1 - \text{cdf}(B)$ . See Figure 1.2 for an illustration.

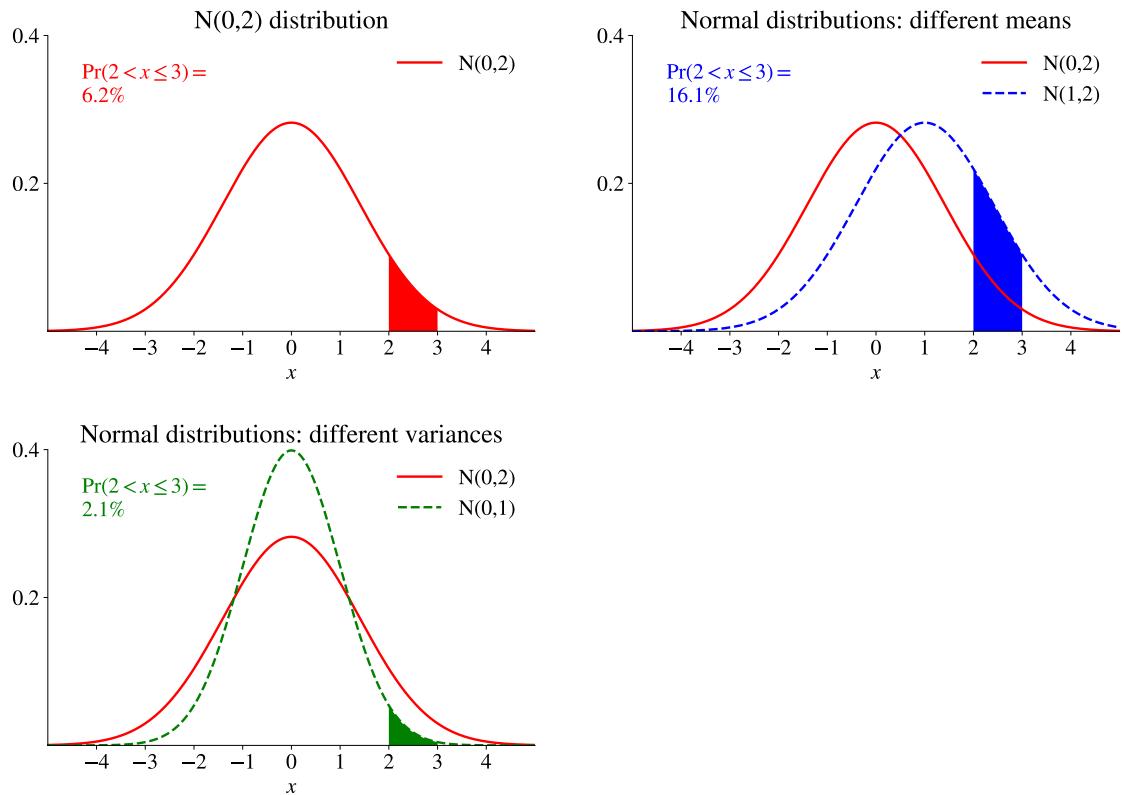


Figure 1.1: A few different normal distributions

If we invert the cdf, then we get the *quantiles* of the random variable. For instance, the 0.05th quantile of a  $N(0, 1)$  variable is  $-1.645$ , while the 0.5th quantile (also called the median) is 0.

### 1.1.2 The Joint Distribution of Several Random Variables

A bivariate distribution of the random variables  $x$  and  $y$  contains the same information as the two respective univariate distributions, but also information on how  $x$  and  $y$  are related. Let  $h(x, y)$  be the joint density function, then the probability that  $x$  is between  $A$  and  $B$  and  $y$  is between  $C$  and  $D$  is calculated as the volume under the surface of the density function

$$\Pr(A < x \leq B \text{ and } C < y \leq D) = \int_A^B \int_C^D h(x, y) dy dx. \quad (1.2)$$

See Figure 1.3 for an example.

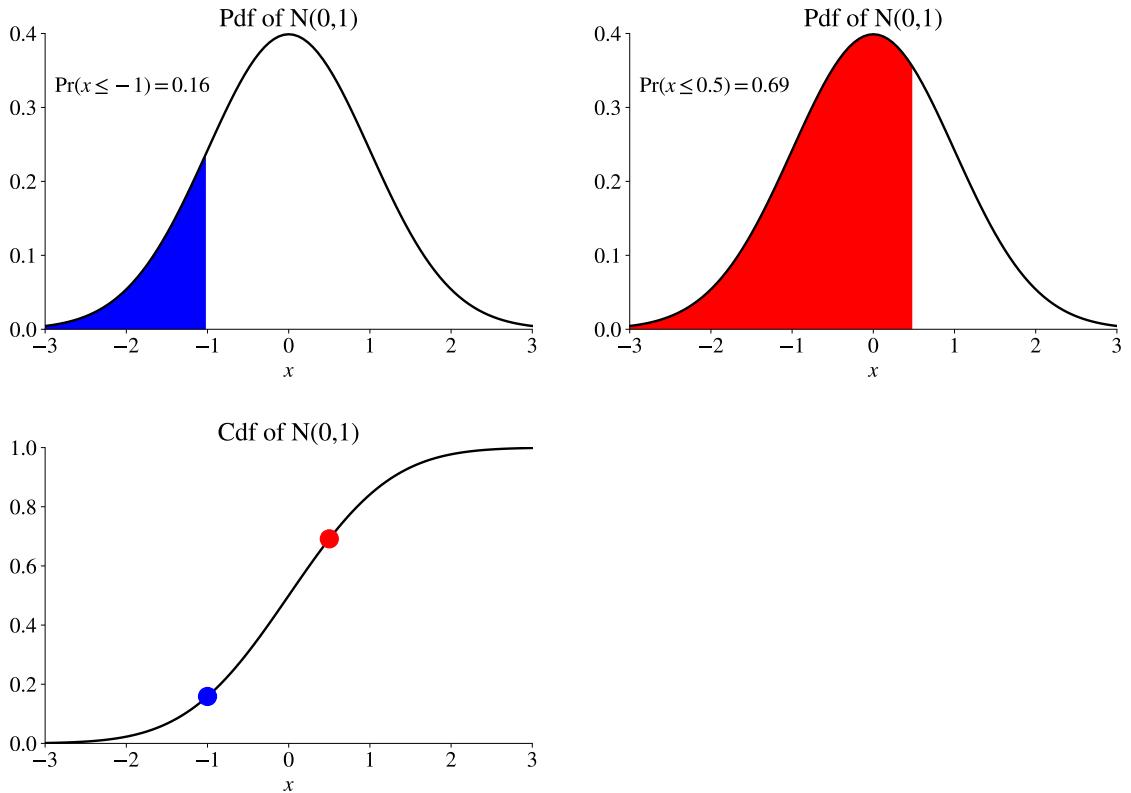


Figure 1.2: Pdf and cdf of  $N(0,1)$

A joint normal distributions is completely described by the means and the covariance matrix

$$\begin{bmatrix} x \\ y \end{bmatrix} \sim N \left( \begin{bmatrix} \mu_x \\ \mu_y \end{bmatrix}, \begin{bmatrix} \sigma_x^2 & \sigma_{xy} \\ \sigma_{xy} & \sigma_y^2 \end{bmatrix} \right), \quad (1.3)$$

where  $\mu_x$  and  $\mu_y$  denote means of  $x$  and  $y$ ,  $\sigma_x^2$  and  $\sigma_y^2$  denote the variances of  $x$  and  $y$  and  $\sigma_{xy}$  denotes their covariance. Sometimes alternative notations are used:  $E x$  for the mean,  $Std(x)$  for the standard deviation,  $Var(x)$  for the variance and  $Cov(x, y)$  for the covariance. See Figure 1.4 for an example.

Clearly, if the covariance  $\sigma_{xy}$  is zero, then the variables are (linearly) unrelated to each other. Otherwise, information about  $x$  can help us to make a better guess of  $y$ . The correlation of  $x$  and  $y$  is defined as

$$\rho_{xy} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}. \quad (1.4)$$

See Figure 1.4 for an example.

If two random variables happen to be independent of each other, then the joint density function is just the product of the two univariate densities (here denoted  $f(x)$  and  $k(y)$ )

$$h(x, y) = f(x)k(y) \text{ if } x \text{ and } y \text{ are independent.} \quad (1.5)$$

This is useful in many cases, for instance, when we construct likelihood functions for maximum likelihood estimation.

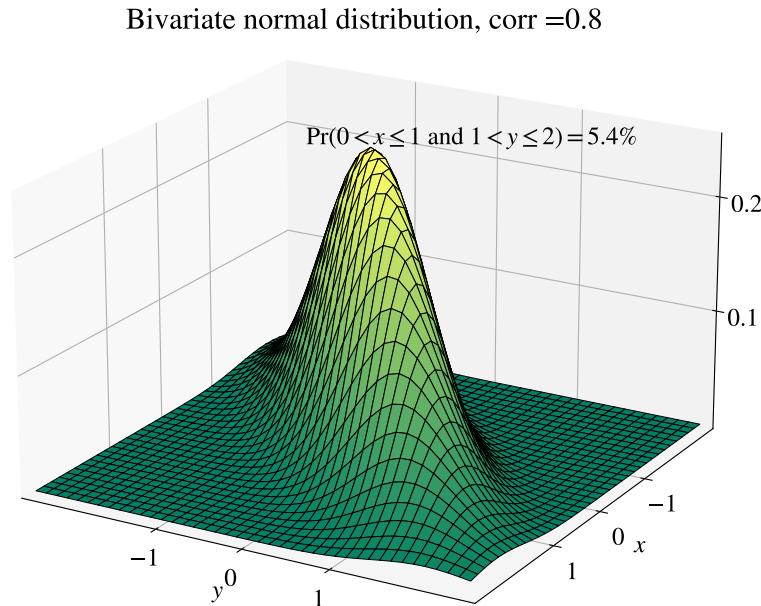


Figure 1.3: Density function bivariate normal distribution

### 1.1.3 Conditional Distributions\*

If  $h(x, y)$  is the joint density function and  $f(x)$  the (marginal) density function of  $x$ , then the conditional density function is

$$g(y|x) = h(x, y)/f(x). \quad (1.6)$$

Notice that the conditional mean can be interpreted as the best guess of  $y$  given that we know  $x$ . Similarly, the conditional variance can be interpreted as the variance of the

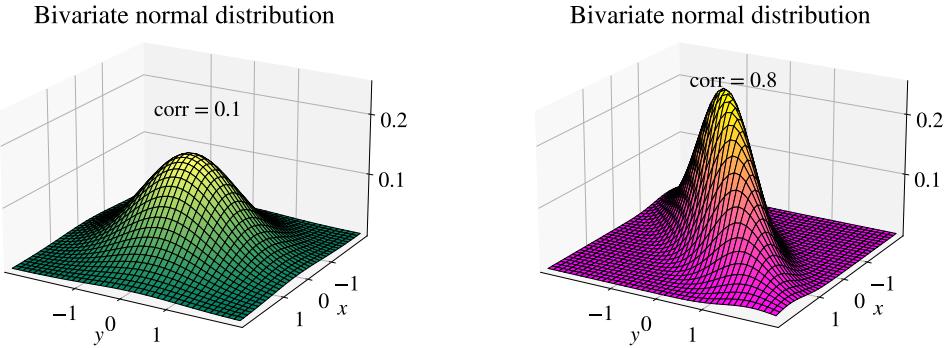


Figure 1.4: Density function bivariate normal distributions

forecast error (using the conditional mean as the forecast). The conditional and marginal distribution coincide if  $x$  and  $y$  are independent. (This follows directly from combining (1.5) and (1.6).)

For the bivariate normal distribution (1.3) we have the distribution of  $y$  conditional on a given value of  $x$  as

$$y|x \sim N\left(\mu_y + \frac{\sigma_{xy}}{\sigma_x^2}(x - \mu_x), \sigma_y^2 - \frac{\sigma_{xy}\sigma_{xy}}{\sigma_x^2}\right). \quad (1.7)$$

In this case, the mean depends on  $x$ , while the variance does not. Also notice that the variance is lower than in the unconditional distribution (we have more information). Independence of  $x$  and  $y$  would here mean a zero covariance: set  $\sigma_{xy} = 0$  in (1.7) to see that the conditional and unconditional distributions coincide. See Figure 1.5 for an illustration: notice how the location and the width of the conditional distribution of  $y$  changes as a function of the correlation and the value of  $x$ .

**Remark 1.2** (*Relation of (1.7) to a linear regression\**) Suppose you regress  $y = a + bx + u$ . The mean in (1.7) is the same as  $a + bx$  and the variance is the same as  $\text{Var}(u)$ .

#### 1.1.4 Illustrating a Distribution

If we know the type of distribution (uniform, normal, etc) a variable has, then the best way of illustrating the distribution is to estimate its parameters (mean, variance and whatever more—see below) and then draw the density function.

In case we are not sure about which distribution to use, the first step is typically to draw

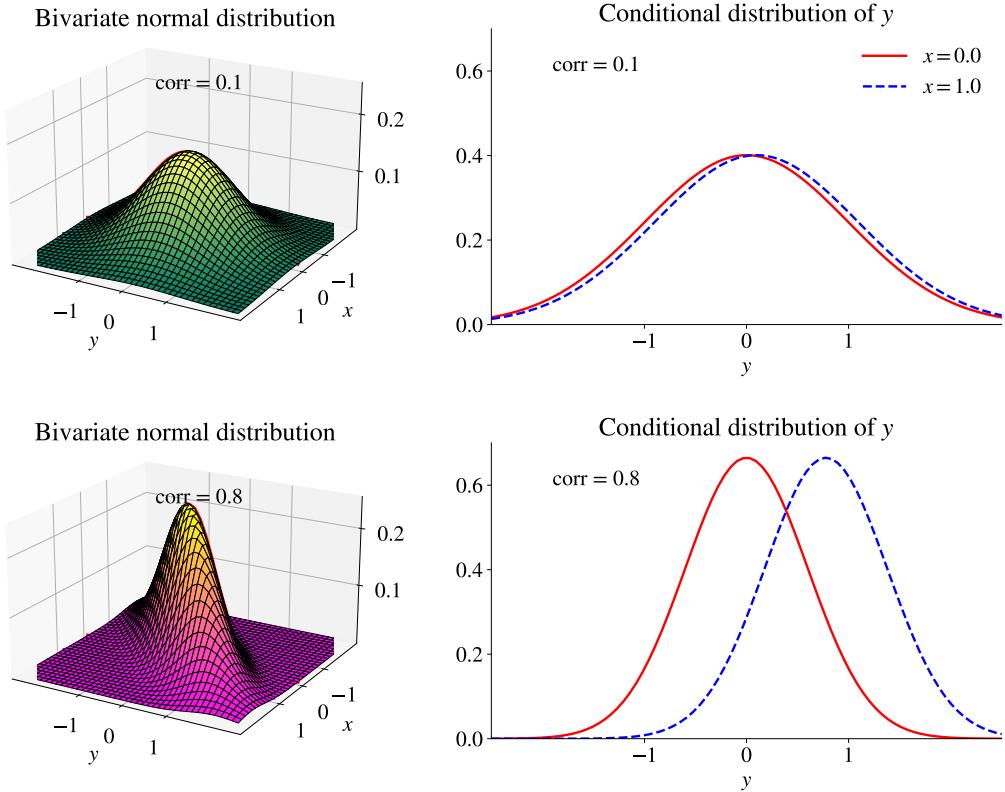


Figure 1.5: Density functions of normal distributions

a histogram: it shows the relative frequencies for different bins (intervals). For instance, it could show the relative frequencies of a variable  $x_t$  being in each of the follow intervals: -0.5 to 0, 0 to 0.5 and 0.5 to 1.0. Clearly, the relative frequencies should sum to unity (or 100%), but they are sometimes normalized so the area under the histogram has an area of unity (as a probability density function).

**Empirical Example 1.3** (*Histogram of equity returns*) See Figure 1.6.

### 1.1.5 Confidence Bands and t-tests

For a symmetric distribution, a 90% (two-sided) confidence band is constructed by finding a critical value  $c$  such that

$$\Pr(\mu - c < x \leq \mu + c) = 0.9. \quad (1.8)$$

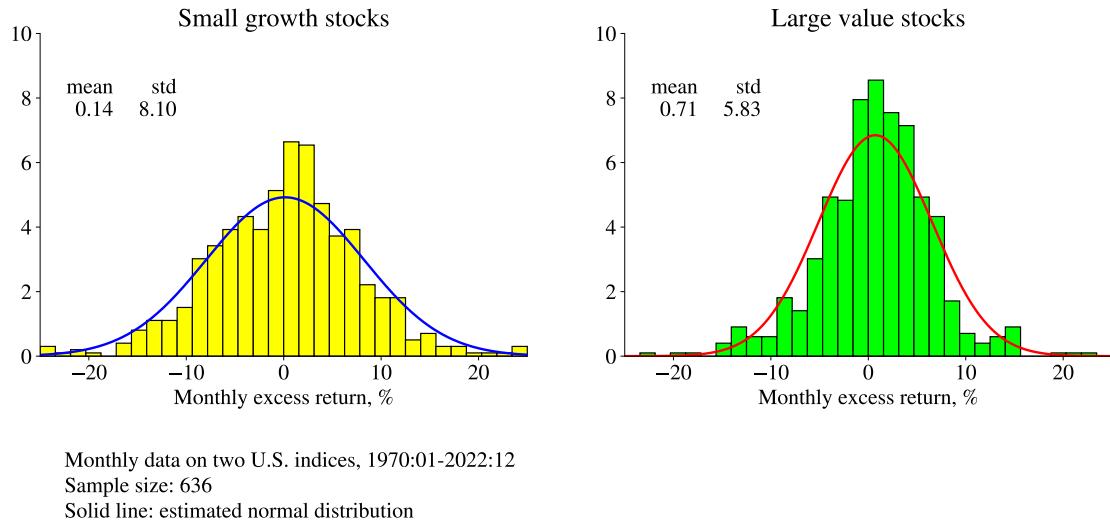


Figure 1.6: Histogram of returns, the curve is a normal distribution with the same mean and standard deviation as the return series

Replace 0.9 by 0.95 to get a 95% confidence band—and similarly for other confidence levels. In particular, if  $x \sim N(\mu, \sigma^2)$ , then

$$\begin{aligned} \Pr(\mu - 1.64\sigma < x \leq \mu + 1.64\sigma) &= 0.9 \text{ and} \\ \Pr(\mu - 1.96\sigma < x \leq \mu + 1.96\sigma) &= 0.95. \end{aligned} \quad (1.9)$$

As an example, suppose  $x$  is not a data series but a regression coefficient (denoted  $\hat{\beta}$ )—and we know that the standard error equals some number  $\sigma$ . We could then construct a 90% confidence band around the point estimate ( $\hat{\beta}$ ) as

$$[\hat{\beta} - 1.64\sigma, \hat{\beta} + 1.64\sigma]. \quad (1.10)$$

In case this band does not include your null hypothesis  $\beta = q$  ( $q = 0$  is a commonly used special case), then we would be 90% that the (true) regression coefficient is different from  $q$ .

Alternatively, suppose we instead construct the 90% confidence band around  $q$  as

$$[q - 1.64\sigma, q + 1.64\sigma]. \quad (1.11)$$

If this band does not include the point estimate ( $\hat{\beta}$ ), then we are also 90% sure that the (true) regression coefficient is different from  $q$ .

A third way to create a confidence band is to first create a standardized variable

$$t = \frac{\hat{\beta} - q}{\sigma}, \quad (1.12)$$

and then notice that we are 90% sure that  $t$  is in the interval

$$[-1.64, 1.64]. \quad (1.13)$$

(Provided the null hypothesis is true, that is,  $\beta = q$ .) This is a  $t$ -test. Testing the null hypothesis by using (1.10), (1.11) or (1.13) should give the same answer to the question: is there sufficient statistical evidence against the null hypothesis.

### 1.1.6 The Idea behind Confidence Bands and t-tests

Suppose we have estimated a parameter ( $\hat{\beta}$ ) from a particular sample of data (observations 1 to  $T$ , say). The parameter could, for instance, be the mean or a regression coefficient. This estimate is actually a random variable so it makes sense to construct a confidence band as in (1.10). The reason for why it is a random variable is that another sample is most likely to produce a different estimate—and that if we could try all possible samples then the different estimates would have some sort of distribution. *If* we are willing to assume that data for those other samples would be similar (scattered around the same mean, showing the same degree of dispersion, etc) to the sample we actually study (observations 1 to  $T$ ), then we can use our sample to guess how much other samples would differ. For instance, we can estimate the variance of the data ( $\sigma^2$ ) and draw the conclusions about how different the sample averages would be in different samples (it would have a variance of  $\sigma^2/T$  as discussed in (1.16)).

### 1.1.7 Hypothesis Testing

We are here interested in testing the null hypothesis that  $\beta = q$ , where  $q$  is a number of interest (0.27, say). A null hypothesis is often denoted  $H_0$ . (Econometric programs often automatically report results for  $H_0: \beta = 0$ .) We here consider the alternative hypothesis (denoted  $H_1$  or perhaps  $H_A$ ) that  $\beta \neq q$ . This leads to a two-sided (or two-tailed) test.

Typically, we assume that the estimates are normally distributed. To be able to easily compare with printed tables of probabilities, transform to a  $N(0, 1)$  variable. In particular, if the true coefficient is really  $q$ , then  $\hat{\beta} - q$  should have a zero mean (recall that  $E \hat{\beta}$  equals

the true value). Dividing by the standard error (deviation) of  $\hat{\beta}$ , we should have

$$t = \frac{\hat{\beta} - q}{\text{Std}(\hat{\beta})} \sim N(0, 1) \quad (1.14)$$

In case  $|t|$  is very large (say, 1.64 or larger), then our estimate  $\hat{\beta}$  is a very unlikely outcome if  $E \hat{\beta}$  (which equals the true coefficient value,  $\beta$ ) is indeed  $q$ . We therefore draw the conclusion that the true coefficient is not  $q$ , that is, we *reject the null hypothesis*.

## 1.2 Moments

### 1.2.1 Mean and Standard Deviation

The mean and variance of a series are estimated as

$$\bar{x} = \sum_{t=1}^T x_t / T \text{ and } \hat{\sigma}^2 = \sum_{t=1}^T (x_t - \bar{x})^2 / T. \quad (1.15)$$

The standard deviation (the square root of the variance) is the most common measure of volatility. (Sometimes we use  $T - 1$  in the denominator of the sample variance instead of  $T$ .) See Figure 1.6 for an illustration.

A sample mean is normally distributed if  $x_t$  is normally distributed,  $x_t \sim N(\mu, \sigma^2)$ . The reason is that a linear combination of normally distributed variables is (typically) also normally distributed. However, a sample average is often approximately normally distributed even if the variable is not (discussed below). If  $x_t$  is iid (independently and identically distributed), then the variance of a sample mean is

$$\text{Var}(\bar{x}) = \sigma^2 / T, \text{ if } x_t \text{ is iid.} \quad (1.16)$$

Sometimes, we instead report the variance of  $\sqrt{T}\bar{x}$ , which is

$$\text{Var}(\sqrt{T}\bar{x}) = \sigma^2, \text{ if } x_t \text{ is iid.} \quad (1.17)$$

(To see the link, factor out  $T$  from the left hand side of (1.17) to get  $T \text{Var}(\bar{x})$ . Then divide by sides by  $T$  to get (1.16).)

A sample average is (typically) *unbiased*, that is, the expected value of the sample average equals the population mean, that is,

$$E \bar{x} = E x_t = \mu. \quad (1.18)$$

Since sample averages are typically normally distributed in large samples, we thus have

$$\bar{x} \sim N(\mu, \sigma^2/T), \quad (1.19)$$

so we can construct a *t-stat* as

$$t = \frac{\bar{x} - \mu}{\sigma/\sqrt{T}}, \quad (1.20)$$

which has an  $N(0, 1)$  distribution. An alternative way of expressing (1.19) is

$$\sqrt{T}(\bar{x} - \mu) \sim N(0, \sigma^2). \quad (1.21)$$

This is often used in the context of the central limit theorem.

**Proof.** (of (1.16)–(1.18)) To prove (1.16), notice that

$$\begin{aligned} \text{Var}(\bar{x}) &= \text{Var}\left(\sum_{t=1}^T x_t / T\right) \\ &= \sum_{t=1}^T \text{Var}(x_t / T) \\ &= T \text{Var}(x_t) / T^2 \\ &= \sigma^2 / T. \end{aligned}$$

The first equality is just a definition and the second equality follows from the assumption that  $x_t$  and  $x_s$  are independently distributed. This means, for instance, that  $\text{Var}(x_2 + x_3) = \text{Var}(x_2) + \text{Var}(x_3)$  since the covariance is zero. The third equality follows from the assumption that  $x_t$  and  $x_s$  are identically distributed (so their variances are the same). The fourth equality is a trivial simplification.

To prove (1.18)

$$\begin{aligned} E\bar{x} &= E\sum_{t=1}^T x_t / T \\ &= \sum_{t=1}^T E x_t / T \\ &= E x_t. \end{aligned}$$

The first equality is just a definition and the second equality is always true (the expectation of a sum is the sum of expectations), and the third equality follows from the assumption of identical distributions which implies identical expectations. ■

### 1.2.2 Skewness and Kurtosis

The skewness, kurtosis and Bera-Jarque test for normality are useful diagnostic tools. They are

$$\begin{array}{ll}
 & \text{Test statistic} \\
 \text{skewness} & = \frac{1}{T} \sum_{t=1}^T \left( \frac{x_t - \mu}{\sigma} \right)^3 & N(0, 6/T) \\
 \text{kurtosis} & = \frac{1}{T} \sum_{t=1}^T \left( \frac{x_t - \mu}{\sigma} \right)^4 & N(3, 24/T) \\
 \text{Bera-Jarque} & = \frac{T}{6} \text{skewness}^2 + \frac{T}{24} (\text{kurtosis} - 3)^2 & \chi_2^2.
 \end{array} \tag{1.22}$$

This is implemented by using the estimated mean and standard deviation. See Figure 1.6 for an illustration.

The distributions stated on the right hand side of (1.22) are under the null hypothesis that  $x_t$  is iid  $N(\mu, \sigma^2)$ . The “excess kurtosis” is defined as the kurtosis minus 3. The test statistic for the normality test (Bera-Jarque) can be compared with 4.6 or 6.0, which are the 10% and 5% critical values of a  $\chi_2^2$  distribution.

Clearly, we can test the skewness and kurtosis by traditional t-stats as in

$$t = \frac{\text{skewness}}{\sqrt{6/T}} \text{ and } t = \frac{\text{kurtosis} - 3}{\sqrt{24/T}}, \tag{1.23}$$

which both have  $N(0, 1)$  distribution under the null hypothesis of a normal distribution.

### 1.2.3 Covariance and Correlation

The covariance of two variables (here  $x$  and  $y$ ) is typically estimated as

$$\hat{\sigma}_{xy} = \sum_{t=1}^T (x_t - \bar{x})(y_t - \bar{y}) / T. \tag{1.24}$$

(Sometimes we use  $T - 1$  in the denominator of the sample covariance instead of  $T$ .)

The correlation of two variables is then estimated as

$$\hat{\rho}_{xy} = \frac{\hat{\sigma}_{xy}}{\hat{\sigma}_x \hat{\sigma}_y}, \tag{1.25}$$

where  $\hat{\sigma}_x$  and  $\hat{\sigma}_y$  are the estimated standard deviations. A correlation must be between  $-1$  and  $1$ . Note that covariance and correlation measure the degree of *linear* relation only. This is illustrated in Figure 1.7.

**Empirical Example 1.4** (*Scatter plot of equity returns*) See Figure 1.8.

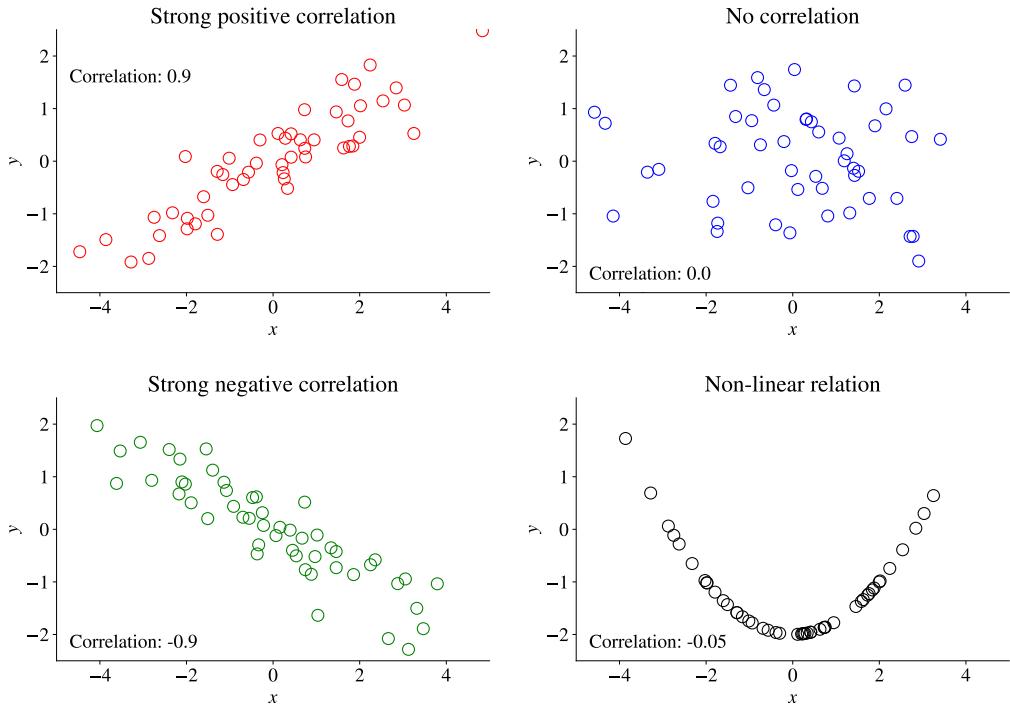


Figure 1.7: Example of correlations.

Under the null hypothesis of no correlation—and if the data is approximately normally distributed, then

$$\frac{\hat{\rho}}{\sqrt{1 - \hat{\rho}^2}} \sim N(0, 1/T), \quad (1.26)$$

so we can form a t-stat as

$$t = \sqrt{T} \frac{\hat{\rho}}{\sqrt{1 - \hat{\rho}^2}}, \quad (1.27)$$

which has an  $N(0, 1)$  distribution.

#### 1.2.4 Correlations vs. Causality

Notice that a correlation between  $x$  and  $y$  does not say anything about causality. There are several possibilities, including

$$(x, \varepsilon) \Rightarrow y \quad (1.28)$$

$$(y, u) \Rightarrow x$$

$$(z, u) \Rightarrow x \text{ and } (z, \varepsilon) \Rightarrow y$$

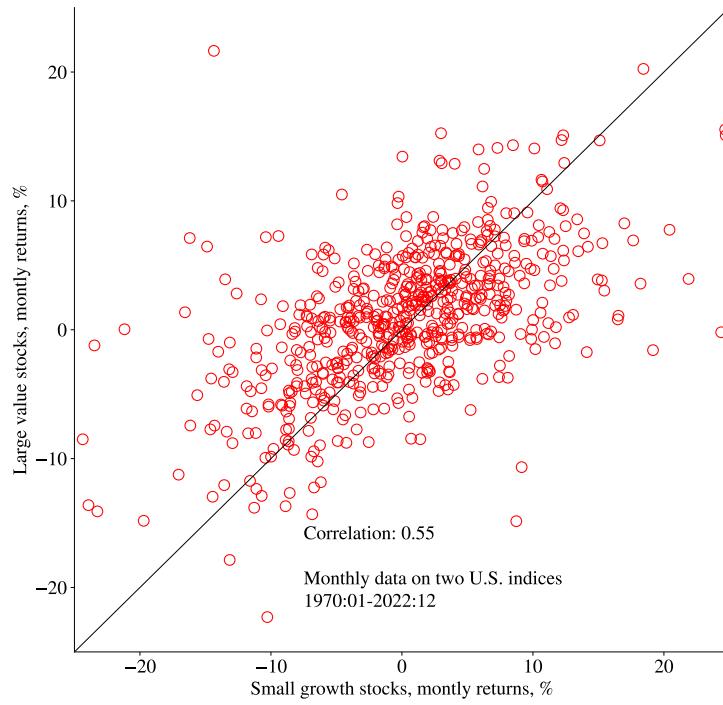


Figure 1.8: Scatter plot of two different portfolio returns

In the first case,  $x$  and some other variables (here labelled  $\varepsilon$ ) are indeed causing  $y$ , so changes in  $x$  are likely to be accompanied by changes in  $y$ . The second case shows the opposite:  $y$  is causing  $x$ . The third case is when some other variable  $z$  is driving the correlation between  $x$  and  $y$ . However, an independent move in  $x$  (due to  $u$ ) will not lead to moves in  $y$ . This reasoning carries over to regression analysis too. In many regressions we would like to capture the causality, although forecasting models are more focused on the correlation per se.

### 1.2.5 Correlations and the Variance of a Sample Average

The result in (1.16) that  $\text{Var}(\bar{x}) = \sigma^2/T$  does not hold if  $x_t$  and  $x_{t-s}$  are correlated. To see that, consider the case when the sample has just two observations

$$\begin{aligned}\bar{x} &= (x_1 + x_2)/2 \text{ and} \\ \text{Var}(\bar{x}) &= (\sigma^2 + \sigma^2 + \sigma_{12} + \sigma_{21})/4.\end{aligned}\tag{1.29}$$

In the iid case we *assume* that  $\sigma_{12} = \sigma_{21} = 0$ , so  $\text{Var}(\bar{x}) = \sigma^2/2$ . In the other extreme case of perfect correlations,  $\sigma_{12} = \sigma^2$  so the variance of the sample average is the same

as for the data (no precision is gained by averaging),  $\text{Var}(\bar{x}) = \sigma^2$ .

More generally, with  $T$  observations, we have

$$\text{Var}(\bar{x}) = \sum_{i=1}^T \sum_{j=1}^T \sigma_{ij} / T^2, \quad (1.30)$$

which is sum of all the elements of the covariance matrix, divided by  $T^2$ . This can be written as

$$\text{Var}(\bar{x}) = \frac{\bar{\sigma}^2 - \bar{\sigma}_{ij}}{T} + \bar{\sigma}_{ij}, \quad (1.31)$$

where  $\bar{\sigma}^2$  is the average variance and  $\bar{\sigma}_{ij}$  the average covariance of any two observations ( $x_t$  and  $x_{t-s}$ , say). This carries over to the variance of regression coefficients—when the residuals are correlated (over time or over cross sectional units).

**Example 1.5** (Covariance matrix with  $T = 2$ ) The covariance matrix of  $x_1$  and  $x_2$  is

$$\begin{bmatrix} \sigma^2 & \sigma_{12} \\ \sigma_{21} & \sigma^2 \end{bmatrix},$$

if we assume that  $x_1$  and  $x_2$  have the same variance ( $\sigma^2$ ). Also, notice that  $\sigma_{12} = \sigma_{21}$ .

**Example 1.6** ( $\text{Var}(\bar{x})$ ) Assume  $\bar{\sigma}^2 = 1$ , then  $\text{Var}(\bar{x})$  is

$$\begin{array}{ll} \bar{\sigma}_{ij} = 0 & \bar{\sigma}_{ij} = 0.10 \\ T = 10 : & \begin{array}{cc} 0.1 & 0.19 \end{array} \\ T = 100 : & \begin{array}{cc} 0.01 & 0.109 \end{array} \end{array}$$

## 1.3 Distributions Commonly Used in Tests

### 1.3.1 Standard Normal Distribution, $N(0, 1)$

Suppose the random variable  $x$  has a  $N(\mu, \sigma^2)$  distribution. Then, the the *standardized variable*  $(x - \mu)/\sigma$  has a standard normal distribution

$$t = \frac{x - \mu}{\sigma} \sim N(0, 1). \quad (1.32)$$

To see this, notice that  $x - \mu$  has a mean of zero and that  $x/\sigma$  has a standard deviation of unity. (This result is the motivation for why the confidence band (1.13) gives the same result as (1.11).)

### 1.3.2 $t$ -distribution

If we instead need to estimate  $\sigma$  to use in (1.32), then the test statistic has  $t_n$ -distribution

$$t = \frac{x - \mu}{\hat{\sigma}} \sim t_n, \quad (1.33)$$

where  $n$  denotes the “degrees of freedom,” that is the number of observations minus the number of estimated parameters. For instance, if we have a sample with  $T$  data points and only estimate the mean, then  $n = T - 1$ .

The  $t$ -distribution has more probability mass in the tails than an  $N(0, 1)$  distribution. It therefore gives a more “conservative” test (harder to reject the null hypothesis), but the difference vanishes as the degrees of freedom (sample size) increases. See Figure 1.9 for a comparison and Table 1.1 for critical values.

**Example 1.7 ( $t$ -distribution)** If  $t = 2.0$  and  $n = 50$ , then this is larger than the 10% critical value (but not the 5% critical value) for a 2-sided test in Table 1.1.

### 1.3.3 Chi-square Distribution

If  $z \sim N(0, 1)$ , then  $z^2 \sim \chi_1^2$ , that is,  $z^2$  has a chi-square distribution with one degree of freedom. This can be generalized in several ways. For instance, if  $x \sim N(\mu_x, \sigma_{xx})$  and  $y \sim N(\mu_y, \sigma_{yy})$  and they are uncorrelated, then  $[(x - \mu_x)/\sigma_x]^2 + [(y - \mu_y)/\sigma_y]^2 \sim \chi_2^2$ .

More generally, we have

$$v' \Sigma^{-1} v \sim \chi_n^2, \text{ if the } n \times 1 \text{ vector } v \sim N(0, \Sigma). \quad (1.34)$$

See Figure 1.9 for an illustration and Table 1.2 for critical values.

**Example 1.8 ( $\chi_2^2$  distribution)** Suppose  $x$  is a  $2 \times 1$  vector

$$\begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \sim N \left( \begin{bmatrix} 4 \\ 2 \end{bmatrix}, \begin{bmatrix} 5 & 3 \\ 3 & 4 \end{bmatrix} \right).$$

If  $x_1 = 3$  and  $x_2 = 5$ , then

$$\begin{bmatrix} 3 - 4 \\ 5 - 2 \end{bmatrix}' \begin{bmatrix} 5 & 3 \\ 3 & 4 \end{bmatrix}^{-1} \begin{bmatrix} 3 - 4 \\ 5 - 2 \end{bmatrix} \approx 6.1$$

has a  $\chi_2^2$  distribution. Notice that 6.1 is higher than the 5% critical value (but not the 1% critical value) in Table 1.2.

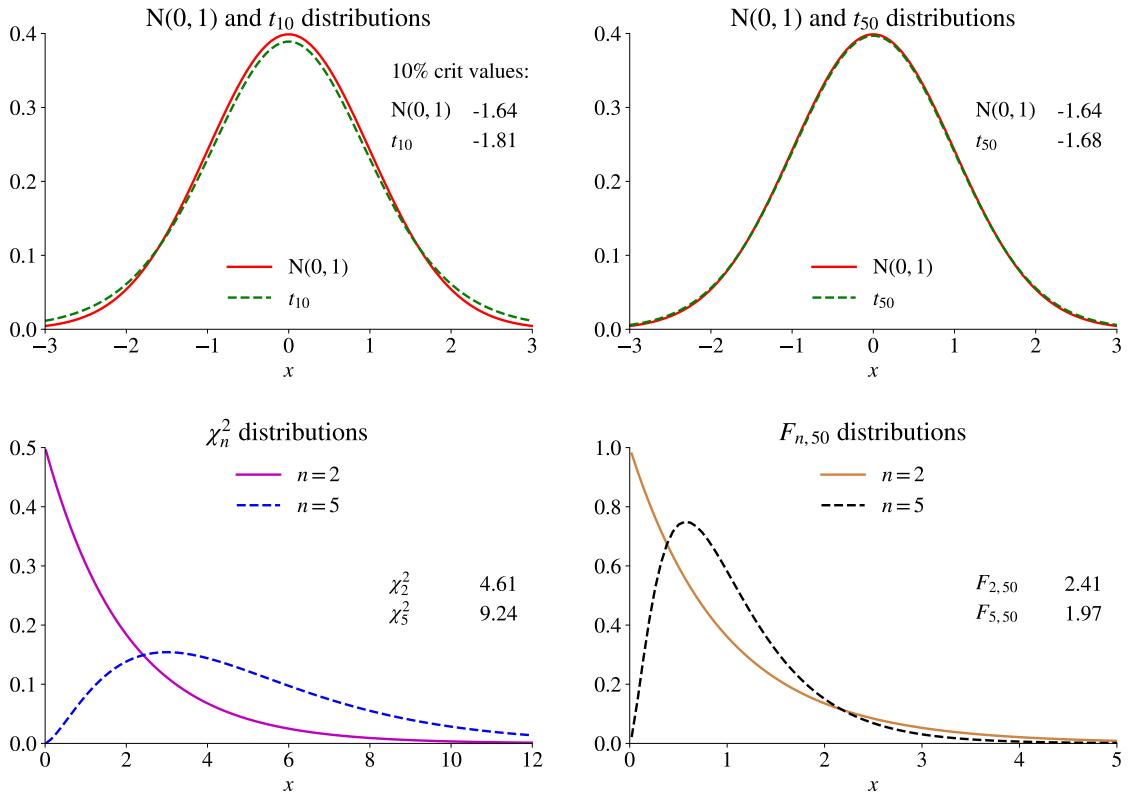


Figure 1.9: Probability density functions

### 1.3.4 $F$ -distribution

If  $x \sim \chi^2_{n_1}$  and  $y \sim \chi^2_{n_2}$ , then  $(x/n_1)/(y/n_2)$  has an  $F_{n_1, n_2}$  distribution with  $(n_1, n_2)$  degrees of freedom. See Figure 1.9 for an illustration and Tables 1.3–1.4 for critical values.

## 1.4 Normal Distribution of the Sample Mean

In many cases, it is unreasonable to assume that a random variable  $x_t$  is normally distributed. The nice thing with a sample mean (or sample average), here denoted  $\bar{x}$ , is that it has very useful properties (in a reasonably large sample). This section gives a short summary of what happens to sample means as the sample size increases (often called “asymptotic theory”).

The *law of large numbers* (LLN) says that the sample mean converges to the true population mean as the sample size goes to infinity. This holds for a very large class

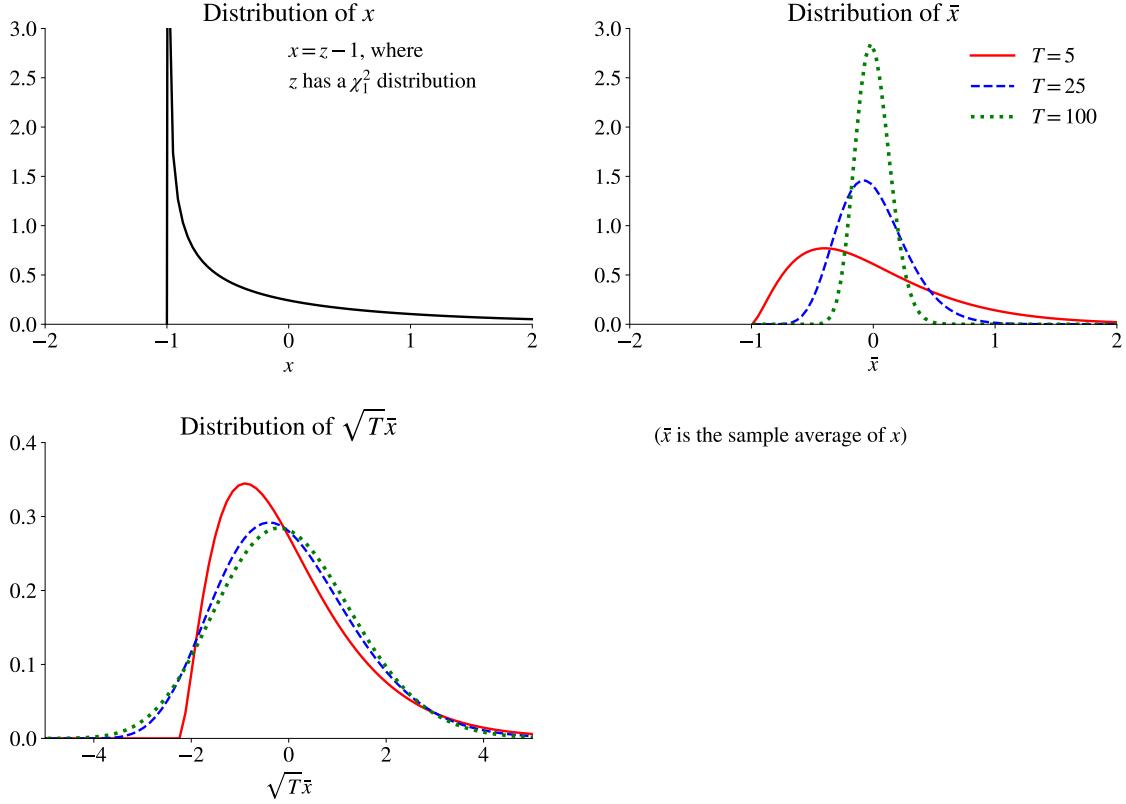


Figure 1.10: Sampling distributions

of random variables, but there are exceptions. A sufficient (but not necessary) condition for this convergence is that the sample average is unbiased (as in (1.18)) and that the variance goes to zero as the sample size goes to infinity (as in (1.16)). (This is also called convergence in mean square.) To see the LLN in action, see Figure 1.10.

The *central limit theorem* (CLT) says that  $\sqrt{T}\bar{x}$  converges in distribution to a normal distribution as the sample size increases. See Figure 1.10 for an illustration. This also holds for a large class of random variables—and it is a very useful result since it allows us to test hypotheses by assuming that  $\sqrt{T}\bar{x}$  is normally distributed. Most estimators (including least squares and other methods) are effectively some kind of sample average, so the CLT can be applied. If the population mean is  $\mu$ , then this is often written

$$\sqrt{T}(\bar{x} - \mu) \xrightarrow{d} N(0, \sigma^2), \quad (1.35)$$

where  $\xrightarrow{d}$  denotes that the distribution converges to a normal as  $T$  goes to infinity. If  $x$  is

iid, then  $\sigma^2$  is the same as the variance of  $x$ . This is often expressed as

$$\bar{x} \xrightarrow{a} N(\mu, \sigma^2/T),$$

where  $\xrightarrow{a}$  means “is asymptotically distributed as”. (This follows from: (a) if the variance of  $\sqrt{T}\bar{x}$  is  $\sigma^2$ , then the variance of  $\bar{x}$  is  $\sigma^2/T$ ; (b) adding  $\mu$  to  $\bar{x} - \mu$  increases the mean by  $\mu$ .)

## 1.5 Appendix: Notation

Here is an incomplete list of the notation used in these notes.

- $\sum_{t=1}^T x_t$  denotes the sum  $x_1 + \dots + x_T$ . In the running text, this is sometimes written as just  $\Sigma_t x_t$ . It also happens that  $\Sigma$  is used to denote a variance-covariance matrix. The distinction should be clear from the context.
- $\text{Var}(x)$  denotes either the variance of a single random variable, or the  $n \times n$  variance-covariance matrix of a  $n$ -vector  $x$ .
- $\text{Cov}(x, z)$  denotes either the covariance of single random variables  $x$  and  $z$ , or the  $n_x \times n_z$  matrix of covariances when  $x$  is an  $n_x$ -vector and  $z$  is an  $n_z$ -vector.
- $E x$  denotes the expectation (population mean) of  $x$  (which could be a single random variable, or a vector/matrix). When  $x$  is a vector/matrix, then  $E x$  is the vector/matrix of expectation of each element of  $x$ . Sample means are typically denoted by  $\bar{x}$ .

## 1.6 Appendix: Statistical Tables

<u><math>n</math></u>	Significance level		
	10%	5%	1%
10	1.81	2.23	3.17
20	1.72	2.09	2.85
30	1.70	2.04	2.75
40	1.68	2.02	2.70
50	1.68	2.01	2.68
60	1.67	2.00	2.66
70	1.67	1.99	2.65
80	1.66	1.99	2.64
90	1.66	1.99	2.63
100	1.66	1.98	2.63
Normal	1.64	1.96	2.58

Table 1.1: Critical values (two-sided test) of t distribution (different degrees of freedom) and normal distribution.

<u><i>n</i></u>	<u>Significance level</u>		
	10%	5%	1%
1	2.71	3.84	6.63
2	4.61	5.99	9.21
3	6.25	7.81	11.34
4	7.78	9.49	13.28
5	9.24	11.07	15.09
6	10.64	12.59	16.81
7	12.02	14.07	18.48
8	13.36	15.51	20.09
9	14.68	16.92	21.67
10	15.99	18.31	23.21

Table 1.2: Critical values of chisquare distribution (different degrees of freedom,  $n$ ).

## 1.7 Appendix: Data Sources

The data used in these lecture notes are from the following sources:

1. website of Kenneth French,  
[http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data\\_library.html](http://mba.tuck.dartmouth.edu/pages/faculty/ken.french/data_library.html)
2. Bloomberg
3. Datastream
4. Federal Reserve Bank of St. Louis (FRED), <http://research.stlouisfed.org/fred2/>
5. website of Robert Shiller, <http://www.econ.yale.edu/~shiller/data.htm>
6. yahoo! finance, <http://finance.yahoo.com/>
7. OlsenData, <http://www.olsendata.com>

<u><math>n_1</math></u>	<u><math>n_2</math></u>					<u><math>\chi^2_{n_1}/n_1</math></u>
	10	30	50	100	300	
1	4.96	4.17	4.03	3.94	3.87	3.84
2	4.10	3.32	3.18	3.09	3.03	3.00
3	3.71	2.92	2.79	2.70	2.63	2.60
4	3.48	2.69	2.56	2.46	2.40	2.37
5	3.33	2.53	2.40	2.31	2.24	2.21
6	3.22	2.42	2.29	2.19	2.13	2.10
7	3.14	2.33	2.20	2.10	2.04	2.01
8	3.07	2.27	2.13	2.03	1.97	1.94
9	3.02	2.21	2.07	1.97	1.91	1.88
10	2.98	2.16	2.03	1.93	1.86	1.83

Table 1.3: 5% Critical values of  $F_{n_1,n_2}$  distribution (different degrees of freedom).

<u><math>n_1</math></u>	<u><math>n_2</math></u>					<u><math>\chi^2_{n_1}/n_1</math></u>
	10	30	50	100	300	
1	3.29	2.88	2.81	2.76	2.72	2.71
2	2.92	2.49	2.41	2.36	2.32	2.30
3	2.73	2.28	2.20	2.14	2.10	2.08
4	2.61	2.14	2.06	2.00	1.96	1.94
5	2.52	2.05	1.97	1.91	1.87	1.85
6	2.46	1.98	1.90	1.83	1.79	1.77
7	2.41	1.93	1.84	1.78	1.74	1.72
8	2.38	1.88	1.80	1.73	1.69	1.67
9	2.35	1.85	1.76	1.69	1.65	1.63
10	2.32	1.82	1.73	1.66	1.62	1.60

Table 1.4: 10% Critical values of  $F_{n_1,n_2}$  distribution (different degrees of freedom).

	0.0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
-3.0	0.0013	0.0014	0.0014	0.0015	0.0015	0.0016	0.0016	0.0017	0.0018	0.0018
-2.9	0.0019	0.0019	0.0020	0.0021	0.0021	0.0022	0.0023	0.0023	0.0024	0.0025
-2.8	0.0026	0.0026	0.0027	0.0028	0.0029	0.0030	0.0031	0.0032	0.0033	0.0034
-2.7	0.0035	0.0036	0.0037	0.0038	0.0039	0.0040	0.0041	0.0043	0.0044	0.0045
-2.6	0.0047	0.0048	0.0049	0.0051	0.0052	0.0054	0.0055	0.0057	0.0059	0.0060
-2.5	0.0062	0.0064	0.0066	0.0068	0.0069	0.0071	0.0073	0.0075	0.0078	0.0080
-2.4	0.0082	0.0084	0.0087	0.0089	0.0091	0.0094	0.0096	0.0099	0.0102	0.0104
-2.3	0.0107	0.0110	0.0113	0.0116	0.0119	0.0122	0.0125	0.0129	0.0132	0.0136
-2.2	0.0139	0.0143	0.0146	0.0150	0.0154	0.0158	0.0162	0.0166	0.0170	0.0174
-2.1	0.0179	0.0183	0.0188	0.0192	0.0197	0.0202	0.0207	0.0212	0.0217	0.0222
-2.0	0.0228	0.0233	0.0239	0.0244	0.0250	0.0256	0.0262	0.0268	0.0274	0.0281
-1.9	0.0287	0.0294	0.0301	0.0307	0.0314	0.0322	0.0329	0.0336	0.0344	0.0351
-1.8	0.0359	0.0367	0.0375	0.0384	0.0392	0.0401	0.0409	0.0418	0.0427	0.0436
-1.7	0.0446	0.0455	0.0465	0.0475	0.0485	0.0495	0.0505	0.0516	0.0526	0.0537
-1.6	0.0548	0.0559	0.0571	0.0582	0.0594	0.0606	0.0618	0.0630	0.0643	0.0655
-1.5	0.0668	0.0681	0.0694	0.0708	0.0721	0.0735	0.0749	0.0764	0.0778	0.0793
-1.4	0.0808	0.0823	0.0838	0.0853	0.0869	0.0885	0.0901	0.0918	0.0934	0.0951
-1.3	0.0968	0.0985	0.1003	0.1020	0.1038	0.1056	0.1075	0.1093	0.1112	0.1131
-1.2	0.1151	0.1170	0.1190	0.1210	0.1230	0.1251	0.1271	0.1292	0.1314	0.1335
-1.1	0.1357	0.1379	0.1401	0.1423	0.1446	0.1469	0.1492	0.1515	0.1539	0.1562
-1.0	0.1587	0.1611	0.1635	0.1660	0.1685	0.1711	0.1736	0.1762	0.1788	0.1814
-0.9	0.1841	0.1867	0.1894	0.1922	0.1949	0.1977	0.2005	0.2033	0.2061	0.2090
-0.8	0.2119	0.2148	0.2177	0.2206	0.2236	0.2266	0.2296	0.2327	0.2358	0.2389
-0.7	0.2420	0.2451	0.2483	0.2514	0.2546	0.2578	0.2611	0.2643	0.2676	0.2709
-0.6	0.2743	0.2776	0.2810	0.2843	0.2877	0.2912	0.2946	0.2981	0.3015	0.3050
-0.5	0.3085	0.3121	0.3156	0.3192	0.3228	0.3264	0.3300	0.3336	0.3372	0.3409
-0.4	0.3446	0.3483	0.3520	0.3557	0.3594	0.3632	0.3669	0.3707	0.3745	0.3783
-0.3	0.3821	0.3859	0.3897	0.3936	0.3974	0.4013	0.4052	0.4090	0.4129	0.4168
-0.2	0.4207	0.4247	0.4286	0.4325	0.4364	0.4404	0.4443	0.4483	0.4522	0.4562
-0.1	0.4602	0.4641	0.4681	0.4721	0.4761	0.4801	0.4840	0.4880	0.4920	0.4960

Table 1.5: Values of the standard normal distribution function at  $x$  where  $x$  is the sum of the values in the first column and the first row.

	0.0	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9925	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9959	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986

Table 1.6: Values of the standard normal distribution function at  $x$  where  $x$  is the sum of the values in the first column and the first row.

# Chapter 2

## Least Squares Estimation

Reference: Verbeek (2012) 2 and 4; Greene (2018) 2-4.

More advanced material is denoted by a star (\*). It is not required reading.

### 2.1 Least Squares: The Optimization Problem and Its Solution

#### 2.1.1 Simple Regression

The simplest regression model is

$$y_t = \beta_0 + \beta_1 x_t + u_t, \text{ where } E u_t = 0 \text{ and } \text{Cov}(x_t, u_t) = 0, \quad (2.1)$$

where we can observe (have data on) the dependent variable  $y_t$  and the regressor  $x_t$  but not the residual  $u_t$ . In principle, the residual should account for all the movements in  $y_t$  that we cannot explain by  $x_t$ . The subscript  $t$  refers to observation  $t$ , which could represent period  $t$  (when data is a time series) or investor  $t$  (when data is a cross-section). In the latter case, it is common to instead use  $i$  as subscript.

**Remark 2.1** (*On notation*) These notes sometimes use alternative notations for the regression equation, for instance,  $y_t = \alpha + \beta x_t + u_t$  (as is typical in CAPM regressions) or  $y_i = a + b x_i + u_i$ .

Notice the two very important assumptions: (i) the mean of the residual is zero; and (ii) the residual is not correlated with the regressor,  $x_t$ . This basically says that the residual is pure noise. In contrast, if the average of  $u_t$  was non-zero, then  $\beta_0 + \beta_1 x_t$  would get the general level of  $y_t$  wrong. Also, if  $x_t$  and  $u_t$  were correlated, then the best guess of  $y_t$  based on  $x_t$  would not be  $\beta_0 + \beta_1 x_t$ .

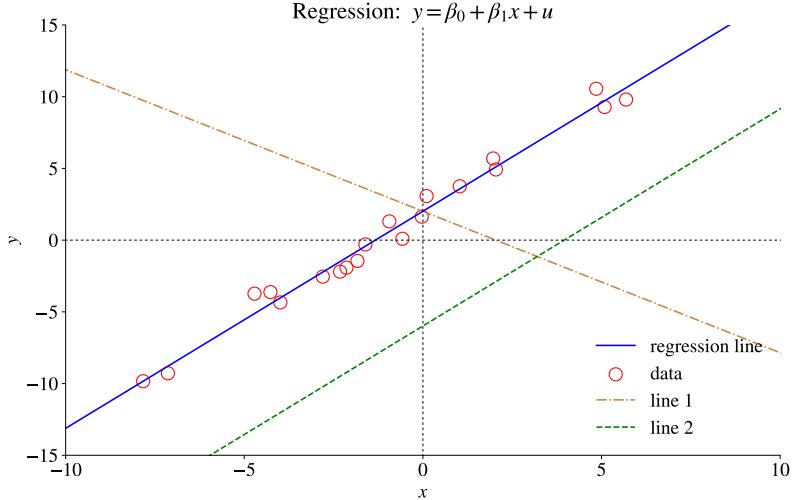


Figure 2.1: Example of OLS

Suppose you do not know  $\beta_0$  or  $\beta_1$ , and that you have a sample of data:  $y_t$  and  $x_t$  for  $t = 1, \dots, T$ . The LS estimator of  $\beta_0$  and  $\beta_1$  minimizes the loss function

$$\sum_{t=1}^T (y_t - b_0 - b_1 x_t)^2 = (y_1 - b_0 - b_1 x_1)^2 + (y_2 - b_0 - b_1 x_2)^2 + \dots \quad (2.2)$$

by choosing  $b_0$  and  $b_1$  to make the loss function value as small as possible. The objective is thus to pick values of  $b_0$  and  $b_1$  in order to make the model fit the data as closely as possible—where close is taken to be a small variance of the unexplained part (the residual). See Figures 2.1–2.2 for illustrations. (Least squares is only one of many possible ways to estimate regression coefficients. We will discuss other methods later on.)

**Remark 2.2** (On notation) These notes use  $\sum_{t=1}^T x_t$  to denote the sum  $x_1 + \dots + x_T$ . In the running text, this is sometimes written as just  $\Sigma x_t$ . It also happens that  $\Sigma$  is used to denote a variance-covariance matrix. The distinction should be clear from the context.

**Remark 2.3** Note that  $\beta_i$  is the true (unobservable) value which we estimate to be  $\hat{\beta}_i$ . Whereas  $\beta_i$  is an unknown (deterministic) number;  $\hat{\beta}_i$  is a random variable since it is calculated as a function of the random sample of  $y_t$  and  $x_t$ . We use  $b_i$  as an argument in the loss function (so we contemplate different values of  $b_i$ ) —and the optimal value is clearly  $\hat{\beta}_i$ .

**Remark 2.4** (First order condition for minimizing a differentiable function). We want to find the value of  $b$  in the interval  $b_{\text{low}} \leq b \leq b_{\text{high}}$ , which makes the value of the

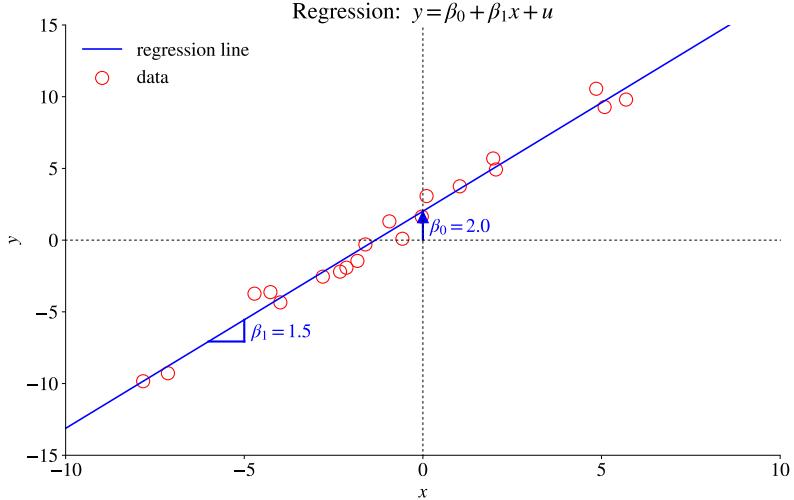


Figure 2.2: Example of OLS

differentiable function  $f(b)$  as small as possible. The answer is  $b_{low}$ ,  $b_{high}$ , or a value of  $b$  where  $df(b)/db = 0$ . See Figure 2.3.

The first order conditions for a minimum are that the derivatives of this loss function with respect to  $b_0$  and  $b_1$  should be zero. Notice that

$$\frac{\partial}{\partial b_0} (y_t - b_0 - b_1 x_t)^2 = -2(y_t - b_0 - b_1 x_t) \mathbf{1} \quad (2.3)$$

$$\frac{\partial}{\partial b_1} (y_t - b_0 - b_1 x_t)^2 = -2(y_t - b_0 - b_1 x_t) x_t. \quad (2.4)$$

Let  $(\hat{\beta}_0, \hat{\beta}_1)$  be the values of  $(b_0, b_1)$  where the derivatives are zero (that is,  $(\hat{\beta}_0, \hat{\beta}_1)$  are the optimal values)

$$\frac{\partial}{\partial \beta_0} \sum_{t=1}^T (y_t - \hat{\beta}_0 - \hat{\beta}_1 x_t)^2 = -2 \sum_{t=1}^T \mathbf{1}(y_t - \hat{\beta}_0 - \hat{\beta}_1 x_t) = 0 \quad (2.5)$$

$$\frac{\partial}{\partial \beta_1} \sum_{t=1}^T (y_t - \hat{\beta}_0 - \hat{\beta}_1 x_t)^2 = -2 \sum_{t=1}^T x_t(y_t - \hat{\beta}_0 - \hat{\beta}_1 x_t) = 0, \quad (2.6)$$

which are two equations in two unknowns ( $\hat{\beta}_0$  and  $\hat{\beta}_1$ ), which must be solved simultaneously. These equations show that both the constant and  $x_t$  should be *orthogonal* to the fitted residuals,  $\hat{u}_t = y_t - \hat{\beta}_0 - \hat{\beta}_1 x_t$ . This is indeed a defining feature of LS and can be seen as the sample analogues of the assumptions in (2.1) that  $E u_t = 0$  and  $Cov(x_t, u_t) = 0$ . To see this, note that (2.5) says that the sample average of  $\hat{u}_t$  should be zero. Similarly,

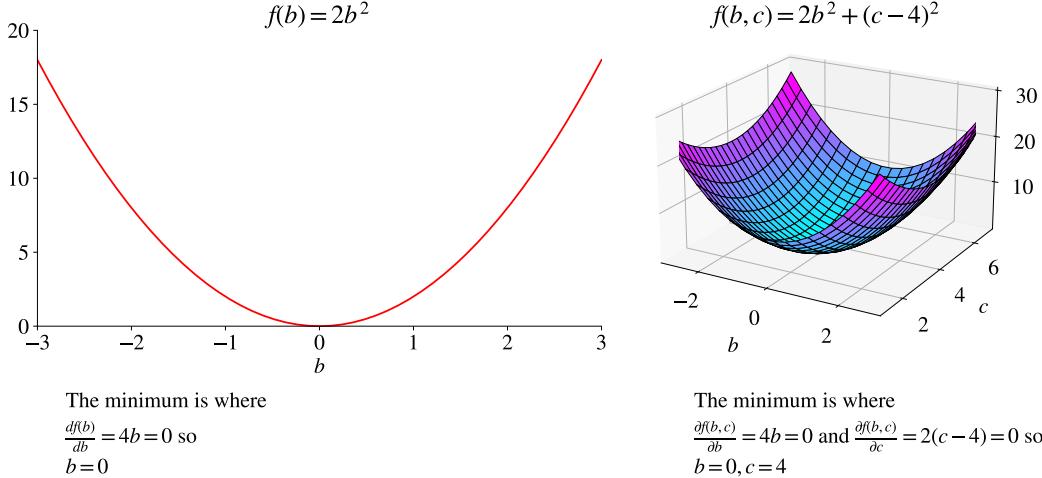


Figure 2.3: Quadratic loss function. Subfigure a: 1 coefficient; Subfigure b: 2 coefficients

(2.6) says that the sample cross moment of  $\hat{u}_t$  and  $x_t$  (that is,  $\sum_{t=1}^T \hat{u}_t x_t / T$ ) should also be zero, which implies that the sample covariance is zero as well since  $\hat{u}_t$  has a zero sample mean (see Remark 2.5).

**Remark 2.5** (*Cross moments and covariance*) A covariance is defined as

$$\begin{aligned}\text{Cov}(x, y) &= E[(x - E x)(y - E y)] \\ &= E xy - E x E y.\end{aligned}$$

If  $E x = 0$  or  $E y = 0$ , then  $\text{Cov}(x, y) = E xy$ . When  $x = y$ , then we get  $\text{Var}(x) = E x^2 - (E x)^2$ . These results hold for sample moments too.

When the means of  $y$  and  $x$  are zero, then we know that intercept is zero ( $\beta_0 = 0$ ). In this case, (2.6) with  $\hat{\beta}_0 = 0$  immediately gives

$$\begin{aligned}\sum_{t=1}^T x_t y_t &= \hat{\beta}_1 \sum_{t=1}^T x_t x_t \text{ or} \\ \hat{\beta}_1 &= \frac{\sum_{t=1}^T x_t y_t / T}{\sum_{t=1}^T x_t x_t / T}.\end{aligned}\tag{2.7}$$

In this case, the coefficient estimator is the sample covariance (recall: means are zero) of  $y_t$  and  $x_t$ , divided by the sample variance of the regressor  $x_t$  (this statement is actually true even if the means are not zero and a constant is included on the right hand side—just more tedious to show it).

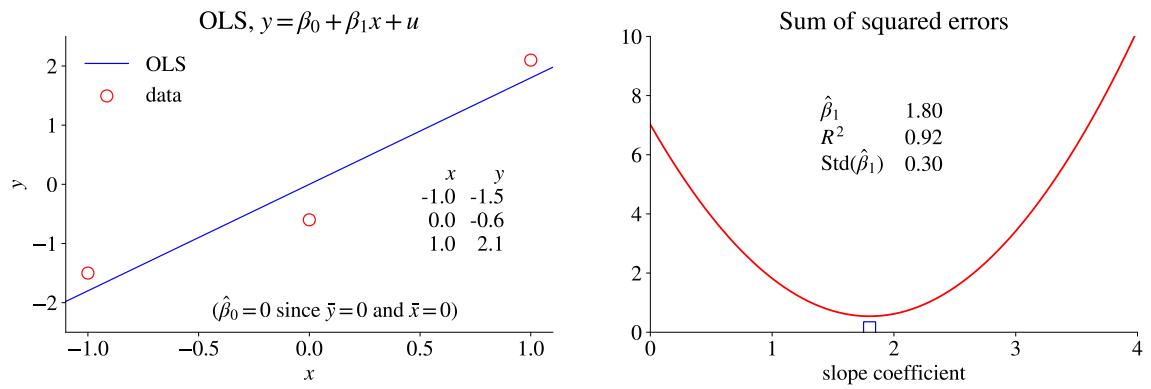


Figure 2.4: Example of OLS estimation

**Empirical Example 2.6 (CAPM regressions)** See Table 2.1 and Figure 2.5 for CAPM regressions for two industry portfolios. The betas clearly differ.

	HiTec	Utils
constant	-0.09 (-0.67)	0.26 (1.87)
market return	1.24 (38.15)	0.52 (14.12)
$R^2$	0.76	0.33
obs	636	636

Table 2.1: CAPM regressions, monthly returns, %, US data 1970:01-2022:12. Numbers in parentheses are t-stats.

**Example 2.7 (Simple regression)** Consider the simple regression model (PSLS1). Suppose we have the following data

<u>t</u>	<u>x</u>	<u>y</u>
1	-1	-1.5
2	0	-0.6
3	1	2.1

To calculate the LS estimate according to (2.7) we note that

$$\begin{aligned}\sum_{t=1}^T x_t x_t &= (-1)^2 + 0^2 + 1^1 = 2 \text{ and} \\ \sum_{t=1}^T x_t y_t &= (-1)(-1.5) + 0(-0.6) + 1 \times 2.1 = 3.6\end{aligned}$$

This gives

$$\hat{\beta}_1 = \frac{3.6}{2} = 1.8.$$

The fitted residuals are

$$\begin{bmatrix} \hat{u}_1 \\ \hat{u}_2 \\ \hat{u}_3 \end{bmatrix} = \begin{bmatrix} -1.5 \\ -0.6 \\ 2.1 \end{bmatrix} - 1.8 \begin{bmatrix} -1 \\ 0 \\ 1 \end{bmatrix} = \begin{bmatrix} 0.3 \\ -0.6 \\ 0.3 \end{bmatrix}.$$

The fitted residuals indeed obey the first order condition (2.6) since

$$\sum_{t=1}^T x_t \hat{u}_t = (-1) \times 0.3 + 0(-0.6) + 1 \times 0.3 = 0.$$

See Figure 2.4 for an illustration.

**Example 2.8** Using the same data as in Example 2.7 we can also calculate the sums of squared residuals for different values of the slope coefficient. With  $\beta_1 = 1.6$  we get

$t$	$\underline{u}_t$	$\underline{u}_1^2$
1	$-1.5 - \mathbf{1.6} \times (-1) = 0.1$	0.01
2	$-0.6 - \mathbf{1.6} \times 0 = -0.6$	0.36
3	$2.1 - \mathbf{1.6} \times 1 = 0.5$	0.25
sum	0	0.62

With  $\beta = 1.8$  and  $\beta = 2.0$  we instead get

$t$	$\underline{u}_t$	$\underline{u}_1^2$
1	$-1.5 - \mathbf{1.8} \times (-1) = 0.3$	0.09
2	$-0.6 - \mathbf{1.8} \times 0 = -0.6$	0.36
3	$2.1 - \mathbf{1.8} \times 1 = 0.3$	0.09
sum	0	0.54

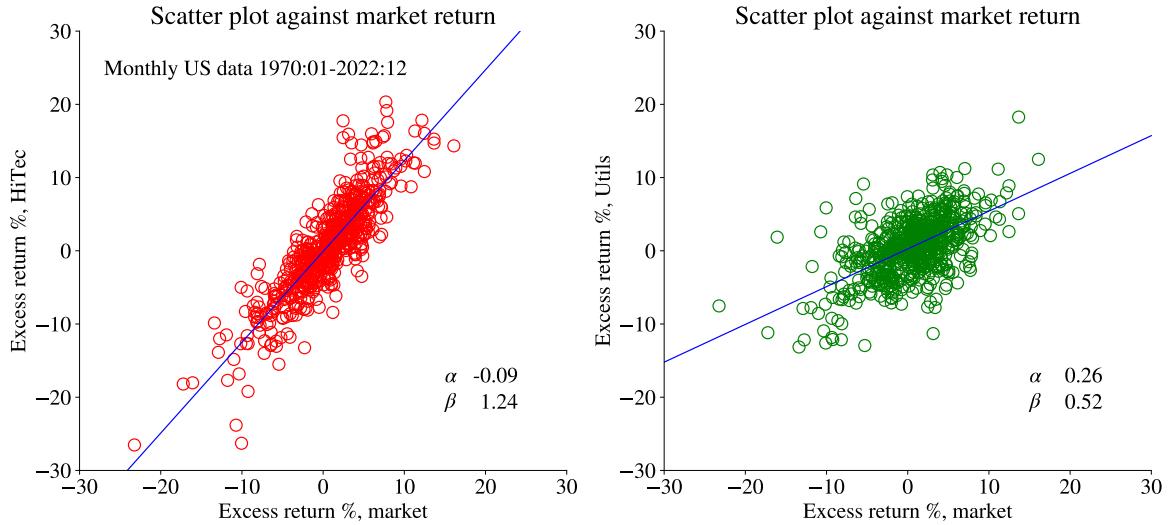


Figure 2.5: Scatter plot against market return

$t$	$u_t$	$u_1^2$
1	$-1.5 - 2.0 \times (-1) = 0.5$	0.25
2	$-0.6 - 2.0 \times 0 = -0.6$	0.36
3	$2.1 - 2.0 \times 1 = 0.1$	0.01
sum	0	0.62

Among these alternatives,  $\beta = 1.8$  has the lowest sum of squared residuals (it is actually the optimum). See Figure 2.4.

### 2.1.2 Multiple Regression

All the previous results still hold in a multiple regression—with suitable reinterpretations of the notation.

Consider the linear model

$$\begin{aligned} y_t &= x_{1t}\beta_1 + x_{2t}\beta_2 + \cdots + x_{kt}\beta_k + u_t \\ &= x'_t\beta + u_t, \end{aligned} \tag{2.8}$$

where  $y_t$  and  $u_t$  are scalars,  $x_t$  a  $k \times 1$  vector, and  $\beta$  is a  $k \times 1$  vector of the true coefficients. In this expression, one of the elements of  $x_t$  is typically a constant equal to one (and the intercept is its coefficient).

**Remark 2.9** (On notation) These notes typically denote a vector of regression coefficients by  $\beta$ . The distinction from the  $y_t = \alpha + \beta x_t + u_t$  notation (sometimes used for simple regressions) should be clear from the context.

Least squares minimizes the sum of the squared fitted residuals

$$\sum_{t=1}^T (y_t - x_t' b)^2, \quad (2.9)$$

by choosing the vector  $b$ . The first order conditions (zero derivatives) hold at the (optimal) values  $\hat{\beta}$ , and can then be written

$$0_{kx1} = \sum_{t=1}^T x_t (y_t - x_t' \hat{\beta}) \text{ or } \sum_{t=1}^T x_t y_t = \sum_{t=1}^T x_t x_t' \hat{\beta}. \quad (2.10)$$

Solve this as

$$\hat{\beta} = \left( \sum_{t=1}^T x_t x_t' \right)^{-1} \sum_{t=1}^T x_t y_t. \quad (2.11)$$

If the regressors are orthogonal (for instance,  $\sum x_{1t} x_{2t} = 0$ ) then the results from the multiple regression (2.31) are the same as those from a series of simple regressions:  $y_t$  regressed on  $x_{1t}$ ,  $y_t$  regressed on  $x_{2t}$ , etc. (This is easy to see since in this case  $\sum x_t x_t'$  is a diagonal matrix which carries over to the inverse.) This is an unlikely case, unless the regressors have been pre-processed to indeed be orthogonal.

**Example 2.10** ( $x_t = 1$ ) With a constant as the only regressor,  $x_t y_t = y_t$  and  $x_t x_t' = 1$ . We then get  $\hat{\beta} = \sum_{t=1}^T y_t / T$ , that is, the sample average of  $y_t$ .

**Empirical Example 2.11** (Factor model) Table 2.2 shows results from estimating a multi-factor model for the returns of two sector indices.

**Remark 2.12** (Matrix notation\*) Let  $X$  be a  $T \times k$  matrix where row  $t$  is filled with the elements of  $x_t$  and let  $Y$  be a  $T \times 1$  where element  $t$  is  $y_t$ . Then,  $X'X = \sum_{t=1}^T x_t x_t'$  and  $X'Y = \sum_{t=1}^T x_t y_t$ , so (2.11) can also be written  $\hat{\beta} = (X'X)^{-1} X'Y$ .

$\widehat{\text{Var}}$

**Remark 2.13** (Alternative expression for  $\beta^*$ ) Consider the regression  $y_t = \alpha + z_t' \gamma + u_t$ . It is straightforward to show that (2.11) with  $x_t = [1; z_t]$  can be rewritten as  $\hat{\gamma} = \widehat{\text{Var}}(z_t)^{-1} \widehat{\text{Cov}}(z_t, y_t)$  and  $\hat{\alpha} = \bar{y}_t - \bar{z}_t' \hat{\gamma}$ , where  $\widehat{\text{Var}}(z_t)$  denotes the sample variance-covariance matrix of  $z_t$  and  $\widehat{\text{Cov}}(z_t, y_t)$  is the vector of sample covariances of  $z_t$  and  $y_t$ . Clearly,  $\beta = [\alpha, \gamma]$ . See also Example 2.15.

	HiTec	Utils
constant	0.11 (1.04)	0.14 (1.06)
market return	1.13 (37.72)	0.60 (17.24)
SMB	0.20 (4.02)	-0.21 (-4.05)
HML	-0.50 (-10.56)	0.30 (5.33)
$R^2$	0.82	0.41
obs	636	636

Table 2.2: Fama-French regressions, monthly returns, %, US data 1970:01-2022:12. Numbers in parentheses are t-stats.

**Example 2.14 (OLS with 2 regressors)** With 2 regressors ( $k = 2$ ) denoted  $x_{1t}$  and  $x_{2t}$ ,

$$x_t y_t = \begin{bmatrix} x_{1t} y_t \\ x_{2t} y_t \end{bmatrix} \text{ and } x_t x'_t = \begin{bmatrix} x_{1t} \\ x_{2t} \end{bmatrix} \begin{bmatrix} x_{1t} & x_{2t} \end{bmatrix} = \begin{bmatrix} x_{1t} x_{1t} & x_{1t} x_{2t} \\ x_{2t} x_{1t} & x_{2t} x_{2t} \end{bmatrix}.$$

This means that (2.10) is

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \sum_{t=1}^T \begin{bmatrix} x_{1t}(y_t - x_{1t}\hat{\beta}_1 - x_{2t}\hat{\beta}_2) \\ x_{2t}(y_t - x_{1t}\hat{\beta}_1 - x_{2t}\hat{\beta}_2) \end{bmatrix}$$

and (2.11) is

$$\begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{bmatrix} = \left( \sum_{t=1}^T \begin{bmatrix} x_{1t} x_{1t} & x_{1t} x_{2t} \\ x_{2t} x_{1t} & x_{2t} x_{2t} \end{bmatrix} \right)^{-1} \sum_{t=1}^T \begin{bmatrix} x_{1t} y_t \\ x_{2t} y_t \end{bmatrix}.$$

**Example 2.15 (OLS with constant and one more regressor)** In Example 2.14, let  $x_{1t} = 1$  use the same notation as in Remark 2.13 (that is,  $y_t = \alpha + z_t\gamma + u_t$ ). The first order conditions are then

$$\begin{bmatrix} 0 \\ 0 \end{bmatrix} = \sum_{t=1}^T \begin{bmatrix} y_t - \hat{\alpha} - z_t \hat{\gamma} \\ z_t(y_t - \hat{\alpha} - z_t \hat{\gamma}) \end{bmatrix}.$$

The first line implies that  $\hat{\alpha} = \bar{y}_t - \bar{z}_t \hat{\gamma}$ . Using this in the second line to replace  $\hat{\alpha}$  and noticing that it does not matter if the term outside the parenthesis is  $z_t$  or  $z_t - \bar{z}_t$  (since the term in parenthesis is zero on average) gives  $\Sigma(z_t - \bar{z}_t)[(y_t - \bar{y}_t) - (z_t - \bar{z}_t)\hat{\gamma}] = 0$ . We can then solve as  $\hat{\gamma} = \Sigma(z_t - \bar{z}_t)(y_t - \bar{y}_t)/\Sigma(z_t - \bar{z}_t)^2$ , which is the same as the sample covariance of  $z_t$  and  $y_t$  divided by the sample variance of  $z_t$  (divide both numerator and

denominator by  $T$  to see this).

**Example 2.16** (Regression with an intercept and slope) Suppose we have the following data:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \end{bmatrix} = \begin{bmatrix} -1.5 \\ -0.6 \\ 2.1 \end{bmatrix}, x_1 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}, x_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \text{ and } x_3 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

This is clearly the same as in Example 2.7, except that we allow for an intercept (which turns out to be zero in this particular example). The notation we need to solve this problem is the same as for a general multiple regression. Therefore, calculate the following:

$$\begin{aligned} \sum_{t=1}^T x_t x_t' &= \begin{bmatrix} 1 \\ -1 \end{bmatrix} \begin{bmatrix} 1 & -1 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix} \end{aligned}$$

$$\begin{aligned} \sum_{t=1}^T x_t y_t &= \begin{bmatrix} 1 \\ -1 \end{bmatrix} (-1.5) + \begin{bmatrix} 1 \\ 0 \end{bmatrix} (-0.6) + \begin{bmatrix} 1 \\ 1 \end{bmatrix} 2.1 \\ &= \begin{bmatrix} -1.5 \\ 1.5 \end{bmatrix} + \begin{bmatrix} -0.6 \\ 0 \end{bmatrix} + \begin{bmatrix} 2.1 \\ 2.1 \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ 3.6 \end{bmatrix} \end{aligned}$$

To calculate the LS estimate, notice that the inverse of the  $\sum_{t=1}^T x_t x_t'$  is

$$\begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix}^{-1} = \begin{bmatrix} 1/3 & 0 \\ 0 & 1/2 \end{bmatrix},$$

which can be verified by

$$\begin{bmatrix} 1/3 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}.$$

The LS estimate is therefore

$$\begin{aligned}\hat{\beta} &= \left( \sum_{t=1}^T x_t x_t' \right)^{-1} \sum_{t=1}^T x_t y_t \\ &= \begin{bmatrix} 1/3 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} 0 \\ 3.6 \end{bmatrix} \\ &= \begin{bmatrix} 0 \\ 1.8 \end{bmatrix}.\end{aligned}$$

### The Frisch-Waugh-Lovell theorem\*

Split up  $x_t$  into the vectors  $x_{1t}$  and  $x_{2t}$  and write (2.8) as

$$y_t = x_{1t}' \beta_1 + x_{2t}' \beta_2 + u_t. \quad (2.12)$$

First, regress  $y_t$  on  $x_{1t}$  and get the residuals  $\tilde{e}_{yt}$ . Second, regress  $x_{2t}$  on  $x_{1t}$  and get the residuals  $\tilde{e}_{2t}$ . (If  $x_{2t}$  is a vector, then this is one regression per element in  $x_{2t}$  and  $\tilde{e}_{2t}$  is the corresponding vector of residuals.) Third, regress  $\tilde{e}_{yt}$  on  $\tilde{e}_{2t}$ . This gives the same estimates as  $\beta_2$  from the multiple regression of  $y_t$  on both  $x_{1t}$  and  $x_{2t}$ . (The proof is a straightforward reshuffling of the first order conditions, see, for instance, Greene (2018) 3.)

	HiTec	Utils
SMB residual	0.20 (4.02)	-0.21 (-4.05)
HML residual	-0.50 (-10.56)	0.30 (5.33)
$R^2$	0.27	0.12
obs	636	636

Table 2.3: 3rd step in Frisch-Waugh regressions, monthly returns, %, US data 1970:01-2022:12. 1st step: regress the sector returns on (c,market return) and extract the residuals. 2nd step: regress SMB and HML returns on (c,market return) and extract the residuals. 3rd step: regress step 1 residuals on step 2 residuals. Numbers in parentheses are t-stats.

**Empirical Example 2.17** (*Factor model regression*) Table 2.3. Shows the results from the third step for the same data as used in Table 2.2. Both the point estimates and the standard errors should be the same.

The perhaps most common application of this is when  $x_{1t}$  contains various dummy variables (for instance, for different cross-sectional units) and  $x_{2t}$  are the variables of key interest. It can then be convenient to apply this 3-step approach. This is used in the fixed effects estimator for panel data.

### 2.1.3 Least Squares: Goodness of Fit

The quality of a regression model is often measured in terms of its ability to explain the movements of the dependent variable.

Let  $\hat{y}_t$  be the fitted (predicted) value of  $y_t$ . For instance, with (2.1) it would be  $\hat{y}_t = \hat{\beta}_0 + \hat{\beta}_1 x_t$ . If a constant is included in the regression (or the means of  $y$  and  $x$  are zero), then a check of the *goodness of fit* of the model is given by the fraction of the variation in  $y_t$  that is explained by the model

$$R^2 = \frac{\widehat{\text{Var}}(\hat{y}_t)}{\widehat{\text{Var}}(y_t)} = 1 - \frac{\widehat{\text{Var}}(\hat{u}_t)}{\widehat{\text{Var}}(y_t)}, \quad (2.13)$$

where  $\widehat{\text{Var}}()$  denotes a sample variance.

This can also be rewritten as the squared (sample) correlation of the actual and fitted values

$$R^2 = \widehat{\text{Corr}}(y_t, \hat{y}_t)^2. \quad (2.14)$$

Notice that we must have constant in regression (unless both  $y_t$  and  $x_t$  have zero means) for  $R^2$  to make sense.

A low variance of the residuals will be important for getting low standard errors of the estimates ( $\hat{\beta}_0, \hat{\beta}_1, \dots$ ), since signal only little “noise” in the model. (The details are discussed in later sections.) Equation (2.13) shows that the variance of the residuals and  $R^2$  are negatively related, so it follows that a high  $R^2$  will be associated with low standard errors of the estimates.

**Example 2.18** ( $R^2$ ) From Example 2.7 we have  $\widehat{\text{Var}}(\hat{u}_t) = 0.18$  and  $\widehat{\text{Var}}(y_t) = 2.34$ , so

$$R^2 = 1 - 0.18/2.34 \approx 0.92.$$

See Figure 2.4.

**Proof.** (of (2.13)–(2.14)) Write the regression equation as

$$y_t = \hat{y}_t + \hat{u}_t,$$

where hats denote fitted values. Since  $\hat{y}_t$  and  $\hat{u}_t$  are uncorrelated (always true in OLS—provided the regression includes a constant), we have

$$\text{Var}(y_t) = \text{Var}(\hat{y}_t) + \text{Var}(\hat{u}_t),$$

where  $\text{Var}()$  here should be understood as a sample variance.  $R^2$  is defined as the fraction of  $\text{Var}(y_t)$  that is explained by the model

$$R^2 = \frac{\text{Var}(\hat{y}_t)}{\text{Var}(y_t)} = \frac{\text{Var}(y_t) - \text{Var}(\hat{u}_t)}{\text{Var}(y_t)} = 1 - \frac{\text{Var}(\hat{u}_t)}{\text{Var}(y_t)}.$$

Equivalently, we can rewrite  $R^2$  by noting that

$$\text{Cov}(y_t, \hat{y}_t) = \text{Cov}(\hat{y}_t + \hat{u}_t, \hat{y}_t) = \text{Var}(\hat{y}_t).$$

Use this in the numerator of  $R^2$  and multiply by  $\text{Cov}(y_t, \hat{y}_t) / \text{Var}(\hat{y}_t) = 1$

$$R^2 = \frac{\text{Cov}(y_t, \hat{y}_t)^2}{\text{Var}(y_t) \text{Var}(\hat{y}_t)} = \text{Corr}(y_t, \hat{y}_t)^2.$$

■

To understand this result, suppose that  $x_t$  has no explanatory power, so  $R^2$  should be zero. How does that happen? Well, if  $x_t$  is uncorrelated with  $y_t$ , then  $\hat{\beta}_1 = 0$ . As a consequence  $\hat{y}_t = \hat{\beta}_0$ , which is a constant. This means that  $R^2$  in (2.13) is zero, since the fitted residual has the same variance as the dependent variable ( $\hat{y}_t$  captures nothing of the movements in  $y_t$ ). Similarly,  $R^2$  in (2.14) is also zero, since a constant is always uncorrelated with anything else (as correlations measure comovements around the means).

**Remark 2.19** ( $R^2$  from simple regression\*) Suppose  $\hat{y}_t = \beta_0 + \beta_1 x_t$ , so (2.14) becomes

$$R^2 = \widehat{\text{Corr}}(y_t, x_t)^2.$$

The  $R^2$  can never decrease as we add more regressors, which might make it attractive to add more and more regressors. To avoid that, some researchers advocate using an ad hoc punishment for many regressors,  $\bar{R}^2 = 1 - (1 - R^2)(T - 1)/(T - k)$ , where  $k$  is the number of regressors (including the constant). This measure can be negative.

**Empirical Example 2.20** (CAPM regressions) See Table 2.1 for CAPM regressions for two industry portfolios where the  $R^2$  values clearly differ. This is seen also from the dispersion around the regression line in Figure 2.5.

## 2.2 Missing Data

It is often the case that some data is missing. For instance, we may not have data on regressor 3 for observation  $t = 7$ . If data is *missing in a random way*, then we can simply exclude  $(y_t, x_t)$  for the  $t$  with some missing data. In contrast, if data is missing in a non-random way (for instance, depending on the value of  $y_{it}$ ), then we have to apply more sophisticated sample-selection models (not discussed in this chapter).

**Remark 2.21** (*Replacing missing values with 0\**) *Instead of excluding  $(y_t, x_t)$  for the  $t$  with some missing data, we could set  $(y_t, x_t) = (0, \mathbf{0}_k)$ . This would not change the estimates. However, we must then be careful with how to estimate the variance of the residuals ( $\sigma^2$ ): the estimation should divide by the effective number of observations (non-zero  $y_t$  values).*

## 2.3 The Distribution of $\hat{\beta}$

Note that the estimated coefficients are random variables since they depend on which particular sample that has been “drawn.” For instance, if our sample gives  $\hat{\beta}_1 = 0.85$  and we know that the standard deviation across samples is 0.1 then we are pretty sure that the true value  $\beta_1$  is not 0. In contrast, if the standard deviation across samples is 2.1, then our result is not such an unlikely outcome even if the true value  $\beta_1$  is 0.

It is important to remember that we always assume that there are some true (but unknown) parameter values that would be the same across samples. The only reason why the estimates differ across samples is that the model is not perfect: there are residuals and they differ (randomly) across observations and thus also across different samples. See Figure 2.6 for an illustration from a computer simulation (Monte Carlo simulation).

We usually do not have several samples, so the variation across samples is not directly observable. However, we can (under some assumptions) use the *variation within our sample to figure out how the variation across samples ought to be*. This can help us testing hypotheses about the coefficients, for instance, that  $\beta_1 = 0$ .

To see where the uncertainty comes from, consider the simple case of only one regres-

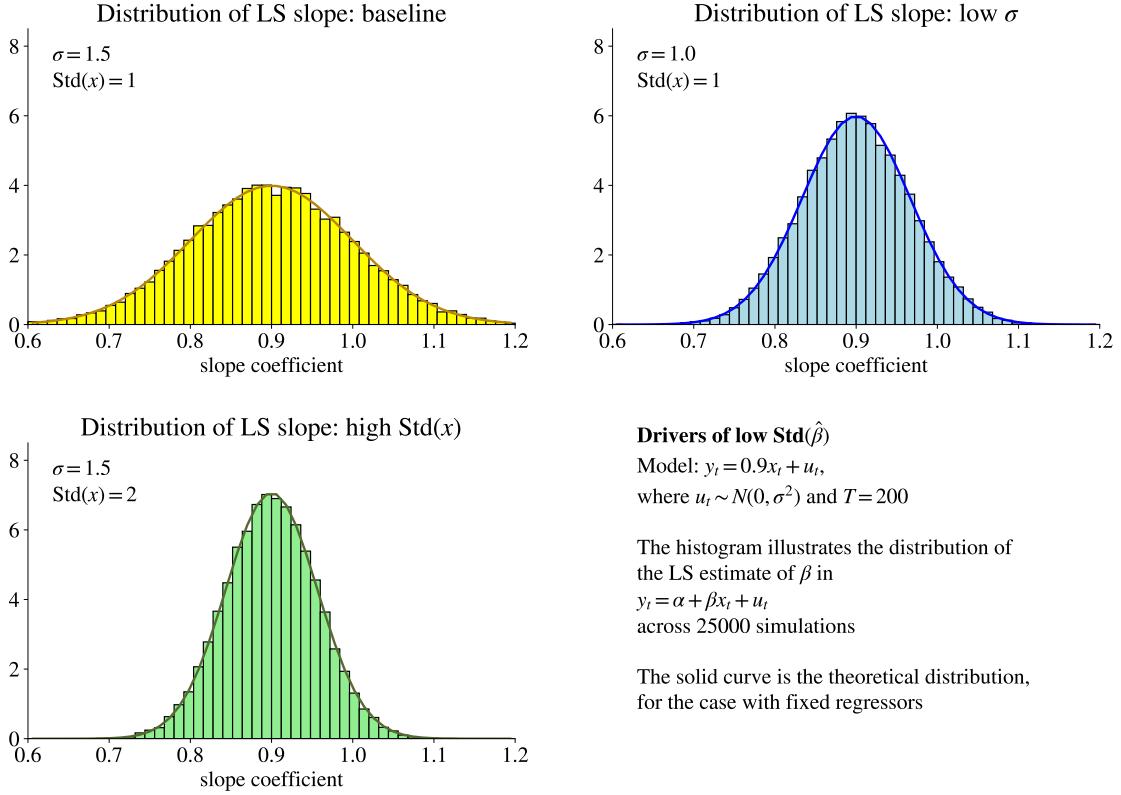


Figure 2.6: Distribution of OLS estimate, from simulation and theory

sor and a zero constant in (2.7). Use (2.1) to substitute for  $y_t$  (recall  $\beta_0 = 0$ )

$$\begin{aligned}\hat{\beta}_1 &= \frac{1}{\sum_{t=1}^T x_t x_t} \sum_{t=1}^T x_t (\beta_1 x_t + u_t) \\ &= \beta_1 + \frac{1}{\sum_{t=1}^T x_t x_t} \sum_{t=1}^T x_t u_t,\end{aligned}\tag{2.15}$$

so the OLS estimate,  $\hat{\beta}_1$ , equals the true value,  $\beta_1$ , plus the sample covariance of  $x_t$  and  $u_t$  divided by the sample variance of  $x_t$ . Since  $u_t$  is a random variable,  $\hat{\beta}_1$  is too. Clearly, we do not know the true value  $\beta_1$ , so this decomposition is just conceptual.

When there are several regressors ( $x_t$  is a vector with  $k$  elements), then (2.15) becomes an expression for the vector

$$\hat{\beta} = \beta + \left( \sum_{t=1}^T x_t x_t' \right)^{-1} \sum_{t=1}^T x_t u_t,\tag{2.16}$$

where  $\Sigma x_t x_t'$  is a  $k \times k$  matrix and  $\Sigma x_t u_t$  is a  $k \times 1$  vector.

One of the basic assumptions in (2.1) is that the covariance of the regressor and the residual is zero. This should hold in a very large sample (or else OLS cannot be used to estimate  $\beta_1$ ), but in a small sample it may be different from zero. Only as the sample gets very large can we be (almost) sure that the second term in (2.15) vanishes.

Equation (2.15) will give different values of  $\hat{\beta}$  when we use different samples, that is different draws of the random variable  $y_t$  (and thus  $u_t$ ), and perhaps also different values of  $x_t$  (if the regressors are also random). Since the true value,  $\beta$ , is a fixed constant, the distribution of these estimates across samples would describe the uncertainty we should have about the true value after having obtained a specific estimated value. However, we cannot observe this distribution directly (we do not have a lot of different samples). However, we can use the idea of this distribution to discuss the general properties of OLS—and we can (with some added assumptions) provide a good estimate of how that distribution could look like.

The first conclusion from (2.15) is that, with  $u_t = 0$  the estimate would always be perfect. In contrast, with large movements in  $u_t$  we will see large movements in  $\hat{\beta}$  (across samples). The second conclusion is that a small sample (small  $T$ ) will also lead to large random movements in  $\hat{\beta}_1$ —in contrast to a large sample where the randomness in  $\sum_{t=1}^T x_t u_t / T$  is averaged out more effectively (should be zero in a large sample).

There are three main routes to learn more about the distribution of  $\hat{\beta}$ : (i) set up a small “experiment” in the computer and simulate the distribution (Monte Carlo or bootstrap simulations); (ii) pretend that the regressors can be treated as fixed numbers (or treat all results as being conditional on the particular sample of regressor values that we have observed) and then assume something about the distribution of the residuals; or (iii) use the asymptotic (large sample) distribution as an approximation. The asymptotic distribution can often be derived, in contrast to the exact distribution in a sample of a given size. If the actual sample is large, then the asymptotic distribution may be a good approximation.

The simulation approach has the advantage of giving a precise answer—but the disadvantage of requiring a very precise question (must write computer code that is tailor made for the particular model we are looking at, including the specific parameter values). See Figures 2.6, 2.9 and 2.7 for examples.

In contrast, asymptotic theory give more general results—but arriving there is hard. Treating the regressors as fixed is easier—and is often good enough for illustrating the main properties of the estimation method.

The typical outcome of all three approaches will (under strong assumptions, to be

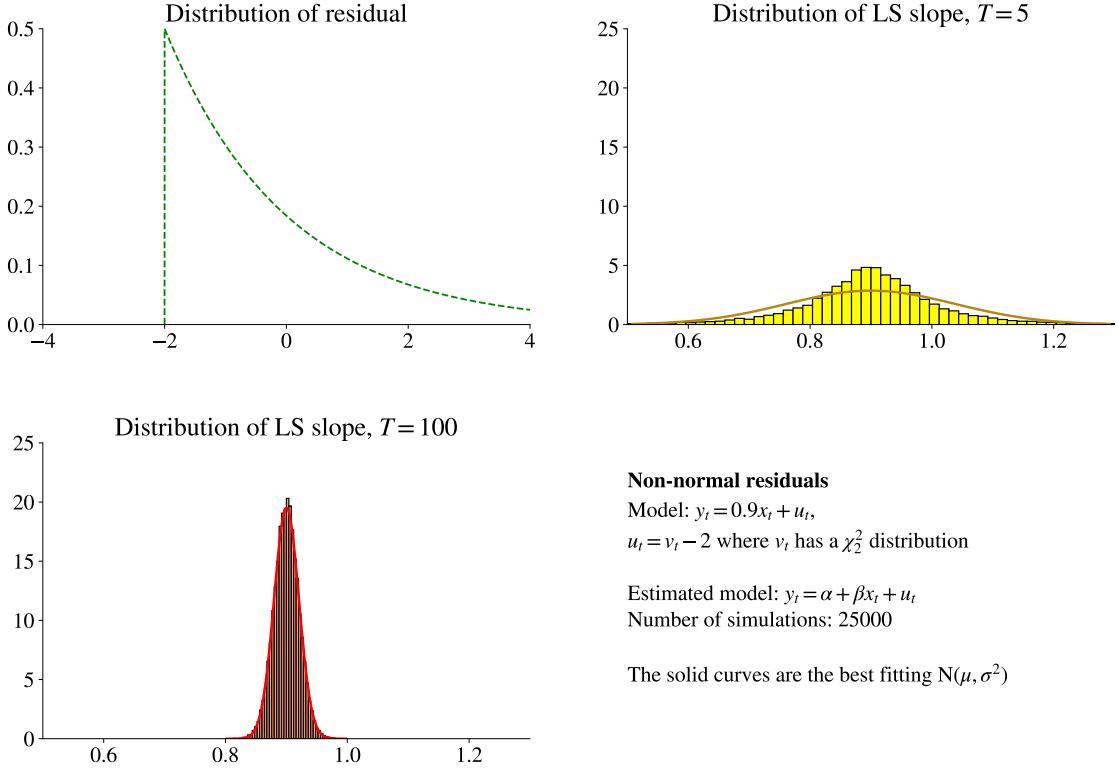


Figure 2.7: Distribution of OLS estimate, from simulations

discussed below) be that

$$\hat{\beta} \sim N \left[ \beta, \left( \sum_{t=1}^T x_t x_t' \right)^{-1} \sigma^2 \right], \quad (2.17)$$

where  $\sigma^2 = \text{Var}(u_t)$  denotes the variance of the residuals. This expression allows for  $x_t$  to be a vector with  $k$  elements. Clearly, with  $k = 1$ ,  $x_t$  is a scalar (and  $x_t' = x_t$ ). In practice, we calculate/estimate both  $\sum_{t=1}^T x_t x_t'$  and  $\sigma^2$  from the available data (the latter as the variance of the fitted residuals). See Table 2.1 for an empirical example and Figure 2.6 for an illustration of how the results depend on  $\sigma$  and the standard deviation of  $x_t$ .

**Remark 2.22** (*On notation,  $\text{Var}(\hat{\beta})$  and  $\text{Std}(\hat{\beta})$* ) These notes use  $\text{Var}(\hat{\beta})$  to denote the variance-covariance matrix of the vector of estimated coefficients, for instance, the last term in (2.17). With  $k$  regressors, this matrix is  $k \times k$ . In addition,  $\text{Std}(\hat{\beta})$  is used to denote the vector ( $k$  elements) of standard errors. Clearly, those standard errors are the square roots of the diagonal elements of the  $\text{Var}(\hat{\beta})$  matrix.

**Remark 2.23** (*Matrix notation\**) Let  $X$  be a  $T \times k$  matrix where row  $t$  is filled with

the elements of  $x_t$ . Then, the variance-covariance matrix in (2.17) can also be written  $(X'X)^{-1}\sigma^2$ .

**Example 2.24** (Applying (2.17)) When the regressor is just a constant (equal to one)  $x_t = 1$ , then we have

$$\sum_{t=1}^T x_t x'_t = \sum_{t=1}^T 1 \times 1' = T \text{ so } \text{Var}(\hat{\beta}) = \sigma^2 / T.$$

(This is the classical expression for the variance of a sample mean.)

**Example 2.25** (Applying (2.17)) When the regressor is a zero mean variable, then we have

$$\sum_{t=1}^T x_t x'_t = \widehat{\text{Var}}(x_t)T \text{ so } \text{Var}(\hat{\beta}) = \sigma^2 / [\widehat{\text{Var}}(x_t)T],$$

where  $\widehat{\text{Var}}(x_t)$  is the sample variance. Clearly,  $\text{Var}(\hat{\beta})$  is increasing in  $\sigma^2$ , but decreasing in both  $T$  and  $\widehat{\text{Var}}(x_t)$ .

**Example 2.26** (\*Applying (2.17)) When the regressor is just a constant (equal to one) and one variable regressor with zero mean,  $f_t$ , so  $x_t = [1, f_t]$ , then we have

$$\begin{aligned} \sum_{t=1}^T x_t x'_t &= \sum_{t=1}^T \begin{bmatrix} 1 & f_t \\ f_t & f_t^2 \end{bmatrix} = T \begin{bmatrix} 1 & 0 \\ 0 & \text{Var}(f_t) \end{bmatrix}, \text{ so} \\ \text{Var} \left( \begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{bmatrix} \right) &= \sigma^2 \left( \sum_{t=1}^T x_t x'_t \right)^{-1} = \begin{bmatrix} \sigma^2 / T & 0 \\ 0 & \sigma^2 / [\widehat{\text{Var}}(f_t)T] \end{bmatrix}, \end{aligned}$$

where  $\widehat{\text{Var}}(f_t)$  is the sample variance. This is combination of the two previous examples. As before,  $\text{Var}(f_t)$  could be interpreted as a sample variance.

**Example 2.27** (Distribution of slope coefficient) From Example 2.7 we have  $\text{Var}(\hat{u}_t) = \sigma^2 = 0.18$  and  $\sum_{t=1}^T x_t x_t = 2$ , so  $\text{Var}(\hat{\beta}_1) = 0.18/2 = 0.09$ , which gives  $\text{Std}(\hat{\beta}_1) = 0.3$ .

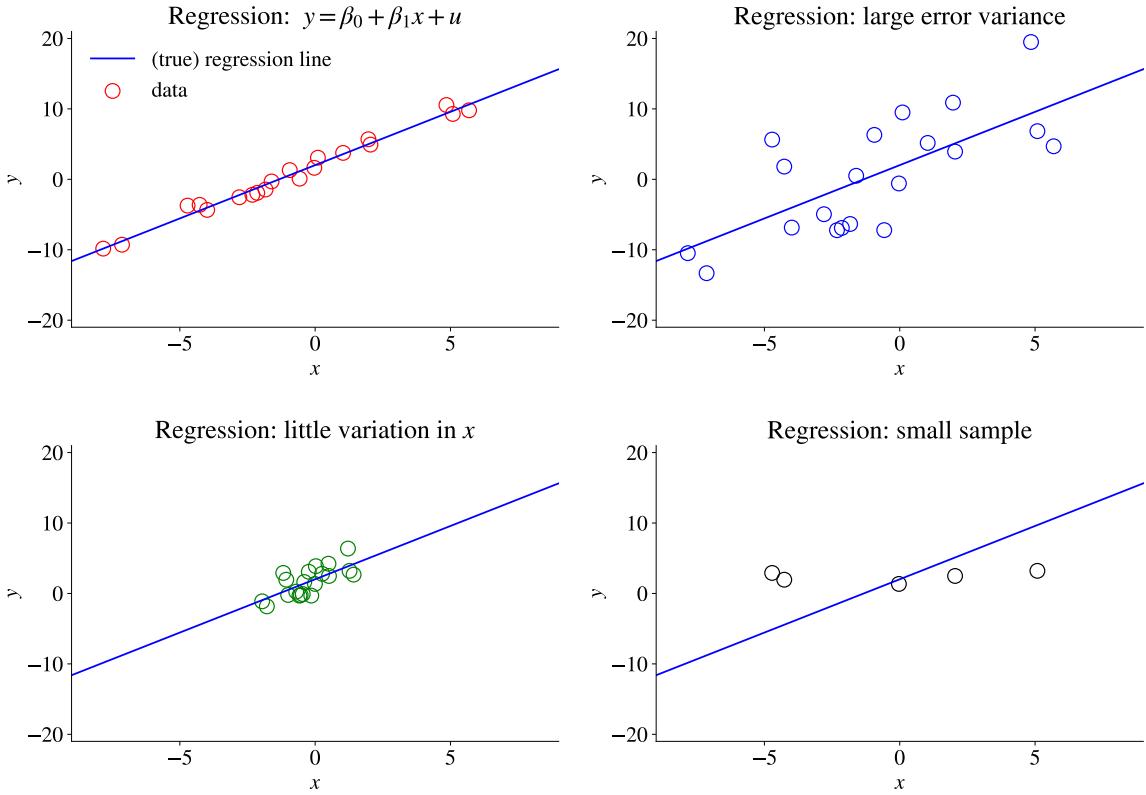


Figure 2.8: Regressions: importance of error variance and variation of regressor

**Example 2.28** (*Covariance matrix of  $\hat{\beta}_1$  and  $\hat{\beta}_2$* ) From Example 2.16

$$\begin{aligned} \sum_{t=1}^T x_t x_t' &= \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix} \text{ and } \sigma^2 = 0.18, \text{ then} \\ \text{Var}\left(\begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{bmatrix}\right) &= \begin{bmatrix} \text{Var}(\hat{\beta}_1) & \text{Cov}(\hat{\beta}_1, \hat{\beta}_2) \\ \text{Cov}(\hat{\beta}_1, \hat{\beta}_2) & \text{Var}(\hat{\beta}_2) \end{bmatrix} \\ &= \begin{bmatrix} 1/3 & 0 \\ 0 & 1/2 \end{bmatrix} 0.18 = \begin{bmatrix} 0.06 & 0 \\ 0 & 0.09 \end{bmatrix}. \end{aligned}$$

The standard deviations (also called standard errors) are therefore

$$\begin{bmatrix} \text{Std}(\hat{\beta}_1) \\ \text{Std}(\hat{\beta}_2) \end{bmatrix} = \begin{bmatrix} 0.24 \\ 0.3 \end{bmatrix}.$$

### 2.3.1 The Distribution of $\hat{\beta}$ with Fixed Regressors

Assuming fixed regressors is mostly a simplifying (teaching) device, since econometrics is typically not applied to controlled experiments. However, it is easy to derive results for this case—and those results are often similar to what asymptotic theory gives.

A version of the “fixed regressors” assumption is to treat all results as *conditional* on the regressor values that we have in the sample. This does not rule out the possibility that samples of  $x_t$  differ, but we only bother with those that look like the one we have. This is effectively treating  $x_t$  as fixed.

The results we derive below are based on the *Gauss-Markov assumptions* : (a) the residuals have zero means, (b) have constant variances and (c) are not correlated across observations. In other words, the *residuals are zero mean iid variables*. We will also assume that the residuals are normally distributed (not part of the typical Gauss-Markov assumptions).

For notational convenience, write (2.16) as

$$\hat{\beta} = \beta + S_{xx}^{-1} (x_1 u_1 + x_2 u_2 + \dots + x_T u_T), \text{ where } S_{xx} = \sum_{t=1}^T x_t x_t' \quad (2.18)$$

Since  $x_t$  is assumed to be fixed, the expected value of this expression is

$$E \hat{\beta} = \beta + S_{xx}^{-1} (x_1 E u_1 + x_2 E u_2 + \dots + x_T E u_T) = \beta \quad (2.19)$$

since we always assume that the residuals have zero means (see (2.1)). This says that OLS is unbiased when the regressors are fixed (which does not always carry over to the case of stochastic regressors). The interpretation is that we can expect OLS to give (on average) a correct answer. That is, if we could draw many different samples and estimate the slope coefficient in each of them, then the average of those estimates would be the correct number ( $\beta$ ). Clearly, this is something we want from an estimation method (a method that was systematically wrong would not be very attractive).

**Remark 2.29** (*Linear combination of normally distributed variables.*) *If the random variables  $z_t$  and  $v_t$  are normally distributed and independent of each other, then  $a + bz_t + cv_t$  is normally distributed with a mean of  $a + b\mu_z + c\mu_v$  and a variance of  $b^2\sigma_z^2 + c^2\sigma_v^2$ .*

Suppose  $u_t \sim N(0, \sigma^2)$  and that the residuals are independent of each other, then (2.18) shows that  $\hat{\beta}$  is normally distributed. The reason is that  $\hat{\beta}$  is just a constant ( $\beta$ ) plus a linear combination of independent normally distributed residuals (with fixed regressors

$x_t$  and thus  $S_{xx}^{-1}$  can be treated as constants). It is clear that the mean of this normal distribution is  $\beta$  (the true value), since  $\hat{\beta}$  is unbiased.

Finding the variance-covariance matrix of  $\hat{\beta}$  is slightly more complicated. Remember that we treat  $x_t$  as fixed numbers (non-random) and assume that the residuals are iid: they are uncorrelated with each other (follows from independently distributed) and have the same variances (follows from identically distributed). We also notice that the variance-covariance matrix of  $x_t u_t$  equals

$$\text{Var}(x_t u_t) = x_t x_t' \sigma_t^2. \quad (2.20)$$

where  $\sigma_t^2 = \text{Var}(u_t)$  and where we use the fact that the vector  $x_t$  is non-random.

**Example 2.30** (of (2.20)) With

$$x_t = \begin{bmatrix} 1 \\ 2 \end{bmatrix} \text{ and } \sigma_t^2 = 0.18, \text{ we get}$$

$$\text{Var}(x_t u_t) = \begin{bmatrix} 1 \\ 2 \end{bmatrix} \begin{bmatrix} 1 & 2 \end{bmatrix} \times 0.18 = \begin{bmatrix} 1 & 2 \\ 2 & 4 \end{bmatrix} \times 0.18.$$

The variance of (2.18) can then be written

$$\begin{aligned} \text{Var}(\hat{\beta}) &= S_{xx}^{-1} \text{Var}(x_1 u_1 + x_2 u_2 + \dots + x_T u_T) S_{xx}^{-1} \\ &= S_{xx}^{-1} (x_1 x_1' \sigma_1^2 + x_2 x_2' \sigma_2^2 + \dots + x_T x_T' \sigma_T^2) S_{xx}^{-1} \\ &= S_{xx}^{-1} (x_1 x_1' \sigma^2 + x_2 x_2' \sigma^2 + \dots + x_T x_T' \sigma^2) S_{xx}^{-1} \\ &= S_{xx}^{-1} \left( \sum_{t=1}^T x_t x_t' \right) \sigma^2 S_{xx}^{-1} \\ &= S_{xx}^{-1} \sigma^2. \end{aligned} \quad (2.21)$$

The first line follows directly from (2.18), since  $\beta$  is a constant. The second line follows from assuming that the residuals are uncorrelated with each other ( $\text{Cov}(u_i, u_j) = 0$  if  $i \neq j$ ), so all cross terms ( $x_i x_j \text{Cov}(u_i, u_j)$ ) are zero. The third line follows from assuming that the variances are the same across observations ( $\sigma_i^2 = \sigma_j^2 = \sigma^2$ ). The fourth and fifth lines are just algebraic simplifications which use the definition of  $S_{xx}$ .

There are three main ways of getting a low uncertainty (low  $\text{Var}(\hat{\beta})$ ). For simplicity, focus on the case with just one regressor. We then have the following results. First, a large sample ( $T$  is large), decreases the  $S_{xx}^{-1}$  factor (since  $S_{xx} = \sum_{t=1}^T x_t x_t'$  increases with  $T$ ) while  $\sigma^2$  stays constant: a larger sample gives a smaller uncertainty about the estimate.

Second, large movements in the regressors (large value of  $S_{xx} = \sum_{t=1}^T x_t x'_t$ ) should help us estimate the link between  $x$  and  $y$  since the movements in  $y$  driven by  $x$  should then dominate over the movements in  $y$  driven by the residual. Third, a lower volatility of the residuals (lower  $\sigma^2$ ) also gives a lower uncertainty about the estimate. See Figures 2.6 and 2.8.

**Remark 2.31** (\*Notation for conditional on  $X$ ) Some texts emphasize the “conditional on  $X$ ” interpretation instead of the fixed regressor interpretation. The notation is then often  $E(\hat{\beta}|X)$  and  $\text{Var}(\hat{\beta}|X)$  where the “ $|X$ ” denotes that the expectation/variance is conditional on the sample of  $x_1, \dots, x_T$  at hand.

A key assumption in regression analysis is that our sample is “representative” of the population. In practice, this means that *we can estimate  $\sigma^2$  in (2.21) from the data in the sample*. This is the main “trick” behind using our (one and only) sample to inform us about how the distribution of  $\hat{\beta}$  (across samples) looks like. This is a plausible assumption when our sample is a random draw from the population (say, 700 out of a total of 10,000 firms). It is perhaps a stronger assumption when the sample is a time series of data points. Then we basically assume that the past (before the sample) and the future (after the sample) will have the same structure. In case you are not willing to accept those assumptions, the  $t$ -stats are useless for you.

### 2.3.2 Multicollinearity

When the regressors in a multiple regression are highly correlated, then we have a practical problem: the standard errors of individual coefficients tend to be large, even if the  $R^2$  suggests that the regression does fairly well.

As a simple example, consider the regression

$$y_t = \beta_1 x_{1t} + \beta_2 x_{2t} + u_t, \quad (2.22)$$

where (for simplicity) the dependent variable and the regressors have zero means. In this case, the variance (assuming iid errors) is

$$\text{Var}(\hat{\beta}_2) = \frac{\sigma^2}{T \widehat{\text{Var}}(x_{2t})} \frac{1}{1 - \gamma^2}, \quad (2.23)$$

where  $\gamma$  is the sample correlation of  $x_{1t}$  and  $x_{2t}$ . If the regressors are highly correlated, then the uncertainty about the slope coefficient is high. The basic reason is that we see

that the regressors have an effect on  $y_t$ , but it is hard to tell if that effect is from regressor one or two (since they are so similar). This can well lead to a situation where the  $R^2$  is high and a joint test easily rejects the null hypothesis that all slopes are zero—but each individual slope coefficient is insignificant.

**Remark 2.32** ( $\text{Cov}(\hat{\beta}_1, \hat{\beta}_2)$ ) *To simplify the notation, let the sample variance of  $x_{1t}$  and  $x_{2t}$  be equal to one. It can then be shown (see proof below) that*

$$\text{Cov}(\hat{\beta}_1, \hat{\beta}_2) = -\frac{\sigma^2}{T} \frac{\gamma}{1 - \gamma^2}.$$

*This says that when the regressors are positively correlated ( $\gamma > 0$ ), then the coefficients tend to be negatively correlated (notice the leading minus sign).*

More generally, in the multiple regression

$$y_t = x_t' \beta + u_t, \quad (2.24)$$

it is straightforward to show that for all slope coefficients (not the intercept)

$$\text{Var}(\hat{\beta}_i) = \frac{\sigma^2}{T \widehat{\text{Var}}(x_{it})} \frac{1}{1 - R_i^2}, \quad (2.25)$$

where  $R_i^2$  is the  $R^2$  value obtained from regressing  $x_{it}$  on the *other* regressors (including a constant). The last term ( $1/(1 - R_i^2)$ ) is often called the *variance inflation factor* and some regression packages report the maximum across the regressors, and a value of 10 or larger ( $R_i^2 \geq 0.9$ ) is considered highly problematic. (The name variance inflation factor is meant to indicate how much the variance increases compared to a simple regression, assuming  $\sigma^2$  is unchanged. In practice, the estimated  $\sigma^2$  often change considerably.)

**Proof.** (of (2.23) and Remark 2.32\*). Recall that for a  $2 \times 2$  matrix we have

$$\begin{bmatrix} a & b \\ c & d \end{bmatrix}^{-1} = \frac{1}{ad - bc} \begin{bmatrix} d & -b \\ -c & a \end{bmatrix}.$$

For the regression (2.22) we get

$$\begin{bmatrix} \sum_{t=1}^T x_{1t}^2 & \sum_{t=1}^T x_{1t}x_{2t} \\ \sum_{t=1}^T x_{1t}x_{2t} & \sum_{t=1}^T x_{2t}^2 \end{bmatrix}^{-1} = \frac{1}{\sum_{t=1}^T x_{1t}^2 \sum_{t=1}^T x_{2t}^2 - (\sum_{t=1}^T x_{1t}x_{2t})^2} \begin{bmatrix} \sum_{t=1}^T x_{2t}^2 & -\sum_{t=1}^T x_{1t}x_{2t} \\ -\sum_{t=1}^T x_{1t}x_{2t} & \sum_{t=1}^T x_{1t}^2 \end{bmatrix}.$$

The variance of the second slope coefficient is  $\sigma^2$  time the lower right element of this matrix. Multiply and divide by  $T$  to get

$$\begin{aligned} \text{Var}(\hat{\beta}_2) &= \frac{\sigma^2}{T} \frac{\sum_{t=1}^T x_{1t}^2 / T}{\sum_{t=1}^T \frac{1}{T} x_{1t}^2 \sum_{t=1}^T \frac{1}{T} x_{2t}^2 - \left( \sum_{t=1}^T \frac{1}{T} x_{1t} x_{2t} \right)^2} \\ &= \frac{\sigma^2}{T} \frac{\text{Var}(x_{1t})}{\text{Var}(x_{1t}) \text{Var}(x_{2t}) - \text{Cov}(x_{1t}, x_{2t})^2}, \end{aligned}$$

where  $\text{Var}()$  and  $\text{Cov}()$  here are short hand notation for sample variances and covariances. Divide both numerator and denominator by  $\text{Var}(x_{1t}) \text{Var}(x_{2t})$  to get

$$\text{Var}(\hat{\beta}_2) = \frac{\sigma^2}{T} \frac{1 / \text{Var}(x_{2t})}{1 - \frac{\text{Cov}(x_{1t}, x_{2t})^2}{\text{Var}(x_{1t}) \text{Var}(x_{2t})}},$$

which is the same as (2.23). Similarly, we get

$$\text{Cov}(\hat{\beta}_1, \hat{\beta}_2) = -\frac{\sigma^2}{T} \frac{\text{Cov}(x_{1t}, x_{2t})}{\text{Var}(x_{1t}) \text{Var}(x_{2t}) - \text{Cov}(x_{1t}, x_{2t})^2},$$

which gives the result in Remark 2.32. ■

## 2.4 The Distribution of $\hat{\beta}$ : More General Results

### 2.4.1 Problems with the Gauss-Markov (iid) and Normality Assumptions

The previous results on the distribution of  $\hat{\beta}$  have several weak points—which will be briefly discussed here.

*First*, the Gauss-Markov assumptions of iid residuals (constant volatility and no correlation across observations) are likely to be false in many cases.

*Second*, the idea of fixed regressor is clearly just a simplifying assumption—and unlikely to be relevant for economics and financial data. If the regressors are random vari-

ables then we typically not rule out that  $u_t$  and  $x_{t+s}$  are correlated, for instance, when the regressors include the lagged dependent variable. This can make OLS biased.

*Third*, there are no particularly strong reasons for why the residuals should be normally distributed. If not, the estimates are unlikely to be normally distributed in small samples, but may well be in large samples (due to the central limit theorem).

The next few sections introduce these issues, but later chapters will discuss them in more detail.

### 2.4.2 Failure of the Gauss-Markov Assumptions

If the residuals are not iid, then we have to stop at the first line of (2.21), so

$$\text{Var}(\hat{\beta}) = S_{xx}^{-1} S S_{xx}^{-1}, \text{ where } S = \text{Var}\left(\sum_{t=1}^T x_t u_t\right). \quad (2.26)$$

The  $S$  matrix is estimated in different ways (for instance, using White's or Newey-West's methods) depending on the properties of the residuals (heteroskedasticity or autocorrelation).

### 2.4.3 Bias

If an estimation method is *biased*, then it produces systematically wrong (say, too low) coefficients. Sometimes, this bias disappears in large samples, so it's only a small sample bias.

Figure 2.9 illustrates some simulation results from estimating an AR(1)

$$y_t = \beta_0 + \beta_1 y_{t-1} + u_t \quad (2.27)$$

on artificial samples where “data” is generated from

$$y_t = 0.9y_{t-1} + u_t, \text{ where } u_t \text{ is iid.} \quad (2.28)$$

In this case, the regressor is a (stochastic) random variable (not fixed). Figure 2.9 suggests that the estimates are biased (not centered on the true value) in small samples, but the bias appears to decrease as the sample size increases.

To understand these results, recall that (2.16) says that

$$\hat{\beta} = \beta + \left(\sum_{t=1}^T x_t x_t'\right)^{-1} \sum_{t=1}^T x_t u_t \quad (2.29)$$

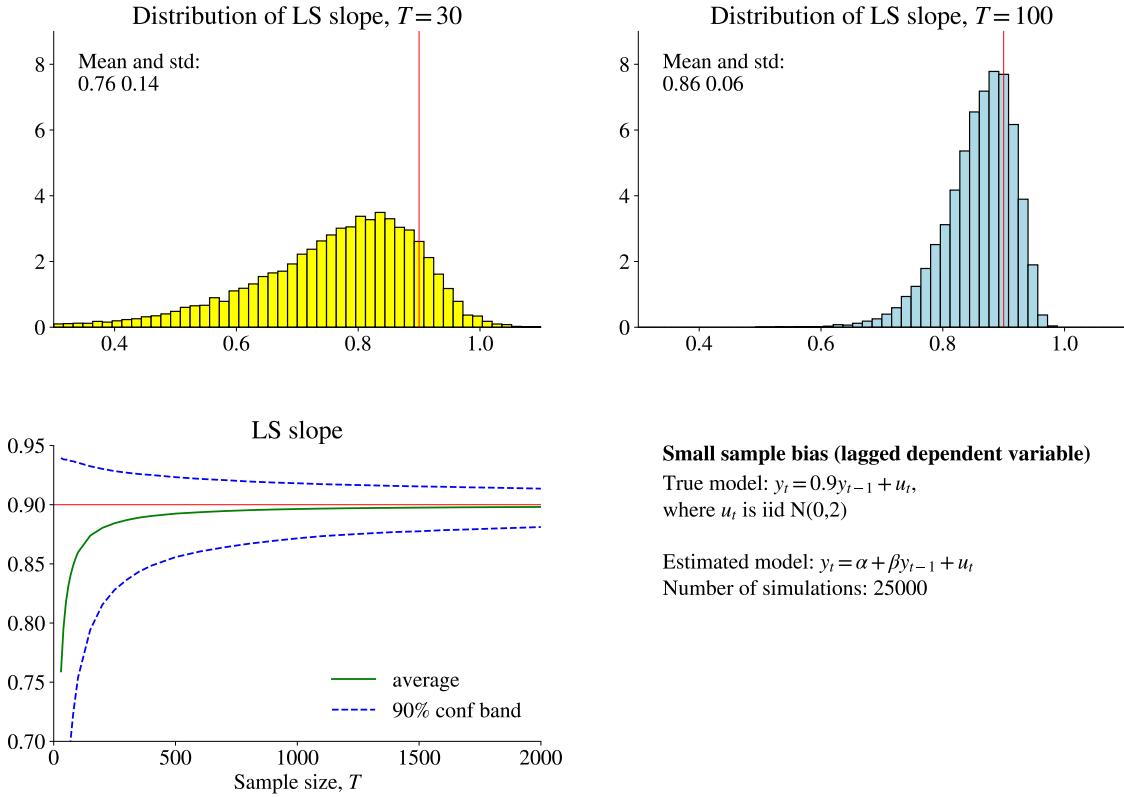


Figure 2.9: Results from a Monte Carlo experiment of LS estimation of the AR coefficient.

where  $u_t$  are the true residuals. (We will never observe the true residuals, so (2.29) can only be used for a conceptual discussion.)

To get *unbiased estimates* ( $E\hat{\beta} = \beta$ ), the second term of the right hand side of (2.29) should have an expectation of zero. This would happen when  $u_t$  and  $x_{t+s}$  (for all  $s$ ) are independent. This is hard to guarantee when the regressors are random variables. For instance, in the AR(1) example, then  $u_t$  affects  $x_{t+1}$  so there is an interaction between the numerator and denominator. This is probably most easily investigated by simulations.

**Remark 2.33** (\*Bias of AR(1)) It can be shown (see, for instance, Pesaran (2015) 14) that a bias corrected estimate of the AR(1) coefficient can be calculated as  $(1 + T\hat{\beta}_1)/(T - 3)$ .

**Remark 2.34** (Unbiasedness with stochastic regressors\*)  $\hat{\beta}_1$  in (2.29) is unbiased if  $x_\tau$  (all  $\tau$  in the sample) does not help predict  $u_t$ . We can use the law of iterated expectations

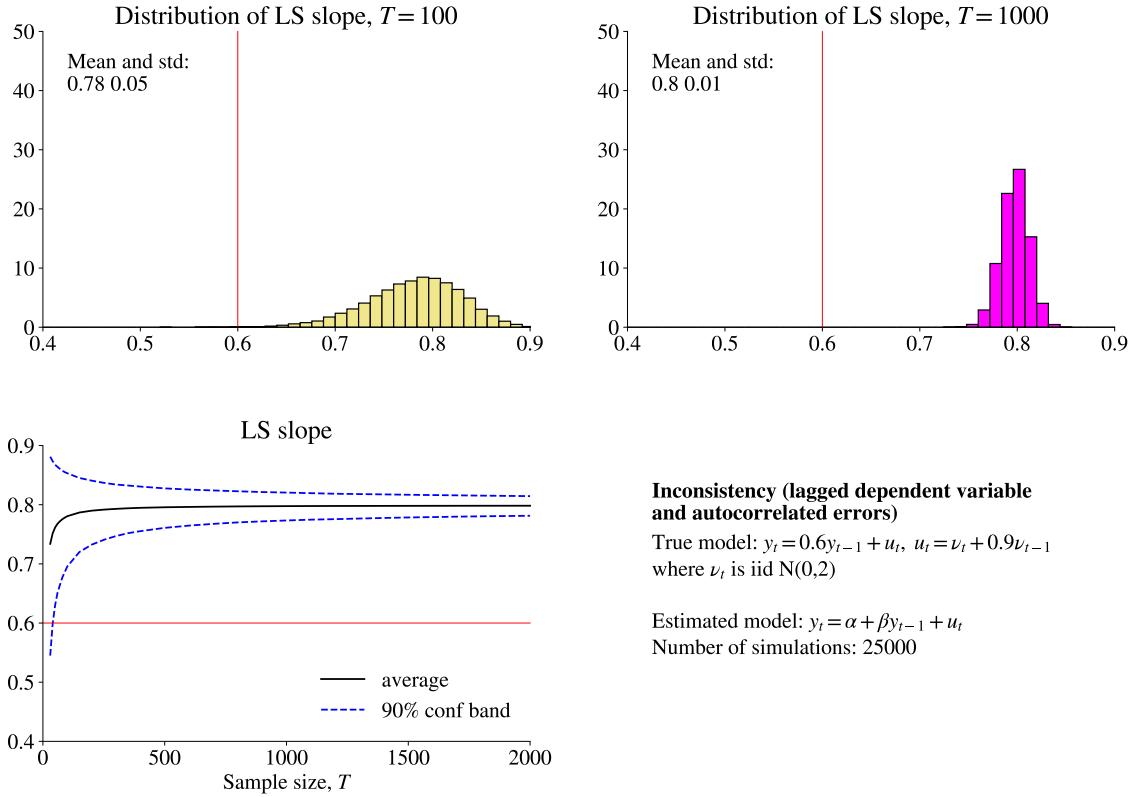


Figure 2.10: Results from a Monte Carlo experiment of LS estimation of the AR coefficient when data is from an ARMA process.

$(E_x(E u|x) = E u)$  to write

$$E \hat{\beta} = \beta + E_x \left( \sum_{t=1}^T x_t x_t' \right)^{-1} \sum_{t=1}^T x_t E(u_t|x),$$

where  $x$  here denotes the full sample of  $x_t$ . If  $E(u_t|x) = 0$  then  $E \hat{\beta} = \beta$ . Clearly, for an AR(1) this does not hold since  $u_t$  affects  $y_t$  which is the regressor in  $t+1$  ( $x_{t+1}$ ).

#### 2.4.4 Consistency

If an estimation method is *inconsistent*, then it produces systematically wrong (say, too low) coefficients also in very large samples (actually, in the limit as  $T \rightarrow \infty$ ).

Figure 2.9 suggests that the problem with the AR(1) estimation vanishes as the sample size increases. This shows the importance of doing simulations (to understand the properties of the estimation method)—and perhaps also of using large data sets.

To get *consistent estimates* (which is defined as the bias and the variance of  $\hat{\beta}_1$  go to

zero as  $T \rightarrow \infty$ ), then it is enough if  $x_t$  and  $u_t$  (in the same period) are uncorrelated. This is indeed the case in the AR(1) simulations discussed before. To see this from (2.29), notice that a “law of large numbers” makes the numerator ( $\sum_{t=1}^T x_t u_t / T$ ) converge to the population covariance of  $u_t$  and  $x_t$ . (Also, the denominator converges to a fixed number, so we can focus on the numerator.)

This means that *if* we knew that  $\text{Cov}(x_t, u_t) = 0$  (in the population), then we would also know that OLS is consistent. However, since the true errors are never observed, this cannot be shown by empirical methods. (Recall OLS always construct fitted errors so they are uncorrelated with the regressors.) Instead, we have to rely on theoretical arguments that make it plausible to *believe or not* in consistency.

To make matters worse, it is often the case that  $\hat{\beta}_1$  converges (as  $T$  increases), but perhaps not to what you hoped for. As an illustration of how tricky this can be, consider the case in Figure 2.10. It estimates the same AR(1) as in (2.27) but where the simulated “data” now follows

$$y_t = \rho y_{t-1} + \varepsilon_t, \text{ where } \varepsilon_t = v_t + \theta v_{t-1} \text{ where } v_t \text{ is iid.} \quad (2.30)$$

In this case, the residuals (here called  $\varepsilon_t$ ) are themselves autocorrelated. The figure clearly shows that the OLS estimate of the slope  $\beta_1$  in (2.27) does *not* converge to the true value  $\rho$  as the sample sizes increases: OLS is inconsistent. The reason in this case is that  $\varepsilon_t$  and  $y_{t-1}$  (the regressor) both depend on  $v_{t-1}$  so they are correlated.

An a priori argument for why OLS should be able to estimate a model consistently thus require a careful discussion of the model properties: how can we explain that the residuals are uncorrelated with the regressors? (Alternatively, we use an instrumental variables technique, which is discussed later on.) This typically involves a discussion of the following.

1. Have we excluded (omitted) some relevant regressors? If so, their effect is captured by the residual. If these excluded regressors are correlated to some of the included regressors, then we have a problem.
2. Do we use a lagged dependent variable as regressor at the same time as the residual is autocorrelated? (This is the previous example.)
3. Does  $y_t$  affect  $x_t$ ? If so a shock to the equation that explains  $y_t$  also drives  $x_t$  and we get a correlation between the regressor ( $x_t$ ) and the residual. A classical case is when we try to estimate how the demand for a product depends on its price.

In fact, such an equation actually estimates a mix between the demand and supply elasticities.

4. Is the regressor measured without (important) errors? If not, we again have a correlation between (the used) regressor and the residual.

#### 2.4.5 Normality

If the regressors  $x_t$  are fixed numbers and  $u_t$  is normally distributed, then the second term in (2.29) shows that the normality carries over to  $\hat{\beta}$  also in small samples. We can test the assumption of normally distributed residuals by using a Bera-Jarque test

$$BJ = \frac{T}{6} \text{skewness}^2 + \frac{T}{24} (\text{kurtosis} - 3)^2, \quad (2.31)$$

which has  $\chi_2^2$  distribution under the null hypothesis that both the skewness and excess kurtosis (that is, kurtosis–3) are zero.

#### 2.4.6 Asymptotic Normality

Even if the normality test fails or if the regressors are stochastic, we can often still hope for a (close to) normal distribution of  $\hat{\beta}_1$  if the sample is large—due to the central limit theorem. This is illustrated in Figure 2.7. It is based on simulations where the residual is drawn from a very non-normal distribution. For a small sample, this carries over to  $\hat{\beta}$  and the  $t$ -stat for the hypothesis that  $\beta_i = 0$ . However, already a moderately sized sample tend to give an almost normal distribution.

To understand the theory of this rewrite (2.29) by subtracting  $\beta$  from both sides and then multiply both sides by  $\sqrt{T}$

$$\sqrt{T}(\hat{\beta} - \beta) = \left( \frac{1}{T} \sum_{t=1}^T x_t x_t' \right)^{-1} \sqrt{T} \frac{1}{T} \sum_{t=1}^T x_t u_t. \quad (2.32)$$

The inverted term is the sample average of  $x_t x_t'$  which will converge to a matrix of fixed numbers (the population mean of  $x_t x_t'$ ) as  $T \rightarrow \infty$ . We can therefore focus on what happens to the numerator. It is  $\sqrt{T}$  times the sample average of  $x_t u_t$  (a vector). Under weak conditions a central limit theorem applies to  $\sqrt{T} \times$  a sample average: it typically converges to a normal distribution.

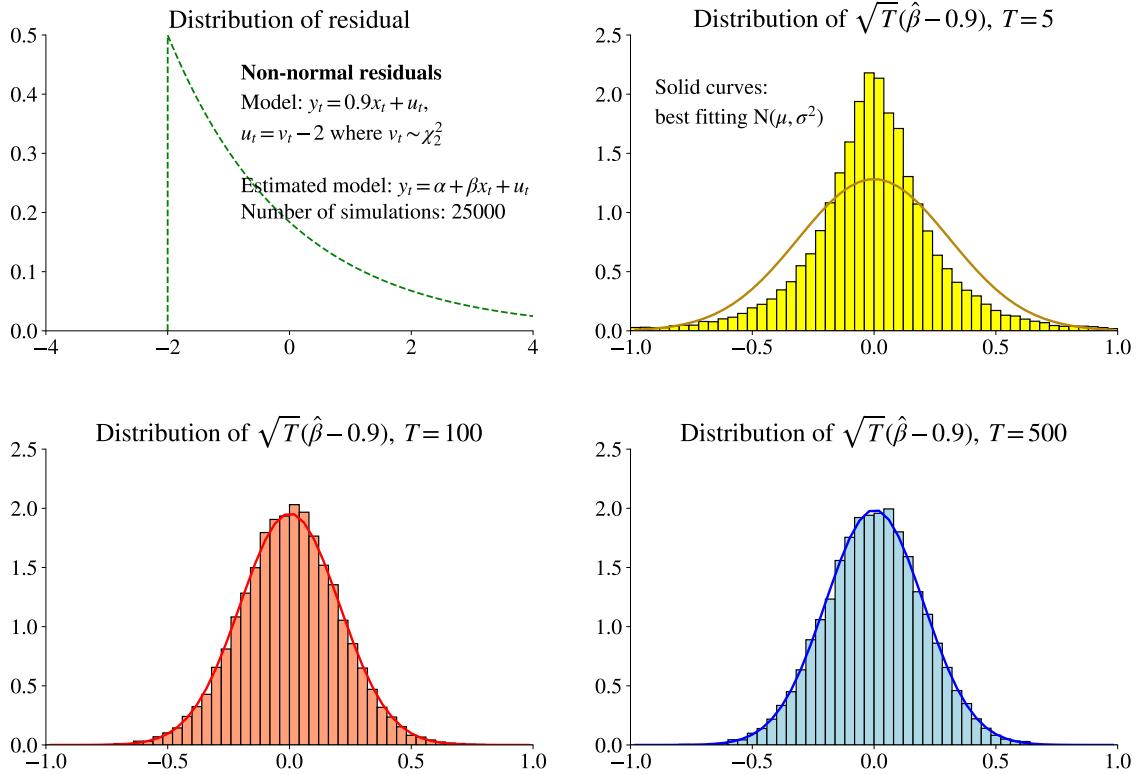


Figure 2.11: Distribution of OLS estimate, from simulations

This shows that  $\sqrt{T}(\hat{\beta} - \beta)$  has an *asymptotic normal distribution*

$$\sqrt{T}(\hat{\beta} - \beta) \xrightarrow{d} N(0, W), \quad (2.33)$$

where  $\xrightarrow{d}$  indicates that the random variable  $\sqrt{T}(\hat{\beta} - \beta)$  converges to a normal distribution as  $T$  increases. This often holds as a reasonable approximation also in moderately sized samples. See Figure 2.11 for an illustration. Actually, it turns out that this is a property of many estimators (not just OLS), basically because most estimators are some kind of sample average.

The variance-covariance matrix  $W$  in (2.33) can be understood from (2.32). It has the form

$$W = \left( \frac{S_{xx}^*}{T} \right)^{-1} \frac{S}{T} \left( \frac{S_{xx}^*}{T} \right)^{-1}, \quad (2.34)$$

where  $S_{xx}^*/T$  is the limit of  $\sum_{t=1}^T x_t x_t' / T$  as  $T \rightarrow \infty$  and  $S/T$  is the variance-covariance matrix of  $\sum_{t=1}^T x_t u_t / \sqrt{T}$ , that is the last term in (2.32).

Except for that this expression involves limits and the  $T$  terms, it is reminiscent of the expression based on the assumption of fixed regressors (2.26). In fact, cancelling  $T$  terms and adding  $\beta$  in (2.33)–(2.34) give

$$\hat{\beta} \xrightarrow{a} N(\beta, S_{xx}^{*-1} S S_{xx}^{*-1}), \quad (2.35)$$

where  $\xrightarrow{a}$  means “is asymptotically distributed as”.

We cannot observe the limit  $S_{xx}^*$ , so in practice we estimate this by using the information from the available sample:  $S_{xx}^*$  is estimated as  $S_{xx} = \sum_{t=1}^T x_t x_t'$  and  $S$  by some other way (depending on the degree of autocorrelation and heteroskedasticity). A more precise statement is thus that  $S_{xx}^{-1} \hat{S} S_{xx}^{-1}$  is an *estimate* of the variance-covariance matrix. In practice, we then have the same estimate of the variance-covariance matrix as in (2.26) which was derived under the assumption of fixed regressors.

**Proof.** (of (2.35)\*) Notice that  $W = \text{Var}(\sqrt{T}\hat{\beta}) = T \text{Var}(\hat{\beta})$ . Therefore, divide both sides of (2.34) by  $T$  to get

$$\text{Var}(\hat{\beta}) = \frac{1}{T} \left( \frac{S_{xx}^*}{T} \right)^{-1} \frac{S}{T} \left( \frac{S_{xx}^*}{T} \right)^{-1}.$$

Cancel the  $T$  terms. Finally, add  $\beta$  to shift the distribution from being centered on 0 to  $\beta$ . This is (2.34). ■

## 2.5 Appendix: A Primer in Matrix Algebra\*

### 2.5.1 Adding and Multiplying: A Matrix and a Scalar

For this appendix, let  $c$  be a scalar and define the matrices

$$x = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}, z = \begin{bmatrix} z_1 \\ z_2 \end{bmatrix}, A = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}, \text{ and } B = \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix}.$$

*Multiplying a matrix by a scalar* means multiplying each element by the scalar

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} c = \begin{bmatrix} A_{11}c & A_{12}c \\ A_{21}c & A_{22}c \end{bmatrix}.$$

**Example 2.35** (*Matrix  $\times$  scalar*)

$$\begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} 10 = \begin{bmatrix} 10 & 30 \\ 30 & 40 \end{bmatrix}.$$

*Adding/subtracting a scalar to each element of a matrix* can be done by

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} + c J = \begin{bmatrix} A_{11} + c & A_{12} + c \\ A_{21} + c & A_{22} + c \end{bmatrix},$$

where  $J$  is a matrix (of the same size as  $A$ ) filled with ones. This is sometimes written  $A + c$ , although that notation is not universally liked. In some applications,  $\mathbf{1}_n$  (or just  $\mathbf{1}$ ) is used to denote a vector of  $n$  ones.

**Example 2.36** (*Matrix  $\pm$  scalar*)

$$\begin{aligned} \begin{bmatrix} 10 \\ 11 \end{bmatrix} - 10 \begin{bmatrix} 1 \\ 1 \end{bmatrix} &= \begin{bmatrix} 0 \\ 1 \end{bmatrix} \\ \begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} + 10 \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} &= \begin{bmatrix} 11 & 13 \\ 13 & 14 \end{bmatrix}. \end{aligned}$$

### 2.5.2 Adding and Multiplying: Two Matrices

Matrix *addition* (or subtraction) is element by element

$$A + B = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} + \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} A_{11} + B_{11} & A_{12} + B_{12} \\ A_{21} + B_{21} & A_{22} + B_{22} \end{bmatrix}.$$

**Example 2.37** (*Matrix addition and subtraction*)

$$\begin{aligned} \begin{bmatrix} 10 \\ 11 \end{bmatrix} - \begin{bmatrix} 2 \\ 5 \end{bmatrix} &= \begin{bmatrix} 8 \\ 6 \end{bmatrix} \\ \begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} + \begin{bmatrix} 1 & 2 \\ 3 & -2 \end{bmatrix} &= \begin{bmatrix} 2 & 5 \\ 6 & 2 \end{bmatrix} \end{aligned}$$

To turn a column into a row vector, use the *transpose* operator like in  $x'$

$$x' = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}' = [x_1 \ x_2].$$

Matrix *multiplication* requires the two matrices to be conformable: the first matrix has as many columns as the second matrix has rows. Element  $ij$  of the result is the multiplication of the  $i$ th row of the first matrix with the  $j$ th column of the second matrix

$$AB = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} B_{11} & B_{12} \\ B_{21} & B_{22} \end{bmatrix} = \begin{bmatrix} A_{11}B_{11} + A_{12}B_{21} & A_{11}B_{12} + A_{12}B_{22} \\ A_{21}B_{11} + A_{22}B_{21} & A_{21}B_{12} + A_{22}B_{22} \end{bmatrix}.$$

Multiplying a square matrix  $A$  with a column vector  $z$  gives a column vector

$$Az = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \begin{bmatrix} A_{11}z_1 + A_{12}z_2 \\ A_{21}z_1 + A_{22}z_2 \end{bmatrix}.$$

**Example 2.38** (*Matrix multiplication*)

$$\begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 1 & 2 \\ 3 & -2 \end{bmatrix} = \begin{bmatrix} 10 & -4 \\ 15 & -2 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 2 \\ 5 \end{bmatrix} = \begin{bmatrix} 17 \\ 26 \end{bmatrix}$$

### 2.5.3 Transpose

Similarly, transposing a matrix is like flipping it around the main diagonal

$$A' = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}' = \begin{bmatrix} A_{11} & A_{21} \\ A_{12} & A_{22} \end{bmatrix}.$$

**Example 2.39** (*Matrix transpose*)

$$\begin{bmatrix} 10 \\ 11 \end{bmatrix}' = \begin{bmatrix} 10 & 11 \end{bmatrix}$$

$$\begin{bmatrix} 1 & 2 & 3 \\ 4 & 5 & 6 \end{bmatrix}' = \begin{bmatrix} 1 & 4 \\ 2 & 5 \\ 3 & 6 \end{bmatrix}$$

### 2.5.4 Inner and Outer Products, Quadratic Forms

For two column vectors  $x$  and  $z$ , the product  $x'z$  is called the *inner product* (a scalar)

$$x'z = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = x_1z_1 + x_2z_2,$$

and  $xz'$  the *outer product* (a matrix)

$$xz' = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} \begin{bmatrix} z_1 & z_2 \end{bmatrix} = \begin{bmatrix} x_1z_1 & x_1z_2 \\ x_2z_1 & x_2z_2 \end{bmatrix}.$$

(Notice that  $xz$  does not work).

**Example 2.40** (*Inner and outer products*)

$$\begin{bmatrix} 10 \\ 11 \end{bmatrix}' \begin{bmatrix} 2 \\ 5 \end{bmatrix} = \begin{bmatrix} 10 & 11 \end{bmatrix} \begin{bmatrix} 2 \\ 5 \end{bmatrix} = 75$$

$$\begin{bmatrix} 10 \\ 11 \end{bmatrix} \begin{bmatrix} 2 \\ 5 \end{bmatrix}' = \begin{bmatrix} 10 \\ 11 \end{bmatrix} \begin{bmatrix} 2 & 5 \end{bmatrix} = \begin{bmatrix} 20 & 50 \\ 22 & 55 \end{bmatrix}$$

If  $x$  is a column vector and  $A$  a square matrix, then the product  $x'Ax$  is a quadratic form (a scalar).

**Example 2.41** (*Quadratic form*)

$$\begin{bmatrix} 10 \\ 11 \end{bmatrix}' \begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} 10 \\ 11 \end{bmatrix} = 1244$$

### 2.5.5 Kronecker Product

Let  $\otimes$  denote the Kronecker product, that is, if  $A$  and  $B$  are matrices, then

$$A \otimes B = \begin{bmatrix} a_{11}B & \cdots & a_{1n}B \\ \vdots & & \vdots \\ a_{m1}B & \cdots & a_{mn}B \end{bmatrix}.$$

**Example 2.42** (*Kronecker product*)

$$A = \begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix} \text{ and } B = \begin{bmatrix} 10 & 11 \end{bmatrix}, \text{ we get } A \otimes B = \begin{bmatrix} 10 & 11 & 30 & 33 \\ 20 & 22 & 40 & 44 \end{bmatrix}.$$

### 2.5.6 Matrix Inverse

A matrix *inverse* is the closest we get to “dividing” by a matrix. The inverse of a matrix  $A$ , denoted  $A^{-1}$ , is such that

$$AA^{-1} = I \text{ and } A^{-1}A = I,$$

where  $I$  is the *identity matrix* (ones along the diagonal, and zeros elsewhere). The matrix inverse is useful for solving systems of linear equations,  $y = Ax$  as  $x = A^{-1}y$ .

For a  $2 \times 2$  matrix we have

$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix}^{-1} = \frac{1}{A_{11}A_{22} - A_{12}A_{21}} \begin{bmatrix} A_{22} & -A_{12} \\ -A_{21} & A_{11} \end{bmatrix}.$$

**Example 2.43** (*Matrix inverse*) We have

$$\begin{bmatrix} -4/5 & 3/5 \\ 3/5 & -1/5 \end{bmatrix} \begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}, \text{ so}$$

$$\begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix}^{-1} = \begin{bmatrix} -4/5 & 3/5 \\ 3/5 & -1/5 \end{bmatrix}.$$

### 2.5.7 Solving Systems of Linear Equations

If  $A$  is  $n \times n$  and invertible and  $b$  and  $y$  are  $n \times 1$  vectors, then we can solve

$$Ab = y \text{ as } b = A^{-1}y.$$

This solution is unique.

$$\begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix} \begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 10 \\ 11 \end{bmatrix}, \text{ gives}$$

$$\begin{bmatrix} b_1 \\ b_2 \end{bmatrix} = \begin{bmatrix} 1 & 3 \\ 3 & 4 \end{bmatrix}^{-1} \begin{bmatrix} 10 \\ 11 \end{bmatrix} = \begin{bmatrix} -1.4 \\ 3.8 \end{bmatrix}.$$

### 2.5.8 OLS Notation: $X'X$ or $\sum_{t=1}^T x_t x'_t$ ?

Let  $x_t$  be a  $K \times 1$  vector of (of data in period  $t$ ). We can calculate the outer product ( $K \times K$ ) as  $x_t x'_t$  and summing each element across  $T$  observations gives the  $K \times K$  matrix  $S_{xx} = \sum_{t=1}^T x_t x'_t$ .

Alternatively, let  $X$  be a  $T \times K$  matrix with  $x'_t$  in row  $t$ . Then we can also calculate  $S_{xx}$  as  $X'X$ .

**Example 2.44** (*Sum of outer product,  $\sum_{t=1}^T x_t x'_t$* )

$$x_1 = \begin{bmatrix} 1 \\ -1 \end{bmatrix}, x_2 = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \text{ and } x_3 = \begin{bmatrix} 1 \\ 1 \end{bmatrix}.$$

We then have

$$\begin{aligned}\sum_{t=1}^T x_t x_t' &= \begin{bmatrix} 1 \\ -1 \end{bmatrix} \begin{bmatrix} 1 & -1 \end{bmatrix} + \begin{bmatrix} 1 \\ 0 \end{bmatrix} \begin{bmatrix} 1 & 0 \end{bmatrix} + \begin{bmatrix} 1 \\ 1 \end{bmatrix} \begin{bmatrix} 1 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} + \begin{bmatrix} 1 & 0 \\ 0 & 0 \end{bmatrix} + \begin{bmatrix} 1 & 1 \\ 1 & 1 \end{bmatrix} \\ &= \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix}.\end{aligned}$$

In this example, the matrix happens to be diagonal, but that is not a general result. However, it will always be symmetric.

**Example 2.45** (Sum of outer product,  $X'X$ ) Define

$$X = \begin{bmatrix} 1 & -1 \\ 1 & 0 \\ 1 & 1 \end{bmatrix}.$$

It is straightforward to calculate that  $X'X = \begin{bmatrix} 3 & 0 \\ 0 & 2 \end{bmatrix}$ .

### 2.5.9 Derivatives of Matrix Expressions

Let  $z$  and  $x$  be  $n \times 1$  vectors. The *derivative of the inner product* is  $\partial(z'x)/\partial z = x$ .

**Example 2.46** (Derivative of an inner product) With  $n = 2$

$$z'x = z_1 x_1 + z_2 x_2, \text{ so } \frac{\partial(z'x)}{\partial z} = \frac{\partial(z_1 x_1 + z_2 x_2)}{\begin{bmatrix} \partial z_1 \\ \partial z_2 \end{bmatrix}} = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

Let  $x$  be  $n \times 1$  and  $A$  a symmetric  $n \times n$  matrix. The *derivative of the quadratic form* is  $\partial(x'Ax)/\partial x = 2Ax$ .

**Example 2.47** (Derivative of a quadratic form) With  $n = 2$ , the quadratic form is

$$x'Ax = \begin{bmatrix} x_1 & x_2 \end{bmatrix} \begin{bmatrix} A_{11} & A_{12} \\ A_{12} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} = x_1^2 A_{11} + x_2^2 A_{22} + 2x_1 x_2 A_{12}.$$

The derivatives with respect to  $x_1$  and  $x_2$  are

$$\frac{\partial(x'Ax)}{\partial x_1} = 2x_1A_{11} + 2x_2A_{12} \text{ and } \frac{\partial(x'Ax)}{\partial x_2} = 2x_2A_{22} + 2x_1A_{12}, \text{ or}$$

$$\begin{bmatrix} \frac{\partial(x'Ax)}{\partial x_1} \\ \frac{\partial(x'Ax)}{\partial x_2} \end{bmatrix} = 2 \begin{bmatrix} A_{11} & A_{12} \\ A_{12} & A_{22} \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}.$$

# Chapter 3

## Index Models\*

Reference: Elton, Gruber, Brown, and Goetzmann (2010) 7–8, 11

### 3.1 Single-Index Models

The *single-index model* is a way to cut down on the number of parameters that we need to estimate in order to construct the covariance matrix of assets. The model assumes that the co-movement between assets is due to a single common influence (here denoted  $R_{mt}$ )

$$R_{it} = \alpha_i + \beta_i R_{mt} + \varepsilon_{it}, \text{ where} \quad (3.1)$$
$$\mathbb{E} \varepsilon_{it} = 0, \text{ Cov}(\varepsilon_{it}, R_{mt}) = 0, \text{ and } \text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0.$$

In this equation,  $R_{it}$  stands for the return of asset  $i$  in period  $t$ , while  $R_{mt}$  is the market return in the same period. This regression may use the net returns (as indicated above), or the returns in excess of a riskfree rate. The results for the  $\beta$  (which is the focus here) are typically very similar.

The first two assumptions are the standard assumptions for using ordinary least squares: the residual has a zero mean and is uncorrelated with the non-constant regressor. (Together they imply that the residuals are orthogonal to both regressors, which is the standard assumption in econometrics.) Hence, these two properties will be automatically satisfied if (3.1) is estimated by OLS. See Figure 3.1 for an illustration of OLS.

**Remark 3.1** (*A warning about the notation*) When discussing OLS we typically write the regression equation as  $y_t = x'_t \beta + u_t$ . Comparing with (3.1), we notice that  $y_t = R_{it}$ . Also,  $x_t$  equals the column vector  $[1, R_{mt}]'$  and  $u_t = \varepsilon_{it}$ . Finally, notice that we recycle the  $\beta$  symbol: in OLS it is a vector of all coefficients, corresponding to  $[\alpha_i, \beta_i]'$  in the index model.

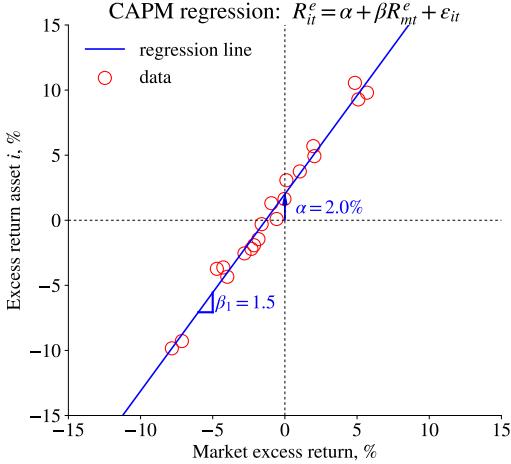


Figure 3.1: CAPM regression

	HiTec	Utils
constant	-0.09 (-0.67)	0.26 (1.87)
market return	1.24 (38.15)	0.52 (14.12)
$R^2$	0.76	0.33
Autocorr	0.39	0.97
White	0.04	0.00
All slopes	0.00	0.00
obs	636	636

Table 3.1: CAPM regressions, monthly returns, %, US data 1970:01-2022:12. Numbers in parentheses are t-stats. Autocorr is the p-value for no autocorrelation; White is the p-value for homoskedasticity; All slopes is the p-value for all slope coefficients being zero.

**Empirical Example 3.2** (*Betas of industry portfolios*) See Figures 3.2 – 3.3 and Table 4.1 for results on U.S. industry portfolios.

The key point of the model, however, is the third assumption: the residuals for different assets are uncorrelated. This means that all comovements of two assets ( $R_{it}$  and  $R_{jt}$ , say) are due to movements in the common “index”  $R_{mt}$ . This is not at all guaranteed by running LS regressions—just an assumption. It is likely to be false—but may be a

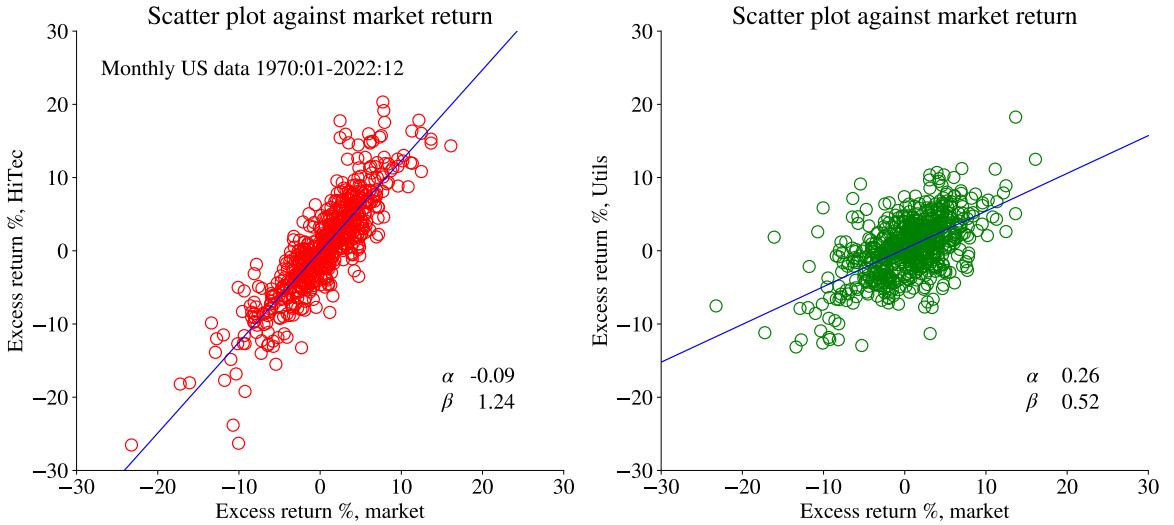


Figure 3.2: Scatter plot against market return

reasonable approximation. In any case, it simplifies the construction of the covariance matrix of the assets enormously—as demonstrated below.

**Remark 3.3** (*The market model*) *The market model is (3.1) without the assumption that  $\text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0$ . This model does not simplify the calculation of a portfolio variance—but will turn out to be important when we want to test CAPM.*

If (3.1) is true, then the variance of asset  $i$  and the covariance of assets  $i$  and  $j$  are

$$\sigma_{ii} = \beta_i^2 \sigma_{mm} + \text{Var}(\varepsilon_{it}) \quad (3.2)$$

$$\sigma_{ij} = \beta_i \beta_j \sigma_{mm} \text{ when } i \neq j, \quad (3.3)$$

where  $\sigma_{mm}$  is the variance of  $R_m$ . Together, these equations show that we can calculate the whole covariance matrix by having just the variance of the index (to get  $\sigma_{mm}$ ) and the output from  $n$  regressions (to get  $\beta_i$  and  $\text{Var}(\varepsilon_{it})$  for each asset). This is, in many cases, much easier to obtain than direct estimates of the covariance matrix. For instance, a new asset does not have a return history, but it may be possible to make intelligent guesses about its beta and residual variance (for instance, from knowing the industry and size of the firm).

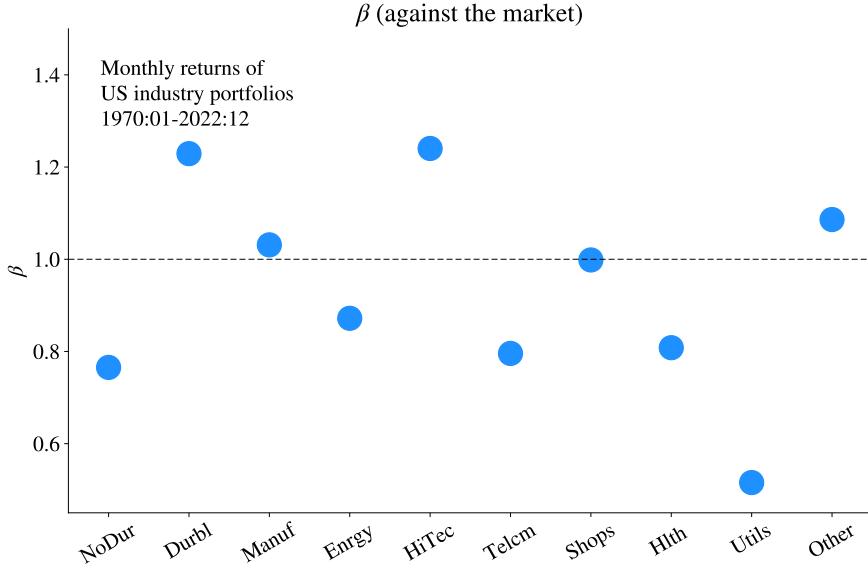


Figure 3.3:  $\beta$ s of US industry portfolios

This gives the covariance matrix (for two assets)

$$\text{Var} \begin{pmatrix} R_{it} \\ R_{jt} \end{pmatrix} = \begin{bmatrix} \beta_i^2 & \beta_i \beta_j \\ \beta_i \beta_j & \beta_j^2 \end{bmatrix} \sigma_{mm} + \begin{bmatrix} \text{Var}(\varepsilon_{it}) & 0 \\ 0 & \text{Var}(\varepsilon_{jt}) \end{bmatrix}, \text{ or} \quad (3.4)$$

$$= \begin{bmatrix} \beta_i \\ \beta_j \end{bmatrix} \begin{bmatrix} \beta_i & \beta_j \end{bmatrix} \sigma_{mm} + \begin{bmatrix} \text{Var}(\varepsilon_{it}) & 0 \\ 0 & \text{Var}(\varepsilon_{jt}) \end{bmatrix} \quad (3.5)$$

More generally, with  $n$  assets we can define  $\beta$  to be an  $n \times 1$  vector of all the betas and  $\Sigma$  to be an  $n \times n$  matrix with the variances of the residuals along the diagonal. We can then write the covariance matrix of the  $n \times 1$  vector of the returns as

$$\text{Var}(R_t) = \beta \beta' \sigma_{mm} + \Sigma. \quad (3.6)$$

**Empirical Example 3.4** (*Single-index model for the 25 FF portfolios*) See Figure 3.4 for an example based on the 25 Fama-French portfolios detailed in Table 3.2.

**Remark 3.5** (*Fama-French portfolios*) The portfolios in Table 3.2 are calculated by annual rebalancing (June/July). The US stock market is divided into  $5 \times 5$  portfolios as follows. First, split up the stock market into 5 groups based on the book value/market value: put the lowest 20% in the first group, the next 20% in the second group etc. Second, split up the stock market into 5 groups based on size: put the smallest 20% in the first

group etc. Then, form portfolios based on the intersections of these groups (also called double sorting). For instance, in Table 3.2 the portfolio in row 2, column 3 (portfolio 8) belong to the 20%-40% largest firms and the 40%-60% firms with the highest book value/market value.

		Book value/Market value				
		1	2	3	4	5
Size	1	1	2	3	4	5
	2	6	7	8	9	10
	3	11	12	13	14	15
	4	16	17	18	19	20
	5	21	22	23	24	25

Table 3.2: Numbering of the FF portfolios.

**Remark 3.6** (*Shrinkage estimators of the covariance matrix\**) The sample covariance matrix,  $S$ , can be very noisy in small samples. One way of handling that is to “shrink” the sample covariance matrix towards a target,  $F$ , as  $\delta F + (1 - \delta)S$ , where  $0 \leq \delta \leq 1$ . Ledoit and Wolf (2003) suggest an  $F$  matrix from the single index model and Ledoit and Wolf (2004) instead suggest an  $F$  matrix which implies the same correlations of all assets. To construct the latter, calculate all correlations  $\rho_{ij} = S_{ij} / \sqrt{S_{ii} S_{jj}}$  for  $i \neq j$ , average across them to get  $\bar{\rho}_{ij}$ , then let  $F_{ij} = \bar{\rho}_{ij} \sqrt{S_{ii} S_{jj}}$ . The diagonal elements of  $F$  are the same as in  $S$ . The articles develop algorithms for calculating an approximately optimal value of  $\delta$ . Table 3.3 suggest that with 25 assets  $\delta$  is small for long samples, but may be non-trivial for shorter samples. With more assets, the  $\delta$  value is likely to be larger.

	Full sample	10-year samples
constant corr	0.11	0.64
single index model	0.03	0.11

Table 3.3: Shrinkage parameter  $\delta$  in Ledoit and Wolf’s (2003,2004) covariance estimator  $\delta F + (1 - \delta)S$ . The target matrix  $F$  is either a constant correlation covariance matrix or the covariance matrix from a single index model. 25 FF portfolios, monthly data for 1970:01-2022:12. The result for the 10-year samples is the average across moving 10-year data windows.

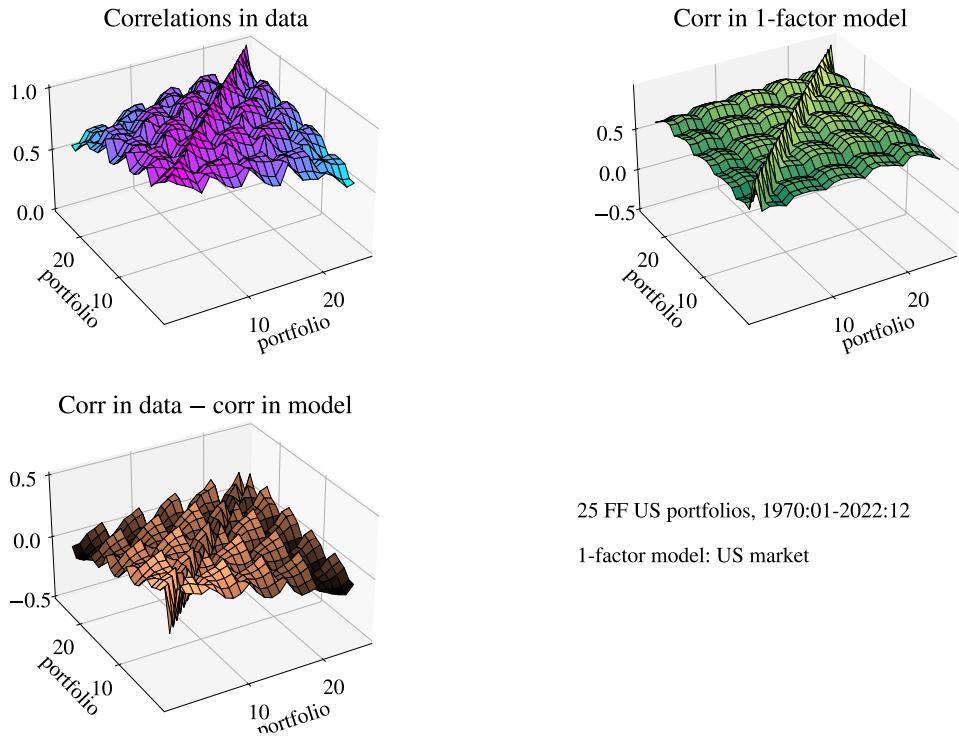


Figure 3.4: Correlations of US portfolios

**Proof.** (of (3.2)–(3.3)) By using (3.1) and recalling that  $\text{Cov}(R_{mt}, \varepsilon_{it}) = 0$  direct calculations give

$$\begin{aligned}\sigma_{ii} &= \text{Var}(R_{it}) \\ &= \text{Var}(\alpha_i + \beta_i R_{mt} + \varepsilon_{it}) \\ &= \text{Var}(\beta_i R_{mt}) + \text{Var}(\varepsilon_{it}) + 2 \times 0 \\ &= \beta_i^2 \sigma_{mm} + \text{Var}(\varepsilon_{it}).\end{aligned}$$

Similarly, the covariance of assets  $i$  and  $j$  ( $i \neq j$ ) is (recalling also that  $\text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0$ )

$$\begin{aligned}\sigma_{ij} &= \text{Cov}(R_{it}, R_{jt}) \\ &= \text{Cov}(\alpha_i + \beta_i R_{mt} + \varepsilon_{it}, \alpha_j + \beta_j R_{mt} + \varepsilon_{jt}) \\ &= \beta_i \beta_j \sigma_{mm} + 0.\end{aligned}$$

■

## 3.2 Estimating Beta

### 3.2.1 Estimating Historical Beta: OLS and Other Approaches

Least Squares (LS) is typically used to estimate  $\alpha_i$ ,  $\beta_i$  and  $\text{Std}(\varepsilon_{it})$  in (3.1)—and the  $R^2$  is used to assess the quality of the regression.

**Remark 3.7** ( $R^2$  of market model)  $R^2$  of (3.1) measures the fraction of the variance (of  $R_{it}$ ) that is due to the systematic part of the regression, that is, relative importance of market risk as compared to idiosyncratic noise ( $1 - R^2$  is the fraction due to the idiosyncratic noise)

$$R^2 = \frac{\text{Var}(\alpha_i + \beta_i R_{mt})}{\text{Var}(R_{it})} = \frac{\beta_i^2 \sigma_m^2}{\beta_i^2 \sigma_m^2 + \sigma_{ei}^2}.$$

To assess the accuracy of historical betas, Blume (1971) and others estimate betas for non-overlapping samples (periods)—and then compare the betas across samples. They find that the correlation of betas across samples is moderate for individual assets, but relatively high for diversified portfolios. It is also found that betas tend to “regress” towards one: an extreme (high or low) historical beta is likely to be followed by a beta that is closer to one. There are several suggestions for how to deal with this problem.

To use *Blume’s ad-hoc technique*, let  $\hat{\beta}_{i1}$  be the estimate of  $\beta_i$  from an early sample, and  $\hat{\beta}_{i2}$  the estimate from a later sample. Then regress

$$\hat{\beta}_{i2} = \gamma_0 + \gamma_1 \hat{\beta}_{i1} + v_i \quad (3.7)$$

and use it for forecasting the beta for yet another sample. Blume found  $(\hat{\gamma}_0, \hat{\gamma}_1) = (0.343, 0.677)$  for his data.

Other authors have suggested averaging the OLS estimate ( $\hat{\beta}_i$ ) with some average beta. For instance,  $(\hat{\beta}_i + 1)/2$  since the average beta must be unity or  $(\hat{\beta}_i + \sum_{j=1}^n \hat{\beta}_j/n)/2$ , which will typically be similar since  $\sum_{j=1}^n \hat{\beta}_j/n$  is likely to be close to one.

The *Bayesian approach* is another (more formal) way of adjusting the OLS estimate. It also uses a weighted average of the OLS estimate,  $\hat{\beta}_i$ , and some other number,  $\beta_0$ ,  $(1 - F)\hat{\beta}_i + F\beta_0$  where  $F$  depends on the precision of the OLS estimator. The general idea of a Bayesian approach (Greene (2018) 16) is to treat both  $R_{it}$  and  $\beta_i$  as random. In this case a Bayesian analysis could go as follows. First, suppose our prior beliefs (before having data) about  $\beta_i$  is that it is normally distributed,  $N(\beta_0, \sigma_0^2)$ , where  $(\beta_0, \sigma_0^2)$  are some numbers. Second, run a LS regression of (3.1). If the residuals are normally distributed, so is the estimator—it is  $N(\hat{\beta}_i, \sigma_{\beta_i}^2)$ , where we have taken the point estimate to be the

mean. If we treat the variance of the LS estimator ( $\sigma_\beta^2$ ) as known, then the Bayesian estimator of beta is

$$b = (1 - F)\hat{\beta}_i + F\beta_0, \text{ where}$$

$$F = \frac{1/\sigma_0^2}{1/\sigma_0^2 + 1/\sigma_\beta^2} = \frac{\sigma_{\beta 1}^2}{\sigma_0^2 + \sigma_\beta^2}. \quad (3.8)$$

When the prior beliefs are very precise ( $\sigma_0^2 \rightarrow 0$ ), then  $F \rightarrow 1$  so the Bayesian estimator is the same as the prior mean. Effectively, when the prior beliefs are so precise, there is no room for data to add any information. In contrast, when the prior beliefs are very imprecise ( $\sigma_0^2 \rightarrow \infty$ ), then  $F \rightarrow 0$ , so the Bayesian estimator is the same as OLS. Effectively, the prior beliefs do not add any information. In the current setting,  $\beta_0 = 1$  and  $\sigma_0^2$  taken from a previous (econometric) study might make sense.

### 3.2.2 Fundamental Betas

Another way to improve the forecasts of the beta over a future period is to bring in information about fundamental firm variables. This is particularly useful when there is little historical data on returns (for instance, because the asset was not traded before).

It is often found that betas are related to fundamental variables as follows (with signs in parentheses indicating the effect on the beta): Dividend payout (-), Asset growth (+), Leverage (+), Liquidity (-), Asset size (-), Earning variability (+), Earnings Beta (slope in earnings regressed on economy wide earnings) (+). Such relations can be used to make an educated guess about the beta of an asset without historical data on the returns—but with data on (at least some of) these fundamental variables.

## 3.3 Multi-Index Models

### 3.3.1 Overview

The multi-index model is just a multivariate extension of the single-index model

$$R_{it} = a_i + b'_i I_t + \varepsilon_{it}, \text{ where} \quad (3.9)$$

$$\mathbb{E} \varepsilon_{it} = 0, \text{ Cov}(\varepsilon_{it}, I_t) = \mathbf{0}, \text{ and } \text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0.$$

As an example, there could be two indices: the stock market return and an interest rate. An ad-hoc approach is to first try a single-index model and then test if the residuals are

approximately uncorrelated. If not, then adding a second index might improve the model.

It is often found that it takes several indices to get a reasonable approximation—but that a single-index model is equally good (or better) at “forecasting” the covariance over a future period. This is much like the classical trade-off between in-sample fit (requires a large model) and forecasting (often better with a small model).

The types of indices vary, but one common set captures the “business cycle” and includes things like the market return, interest rate (or some measure of the yield curve slope), GDP growth, inflation, and so forth. Another common set of indices are industry indices.

It turns out (see below) that the calculations of the covariance matrix are simpler if the indices are transformed to be uncorrelated.

**Remark 3.8** (*Fama-French factors*) *Fama and French (1993) use three factors: the market excess return, the return on a portfolio of small stocks minus the return on a portfolio of big stocks (SMB), and the return on a portfolio with a high ratio of book value to market value minus the return on a portfolio with a low ratio (HML). All three are excess returns (although only the first is in excess of a riskfree return), since they are long-short portfolios.*

### 3.3.2 Using the Multi-Index Model

If  $\Omega$  is the covariance matrix of the indices, then the covariance of assets  $i$  and  $j$  is

$$\sigma_{ij} = b_i' \Omega b_j + \text{Cov}(\varepsilon_{it}, \varepsilon_{jt}), \quad (3.10)$$

where  $b_i$  is the vector of slope coefficients obtained from regressing  $R_{it}$  on the vector of factors ( $I_t$  or  $I_t^*$ ) as in (3.9). For  $i = j$  we set  $\text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = \text{Var}(\varepsilon_{it})$ , but for  $i \neq j$  we set  $\text{Cov}(\varepsilon_{it}, \varepsilon_{jt}) = 0$ .

**Empirical Example 3.9** (*Multi-index model for the 25 FF portfolios*) See Figure 3.5 for results. The multi-index model seems much better than the single-index model at capturing the correlation patterns of the 25 portfolios.

**Remark 3.10** (*With uncorrelated factors*) In case the factors are uncorrelated, then  $\Omega$  is diagonal so (3.10) can be simplified as

$$\sigma_{ij} = \sum_{k=1}^K b_{ik} b_{jk} \text{Var}(I_{kt}) + \text{Cov}(\varepsilon_{it}, \varepsilon_{jt}),$$

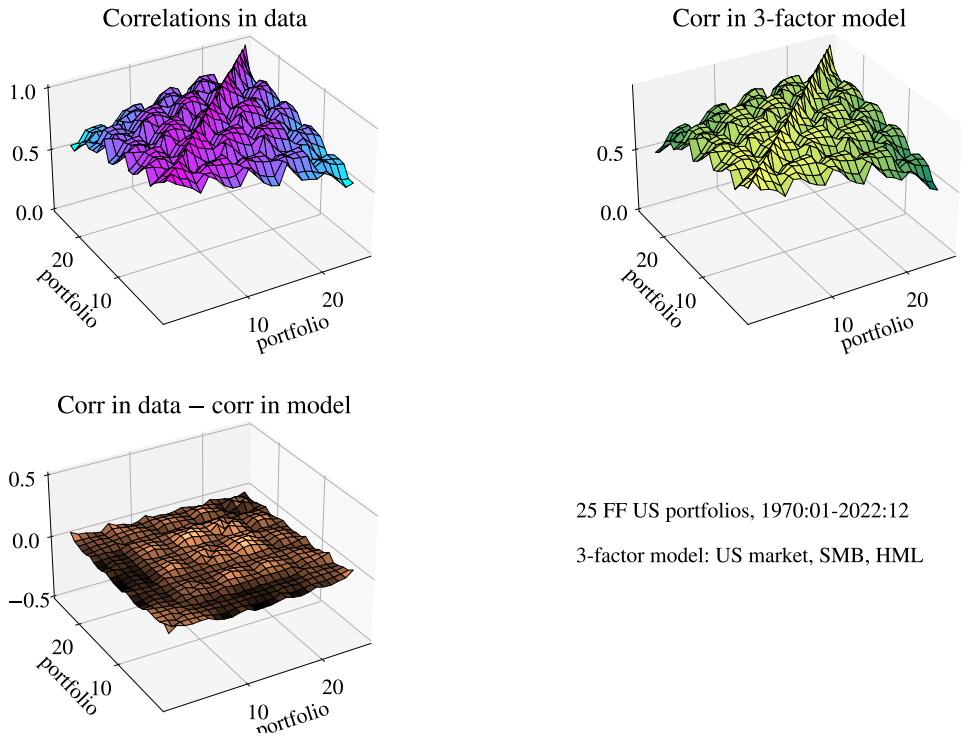


Figure 3.5: Correlations of US portfolios

where  $b_{ik}$  is the coefficient on factor  $k$  in the regression of  $R_{it}$ .

### 3.3.3 Multi-Index Model as a Method for Portfolio Choice

The factor loadings (betas) can be used for more than just constructing the covariance matrix. In fact, the factor loadings are often used directly in portfolio choice. The reason is simple: the betas summarize how different assets are exposed to the big risk factors/return drivers. The betas therefore provide a way to understand the broad features of even complicated portfolios. Combined this with the fact that many analysts and investors have fairly little direct information about individual assets, but are often willing to form opinions about the future relative performance of different asset classes (small vs large firms, equity vs bonds, etc)—and the role for factor loadings becomes clear.

## 3.4 Principal Component Analysis\*

Principal component analysis (PCA) can help us determine how many factors that are needed to explain a cross-section of asset returns.

Let  $z_t = R_t - \bar{R}_t$  be an  $n \times 1$  vector of demeaned returns with covariance matrix  $\Sigma$ . The first principal component ( $pc_{1t}$ ) is the (normalized) linear combinations of  $z_t$  that account for as much of the variability as possible—and its variance is denoted  $\lambda_1$ . The  $j$ th ( $j \geq 2$ ) principal component ( $pc_{jt}$ ) is similar (and its variance is denoted  $\lambda_j$ ), except that it must be uncorrelated with all lower principal components. Remark 3.11 gives a formal definition.

**Remark 3.11** (*Principal component analysis*) Consider the zero mean  $N \times 1$  vector  $z_t$  with covariance matrix  $\Sigma$ . The first (sample) principal component is  $pc_{1t} = w'_1 z_t$ , where  $w_1$  is the eigenvector associated with the largest eigenvalue ( $\lambda_1$ ) of  $\Sigma$ . This value of  $w_1$  solves the problem  $\max_w w' \Sigma w$  subject to the normalization  $w'w = 1$ . The eigenvalue  $\lambda_1$  equals  $\text{Var}(pc_{1t}) = w'_1 \Sigma w_1$ . The  $j$ th principal component solves the same problem, but under the additional restriction that  $w'_i w_j = 0$  for all  $i < j$ . The solution is the eigenvector associated with the  $j$ th largest eigenvalue  $\lambda_j$  (which equals  $\text{Var}(pc_{jt}) = w'_j \Sigma w_j$ ).

Let the  $i$ th eigenvector be the  $i$ th column of the  $n \times n$  matrix

$$W = [ w_1 \ \cdots \ w_n ]. \quad (3.11)$$

We can then calculate the  $n \times 1$  vector of principal components as

$$pc_t = W' z_t. \quad (3.12)$$

Since the eigenvectors are orthogonal it can be shown that  $W' = W^{-1}$ , so the expression can be inverted as

$$z_t = W pc_t. \quad (3.13)$$

This shows that the  $i$ th eigenvector (the  $i$ th column of  $W$ ) can be interpreted as the effect of the  $i$ th principal component on each of the elements in  $z_t$ . However, the sign of column  $j$  of  $W$  can be changed without any effects (except that the  $pc_{jt}$  also changes sign), so we can always reinterpret a negative coefficient as a positive exposure (to  $-pc_{jt}$ ).

**Empirical Example 3.12** (*PCA for the 25 FF portfolios*) See Figure 3.6 for the three most important eigenvectors for the 25 FF portfolios. The first pc seems to capture the average (market), while the other are related to size and growth/value.

**Example 3.13** (*PCA with 2 series*) Let  $w_i^{(j)}$  be the  $t$ th element in the  $i$ th eigenvector.

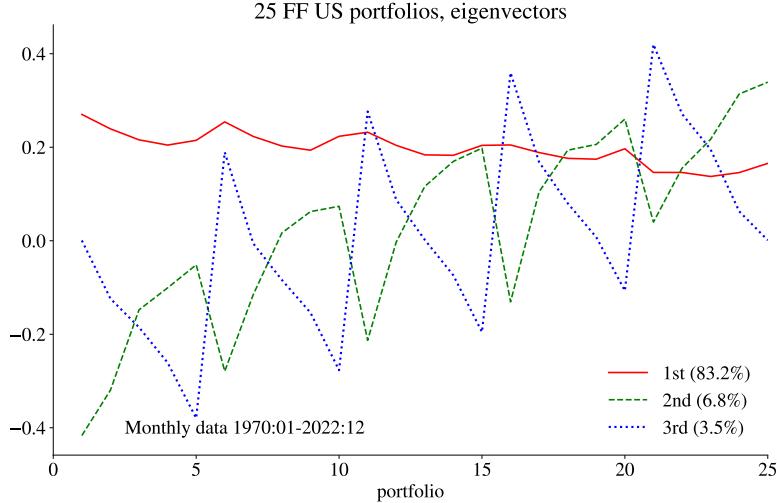


Figure 3.6: Eigenvectors for US portfolio returns

With two series we have

$$\begin{aligned}
 pc_{1t} &= \begin{bmatrix} w_1^{(1)} \\ w_1^{(2)} \end{bmatrix}' \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} \text{ and } pc_{2t} = \begin{bmatrix} w_2^{(1)} \\ w_2^{(2)} \end{bmatrix}' \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} \text{ or} \\
 \begin{bmatrix} pc_{1t} \\ pc_{2t} \end{bmatrix} &= \begin{bmatrix} w_1^{(1)} & w_2^{(1)} \\ w_1^{(2)} & w_2^{(2)} \end{bmatrix}' \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} \text{ and} \\
 \begin{bmatrix} z_{1t} \\ z_{2t} \end{bmatrix} &= \begin{bmatrix} w_1^{(1)} & w_2^{(1)} \\ w_1^{(2)} & w_2^{(2)} \end{bmatrix} \begin{bmatrix} pc_{1t} \\ pc_{2t} \end{bmatrix}
 \end{aligned}$$

For instance, for the two elements in the second eigenvector,  $w_2^{(1)}$  shows how  $pc_{2t}$  affects  $z_{1t}$ , while  $w_2^{(2)}$  shows how the same  $pc_{2t}$  affects  $z_{2t}$ .

**Remark 3.14** (Data in matrices\*) Transpose (3.12) to get  $pc_t' = z_t' W$ , where the dimensions are  $1 \times n$ ,  $1 \times n$  and  $n \times n$  respectively. If we form a  $T \times n$  matrix of data  $Z$  by putting  $z_t$  in row  $t$ , then the  $T \times N$  matrix of principal components can be calculated as  $PC = ZW$ .

Notice that (3.13) shows that all  $n$  data series in  $z_t$  can be written in terms of the  $n$  principal components. Since the principal components are uncorrelated ( $\text{Cov}(pc_{it}, pc_{jt}) = 0$ ), and it can be shown that  $\sum_{i=1}^n \lambda_i = \sum_{i=1}^n \text{Var}(z_{it})$ , we can think of the sum of their variances ( $\sum_{i=1}^n \lambda_i$ ) as the “total variation” of the series in  $z_t$ . In practice, it is common to

report the relative importance of principal component  $j$  as

$$\text{relative importance of } pc_j = \lambda_j / \sum_{i=1}^n \lambda_i. \quad (3.14)$$

For instance, if it is found that the first two principal components account for 75% for the total variation among many asset returns, then a two-factor model is likely to be a good approximation.

# Chapter 4

## Least Squares: Testing

Reference: Verbeek (2012) 2 and 4; Greene (2018) 4-5 and parts of 9 and 20.

More advanced material is denoted by a star (\*). It is not required reading.

### 4.1 Testing a Single Coefficient: A $t$ -test

We are interested in testing the null hypothesis ( $H_0$ ) that  $\beta = q$ , where  $q$  is a number of interest. (Econometric programs typically report results for  $H_0: \beta = 0$ .) Here, the alternative hypothesis is that  $\beta \neq q$ , so this is a two-sided (also called “two-tailed”) test.

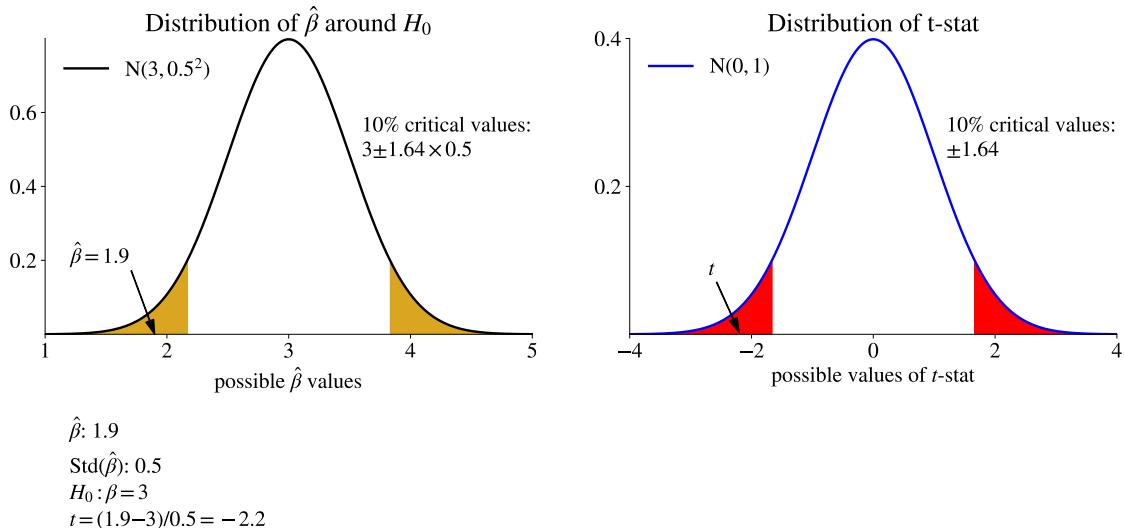


Figure 4.1: Distribution of  $\hat{\beta}$  and t-stat

We assume that the estimates are normally distributed, which may be a good approximation when the sample is large (because of the central limit theorem). If the null

hypothesis is true, then

$$\hat{\beta} \sim N(q, \text{Var}(\hat{\beta})). \quad (4.1)$$

The estimate  $\hat{\beta}$  could be from a linear regression, but could equally well be from some other method.

To be able to easily compare with printed tables of probabilities, we transform to a  $N(0, 1)$  variable. In particular, if the true coefficient is really  $q$ , then  $\hat{\beta} - q$  should have a zero mean. Dividing by the standard error (deviation) of  $\hat{\beta}$ , we should have

$$t = \frac{\hat{\beta} - q}{\text{Std}(\hat{\beta})} \sim N(0, 1) \quad (4.2)$$

We reject the null hypothesis when  $|t|$  is very large, for instance, if  $|t| > 1.64$ .

This decision is driven by (a) how far  $\hat{\beta}$  is from  $q$ ; (b) how uncertain  $\hat{\beta}$  is (as measured by  $\text{Std}(\hat{\beta})$ ); (c) and how we define the cut off (here 1.64). The latter is typically done by first choosing a *significance level* (for instance, 10%) which defines a *critical value* (1.64 for the 10% significance level): reject the null hypothesis if  $|t|$  is larger than the critical value (1.64 on the 10% level, 1.96 on the 5% level). The significance level represents the probability, in a random sample, of falsely rejecting a null hypothesis that is actually true. See Figure 4.1 for an illustration. A lower significance level (5%, giving a critical value of 1.96) is therefore a more conservative test (we require stronger evidence to reject the null hypothesis), and thus run a lower risk of a false rejection. The significance level is thus a trade-off between actually being able of rejecting the null hypothesis and sometime doing it falsely. See Figure 4.2 for an illustration of the probabilities according to an  $N(0, 1)$  distribution.

Otherwise, when  $|t|$  is not very large (for instance,  $|t|$ ), then evidence is not sufficient to reject the null hypothesis. (You may compare with a court of law where the null hypothesis is that the accused is not guilty.)

**Example 4.1** (*t-test*) Let  $\hat{\beta} = 1.9$ ,  $\text{Std}(\hat{\beta}) = 0.5$  and  $q = 3$ . Then,  $t = (1.9 - 3)/0.5 = -2.2$  so  $|t| > 1.64$  and also  $|t| > 1.96$ . The null hypothesis is thus rejected at both the 10% and the 5% significance levels.

**Empirical Example 4.2** (*CAPM regressions for industry portfolios*) See Table 4.1.

**Empirical Example 4.3** (*Multi-factor regressions for industry portfolios*) See Table 4.2.

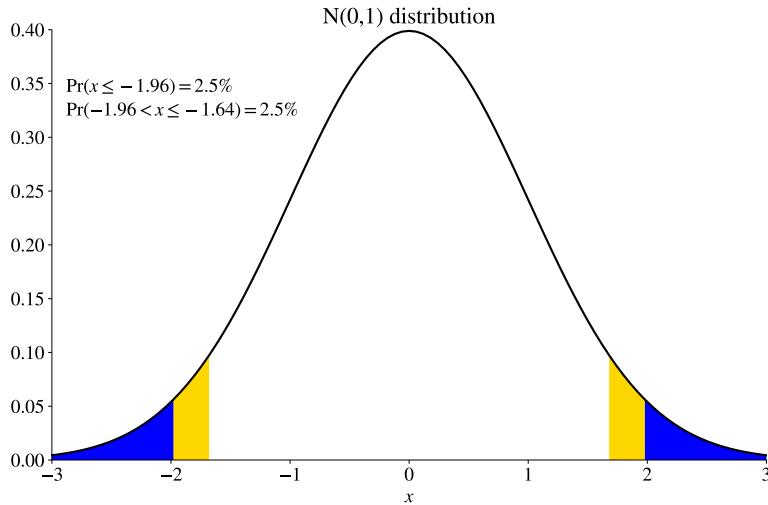


Figure 4.2: Density function of a standard normal distribution

The *p-value* is a related concept. It is the lowest significance level at which we can reject the null hypothesis: a lower number is a stronger rejection. See Figure 4.3 for an illustration.

**Example 4.4** (*p-value*) Continuing Example 4.1, notice that according to a  $N(0,1)$  distribution, the probability of  $-2.2$  or lower is  $1.4\%$ , so the *p-value* is  $2.8\%$ . We thus reject the null hypothesis at the  $10\%$  significance level and also at the  $5\%$  significance level.

We sometimes compare with a *t*-distribution instead of a  $N(0,1)$ , especially when the sample is short. For instance, with 22 data points and two estimated coefficients (so there are 20 degrees of freedom), the  $10\%$  critical value of a *t*-distribution is 1.72 (while it is 1.64 for the standard normal distribution). However, for samples of more than 30–40 data points, the difference is trivial.

**Remark 4.5** (*One-sided test\**) As an examples of a one-sided test let  $H_0 : \beta \leq q$  and  $H_1 : \beta > q$ . Sometimes the null hypothesis is written  $\beta = q$ , but that makes little practical difference. We then reject the null hypothesis at the  $10\%$  significance level if  $t > 1.28$  which is the  $0.90$  quantile of a  $N(0,1)$  distribution. Conversely, when  $H_0 : \beta \geq q$  and  $H_1 : \beta < q$ , then we reject the null hypothesis if  $t < -1.28$ . Since 1.28 is the  $20\%$  critical value in a two-sided test, we can actually use a two sided test (for instance, from a regression package) to also do a one-sided test: (a) if we reject the null hypothesis on the  $20\%$  level in a double sided test; (b) and the sign is right; then (c) this is a rejection on the  $10\%$  level in a one-sided test.

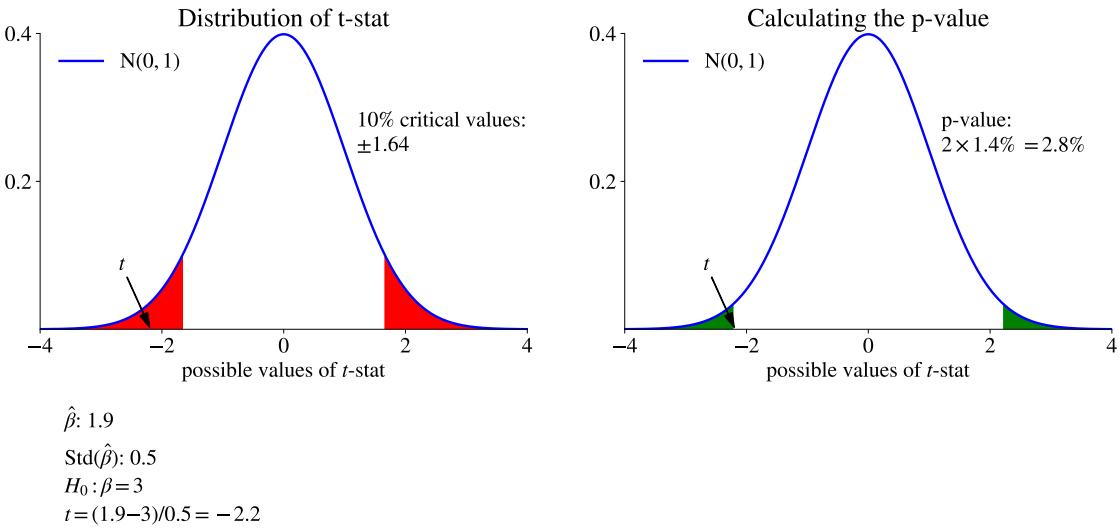


Figure 4.3: Calculating the p-value

## 4.2 Confidence Bands

A significance level of 10% means that there is (if the null hypothesis is true) a 90% probability that the  $t$  value in (4.2) is within the interval (band)  $(-1.64, 1.64)$ , that is,

$$\Pr(-1.64 \leq t \leq 1.64) = 90\%. \quad (4.3)$$

The  $t$ -test discussed above rejects the null hypothesis ( $\beta = q$ ) when  $t$  is outside this confidence band. Notice that

$$t \text{ is outside } [-1.64, 1.64] \iff \quad (4.4)$$

$$\hat{\beta} \text{ is outside } [q - 1.64 \text{ Std}(\hat{\beta}), q + 1.64 \text{ Std}(\hat{\beta})] \text{ and} \quad (4.5)$$

$$q \text{ is outside } [\hat{\beta} - 1.64 \text{ Std}(\hat{\beta}), \hat{\beta} + 1.64 \text{ Std}(\hat{\beta})]. \quad (4.6)$$

The interval in (4.5) is a 90% confidence band of  $\beta$  *centered on the null hypothesis*, while the confidence band in (4.6) is *centered on the point estimate*. These are alternative ways of doing a hypothesis test—and are often used to provide more information than just a reject/no reject decision. For instance, we are 90% sure that the true  $\beta$  value is within the band centered around the point estimate. See Figures 4.1 and 4.4.

**Proof.** (that  $t$  and  $\hat{\beta}$  are outside their confidence bands at the same time) For  $\hat{\beta}$  to be

	HiTec	Utils
constant	-0.09 (-0.67)	0.26 (1.87)
market return	1.24 (38.15)	0.52 (14.12)
$R^2$	0.76	0.33
Autocorr	0.39	0.97
White	0.04	0.00
All slopes	0.00	0.00
obs	636	636

Table 4.1: CAPM regressions, monthly returns, %, US data 1970:01-2022:12. Numbers in parentheses are t-stats. Autocorr is the p-value for no autocorrelation; White is the p-value for homoskedasticity; All slopes is the p-value for all slope coefficients being zero.

outside the band we must have

$$\hat{\beta} < q - 1.64 \text{ Std}(\hat{\beta}) \text{ or } \hat{\beta} > q + 1.64 \text{ Std}(\hat{\beta}).$$

Rearrange this by subtracting  $q$  from both sides of the inequalities and then divide both sides by  $\text{Std}(\hat{\beta})$

$$\frac{\hat{\beta} - q}{\text{Std}(\hat{\beta})} < -1.64 \text{ or } \frac{\hat{\beta} - q}{\text{Std}(\hat{\beta})} > 1.64.$$

■

**Example 4.6** (*t-test and confidence band around  $q$* ) With  $\text{Std}(\hat{\beta}) = 0.5$  and  $q = 3$ , the 90% confidence band is  $3 \pm 1.64 \times 0.5$ , that is,  $[2.18, 3.82]$ . Notice that  $\hat{\beta} = 1.90$  is outside this band, so we reject the null hypothesis. Equivalently,  $t = (1.9 - 3)/0.5 = -2.2$  is outside the band  $[-1.64, 1.64]$ .

**Example 4.7** (*t-test and confidence band around  $\hat{\beta}$* ) With  $\text{Std}(\hat{\beta}) = 0.5$  and  $\hat{\beta} = 1.9$ , the 90% confidence band is  $1.9 \pm 1.64 \times 0.5$ , that is,  $[1.08, 2.72]$ . Notice that  $q = 3$  is outside this band, so we reject the null hypothesis.

### 4.3 Power and Size\*

The *size* is the probability of rejecting a true  $H_0$ . It should be low. Provided you use a valid test (correct standard error, etc), the *size* is the significance level you have cho-

	HiTec	Utils
constant	0.11 (1.04)	0.14 (1.06)
market return	1.13 (37.72)	0.60 (17.24)
SMB	0.20 (4.02)	-0.21 (-4.05)
HML	-0.50 (-10.56)	0.30 (5.33)
$R^2$	0.82	0.41
Autocorr	0.57	0.58
White	0.00	0.00
All slopes	0.00	0.00
obs	636	636

Table 4.2: Fama-French regressions, monthly returns, %, US data 1970:01-2022:12. Numbers in parentheses are t-stats. Autocorr the p-value for no autocorrelation; White is the p-value for homoskedasticity; All slopes is the p-value for all slope coefficients being zero.

sen (which defines the critical values). For instance, with a  $t$ -test with critical values  $(-1.64, 1.64)$ , the size is 10%. (The size is sometime called the type I error.) This means that we run a 10% chance of wrongly rejecting a true null hypothesis. See Table 4.3.

	$H_0$ not rejected	$H_0$ rejected
$H_0$ is true	1 - size	size
$H_0$ is false	1 - power	power

Table 4.3: Size and power

The *power* is the probability of rejecting a false  $H_0$ . It should be high. Typically, it cannot be controlled (but some tests are better than others...). This power depends on how false  $H_0$  is, which we will never know. All we can do is to create (artificial) examples to get an idea of what the power would be for different tests and for different values of the true parameter  $\beta$ . For instance, with a  $t$ -test using the critical values  $-1.64$  and  $1.64$ , the power would be

$$\text{power} = \Pr(t \leq -1.64) + \Pr(t \geq 1.64). \quad (4.7)$$

(1 - power is sometimes called the type II error. This is the probability of not rejecting a

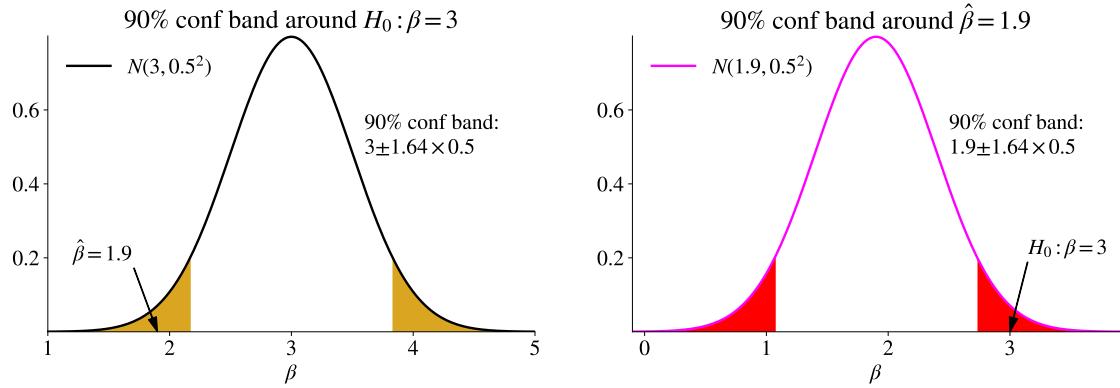


Figure 4.4: Confidence band around the null hypothesis or around the point estimate

false  $H_0$ .)

To make this more concrete, suppose we test the null hypothesis that the coefficient is equal to  $q$ , but the true value happens to be  $\beta$ . Since the OLS estimate,  $\hat{\beta}$  is distributed as  $N[\beta, \text{Std}(\hat{\beta})]$ , it must be the case that the  $t$ -stat is distributed as

$$t = \frac{\hat{\beta} - q}{\text{Std}(\hat{\beta})} \sim N\left(\frac{\beta - q}{\text{Std}(\hat{\beta})}, 1\right). \quad (4.8)$$

We can then calculate the power as the probability that  $t \leq -1.64$  or  $t \geq 1.64$ , when  $t$  has the distribution on the RHS in (4.8). Clearly, the results depend on what the true value  $\beta$  really is. See Figure 4.5.

**Example 4.8** If  $\beta = 3.6$ ,  $q = 3$  and  $\text{Std}(\hat{\beta}) = 0.5$ , then the power is 0.33.

## 4.4 Testing A Linear Combination

We can form linear combinations of the regressions coefficients and apply a t-test.

Let  $R$  be a  $1 \times k$  (row) vector that defines our linear combination and suppose we want to test  $R\beta = q$ . The estimate  $\hat{\beta}$  could be from a linear regression, but could equally well be from some other method. We can test the hypothesis by noting that

$$\text{Var}(R\hat{\beta}) = R \text{Var}(\hat{\beta})R', \quad (4.9)$$

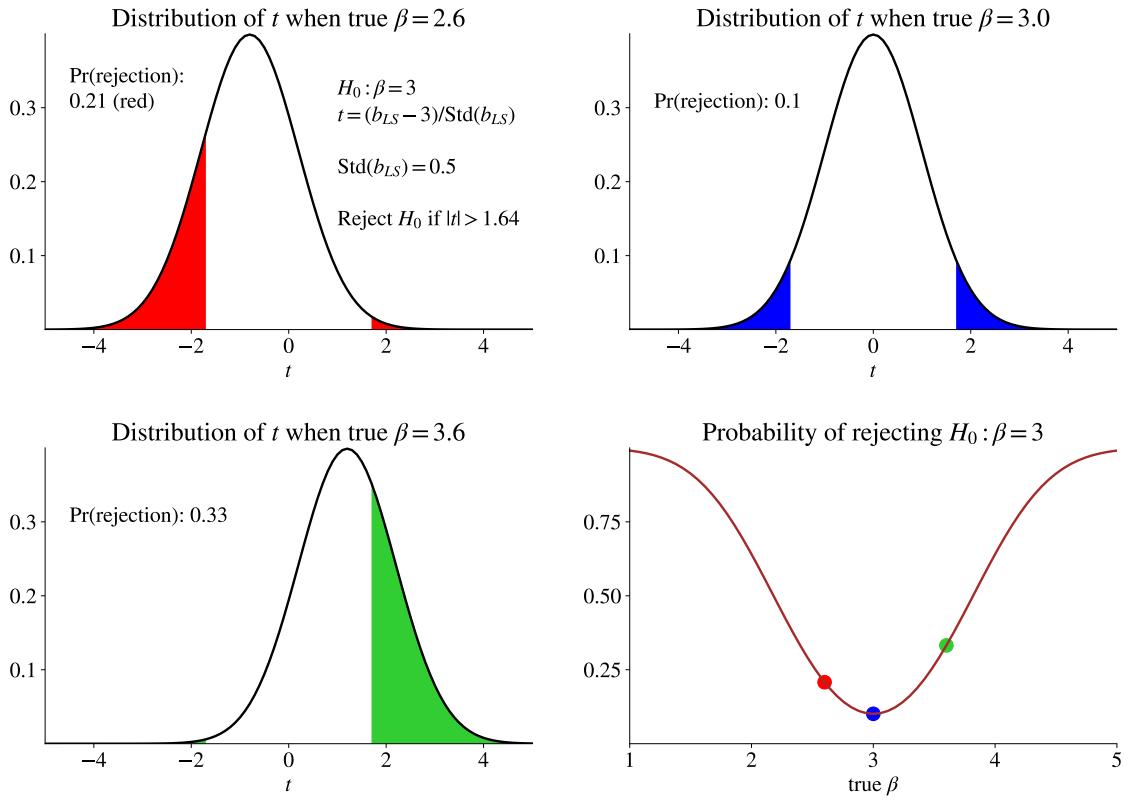


Figure 4.5: Power of t-test, assuming different true parameter values

is a scalar, so the t-test becomes

$$t = \frac{R\hat{\beta} - q}{\sqrt{R \text{Var}(\hat{\beta}) R'}} \sim N(0, 1). \quad (4.10)$$

**Example 4.9** (*Testing a difference*) For simplicity, suppose we have only two coefficients and want to test the difference. Then,  $R = [1 \ -1]$ . Suppose (again for simplicity) that  $\text{Var}(\hat{\beta}) = [\begin{smallmatrix} 1 & \rho \\ \rho & 1 \end{smallmatrix}]$ , where  $\rho = \text{Cov}(\hat{\beta}_1, \hat{\beta}_2)$ . Clearly,  $R \text{Var}(\hat{\beta}) R'$  equals  $\text{Var}(\hat{\beta}_1) + \text{Var}(\hat{\beta}_2) - 2 \text{Cov}(\hat{\beta}_1, \hat{\beta}_2)$  which here is  $2(1 - \rho)$ . A higher covariance means that  $\hat{\beta}_1$  and  $\hat{\beta}_2$  tend to move in the same direction so the difference has a small uncertainty. It is then easy to test the difference. The opposite is true when testing a sum (then  $R = [1 \ 1]$ ).

## 4.5 Joint Test of Several Coefficients

A joint test of several coefficients is different from testing the coefficients one at a time. For instance, suppose your economic hypothesis is that  $\beta_1 = 1$  and  $\beta_3 = 0$ . You could

clearly test each coefficient individually (by a t-test), but that may give conflicting results. In addition, it does not use the information in the sample as effectively as possible. It might well be the case that we cannot reject any of the hypotheses (that  $\beta_1 = 1$  and  $\beta_3 = 0$ ), but that a joint test might be able to reject it. Intuitively, a joint test is like exploiting the power of repeated sampling.

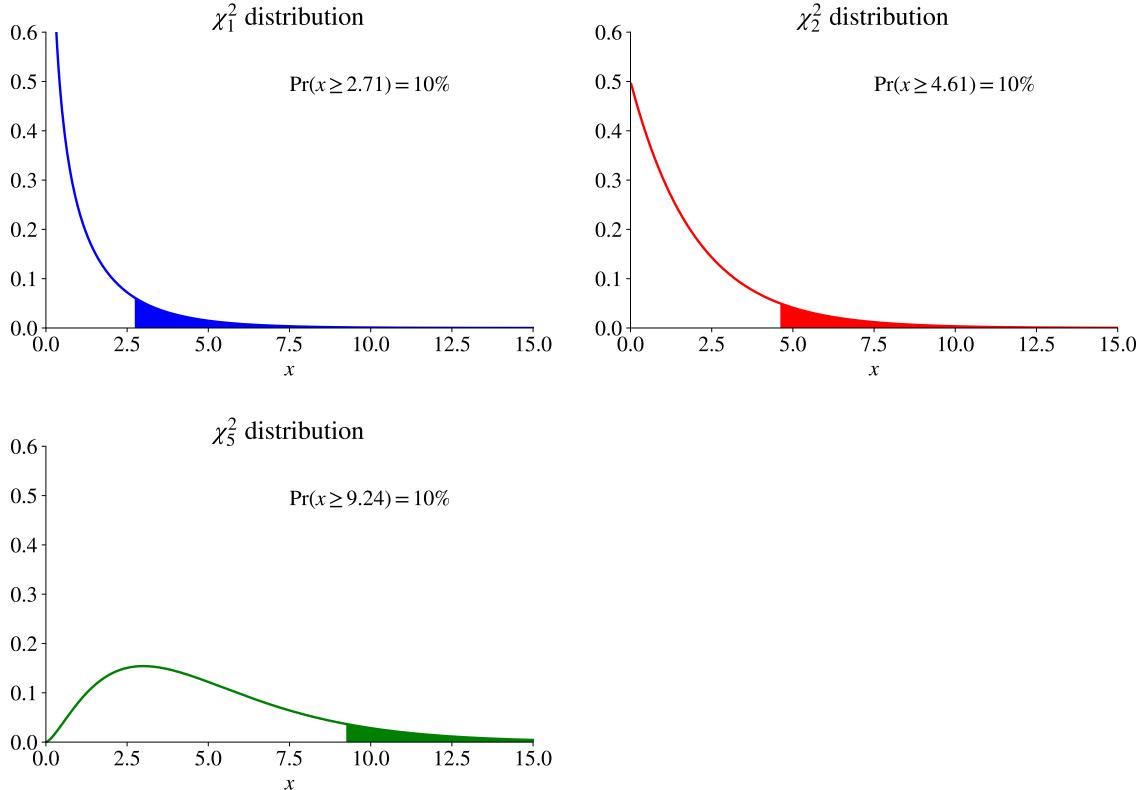


Figure 4.6: Density functions of  $\chi^2$  distributions with different degrees of freedom

A joint test makes use of the following remark.

**Remark 4.10 (Chi-square distribution)** If  $v$  is a zero mean vector with  $n$  elements which are jointly normally distributed ( $v \sim N(0, \Sigma)$ ), then

$$v' \Sigma^{-1} v \sim \chi_n^2.$$

As a special case, suppose the vector only has one element. In this case, the quadratic form can be written  $[v / \text{Std}(v)]^2$ , which is the square of a t-statistic.

**Example 4.11 (Quadratic form with a chi-square distribution)** If the  $2 \times 1$  vector  $v$  has

the following normal distribution

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} \sim N \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix} \right),$$

then the quadratic form

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix}' \begin{bmatrix} 1 & 0 \\ 0 & 1/2 \end{bmatrix} \begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = v_1^2 + v_2^2/2$$

has a  $\chi^2_2$  distribution. (In a more general example, the variables could be correlated.)

For instance, suppose we have estimated a model with three coefficients and the null hypothesis is

$$H_0 : \beta_1 = 1 \text{ and } \beta_3 = 0. \quad (4.11)$$

It is convenient to write this on matrix form as

$$\begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} \beta_1 \\ \beta_2 \\ \beta_3 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \text{ or more generally} \quad (4.12)$$

$$R\beta = q, \quad (4.13)$$

where  $q$  has  $J$  (here 2) rows. Notice that the covariance matrix of these linear combinations is then

$$\text{Var}(R\hat{\beta}) = R \text{Var}(\hat{\beta}) R', \quad (4.14)$$

where  $\text{Var}(\hat{\beta})$  denotes the covariance matrix of the coefficients. As before, the estimate  $\hat{\beta}$  could be from a linear regression, but could equally well be from some other method. Putting together these results we have the test static (a scalar)

$$(R\hat{\beta} - q)'[R \text{Var}(\hat{\beta}) R']^{-1}(R\hat{\beta} - q) \sim \chi^2_J. \quad (4.15)$$

This test statistic is compared to the critical values of a  $\chi^2_J$  distribution. (Alternatively, it can be put in the form of an  $F$  statistic, which is a small sample refinement.)

A particularly important case is the test of the joint hypothesis that all  $k - 1$  slope coefficients in the regression (that is, excluding the intercept) are zero. It can be shown that the test statistic for this hypothesis is (assuming your regression also contains an intercept)

$$TR^2/(1 - R^2) \sim \chi^2_{k-1}. \quad (4.16)$$

**Empirical Example 4.12** (*Test of all slopes*) See Tables 4.1 and 4.2.

**Example 4.13** (*Joint test*) Suppose  $H_0: \beta_1 = 0$  and  $\beta_3 = 0$ ;  $(\hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_3) = (2, 777, 3)$  and

$$R = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \text{ and } \text{Var}(\hat{\beta}) = \begin{bmatrix} 4 & 0 & 0 \\ 0 & 33 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \text{ so}$$

$$R \text{Var}(\hat{\beta}) R' = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 4 & 0 & 0 \\ 0 & 33 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 0 \\ 0 & 1 \end{bmatrix} = \begin{bmatrix} 4 & 0 \\ 0 & 1 \end{bmatrix}.$$

(We assume  $\text{Var}(\hat{\beta})$  is diagonal just because it makes it easier to invert.) Then, (4.15) is

$$\left( \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ 777 \\ 3 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right)' \begin{bmatrix} 4 & 0 \\ 0 & 1 \end{bmatrix}^{-1} \left( \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ 777 \\ 3 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \end{bmatrix} \right)$$

$$\begin{bmatrix} 2 & 3 \end{bmatrix} \begin{bmatrix} 0.25 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} 2 \\ 3 \end{bmatrix} = 10,$$

which is higher than the 10% critical value of the  $\chi^2_2$  distribution (which is 4.61).

**Remark 4.14** (\*An alternative form of (4.15)) Define the standardised values  $z = (R\hat{\beta} - q) / \text{Std}(R\hat{\beta} - q)$ . Then, (4.15) can be also be written  $z' \text{Corr}(z)^{-1} z$ .

**Remark 4.15** (*Power and size of a joint test\**) Suppose  $v \sim N(v_0, \Sigma)$ , where  $v_0$  might be non-zero. Then  $v' \Sigma^{-1} v \sim \chi^2_n(\lambda)$  with  $\lambda = v_0' \Sigma^{-1} v_0$  and where  $\chi^2_n(\lambda)$  is a non-central chi-square distribution with non-centrality parameter  $\lambda$ . (This distribution coincides with the traditional chi-square when  $\lambda = 0$ .) In particular, if  $R\beta - q = q_0$  (instead of zero), then the test static in (4.15) would have a  $\chi^2_J(\lambda)$  distribution with  $\lambda = q_0' [R \text{Var}(\hat{\beta}) R']^{-1} q_0$ . We could then calculate the power of the test in (4.15) for different values of  $q_0$ .

**Proof.** (of (4.16)) Recall that  $R^2 = \text{Var}(\hat{y}_t) / \text{Var}(y_t) = 1 - \text{Var}(\hat{u}_t) / \text{Var}(y_t)$ , where  $\hat{y}_t = x_t' \hat{\beta}$  and  $\hat{u}_t$  are the fitted value and residual respectively. We therefore get  $TR^2/(1 - R^2) = T \text{Var}(\hat{y}_t) / \text{Var}(\hat{u}_t)$ . To simplify the algebra, assume that both  $y_t$  and  $x_t$  are demeaned and that no intercept is used. (We get the same results, but after more work, if we relax this assumption.) In this case we can rewrite as  $TR^2/(1 - R^2) =$

$T\hat{\beta}' \text{Var}(x_t)\hat{\beta}/\sigma^2$ , where  $\sigma^2 = \text{Var}(\hat{u}_t)$ . If the iid assumptions are correct, then the variance-covariance matrix of  $\hat{\beta}$  is  $\text{Var}(\hat{\beta}) = [T \text{Var}(x_t)]^{-1}\sigma^2$ , so we get

$$\begin{aligned} TR^2/(1 - R^2) &= \hat{\beta}' T \text{Var}(x_t)/\sigma^2 \hat{\beta} \\ &= \hat{\beta}' \text{Var}(\hat{\beta})^{-1} \hat{\beta}. \end{aligned}$$

This has the same form as (4.15) with  $R = I$  and  $q = \mathbf{0}$  and  $J$  equal to the number of slope coefficients. ■

#### 4.5.1 A Joint Test of Several Coefficients: F-test\*

The joint test can also be cast in *terms of the F distribution* (which may have better small sample properties).

Divide (4.15) by  $J$  and replace  $\text{Var}(\hat{\beta})$  by the estimated covariance matrix, for instance,  $\hat{V} = \hat{\sigma}^2 \left( \sum_{t=1}^T x_t x_t' \right)^{-1}$  where we use  $\hat{V}$  to denote the estimate, but where we (as in reality) have to estimate the variance of the residuals by the sample variance of the fitted residuals,  $\hat{\sigma}^2$ . This gives

$$\frac{\left( R\hat{\beta} - q \right)' (R\hat{V}R')^{-1} \left( R\hat{\beta} - q \right)}{J} \sim F_{J,T-k}, \text{ where} \quad (4.17)$$

$$\hat{V} = \hat{\sigma}^2 \left( \sum_{t=1}^T x_t x_t' \right)^{-1}.$$

The test of the joint hypothesis that all  $k - 1$  slope coefficients in the regression (that is, excluding the intercept) are zero can be written (assuming your regression also contains an intercept)

$$\frac{R^2/(k-1)}{(1-R^2)/(T-k)} \sim F_{k-1,T-k}. \quad (4.18)$$

**Proof.** (of (4.17)) Equation (4.17) can also be written

$$\frac{(R\hat{\beta} - q)' \left[ R\sigma^2 \left( \sum_{t=1}^T x_t x_t' \right)^{-1} R' \right]^{-1} (R\hat{\beta} - q)/J}{\hat{\sigma}^2/\sigma^2}.$$

The numerator is a  $\chi_J^2$  variable divided by  $J$ . The denominator can be written  $\Sigma_{t=1}^T (\hat{u}_t/\sigma)^2/(T-k)$ . If the residuals are normally distributed (and independent across time), then this is a  $\chi_{T-k}^2$  variable (not  $\chi_T^2$  since we have estimated  $k$  parameters which influence  $\hat{u}_t$ ) divided by  $T - k$ . In addition, if the numerator and denominator are independent (which re-

quires that the residuals are independent of the regressors), then the ratio has an  $F_{J,T-k}$  distribution. ■

**Example 4.16 (Joint F test)** Continuing Example 4.13, and assuming that  $\hat{V} = \text{Var}(\hat{\beta})$ , we have a test statistic of  $10/2 = 5$ . Assume  $T - k = 50$ , then the 10% critical value (from an  $F_{2,50}$  distribution) is 2.4, so the null hypothesis is rejected at the 10% level.

## 4.6 Confidence Bands around a Forecast and a Forecast Error\*

Suppose we have estimated the linear model

$$y_t = x'_t \beta + u_t. \quad (4.19)$$

For a given (known) vector  $x_s$ , our *forecast* of  $y_s$  is

$$\mathbb{E}(y_s | x_s) = x'_s \hat{\beta}.$$

For a given  $x_s$ , this is just a linear combination of the estimated coefficients, so the result in (4.14) holds, but with  $x'_s$  replacing  $R$

$$\text{Var}[\mathbb{E}(y_s | x_s)] = x'_s \text{Var}(\hat{\beta}) x_s. \quad (4.20)$$

Instead, if we want the uncertainty about the *forecast error*

$$y_s - \mathbb{E}(y_s | x_s) = x'_s (\beta - \hat{\beta}) + u_s, \quad (4.21)$$

then we have to add the uncertainty of  $u_s$

$$\text{Var}[y_s - \mathbb{E}(y_s | x_s)] = x'_s \text{Var}(\hat{\beta}) x_s + \sigma^2. \quad (4.22)$$

(To show this last result, notice that  $x_s$  is not random and that  $u_s$  is not correlated with  $\hat{\beta}$  if the latter is estimated from a sample that does not contain period  $s$ .)

## 4.7 Testing (Nonlinear) Joint Hypotheses: The Delta Method\*

Consider an estimator  $\hat{\beta}_{k \times 1}$  which satisfies

$$\sqrt{T}(\hat{\beta} - \beta) \xrightarrow{d} N(0, W). \quad (4.23)$$

As before, the estimate  $\hat{\beta}$  could be from a linear regression, but could equally well be from some other method.

Suppose we want the asymptotic distribution of a function of  $\beta$

$$\gamma = f(\beta), \quad (4.24)$$

where  $f(.)$  has continuous first derivatives. The output from this function could be a vector. We can construct a test by noticing that a first-order Taylor approximation is

$$f(\hat{\beta}) - f(\beta) \approx P(\hat{\beta} - \beta), \quad (4.25)$$

where  $P$  is the matrix of partial derivatives (the Jacobian)

$$P = \begin{bmatrix} \frac{\partial f_1(\beta)}{\partial \beta_1} & \dots & \frac{\partial f_1(\beta)}{\partial \beta_k} \\ \vdots & \ddots & \vdots \\ \frac{\partial f_q(\beta)}{\partial \beta_1} & \dots & \frac{\partial f_q(\beta)}{\partial \beta_k} \end{bmatrix}, \quad (4.26)$$

where  $\partial f_i(\beta) / \partial \beta_j$  is the derivative of output  $i$  from the function  $f()$  with respect to parameter  $j$ . The derivatives can sometimes be found analytically, otherwise numerical differentiation can be used. In principle, the derivatives should be calculated at the true parameter values and using population moments of the data, but in practice we use the point estimates  $\hat{\beta}$  and using the existing sample.

It follows that, as a first order approximation, the variance-covariance matrix of  $f(\hat{\beta}) - f(\beta)$  is  $PWP'$ . In fact, asymptotically all higher-order terms can be disregarded. This means that, under that null hypothesis (that the true value is  $\gamma$ )

$$\sqrt{T}(f(\hat{\beta}) - \gamma) \xrightarrow{d} N(0, PWP'), \text{ where} \quad (4.27)$$

Now, a test can be done by using (4.27), similarly to the linear case. See below for some more details on the proof.

This result could also be expressed in terms of the variance-covariance matrix of  $\hat{\beta}$  (rather than of  $\sqrt{T}\hat{\beta}$ ) as

$$\text{if } \hat{\beta} \xrightarrow{a} N(\beta, V), \text{ then } f(\hat{\beta}) \xrightarrow{a} N(\gamma, PVP'), \quad (4.28)$$

where  $\xrightarrow{a}$  means “is asymptotically distributed as”.

**Example 4.17 (Testing a Sharpe ratio)** Stack the mean and variance as  $\beta = (\mu, \sigma^2)$ .

The Sharpe ratio is calculated as a function of  $\beta$

$$f(\beta) = \frac{\mu}{(\sigma^2)^{1/2}}, \text{ so } P = \begin{bmatrix} \frac{1}{\sigma} & \frac{-\mu}{2\sigma^3} \end{bmatrix}.$$

If  $\hat{\beta}$  is distributed as in (4.23), then (4.27) is straightforward to apply. Also, with the Sharpe ratios for two assets ( $i, j$ ) as outputs of  $f(\beta)$  and  $\beta = (\mu_i, \sigma_i^2, \mu_j, \sigma_j^2)$  we get

$$P = \begin{bmatrix} \frac{1}{\sigma_i} & \frac{-\mu_i}{2\sigma_i^3} & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma_j} & \frac{-\mu_j}{2\sigma_j^3} \end{bmatrix}.$$

**Empirical Example 4.18** (Test of Sharpe ratio) See Table 4.4 for a test of the Sharpe ratio of the US equity market.

SR	0.13
SR (ann.)	0.47
t-stat	3.09

Table 4.4: SR for the US equity market and its t-stat. Monthly US data 1970:01-2021:12. The annualised SR is  $SR\sqrt{12}$

**Example 4.19** (Linear function) When  $f(\beta) = R\beta$ , then the Jacobian is  $P = R$ , just like in (4.14).

**Example 4.20** (Testing a correlation of  $x_t$  and  $y_t$ ) Suppose you have estimated the variances of  $(x_t, y_t)$  and also their covariance. Stack the parameters in the vector  $\beta = [\sigma_{xx}, \sigma_{yy}, \sigma_{xy}]'$ . The correlation and the Jacobian is then

$$\rho(x, y) = f(\beta) = \frac{\sigma_{xy}}{\sigma_{xx}^{1/2}\sigma_{yy}^{1/2}}, \text{ so } P = \begin{bmatrix} -\frac{1}{2}\frac{\sigma_{xy}}{\sigma_{xx}^{3/2}\sigma_{yy}^{1/2}} & -\frac{1}{2}\frac{\sigma_{xy}}{\sigma_{xx}^{1/2}\sigma_{yy}^{3/2}} & \frac{1}{\sigma_{xx}^{1/2}\sigma_{yy}^{1/2}} \end{bmatrix}.$$

### Delta Method Example: Confidence Bands around a Mean-Variance Frontier

A point on the mean-variance frontier at a given expected return is a non-linear function of the means and the second moment matrix. It is therefore straightforward to apply the delta method to calculate a confidence band around the estimate.

**Empirical Example 4.21** (MVF from industry portfolios) Figure 4.7 (lower panel) shows GMM results. The uncertainty is lowest for the minimum variance portfolio. (This is related to the result that in a normal distribution, the uncertainty about an estimated variance is increasing in the true variance,  $\text{Var}(\sqrt{T}\hat{\sigma}^2) = 2\sigma^4$ .)

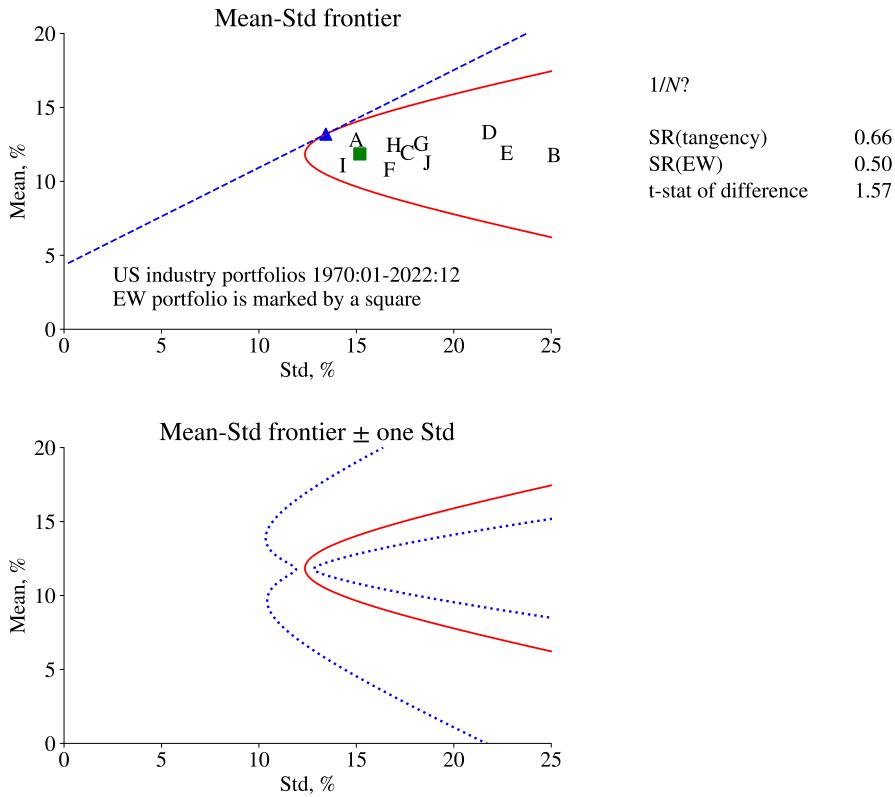


Figure 4.7: Mean-Variance frontier of US industry portfolios. Monthly returns are used in the calculations, but  $100\sqrt{12}\text{Variance}$  is plotted against  $100 * 12*\text{mean}$ .

### Delta Method Example: Testing the $1/N$ vs the Tangency Portfolio

It has been argued that the (naive)  $1/N$  diversification gives a portfolio performance which is not worse than an “optimal” portfolio (see, for instance, DeMiguel, Garlappi, and Uppal (2009)). One way of testing this is to compare the Sharpe ratios of the tangency and equally weighted portfolios. Both are functions of the first and second moments of the basic assets, so a delta method approach similar to the one for the MV frontier (see above) can be applied. Notice that this approach should incorporate the way (and hence the associated uncertainty) the first and second moments affect the portfolio weights of the tangency portfolio.

**Empirical Example 4.22** ( $1/N$  vs. the tangency portfolio) See Figure 4.7.

### Delta Method Example: Testing the Optimal Portfolio Weight

A mean-variance investor combines the riskfree asset with a mix (the tangency portfolio) of risky assets. The optimal portfolio weight on the latter is  $w = E R_m^e / [k \text{Var}(R_m^e)]$ .

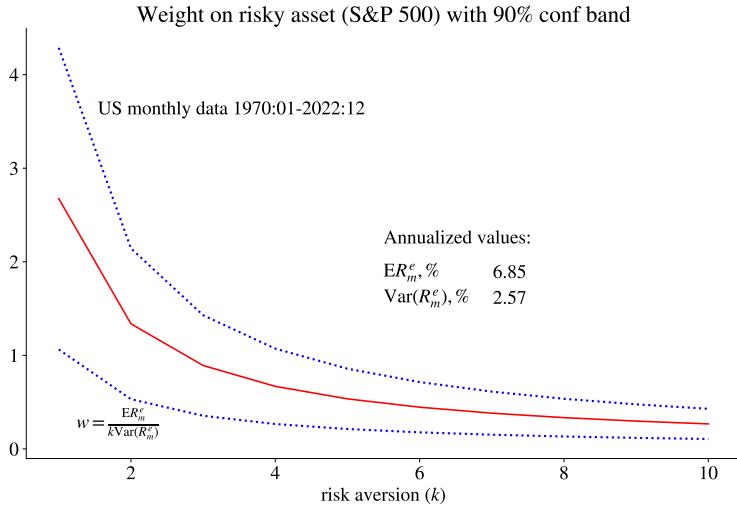


Figure 4.8: Portfolio choice for different risk aversions, with confidence band

where  $R_m^e$  denotes the excess return of the tangency portfolio. If we have estimates and their covariance matrix of  $\mathbb{E} R_m^e$  and  $\text{Var}(R_m^e)$ , then it is straightforward to construct a confidence band around  $w$ .

**Empirical Example 4.23** (*Choosing between the riskfree and a single risky asset (S&P 500)*) See Figure 4.8.

**Proof.** (Sketch of a proof of (4.27), requiring some asymptotics\*) By the mean value theorem we have

$$f(\hat{\beta}) = f(\beta) + \frac{\partial f(\beta^*)}{\partial \beta'} (\hat{\beta} - \beta),$$

where the derivatives are evaluated at  $\beta^*$  which is (weakly) between  $\hat{\beta}$  and  $\beta$ . Premultiply by  $\sqrt{T}$  and rearrange as

$$\sqrt{T}[f(\hat{\beta}) - f(\beta)] = \frac{\partial f(\beta^*)}{\partial \beta'} \sqrt{T}(\hat{\beta} - \beta_0).$$

If  $\hat{\beta}$  is consistent ( $\text{plim } \hat{\beta} = \beta$ ) and  $\partial f(\beta^*) / \partial \beta'$  is continuous, then (by Slutsky's theorem) the probability limit of the derivatives is  $\partial g(\beta) / \partial \beta'$  (that is, evaluated at the true  $\beta$  —and thus a constant). If  $\sqrt{T}(\hat{\beta} - \beta_0)$  is asymptotically normally distributed, then (by the continuous mapping theorem) this carries over to the left hand side. ■

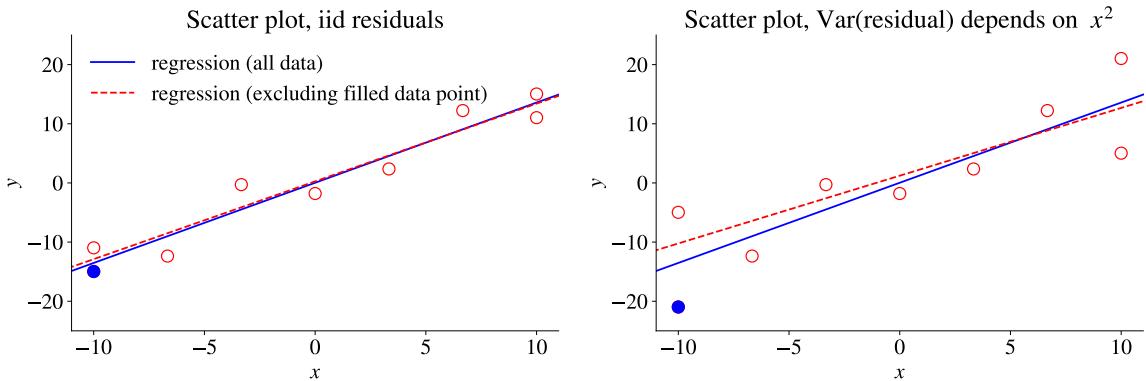


Figure 4.9: Effect of heteroskedasticity on uncertainty about regression line

## 4.8 Heteroskedasticity

Suppose we have a regression model

$$y_t = x'_t b + u_t, \text{ where } E u_t = 0 \text{ and } \text{Cov}(x_{it}, u_t) = 0. \quad (4.29)$$

In the standard case we assume that  $u_t$  is iid (independently and identically distributed), which rules out variation in the volatility of the residual (heteroskedasticity).

In case the residuals actually are heteroskedastic, least squares (LS) is nevertheless a useful estimator: it is still consistent (we get the correct values as the sample becomes really large). However, the standard expression for the standard errors of the coefficients is, except in a special case, not correct. This is illustrated in Table 17.3, which shows results from simulations.

To test for heteroskedasticity, we can use *White's test of heteroskedasticity*. The test assumes that the fitted residuals are from consistent estimates (there is little point in testing residuals from false models...) and that the regressors may be stochastic variables.

The null hypothesis is homoskedasticity, and the alternative hypothesis is the kind of heteroskedasticity which can be explained by the levels, squares, and cross products of the regressors—clearly a special form of heteroskedasticity. The reason for this specification is that if the squared residuals are uncorrelated with the squared regressors, then the usual LS covariance matrix applies—even if the residuals have some other sort of heteroskedasticity (this is the special case mentioned before).

To implement White's test, let  $w_t$  be a vector of the squares and cross products of the regressors (be sure to have a constant among the regressors). The test is then to run a

regression of squared fitted residuals on  $w_t$

$$\hat{u}_t^2 = w_t' \gamma + v_t, \quad (4.30)$$

and to test if all the slope coefficients (not the intercept) in  $\gamma$  are zero. This can be done by using the fact that  $TR^2/(1 - R^2) \sim \chi_p^2$ ,  $p = \dim(w_t) - 1$ . (Some authors prefer to use  $TR^2$  instead, but the difference is likely to be small.)

There are several versions of White's test: (a) using only the linear terms (also called the Breusch-Pagan test); (b) using only the linear and quadratic terms (not the cross products); (c) using only a subset of the regressors.

**Example 4.24** (White's test) If the regressors include  $(1, x_{1t}, x_{2t})$  then  $w_t$  in (4.30) is the vector  $(1, x_{1t}, x_{2t}, x_{1t}^2, x_{1t}x_{2t}, x_{2t}^2)$ .

**Remark 4.25** (\*Duplicate variables in  $w_t$ . If  $x_t$  contains a dummy variable, then its square will be the same. You can still use the same test statistic, but  $p$  should be the number of linearly independent variables in  $w_t$  minus 1.)

**Empirical Example 4.26** (Test of heteroskedasticity) See Tables 4.1 and 4.2.

$\alpha :$	$\underline{\gamma = 0}$		$\underline{\gamma = 1}$	
	0	1	0	1
Simulated	7.1	18.8	13.5	25.1
OLS formula	7.1	13.3	13.4	19.3
White's	7.0	18.5	13.3	24.3
Bootstrap	7.1	18.5	13.4	24.3
Bootstrap 2	7.0	18.5	13.3	24.3
Jackknife	7.1	18.9	13.5	24.8
FGLS	7.5	17.3	14.0	24.2

Table 4.5: Standard error of OLS slope (%) under heteroskedasticity (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t \sim N(0, \sigma_t^2)$ , with  $\sigma_t^2 = (1 + \gamma|z_t| + \alpha|x_t|)^2$ , where  $z_t$  is iid  $N(0,1)$  and independent of  $x_t$ . Sample length: 200. Number of simulations: 25000. The bootstrap draws pairs  $(y_s, x_s)$  with replacement while bootstrap 2 is a wild bootstrap.

There are two ways to handle heteroskedasticity in the residuals. First, we could use some other estimation method than LS that incorporates the structure of the heteroskedasticity. For instance, combining the regression model (4.29) with an ARCH structure of

the residuals—and estimating the whole thing with maximum likelihood (MLE). As a by-product we get the correct standard errors—provided the assumed distribution (in the likelihood function) is correct. Second, we could stick to OLS, but use another expression for the variance of the coefficients: a heteroskedasticity consistent covariance matrix, among which “*White’s covariance matrix*” is the most common. (There is also a third possible solution: using GLS, but that is often a non-robust approach.)

To understand the construction of White’s covariance matrix, recall that the variance of  $\hat{\beta}$  is found from

$$\hat{\beta} = \beta + S_{xx}^{-1} (x_1 u_1 + x_2 u_2 + \dots x_T u_T), \quad (4.31)$$

where  $S_{xx} = \sum_{t=1}^T x_t x_t'$ . If we assume that the residuals are uncorrelated with each other, then

$$\begin{aligned} \text{Var}(\hat{\beta}) &= S_{xx}^{-1} (x_1 x_1' \sigma_1^2 + x_2 x_2' \sigma_2^2 + \dots x_T x_T' \sigma_T^2) S_{xx}^{-1} \\ &= S_{xx}^{-1} \underbrace{\sum_{t=1}^T x_t x_t' \sigma_t^2}_S S_{xx}^{-1}. \end{aligned} \quad (4.32)$$

(Notice that  $S_{xx}$  and  $S$  denote very different things.)

**Remark 4.27** (*Background to (4.32)–(4.33)*) As discussed in earlier chapters, the variance-covariance matrix (4.32) can be motivated by either (a) assuming that  $x_t$  are fixed regressors or (b) by asymptotic results. A more precise statement is thus that  $S_{xx}^{-1} \hat{S} S_{xx}^{-1}$  is an estimate of the variance-covariance matrix. In practice, this gives the same estimate of the variance-covariance matrix as under assumption (a).

Expression (4.32) cannot be simplified further since  $\sigma_t$  is not constant—and also related to  $x_t^2$ . The idea of White’s estimator is to estimate  $S$  by

$$\hat{S} = \sum_{t=1}^T x_t x_t' \hat{u}_t^2. \quad (4.33)$$

It is straightforward to show that the standard expression for the variance underestimates the true variance when there is a positive relation between  $x_t^2$  and  $\sigma_t^2$  (and vice versa). The intuition is that much of the precision (low variance of the estimates) of OLS comes from data points with extreme values of the regressors: think of a scatter plot and notice that the slope depends a lot on fitting the data points with very low and very high values of the regressor. This nice property is destroyed if the data points with extreme

values of the regressor also have lots of noise (high variance of the residual). See Figure 4.9 and Table 17.3.

White's covariance matrix should be applied when White's test (4.30) indicates problems, otherwise perhaps not. While White's covariance estimator provides safety against heteroskedasticity, it also comes at a cost: estimating the  $S$  matrix as in (4.33) risks introducing more noise.

**Remark 4.28** (*Jackknife covariance matrix*) *The jackknife covariance matrix is: (a) reestimate the model  $T$  times, each time with one observation excluded (first exclude observation 1, then put it back and instead exclude observation 2,...), to get a  $T \times K$  matrix of estimates; (b) calculate the covariance matrix of the  $K$  series; (c) multiply the result by  $T - 1$ . This typically leads to results that are very similar to those from (4.32)-(4.33).*

**Remark 4.29** (*Standard OLS vs White's variance\**) *For simplicity, consider the case of only one regressor. If  $x_t^2$  is not related to  $\sigma_t^2$ , then we could write the last term in (4.32) as*

$$\begin{aligned}\sum_{t=1}^T x_t^2 \sigma_t^2 &= \frac{1}{T} \sum_{t=1}^T \sigma_t^2 \sum_{t=1}^T x_t^2 \\ &= \overline{\sigma^2} \sum_{t=1}^T x_t^2\end{aligned}$$

where  $\overline{\sigma^2}$  is the average variance, typically estimated as  $\sum_{t=1}^T u_t^2 / T$ . That is, it is the same as for standard OLS. In addition, notice that

$$\sum_{t=1}^T x_t^2 \sigma_t^2 > \frac{1}{T} \sum_{t=1}^T \sigma_t^2 \sum_{t=1}^T x_t^2$$

if  $x_t^2$  is positively related to  $\sigma_t^2$  (and vice versa). For instance, with  $(x_1^2, x_2^2) = (10, 1)$  and  $(\sigma_1^2, \sigma_2^2) = (5, 2)$ ,  $\sum_{t=1}^T x_t^2 \sigma_t^2 = 10 \times 5 + 1 \times 2 = 52$  while  $\frac{1}{T} \sum_{t=1}^T \sigma_t^2 \sum_{t=1}^T x_t^2 = \frac{1}{2}(5 + 2)(10 + 1) = 38.5$ .

**Remark 4.30** (*GLS\**) *With heteroskedasticity and/or autocorrelation, OLS is still consistent and we can adjust the covariance matrix of the coefficients. However, OLS is less efficient (higher uncertainty of the coefficients) than GLS (Generalized Least Squares) is. The basic idea of GLS is transform regression equation so*

$$y_t^* = x_t^{*\prime} \beta + \varepsilon_t^*,$$

have iid residuals. Estimating  $\beta$  with LS on this transformation is efficient (called GLS) and the traditional expressions of the covariance matrix of the coefficients can be used.

For instance, with heteroskedasticity, the transformation is

$$\frac{y_t}{\sigma_t} = \frac{x'_t}{\sigma_t} \beta + \frac{\varepsilon_t}{\sigma_t}.$$

(Yes, also the constant is divided by  $\sigma_t$ .) Notice that  $\varepsilon_t/\sigma_t$  has a constant variance (equal to one). In practice we don't know  $\sigma_t$ , so we first estimate it (the method is then called "feasible" GLS, FGLS.) FGLS may improve the efficiency, but can be unstable if we model the heteroskedasticity wrongly. A commonly applied approach is the following (a) let  $\hat{\varepsilon}_t$  be the residual from the OLS regression; (b) regress  $\ln(\hat{\varepsilon}_t^2)$  on the regressors and all the squares (and cross-products of them); (c) let  $z_t$  be the fitted values from the regression in (b) and set  $\sigma_t = \sqrt{\exp(z_t)}$ .

## 4.9 Autocorrelation

Autocorrelation of the residuals ( $\text{Cov}(u_t u_{t-s}) \neq 0$ ) is also a violation of the iid assumptions underlying the standard expressions for the variance of  $\hat{\beta}$ . In this case, LS is typically still consistent (exceptions: when the lagged dependent variable is a regressor), but the variances are again wrong.

The typical effect of positively autocorrelated residuals is to increase the uncertainty about the OLS estimates—above what is indicated by the traditional standard errors based on the iid assumption. This is perhaps easiest to understand in the case of estimating the mean of a data series, that is, when regressing a data series on a constant only. If the residual is positively autocorrelated (have long swings), then the sample mean can deviate from the true mean for an extended period of time—perhaps for most of a sample: the estimate is imprecise. See Figure 4.10 for an illustration.

There are several straightforward tests of autocorrelation—all based on using the fitted residuals. The tests all assume that the fitted residuals are from consistent estimates. The null hypothesis is no autocorrelation. First, estimate the autocorrelations of the fitted residuals as

$$\rho_s = \text{Corr}(\hat{u}_t, \hat{u}_{t-s}), s = 1, \dots, L. \quad (4.34)$$

Second, test autocorrelation  $s$  by using the fact that  $\sqrt{T} \hat{\rho}_s$  has a standard normal distribution (in large samples)

$$\sqrt{T} \hat{\rho}_s \sim N(0, 1). \quad (4.35)$$

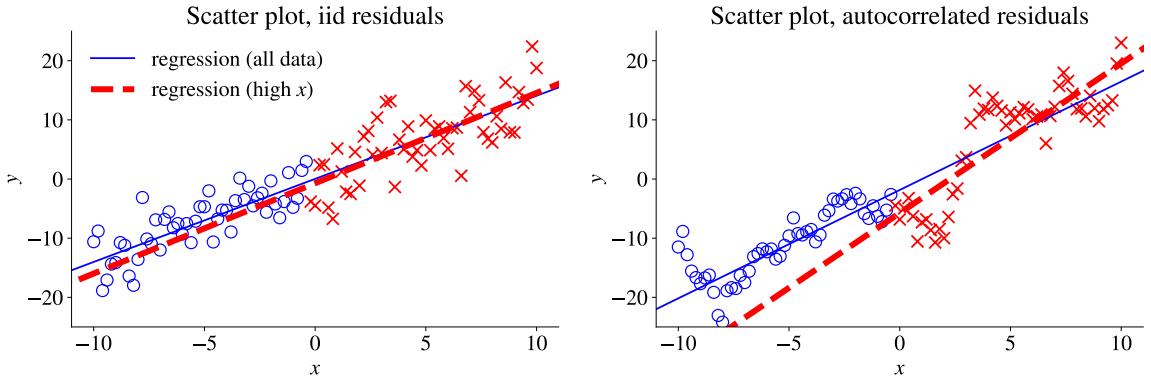


Figure 4.10: Effect of autocorrelation on uncertainty about regression line

To extend (4.35) to higher-order autocorrelation, use the Box-Pierce test

$$Q_L = T \sum_{s=1}^L \hat{\rho}_s^2 \xrightarrow{d} \chi_L^2. \quad (4.36)$$

**Empirical Example 4.31** (*Test of autocorrelation*) See Tables 4.1 and 4.2.

An alternative for testing the first autocorrelation coefficient is the Durbin-Watson. The test statistic is (approximately)

$$DW \approx 2 - 2\hat{\rho}_1, \quad (4.37)$$

and the null hypothesis is rejected in favour of positive autocorrelation if  $DW < 1.5$  or so (depending on sample size and the number of regressors).

These tests can also be applied to each of the elements in  $x_t u_t$  (instead of just  $u_t$ ), since it is actually autocorrelations of these cross terms that matter most (see the discussion below).

If there is autocorrelation, then we can choose to estimate a fully specified model (including how the autocorrelation is generated) by MLE or we can stick to OLS but apply an autocorrelation consistent covariance matrix—for instance, the “*Newey-West covariance matrix*”

To understand the Newey-West covariance matrix, notice that the variance of  $\text{Var}(\hat{\beta})$  is

$$\text{Var}(\hat{\beta}) = S_{xx}^{-1} \underbrace{\text{Var}(x_1 u_1 + x_2 u_2 + \dots + x_T u_T)}_S S_{xx}^{-1}. \quad (4.38)$$

$\rho :$	0.0	0.75
Simulated	5.9	23.0
OLS formula	5.8	8.7
Newey-West	5.7	16.3
VARHAC	5.7	22.4
Bootstrapped	5.5	19.6
FGLS	5.9	23.0

Table 4.6: Standard error of OLS intercept (%) under autocorrelation (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t = \rho\epsilon_{t-1} + \xi_t$ ,  $\xi_t$  is iid  $N()$ . NW uses 5 lags. VARHAC uses 5 lags and a VAR(1). The bootstrap uses blocks of size 20. Sample length: 300. Number of simulations: 25000.

$\rho :$	$\kappa = 0.0$		$\kappa = 0.75$	
	0.0	0.75	0.0	0.75
Simulated	5.8	8.7	3.9	10.9
OLS formula	5.8	8.6	3.9	5.8
Newey-West	5.7	8.4	3.8	8.9
VARHAC	5.7	8.5	3.8	10.5
Bootstrapped	5.8	8.5	3.8	10.1
FGLS	5.8	4.7	3.9	5.9

Table 4.7: Standard error of OLS slope (%) under autocorrelation (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t = \rho\epsilon_{t-1} + \xi_t$ ,  $\xi_t$  is iid  $N()$ .  $x_t = \kappa x_{t-1} + \eta_t$ ,  $\eta_t$  is iid  $N()$ . NW uses 5 lags. VARHAC uses 5 lags and a VAR(1). The bootstrap uses blocks of size 20. Sample length: 300. Number of simulations: 25000.

(Remark 4.27) applies here as well.)

However, there might be correlation across time periods, so the  $S$  term in the middle needs to account for terms like  $\text{Cov}(x_t u_t, x_{t-s} u_{t-s})$ . For instance, for  $T = 3$  the  $S$  term is

$$S = \text{Var}(x_1 u_1) + \text{Var}(x_2 u_2) + \text{Var}(x_3 u_3) + 2 \text{Cov}(x_2 u_2, x_1 u_1) + 2 \text{Cov}(x_3 u_3, x_2 u_2) + 2 \text{Cov}(x_3 u_3, x_1 u_1). \quad (4.39)$$

When data is uncorrelated across time (observations), then all the covariance terms are zero. With autocorrelation, they may not be. For a general  $T$ , the  $S$  term is

$$S = \sum_{t=1}^T \text{Var}(x_t u_t) + 2 \sum_{s=1}^m \sum_{t=s+1}^T \text{Cov}(x_t u_t, x_{t-s} u_{t-s}), \quad (4.40)$$

where  $m$  denotes the number of covariance terms that might be non-zero (at most,  $m = T - 1$ ).

It is clear from (4.40) that what really counts is not so much the autocorrelation in  $u_t$  per se, but the autocorrelation of  $x_t u_t$ . If this is positive, then the standard expression underestimates the true variance of the estimated coefficients (and vice versa). For instance, the autocorrelation of  $x_t u_t$  is likely to be positive when both the residual and the regressor are positively autocorrelated. (Notice that a constant,  $x_t = 1$  is extremely positively autocorrelated, so autocorrelation of the residual along is enough to cause problems with the intercept.) In contrast, when the regressor has no autocorrelation, then the product does not either. This is illustrated in Tables 9.5 – 4.7.

The idea of the Newey-West estimator is to estimate  $S$  by (with several regressors)

$$\hat{S} = A_0 + \sum_{s=1}^m \left(1 - \frac{s}{m+1}\right)(A_s + A'_s), \text{ where} \quad (4.41)$$

$$A_s = \sum_{t=s+1}^T x_t x'_{t-s} \hat{u}_t \hat{u}_{t-s}. \quad (4.42)$$

The weights  $1-s/(m+1)$  are close to 1 for small lags ( $s$  values), but decline linearly (tent shaped weights) to zero. The point of using such weights is to make sure that the  $\hat{S}$  matrix remains invertible (to show this is somewhat involved). This suggests that  $m$  should be somewhat larger than last lag with significant autocorrelation. However, a common rule of thumb is to use round  $m = \text{floor}(0.75T^{1/3})$ , where  $\text{floor}()$  means rounding down to nearest integer (and alternative rule is  $m = \text{floor}(4(T/100)^{2/9})$ ).

For instance, with only one lag ( $m = 1$ ) the calculation is (with several regressors)

$$\hat{S} = \sum_{t=1}^T x_t x'_t \hat{u}_t^2 + \sum_{t=2}^T \left(1 - \frac{1}{2}\right) (x_t x'_{t-1} + x_{t-1} x'_t) \hat{u}_t \hat{u}_{t-1}, \quad (4.43)$$

and by excluding all lags (setting  $m = 0$ ), the Newey-West estimator coincides with White's estimator

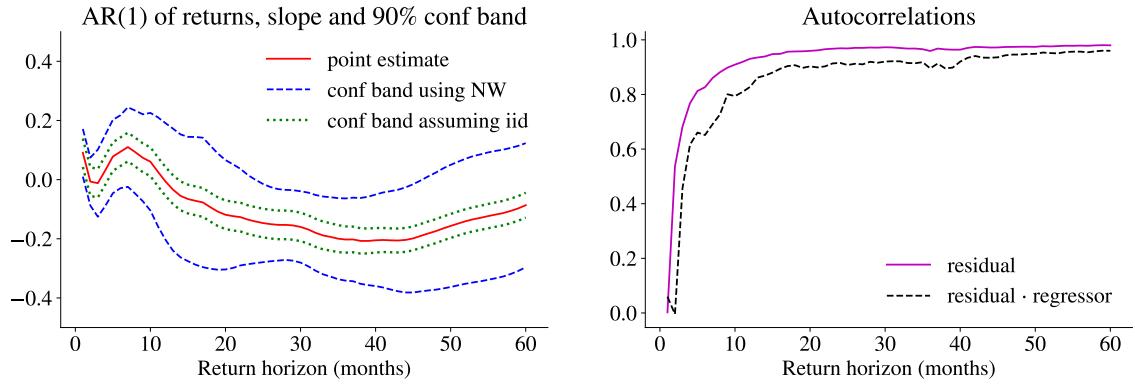
$$\hat{S} = \sum_{t=1}^T x_t x'_t \hat{u}_t^2. \quad (4.44)$$

Hence, Newey-West estimator handles also heteroskedasticity.

**Remark 4.32 (VARHAC\*)** The VARHAC estimator of the covariance matrix (see Andrews and Monahan (1992)) is to first fit a VAR( $p$ ) to  $z_t = x_t \hat{u}_t$

$$z_t = A_0 + \sum_{i=1}^p A_i z_{t-i} + \varepsilon_t$$

and then calculate  $D = I - \sum_{i=1}^p A_i$ . Then,  $\hat{S} = D^{-1} \hat{S}^\varepsilon D^{-1}$ , where  $\hat{S}^\varepsilon$  is Newey-West



US stocks, monthly excess log returns, 1926:01-2022:12, overlapping data

Figure 4.11: Slope coefficient, LS vs Newey-West standard errors

estimate applied to  $\hat{\epsilon}_t$  only (use  $\hat{\epsilon}_t$  instead of  $x_t \hat{u}_t$  in (4.41)).

**Empirical Example 4.33** (*Autocorrelation from overlapping return periods*) Figures 4.11 –4.12 are empirical examples of the importance of using the Newey-West method rather than relying of the iid assumptions. In both cases, the residuals have strong positive autocorrelation.

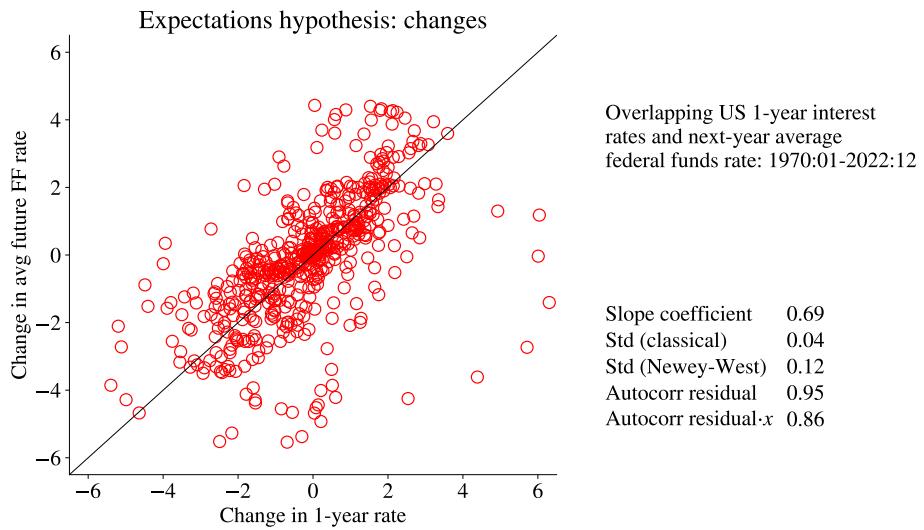


Figure 4.12: US 12-month interest and average federal funds rate (next 12 months)

The Newey-West approach should be applied when the tests of the residuals indicate

autocorrelation, otherwise probably not. The method involves estimating lots of parameters in the  $S$  matrix—and this can in itself introduce noise and uncertainty.

**Remark 4.34** (*GLS\**) *With first-order autocorrelation, ( $\varepsilon_t = \rho\varepsilon_{t-1} + v_t$ , where  $v_t$  is iid), we can implement FGLS by doing a “quasi-difference” of the regression equation*

$$y_t - \rho y_{t-1} = (x_t - \rho x_{t-1})' \beta + (\varepsilon_t - \rho \varepsilon_{t-1}).$$

*This new residual,  $\varepsilon_t - \rho \varepsilon_{t-1}$ , is iid. In practice we don't know  $\rho$ , so we first estimate it.*

# Chapter 5

## A System of OLS Regressions

Reference: Wooldridge (2010) 7.3; Greene (2018) 10

More advanced material is denoted by a star (\*). It is not required reading.

### 5.1 A System of Two OLS Regressions

Consider regressions for two different dependent variables ( $y_{1t}$  and  $y_{2t}$ , for instance, the returns on two different assets) on the same set of regressors ( $x_t$ )

$$y_{1t} = x_t' \beta_1 + u_{1t} \quad (5.1)$$

$$y_{2t} = x_t' \beta_2 + u_{2t}, \quad (5.2)$$

where  $\beta_1$  is the vector of regression coefficients for  $y_{1t}$  and  $\beta_2$  for  $y_{2t}$ .

It is straightforward to show (see below) that if the residuals are iid and independent of all regressors but we allow for  $\text{Cov}(u_{1t}, u_{2t}) \neq 0$ , then

$$\text{Var} \left( \begin{bmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{bmatrix} \right) = \begin{bmatrix} \sigma_{11} S_{xx}^{-1} & \sigma_{12} S_{xx}^{-1} \\ \sigma_{21} S_{xx}^{-1} & \sigma_{22} S_{xx}^{-1} \end{bmatrix}, \quad (5.3)$$

where  $\sigma_{ij} = \text{Cov}(u_{it}, u_{jt})$  and where  $S_{xx} = \sum_{t=1}^T x_t x_t'$ .

**Remark 5.1** (Background to (5.3)) As discussed in earlier chapters, the variance-covariance matrix (5.3) can be motivated by either (a) assuming that  $x_t$  are fixed regressors or (b) by asymptotic results. A more precise statement is thus that  $\hat{\sigma}_{ij} S_{xx}^{-1}$  is an estimate of the variance-covariance matrix. In practice, this gives the same estimate of the variance-covariance matrix as under assumption (a).

More generally, when the residuals are heteroskedastic or autocorrelated,

$$\text{Var} \begin{pmatrix} \hat{\beta}_1 \\ \hat{\beta}_2 \end{pmatrix} = \begin{bmatrix} S_{xx}^{-1} & \mathbf{0} \\ \mathbf{0} & S_{xx}^{-1} \end{bmatrix} \Omega \begin{bmatrix} S_{xx}^{-1} & \mathbf{0} \\ \mathbf{0} & S_{xx}^{-1} \end{bmatrix}, \text{ where} \quad (5.4)$$

$$\begin{aligned} \Omega &= \text{Var} \left( \sum_{t=1}^T \begin{bmatrix} x_t u_{1t} \\ x_t u_{2t} \end{bmatrix} \right) \\ &= \begin{bmatrix} \text{Var}(\Sigma x_t u_{1t}) & \text{Cov}(\Sigma x_t u_{1t}, \Sigma x_t u_{2t}) \\ \text{Cov}(\Sigma x_t u_{2t}, \Sigma x_t u_{1t}) & \text{Var}(\Sigma x_t u_{2t}) \end{bmatrix}. \end{aligned} \quad (5.5)$$

The  $\Omega$  matrix (which is  $2k \times 2k$  if there are  $k$  regressors in  $x_t$ ) could be estimated with the methods of White or Newey-West.

Extensions to more than two regression equations are straightforward.

**Proof.** (of (5.3)–(5.5)) Similarly to the single-equation OLS, we can write

$$\begin{aligned} \hat{\beta}_1 &= \beta_1 + S_{xx}^{-1} \sum_{t=1}^T x_t u_{1t} \\ \hat{\beta}_2 &= \beta_2 + S_{xx}^{-1} \sum_{t=1}^T x_t u_{2t} \end{aligned}$$

The variance (matrix) of  $\hat{\beta}_1$  or of  $\hat{\beta}_2$  follows the same pattern as for single-equation OLS. In contrast, the covariance (matrix) is

$$\text{Cov}(\hat{\beta}_1, \hat{\beta}_1) = S_{xx}^{-1} \text{Cov}(\sum_{t=1}^T x_t u_{1t}, \sum_{t=1}^T x_t u_{2t}) S_{xx}^{-1}.$$

Together, this gives (5.4)–(5.5). If the residuals are iid and independent of the regressors, then  $\Omega$  simplifies to

$$\Omega = \begin{bmatrix} \sigma_{11} S_{xx} & \sigma_{12} S_{xx} \\ \sigma_{21} S_{xx} & \sigma_{22} S_{xx} \end{bmatrix},$$

which gives (5.3). ■

## 5.2 A System of $n$ OLS Regressions

**Remark 5.2** (*Kronecker product*) Let  $\otimes$  denote the Kronecker product, that is, if  $A$  and  $B$  are matrices, then

$$A \otimes B = \begin{bmatrix} a_{11}B & \cdots & a_{1n}B \\ \vdots & & \vdots \\ a_{m1}B & \cdots & a_{mn}B \end{bmatrix}.$$

For instance, with

$$A = \begin{bmatrix} 1 & 3 \\ 2 & 4 \end{bmatrix} \text{ and } B = \begin{bmatrix} 10 & 11 \end{bmatrix}, \text{ we get } A \otimes B = \begin{bmatrix} 10 & 11 & 30 & 33 \\ 20 & 22 & 40 & 44 \end{bmatrix}.$$

Let  $\hat{\theta}$  be the vector of where  $\hat{\beta}_1, \hat{\beta}_2, \dots, \hat{\beta}_n$  are stacked (equation 1 first, then equation 2, etc).

With iid residuals the variance-covariance matrix (instead of (5.3)) is

$$\text{Var}(\hat{\theta}) = \Sigma \otimes S_{xx}^{-1}, \quad (5.6)$$

where  $\Sigma = \text{Var}(u_t)$  is the  $n \times n$  variance-covariance matrix of the  $n$  residuals.

Similarly, with non-iid residuals we get (instead of (5.4))

$$\text{Var}(\hat{\theta}) = (I_n \otimes S_{xx}^{-1}) \Omega (I_n \otimes S_{xx}^{-1}), \quad (5.7)$$

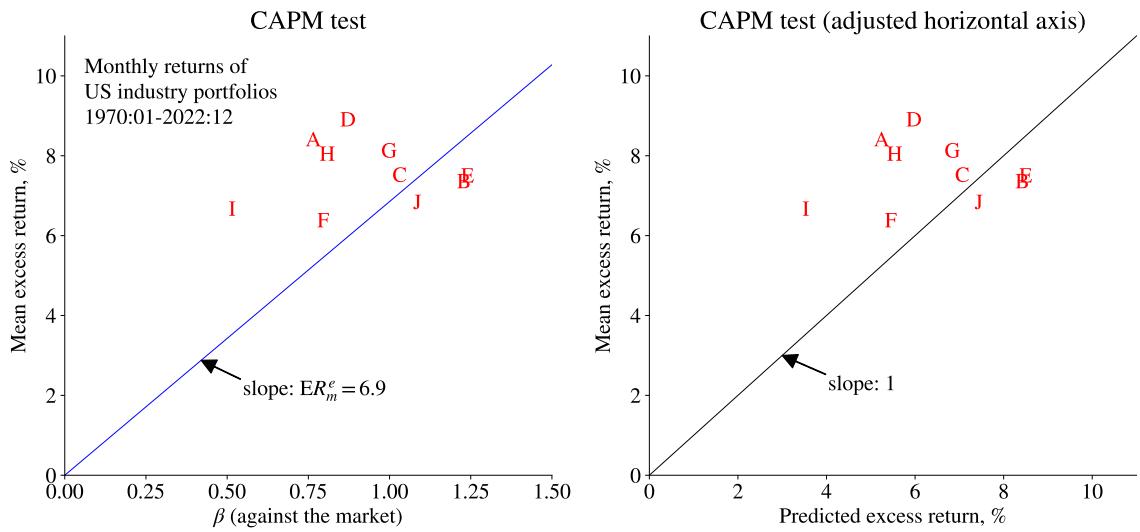
where  $I_n$  is the  $n \times n$  identity matrix. Let  $u_t$  be the vector of the  $n$  residuals in period  $t$  ( $u_{1t}, u_{2t}, \dots, u_{nt}$ ). Then,  $\Omega$  is (instead of (5.5))

$$\Omega = \text{Var} \left( \sum_{t=1}^T u_t \otimes x_t \right), \quad (5.8)$$

which is an  $nk \times nk$  matrix which can be estimated by the methods of White or Newey-West.

**Remark 5.3 (Estimating  $\Omega$ )** To estimate  $\Omega$  in (5.8), create an  $T \times nk$  matrix. Let first  $k$  columns of row  $t$  be  $u_{1t}x'_t$ , the second  $k$  columns be  $u_{2t}x'_t$ . Then apply, for instance, Newey-West to these  $nk$  time series.

**Empirical Example 5.4 (CAPM on industry portfolios)** Figure 5.1 shows results for the intercepts from regressing US industry portfolios on the market. The joint test is for whether all intercepts are zero.



	$\alpha$	t-stat	$\sigma$
A (NoDur)	3.12	2.60	8.66
B (Durlb)	-1.11	-0.51	15.80
C (Manuf)	0.41	0.46	6.34
D (Enrgy)	2.89	1.24	16.83
E (HiTec)	-1.04	-0.67	11.21
F (Telcm)	0.88	0.59	10.78
G (Shops)	1.24	0.99	9.06
H (Hlth)	2.46	1.63	10.95
I (Utils)	3.09	1.91	11.69
J (Other)	-0.65	-0.68	6.87

CAPM:  $R_i^e = \alpha_i + \beta_i R_m^e + e_i$   
Predicted excess return:  $\beta_i ER_m^e$   
 $\alpha$  and  $\sigma$  (std of residual) are in annualized %  
p-val for testing if all  $\alpha_i = 0$ : 0.19  
10% crit. value (Bonferroni): 2.58

Figure 5.1: CAPM regressions on US industry indices

# Chapter 6

## Testing CAPM and Multifactor Models

Reference: Elton, Gruber, Brown, and Goetzmann (2010) 15

More advanced material is denoted by a star (\*). It is not required reading.

### 6.1 Market Model

Let  $R_{it}^e = R_{it} - R_{ft}$  be the excess return on asset  $i$  in excess over the riskfree asset, and let  $R_{mt}^e$  be the excess return on the market portfolio. The basic implication of CAPM is that the expected excess return of an asset ( $E R_{it}^e$ ) is linearly related to the expected excess return on the market portfolio ( $E R_{mt}^e$ ) according to

$$E R_{it}^e = \beta_i E R_{mt}^e, \text{ where } \beta_i = \frac{\text{Cov}(R_i, R_m)}{\text{Var}(R_m)}. \quad (6.1)$$

To test this, consider the regression

$$\begin{aligned} R_{it}^e &= \alpha_i + b_i R_{mt}^e + \varepsilon_{it}, \text{ where} \\ E \varepsilon_{it} &= 0 \text{ and } \text{Cov}(R_{mt}^e, \varepsilon_{it}) = 0. \end{aligned} \quad (6.2)$$

The two last conditions are automatically imposed by LS. Take expectations of the regression (assuming we know the coefficients) to get

$$E R_{it}^e = \alpha_i + b_i E R_{mt}^e. \quad (6.3)$$

Notice that the LS estimate of  $b_i$  is the sample analogue to  $\beta_i$  in (6.1). It is then clear that CAPM implies that the intercept ( $\alpha_i$ ) of the regression should be zero, which is also what empirical tests of CAPM focus on.

This test of CAPM can be given two interpretations. If we assume that  $R_{mt}$  is the

correct benchmark (the tangency portfolio for which (6.1) is true by definition), then it is a test of whether asset  $R_{it}$  is correctly priced. This is typically the perspective in performance analysis of mutual funds. Alternatively, if we assume that  $R_{it}$  is correctly priced, then it is a test of the mean-variance efficiency of  $R_{mt}$ . That is, we test if the market portfolio is the correct “pricing factor” of all the test assets. This is the perspective of CAPM tests.

The test of the null hypothesis that  $\alpha_i = 0$  uses the fact that, under fairly mild conditions, the t-statistic has an asymptotically normal distribution, that is

$$\frac{\hat{\alpha}_i}{\text{Std}(\hat{\alpha}_i)} \xrightarrow{d} N(0, 1) \text{ under } H_0 : \alpha_i = 0. \quad (6.4)$$

We get  $\text{Std}(\hat{\alpha}_i)$  from the OLS regression (possibly with an adjustment due to autocorrelation and/or heteroskedasticity). Note that this is the distribution under the null hypothesis that the true value of the intercept is zero, that is, that CAPM is correct.

The test assets are typically portfolios of firms with similar characteristics, for instance, small size or having their main operations in the retail industry. There are two main reasons for testing the model on such portfolios: individual stocks are extremely volatile and firms can change substantially over time (so the beta changes), whereas the portfolios can be constructed to represent fairly constant characteristics. For instance, a portfolio of small firms could include the firms in the lowest size decile over the previous year (and thus being rebalanced annually). Moreover, it is of interest to see how the deviations from CAPM are related to firm characteristics (size, industry, etc), since that can possibly suggest how the model needs to be changed.

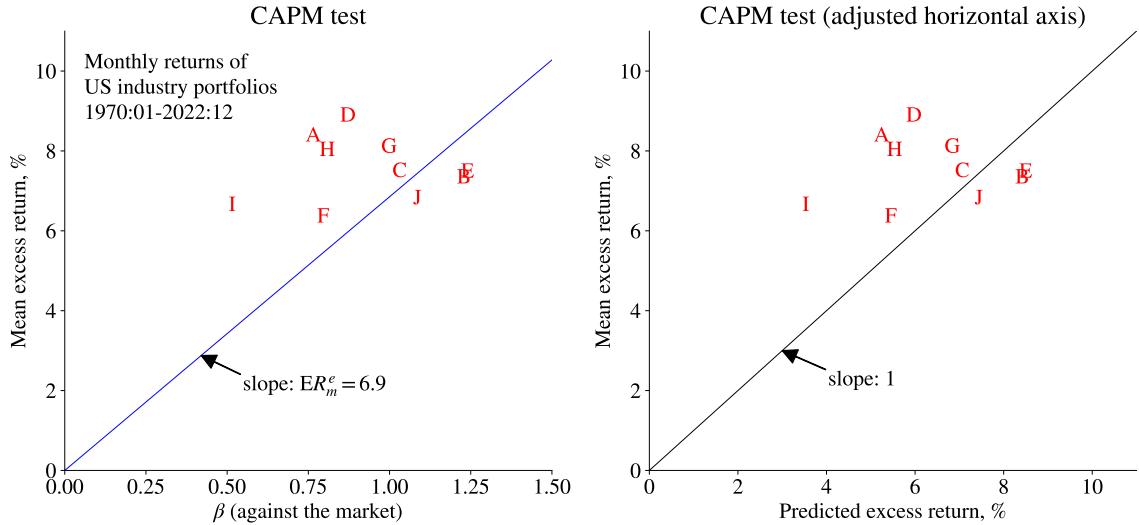
The empirical results from such tests vary with the test assets used. For US portfolios, CAPM seems to work reasonably well for some types of portfolios (for instance, portfolios based on firm size or industry), but much worse for other types of portfolios (for instance, portfolios based on firm dividend yield or book value/market value ratio).

**Empirical Example 6.1 (CAPM on industry portfolios)** Figure 6.1 shows results for US industry portfolios.

In Figure 6.1, the results are presented in two different ways:

	<u>horizontal axis</u>	<u>vertical axis</u>
1 :	$\beta_i$	$\bar{R}_{it}^e$
2 :	$\beta_i \bar{R}_{mt}^e$	$\bar{R}_{it}^e$ ,

(6.5)



	$\alpha$	$t\text{-stat}$	$\sigma$
A (NoDur)	3.12	2.60	8.66
B (Durbl)	-1.11	-0.51	15.80
C (Manuf)	0.41	0.46	6.34
D (Enrgy)	2.89	1.24	16.83
E (HiTec)	-1.04	-0.67	11.21
F (Telcm)	0.88	0.59	10.78
G (Shops)	1.24	0.99	9.06
H (Hlth )	2.46	1.63	10.95
I (Utils)	3.09	1.91	11.69
J (Other)	-0.65	-0.68	6.87

$$\begin{aligned} \text{CAPM: } R_i^e &= \alpha_i + \beta_i R_m^e + e_i \\ \text{Predicted excess return: } \beta_i R_m^e \\ \alpha \text{ and } \sigma \text{ (std of residual) are in annualized \%} \\ \text{p-val for testing if all } \alpha_i = 0: 0.19 \\ 10\% \text{ crit. value (Bonferroni): } 2.58 \end{aligned}$$

Figure 6.1: CAPM regressions on US industry indices

where  $\bar{R}_{it}^e$  is the (time series) average excess return of asset  $i$ . In the first approach, CAPM says that all data points (different assets,  $i$ ) should cluster around a straight line with a slope equal to the average market excess return,  $\bar{R}_{mt}^e$ . In the second approach, CAPM says that all data points should cluster around a line with a slope of one. In either case, the vertical distance to the line is  $\alpha_i$  (which should be zero according to CAPM).

### 6.1.1 Econometric Properties of the CAPM Test

A common finding from Monte Carlo simulations is that these tests tend to reject a true null hypothesis too often when the critical values from the asymptotic distribution are used. The practical consequence is that we should either use adjusted critical values (from Monte Carlo or bootstrap simulations)—or more pragmatically, that we should only believe in strong rejections of the null hypothesis.

It is typically found that these tests require a substantial deviation from CAPM and/or a long sample to get good power. The basic reason for this is that asset returns are very volatile. For instance, suppose that the standard OLS assumptions (iid residuals that are independent of the market return) are correct. Then, it is straightforward to show that the variance of Jensen's alpha is

$$\text{Var}(\hat{\alpha}_i) = [1 + (SR_m)^2]\sigma^2/T, \quad (6.6)$$

where  $\sigma^2$  is the variance of the residual in (6.2) and  $SR_m$  is the Sharpe ratio of the market portfolio. We see that the uncertainty about the alpha is high when the residual is volatile and when the sample is short, but also when the Sharpe ratio of the market is high. Note that a large market Sharpe ratio means that the market asks for a high compensation for taking on risk. A lot of uncertainty about how risky asset  $i$  is then translates in a large uncertainty about what the risk-adjusted return should be.

**Example 6.2** Suppose we have monthly data with  $\hat{\alpha}_i = 0.2\%$  (that is,  $0.2\% \times 12 = 2.4\%$  per year),  $\sigma = 3\%$  (that is,  $3\% \times \sqrt{12} \approx 10\%$  per year) and a market Sharpe ratio of 0.15 (that is,  $0.15 \times \sqrt{12} \approx 0.5$  per year). (This corresponds well to US CAPM regressions for industry portfolios, see Figure 6.1.) A significance level of 10% requires a t-statistic (6.4) of at least 1.64, so

$$\frac{0.2}{\sqrt{1 + 0.15^2} 3 / \sqrt{T}} \geq 1.64 \text{ or } T \geq 626.$$

We need a sample of at least 626 months (52 years)! With a sample of only 26 years (312 months), the alpha needs to be almost 0.3% per month (3.6% per year) or the standard deviation of the residual just 2% (7% per year). Notice that cumulating a 0.3% return over 25 years means almost 2.5 times the initial value.

**Proof.** (\*Proof of (6.6)) Consider the regression equation  $y_t = x'_t b + \varepsilon_t$ . With iid errors that are independent of all regressors (also across observations), the LS estimator,  $\hat{b}_{LS}$ , is asymptotically distributed as

$$\sqrt{T}(\hat{b}_{LS} - b) \xrightarrow{d} N(\mathbf{0}, \sigma^2 \Sigma_{xx}^{-1}), \text{ where } \sigma^2 = \text{Var}(\varepsilon_t) \text{ and } \Sigma_{xx} = \text{plim} \sum_{t=1}^T x_t x'_t / T.$$

When the regressors are just a constant (equal to one) and one variable regressor,  $f_t$ , so

$x_t = [1, f_t]'$ , then we have

$$\Sigma_{xx} = E \sum_{t=1}^T x_t x_t' / T = E \frac{1}{T} \sum_{t=1}^T \begin{bmatrix} 1 & f_t \\ f_t & f_t^2 \end{bmatrix} = \begin{bmatrix} 1 & E f_t \\ E f_t & E f_t^2 \end{bmatrix}, \text{ so}$$

$$\sigma^2 \Sigma_{xx}^{-1} = \frac{\sigma^2}{E f_t^2 - (E f_t)^2} \begin{bmatrix} E f_t^2 & -E f_t \\ -E f_t & 1 \end{bmatrix} = \frac{\sigma^2}{\text{Var}(f_t)} \begin{bmatrix} \text{Var}(f_t) + (E f_t)^2 & -E f_t \\ -E f_t & 1 \end{bmatrix}.$$

(In the last line we use  $\text{Var}(f_t) = E f_t^2 - (E f_t)^2$ .) The upper left element says  $\text{Var}(\sqrt{T} \hat{\alpha}) = \{1 + [E f_t / \text{Std}(f)]^2\} \sigma^2$ , which is (6.6). ■

### 6.1.2 Interpretation of the CAPM Test

Instead of a t-test, we can use the equivalent chi-square test

$$(t\text{-stat})^2 = \frac{\hat{\alpha}_i^2}{\text{Var}(\hat{\alpha}_i)} \xrightarrow{d} \chi_1^2 \text{ under } H_0: \alpha_i = 0. \quad (6.7)$$

It is quite straightforward to use the properties of minimum-variance frontiers (see Gibbons, Ross, and Shanken (1989), and also MacKinlay (1995)) to show that the test statistic in (6.7) can be written

$$\frac{\hat{\alpha}_i^2}{\text{Var}(\hat{\alpha}_i)} = \frac{(SR_c)^2 - (SR_m)^2}{[1 + (SR_m)^2]/T}, \quad (6.8)$$

where  $SR_m$  is the Sharpe ratio of the market portfolio and  $SR_c$  is the Sharpe ratio of the tangency portfolio when investment in both the market return and asset  $i$  is possible. (Recall that the tangency portfolio is the portfolio with the highest possible Sharpe ratio.) If the market portfolio has the same (squared) Sharpe ratio as the tangency portfolio of the mean-variance frontier of  $R_{it}$  and  $R_{mt}$  (so the market portfolio is mean-variance efficient also when we take  $R_{it}$  into account) then the test statistic,  $\hat{\alpha}_i^2 / \text{Var}(\hat{\alpha}_i)$ , is zero—and CAPM is not rejected.

**Proof.** (\*Proof of (6.8)) From the CAPM regression (6.2) we have

$$\text{Var} \left( \begin{bmatrix} R_{it}^e \\ R_{mt}^e \end{bmatrix} \right) = \begin{bmatrix} \beta_i^2 \sigma_m^2 + \text{Var}(\varepsilon_{it}) & \beta_i \sigma_m^2 \\ \beta_i \sigma_m^2 & \sigma_m^2 \end{bmatrix}, \text{ and } \begin{bmatrix} \mu_i^e \\ \mu_m^e \end{bmatrix} = \begin{bmatrix} \alpha_i + \beta_i \mu_m^e \\ \mu_m^e \end{bmatrix}.$$

Suppose we use this information to construct a mean-variance frontier for both  $R_{it}$  and  $R_{mt}$ , and we find the tangency portfolio, with excess return  $R_{ct}^e$ . It is straightforward to show that the square of the Sharpe ratio of the tangency portfolio is  $\mu^{e'} \Sigma^{-1} \mu^e$ , where

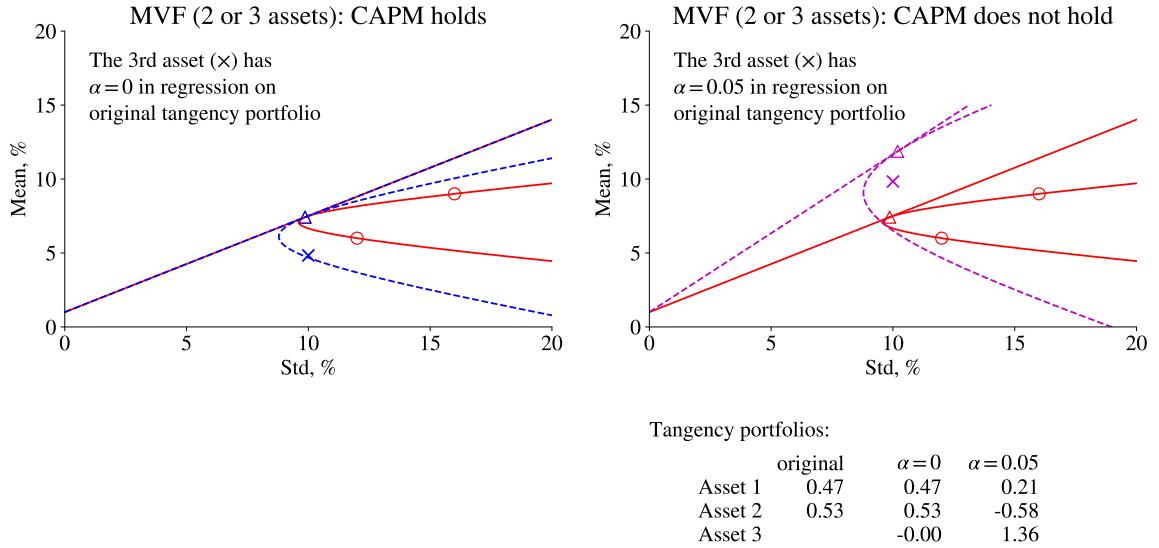


Figure 6.2: Effect on MV frontier of adding assets

$\mu^e$  is the vector of expected excess returns and  $\Sigma$  is the covariance matrix. By using the covariance matrix and mean vector above, we get that the squared Sharpe ratio for the tangency portfolio,  $\mu^{e'} \Sigma^{-1} \mu^e$ , (using both  $R_{it}$  and  $R_{mt}$ ) is

$$\left( \frac{\mu_c^e}{\sigma_c} \right)^2 = \frac{\alpha_i^2}{\text{Var}(\varepsilon_{it})} + \left( \frac{\mu_m^e}{\sigma_m} \right)^2,$$

which we can write as

$$(SR_c)^2 = \frac{\alpha_i^2}{\text{Var}(\varepsilon_{it})} + (SR_m)^2.$$

Combine this with (6.6) which shows that  $\text{Var}(\hat{\alpha}_i) = [1 + (SR_m)^2] \text{Var}(\varepsilon_{it})/T$ . ■

This is illustrated in Figure 6.2 which shows the effect of adding an asset to the investment opportunity set. The basic point is that testing the alphas is the same as testing if the new assets move the location of the tangency portfolio. In general, we would expect that adding an asset to the investment opportunity set would expand the mean-variance frontier (and it does) and that the tangency portfolio changes accordingly. However, the tangency portfolio is not changed by adding an asset with a zero alpha (intercept). The intuition is that such an asset has neutral performance compared to the market portfolio (obeys the beta representation), so investors should stick to the market portfolio.

### 6.1.3 Several Assets

In most cases, there are several ( $n$ ) test assets, and we actually want to test if all the  $\alpha_i$  (for  $i = 1, 2, \dots, n$ ) are zero (otherwise CAPM is not correct). Ideally we then want to take into account the correlation of the different alphas. Such a system based approach is discussed in Section 6.1.4.

Alternatively, we can apply a Bonferroni correction of the individual t-stats: reject CAPM at the 5% significance level only if the largest t-stat (in absolute terms) exceeds the critical value at the  $0.05/n$  significance level. For instance, with  $n = 25$ , the critical value from a standard normal distribution would be 3.09 instead of 1.96.

	1	2	3	4	5
1	-3.24	0.29	0.75	2.50	2.84
2	-2.01	0.75	1.75	2.58	2.23
3	-1.91	1.68	1.59	2.61	2.57
4	-0.52	0.70	1.70	2.20	1.88
5	-0.17	1.38	1.49	0.29	1.02

Table 6.1: t-stats for  $\alpha$  in CAPM, 25 FF portfolios 1970:01-2022:12. NW uses 1 lag. The Bonferroni adjusted 10% and 5% critical values are 2.88 and 3.09.

A quite different approach to study a cross-section of assets is to first estimate CAPM regressions (6.2) for each of the assets ( $i = 1, 2, \dots, n$ ) and then the following cross-sectional regression

$$\bar{R}_i^e = \gamma + \lambda \hat{\beta}_i + u_i, \quad (6.9)$$

where  $\bar{R}_i^e$  is the (sample) average excess return on asset  $i$ . Notice that the estimated betas are used as regressors and that there are as many data points as there are assets ( $n$ ).

There are severe econometric problems with this regression equation since the regressor ( $\hat{\beta}_i$ ) contains measurement errors (it is only an uncertain estimate), which typically tends to bias the slope coefficient ( $\lambda$ ) towards zero. To get the intuition for this bias, consider an extremely noisy measurement of the regressor: it would be virtually uncorrelated with the dependent variable (noise isn't correlated with anything), so the estimated slope coefficient would be close to zero.

If we could overcome this bias (and we can by being careful), then the testable implications of CAPM is that  $\gamma = 0$  and that  $\lambda$  equals the average market excess return. We also want (6.9) to have a high  $R^2$ —since it should be unity in a very large sample (if CAPM holds).

### 6.1.4 Several Assets: SURE Approach

This section outlines how we can set up a formal test of CAPM when there are several test assets. We first estimate (6.2) for each of the assets, and then test the null hypothesis that all the alphas are zero.

For simplicity, suppose we have two test assets. The null hypothesis

$$H_0 : \alpha_1 = 0 \text{ and } \alpha_2 = 0. \quad (6.10)$$

In a large sample, the estimator is normally distributed. Therefore, under the null hypothesis we have the following result.

$$\begin{bmatrix} \hat{\alpha}_1 \\ \hat{\alpha}_2 \end{bmatrix} \sim N \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix} [1 + (SR_m)^2]/T \right). \quad (6.11)$$

Notice that the zero means in (6.11) come from the null hypothesis: the distribution is (as usual) constructed by pretending that the null hypothesis is true. In practice we use the sample moments for the covariance matrix. We can now construct a chi-square test by using the following fact.

**Remark 6.3** If the  $n \times 1$  vector  $v \sim N(0, \Sigma)$ , then  $v' \Sigma^{-1} v \sim \chi_n^2$ .

To apply this, form the test static

$$\begin{bmatrix} \hat{\alpha}_1 \\ \hat{\alpha}_2 \end{bmatrix}' T[1 + (SR_m)^2]^{-1} \begin{bmatrix} \sigma_{11} & \sigma_{12} \\ \sigma_{12} & \sigma_{22} \end{bmatrix}^{-1} \begin{bmatrix} \hat{\alpha}_1 \\ \hat{\alpha}_2 \end{bmatrix} \sim \chi_2^2. \quad (6.12)$$

This can also be transformed into an  $F$  test, which might have better small sample properties.

**Empirical Example 6.4** (*Joint test of CAPM on industry portfolios*) Figure 6.1 reports also a joint test of the hypothesis that the alphas for all industry portfolios are zero.

**Proof.** (of (6.11)) Stack (6.2) for the two assets

$$\begin{aligned} R_{1t}^e &= \alpha_1 + b_1 R_{mt}^e + \varepsilon_{1t}, \\ R_{2t}^e &= \alpha_2 + b_2 R_{mt}^e + \varepsilon_{2t} \end{aligned}$$

where  $E \varepsilon_{it} = 0$  and  $\text{Cov}(R_{mt}^e, \varepsilon_{it}) = 0$ . This is a system of seemingly unrelated regressions (SURE)—with the same regressor (see, for instance, Wooldridge (2002) 7.7). In

this case, the efficient estimator (GLS) is LS on each equation separately. Moreover, the covariance matrix of the coefficients is particularly simple. To see what the covariances of the coefficients are, write the regression equation for asset 1 on a traditional form

$$R_{1t}^e = x_t' \beta_1 + \varepsilon_{1t}, \text{ where } x_t = \begin{bmatrix} 1 \\ R_{mt}^e \end{bmatrix}, \beta_1 = \begin{bmatrix} \alpha_1 \\ b_1 \end{bmatrix},$$

and similarly for the second asset (and any further assets). Define

$$S_{xx} = \sum_{t=1}^T x_t x_t', \text{ and } \hat{\sigma}_{ij} = \sum_{t=1}^T \hat{\varepsilon}_{it} \hat{\varepsilon}_{jt} / T,$$

where  $\hat{\varepsilon}_{it}$  is the fitted residual of asset  $i$ . The key result is then that the (estimated) asymptotic covariance matrix of the vectors  $\hat{\beta}_i$  and  $\hat{\beta}_j$  (for assets  $i$  and  $j$ ) is

$$\text{Cov}(\hat{\beta}_i, \hat{\beta}_j) = \hat{\sigma}_{ij} S_{xx}^{-1}.$$

(In many text books, this is written  $\hat{\sigma}_{ij}(X'X)^{-1}$ .) From (6.6) we know that the upper left element of  $S_{xx}^{-1}$  equals  $[1 + (SR_m)^2]/T$ . ■

### 6.1.5 Representative Results of the CAPM Test

One of the more interesting empirical studies is Fama and French (1993) (see also Fama and French (1996)). They construct 25 stock portfolios according to two characteristics of the firm: the size (by market capitalization) and the book-value-to-market-value ratio (BE/ME). In June each year, they sort the stocks according to size and BE/ME. They then form a  $5 \times 5$  matrix of portfolios, where portfolio  $ij$  belongs to the  $i$ th size quintile (quintiles divide sorted data into fifths of the sample) *and* the  $j$ th BE/ME quintile (so this is a *double-sort*)

$$\begin{bmatrix} \text{small size, low B/M} & \dots & \dots & \dots & \text{small size, high B/M} \\ \vdots & & \ddots & & \\ \vdots & & & \ddots & \\ \vdots & & & & \ddots \\ \text{large size, low B/M} & & & & \text{large size, high B/M} \end{bmatrix}$$

They run a traditional CAPM regression on each of the 25 portfolios (monthly data 1963–1991)—and then study if the expected excess returns are related to the betas as they should according to CAPM (recall that CAPM implies  $E R_{it}^e = \beta_i \lambda$  where  $\lambda$  is the risk

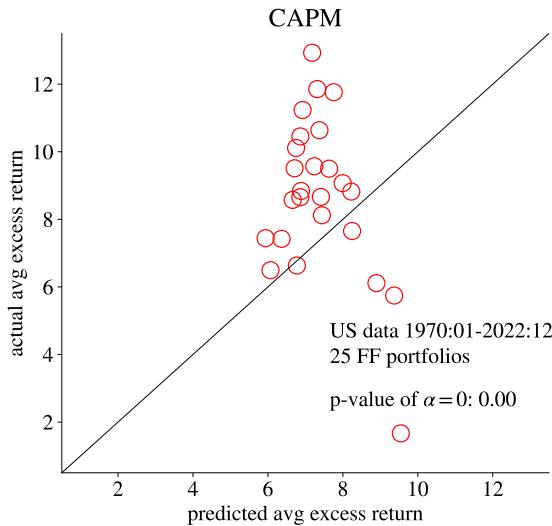


Figure 6.3: CAPM, FF portfolios

premium (excess return) on the market portfolio).

However, it is found that there is almost no relation between  $E R_{it}^e$  and  $\beta_i$  (there is a cloud in the  $\beta_i \times E R_{it}^e$  space). This is due to the combination of two features of the data. First, *within a BE/ME quintile*, there is a positive relation (across size quantiles) between  $E R_{it}^e$  and  $\beta_i$ —as predicted by CAPM. Second, *within a size quintile* there is a negative relation (across BE/ME quantiles) between  $E R_{it}^e$  and  $\beta_i$ —in stark contrast to CAPM.

**Empirical Example 6.5 (Testing CAPM on FF portfolios)** Figures 6.3–6.4 illustrates the CAPM pricing errors (*alphas*) for the 25 FF (US size/book-to-market) portfolios.

### 6.1.6 Representative Results on Mutual Fund Performance

Mutual fund evaluations (estimated  $\alpha_i$ ) typically find (i) on average neutral performance (or less: trading costs&fees); (ii) large funds might be worse; (iii) perhaps better performance on less liquid (less efficient?) markets; and (iv) there is very little persistence in performance:  $\alpha_i$  for one sample does not predict  $\alpha_i$  for subsequent samples (except for bad funds).

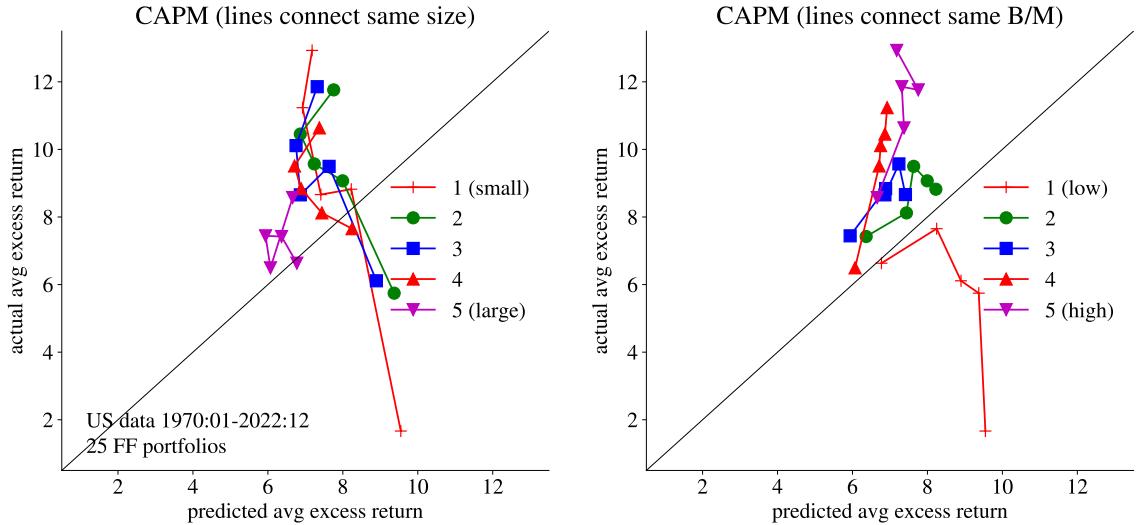


Figure 6.4: CAPM, FF portfolios

## 6.2 Calendar Time Regressions

To investigate how the performance (alpha) or exposure (betas) of different investors/funds are related to investor/fund characteristics, we often use the *calendar time* (CalTime) approach. First define  $M$  discrete investor groups (for instance, age 18–30, 31–40, etc) and calculate their respective average excess returns ( $\bar{R}_{jt}^e$  for group  $j$ )

$$\bar{R}_{jt}^e = \frac{1}{N_j} \sum_{i \in \text{Group } j} R_{it}^e, \quad (6.13)$$

where  $N_j$  is the number of individuals in group  $j$ .

Then, we run a factor model

$$\bar{R}_{jt}^e = x_t' \beta_j + v_{jt}, \text{ for } j = 1, 2, \dots, M \quad (6.14)$$

where  $x_t$  typically includes a constant and various return factors (for instance, excess returns on equity and bonds). By estimating these  $M$  equations as a SURE system with White's (or Newey-West's) covariance estimator, it is straightforward to test various hypotheses, for instance, that the intercept (the “alpha”) is higher for the  $M$ th group than for the first group.

**Example 6.6** (*CalTime with two investor groups*) With two investor groups, estimate the

following SURE system

$$\begin{aligned}\bar{R}_{1t}^e &= x_t' \beta_1 + v_{1t}, \\ \bar{R}_{2t}^e &= x_t' \beta_2 + v_{2t}.\end{aligned}$$

The CalTime approach is straightforward and the cross-sectional correlations are fairly easy to handle (in the SURE approach). However, it forces us to define discrete investor groups—which makes it hard to handle several different types of investor characteristics (for instance, age, trading activity and income) at the same time.

### 6.3 Several Factors

In multifactor models, (6.2) is still valid—provided we reinterpret  $b_i$  and  $R_{mt}^e$  as vectors, so  $b_i R_{mt}^e$  stands for  $b_{io} R_{ot}^e + b_{ip} R_{pt}^e + \dots$

$$R_{it}^e = \alpha + b_{io} R_{ot}^e + b_{ip} R_{pt}^e + \dots + \varepsilon_{it}. \quad (6.15)$$

In this case, (6.2) is a multiple regression, but the test (6.4) still has the same form (the standard deviation of the intercept will be different, though).

Fama and French (1993) also try a multi-factor model. They find that a three-factor model fits the 25 stock portfolios fairly well (two more factors are needed to also fit the seven bond portfolios that they use). The three factors are: the market return, the return on a portfolio of small stocks minus the return on a portfolio of big stocks (SMB), and the return on a portfolio with high BE/ME minus the return on portfolio with low BE/ME (HML). This three-factor model is rejected at traditional significance levels, but it can still capture a fair amount of the variation of expected returns.

**Remark 6.7** (*Returns on long-short portfolios\**) Suppose you invest  $x$  USD into asset  $i$ , but finance that by short-selling asset  $j$ . (You sell enough of asset  $j$  to raise  $x$  USD.) The net investment is then zero, so there is no point in trying to calculate an overall return like “value today/investment yesterday - 1.” Instead, the convention is to calculate an excess return of your portfolio as  $R_i - R_j$  (or equivalently,  $R_i^e - R_j^e$ ). This excess return essentially says: if your exposure (how much you invested) is  $x$ , then you have earned  $x(R_i - R_j)$ . To make this excess return comparable with net returns, you add the riskfree rate:  $R_i - R_j + R_f$ , implicitly assuming that your portfolio includes a riskfree investment of the same size as your long-short exposure ( $x$ ).

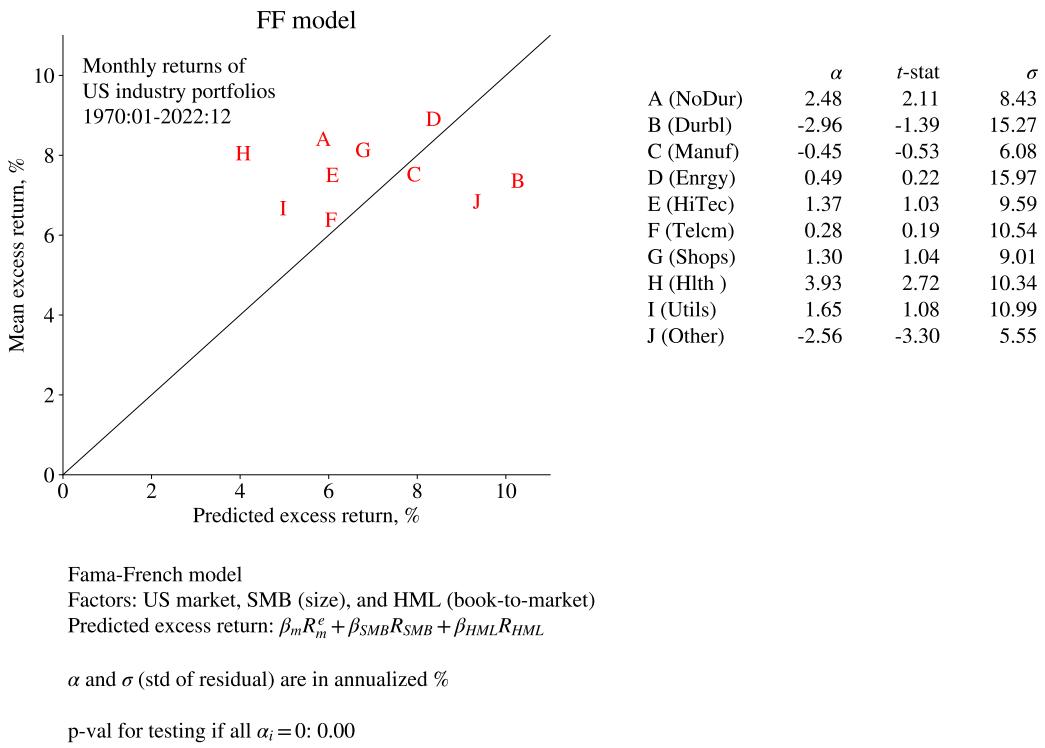


Figure 6.5: Fama-French regressions on US industry indices

Chen, Roll, and Ross (1986) use a number of macro variables as factors—along with traditional market indices. They find that industrial production and inflation surprises are priced factors, while the market index might not be.

**Empirical Example 6.8** (*Testing a 3-factor model*) Figure 6.5 shows results for the Fama-French 3-factor model on US industry portfolios and Figures 6.6–6.7 on the 25 Fama-French portfolios.

## 6.4 Fama-MacBeth\*

Reference: Cochrane (2001) 12.3; Campbell, Lo, and MacKinlay (1997) 5.8; Fama and MacBeth (1973)

The Fama and MacBeth (1973) approach is a bit different from the regression approaches discussed so far. The method has three steps, described below.

- First, estimate the betas  $\beta_i$  ( $i = 1, \dots, n$ ) from (6.2) (this is a time-series regression). This is often done on the whole sample—assuming the betas are constant.

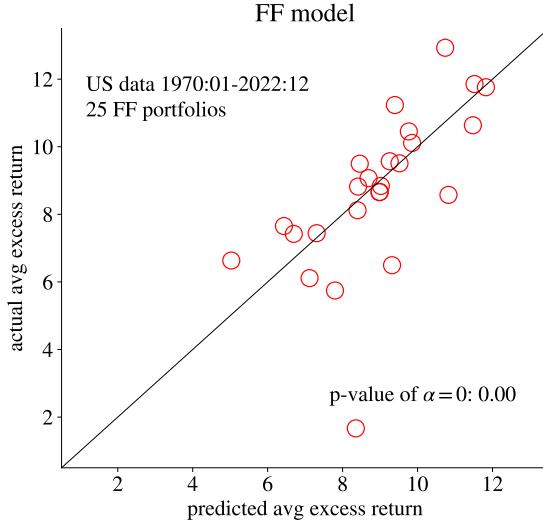


Figure 6.6: FF, FF portfolios

Sometimes, the betas are estimated separately for different sub samples (so we could let  $\hat{\beta}_i$  carry a time subscript in the equations below).

- Second, run a cross sectional regression for every  $t$ . That is, for period  $t$ , estimate  $\lambda_t$  from the cross section (across the assets  $i = 1, \dots, n$ ) regression

$$R_{it}^e = \lambda'_t \hat{\beta}_i + \varepsilon_{it}, \quad (6.16)$$

where  $\hat{\beta}_i$  are the regressors. (Note the difference to the traditional cross-sectional approach discussed in (6.9), where the second stage regression regressed  $E R_{it}^e$  on  $\hat{\beta}_i$ , while the Fama-French approach runs one regression for every time period.)

- Third, estimate the time averages

$$\hat{\varepsilon}_i = \frac{1}{T} \sum_{t=1}^T \hat{\varepsilon}_{it} \text{ for } i = 1, \dots, n, \text{ (for every asset)} \quad (6.17)$$

$$\hat{\lambda} = \frac{1}{T} \sum_{t=1}^T \hat{\lambda}_t. \quad (6.18)$$

The second step, using  $\hat{\beta}_i$  as regressors, creates an errors-in-variables problem since  $\hat{\beta}_i$  are estimated, that is, measured with an error. The effect of this is typically to bias the estimator of  $\lambda_t$  towards zero (and any intercept, or mean of the residual, is biased upward).

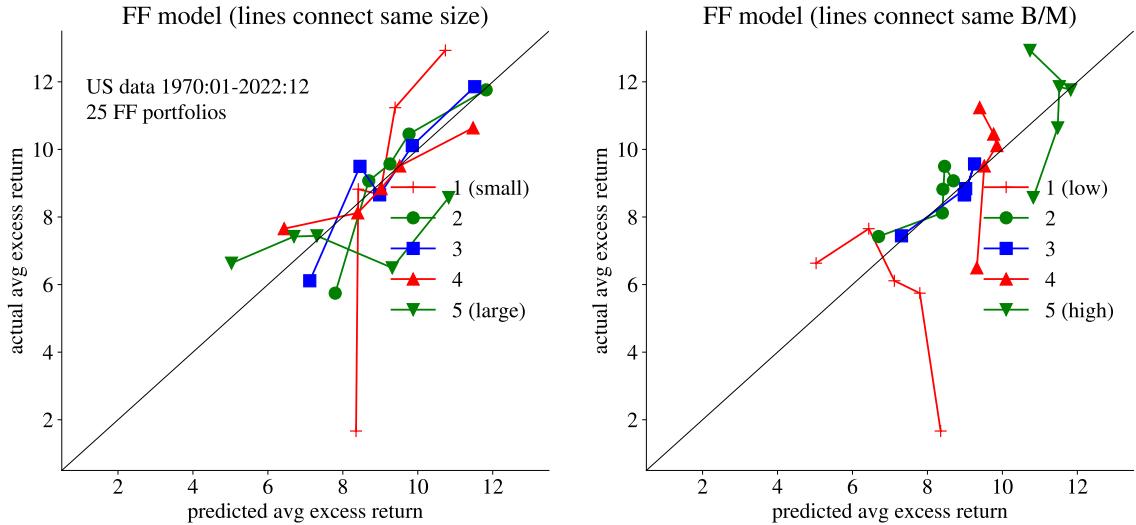


Figure 6.7: FF, FF portfolios

One way to minimize this problem, used by Fama and MacBeth (1973), is to let the assets be portfolios of assets, for which we can expect some of the individual noise in the first-step regressions to average out—and thereby make the measurement error in  $\hat{\beta}_i$  smaller. If CAPM is true, then the return of an asset is a linear function of the market return and an error which should be uncorrelated with the errors of other assets—otherwise some factor is missing. If the portfolio consists of 20 assets with equal error variance in a CAPM regression, then we should expect the portfolio to have an error variance which is 1/20th as large.

We clearly want portfolios which have different betas, or else the second step regression (6.16) does not work. Fama and MacBeth (1973) choose to construct portfolios according to some initial estimate of asset specific betas. Another way to deal with the errors-in-variables problem is to adjust the tests.

We can test the model by studying if  $\varepsilon_i = 0$  (recall from (6.17) that  $\varepsilon_i$  is the time average of the residual for asset  $i$ ,  $\varepsilon_{it}$ ), by forming a t-test  $\hat{\varepsilon}_i / \text{Std}(\hat{\varepsilon}_i)$ . Fama and MacBeth (1973) suggest that the standard deviation should be found by studying the time-variation in  $\hat{\varepsilon}_{it}$ . In particular, they suggest that the variance of  $\hat{\varepsilon}_{it}$  (not  $\hat{\varepsilon}_i$ ) can be estimated by the (average) squared variation around its mean

$$\text{Var}(\hat{\varepsilon}_{it}) = \frac{1}{T} \sum_{t=1}^T (\hat{\varepsilon}_{it} - \hat{\varepsilon}_i)^2. \quad (6.19)$$

Since  $\hat{\varepsilon}_i$  is the sample average of  $\hat{\varepsilon}_{it}$ , the variance of the former is the variance of the latter divided by  $T$  (the sample size)—provided  $\hat{\varepsilon}_{it}$  is iid. That is,

$$\text{Var}(\hat{\varepsilon}_i) = \frac{1}{T} \text{Var}(\hat{\varepsilon}_{it}) = \frac{1}{T^2} \sum_{t=1}^T (\hat{\varepsilon}_{it} - \hat{\varepsilon}_i)^2. \quad (6.20)$$

A similar argument leads to the variance of  $\hat{\lambda}$

$$\text{Var}(\hat{\lambda}) = \frac{1}{T^2} \sum_{t=1}^T (\hat{\lambda}_t - \hat{\lambda})^2. \quad (6.21)$$

Fama and MacBeth (1973) found, among other things, that the squared beta is not significant in the second step regression, nor is a measure of non-systematic risk.

# Chapter 7

## Model Selection and Other Topics\*

Greene (2018) 4-5; Hansen (forthcoming) 3

### 7.1 Model Selection I

*Excluding a relevant regressor* will cause a bias of all coefficients (unless those regressors are uncorrelated with the excluded regressor). In contrast, *including an irrelevant regressor* is not really dangerous, but is likely to decrease the precision.

To select the regressors, consider the following rules. Rule 1: use *economic theory*; rule 2: *avoid data mining* and mechanical searches for the right regressors; rule 3: maybe use a *general-to-specific approach*—start with a general regression and test restrictions,..., keep making it simpler until restrictions are rejected; rule 4: always *include a constant*; rule 5: avoid overfitting by “punishing” models with many parameters.

Remember that  $R^2$  can never decrease by adding more regressors—not really a good guide. To avoid overfitting, we could consider  $\bar{R}^2$  instead

$$\bar{R}^2 = 1 - (1 - R^2) \frac{T - 1}{T - k}, \quad (7.1)$$

where  $T$  is the sample size and  $k$  is the number of regressors (including the constant). This measure includes trade-off between fit and the number of regressors (per data point). Notice that  $\bar{R}^2$  can be negative (while  $0 \leq R^2 \leq 1$ ). Clearly, the model must include a constant for  $R^2$  (and therefore  $\bar{R}^2$ ) to make sense. Alternatively, apply Akaike’s Informa-

tion Criterion (AIC) and the Bayesian information criterion (BIC). They are

$$AIC = \ln \sigma^2 + 2 \frac{k}{T} \quad (7.2)$$

$$BIC = \ln \sigma^2 + \frac{k}{T} \ln T, \quad (7.3)$$

where  $\sigma^2$  is the variance of the fitted residuals.

These measures also involve trade-offs between fit (low  $\sigma^2$ ) and number of parameters ( $k$ , including the intercept). Choose the model with the *highest*  $\bar{R}^2$  or *lowest* AIC or BIC. It can be shown (by using  $R^2 = 1 - \sigma^2 / \text{Var}(y_t)$  so  $\sigma^2 = \text{Var}(y_t)(1 - R^2)$ ) that AIC and BIC can be rewritten as

$$AIC = \ln \text{Var}(y_t) + \ln(1 - R^2) + 2 \frac{k}{T} \quad (7.4)$$

$$BIC = \ln \text{Var}(y_t) + \ln(1 - R^2) + \frac{k}{T} \ln T. \quad (7.5)$$

This shows that both are decreasing in  $R^2$  (which is good), but increasing in the number of regressors per data point ( $k/T$ ). It therefore leads to a similar trade-off as in  $\bar{R}^2$ . Recall that the model should always include a constant.

**Empirical Example 7.1** (*Empirical application of model selection*) See Table 7.1 for an empirical example showing a number of possible model specifications. The dependent variable is the monthly realized variance of S&P 500 returns (calculated from daily returns). The possible regressors are lags of the dependent variable, the VIX index and the the S&P 500 returns. Similarly, Table 7.2 for the the best specification according to AIC. Notice that AIC tend to favour fairly large models with many regressors.

## 7.2 Model Selection II

Reference: Hastie, Tibshirani, and Friedman (2001) 3

In some cases, even good economic theory leaves us with too many potential regressors. This is often the case when developing forecasting models—where it also often noticed models with many predictors tend to fail out of sample. It then becomes crucial to apply some model selection technique, that is, a method that sets some regression coefficients to zero.

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
RV <sub>t-1</sub>	0.66 (8.86)						0.17 (2.06)
RV <sub>t-2</sub>		0.45 (5.59)					-0.03 (-0.38)
VIX <sub>t-1</sub>			0.93 (10.29)				0.97 (3.53)
VIX <sub>t-2</sub>				0.66 (8.85)			-0.26 (-1.19)
R <sub>t-1</sub>					-0.82 (-3.53)		0.00 (0.01)
R <sub>t-2</sub>						-0.46 (-2.30)	-0.08 (-0.93)
constant	5.20 (4.91)	8.39 (6.47)	-2.78 (-1.85)	2.48 (1.89)	15.90 (18.24)	15.61 (17.56)	-0.53 (-0.44)
R <sup>2</sup>	0.44	0.20	0.53	0.27	0.14	0.04	0.55
$\bar{R}^2$	0.43	0.20	0.53	0.26	0.14	0.04	0.54
obs	374	374	374	374	374	374	374

Table 7.1: Regression of monthly realized S&P 500 return volatility 1990:02-2022:12. Numbers in parentheses are t-stats, based on Newey-West with 4 lags.

If there are  $k$  potential regressors, then there are  $2^k$  different models. If the list of models is not too long, then the AIC and BIC in (7.2)–(7.3) can be used, see Table 7.2. Otherwise, we need some sort of sequential approach.

**Example 7.2** (3 potential regressors) If the three potential regressors are 1,  $x_1$  and  $x_2$ , then the list of models has  $2^3 - 1 = 7$  possibilities: (1); ( $x_1$ ); ( $x_2$ ); (1,  $x_1$ ); (1,  $x_2$ ); ( $x_1$ ,  $x_2$ ); (1,  $x_1$ ,  $x_2$ ).

A forward stepwise selection is as follows

- (1) start with an intercept
- (2) add the variable that improves the fit the most
- (3) repeat (2) until the fit does not improve much

To specify a stopping rule, first define the residual sum of squares (for a given vector of coefficients,  $\beta$ ) as

$$RSS(\beta) = \sum_{t=1}^T (y_t - x_t' \beta)^2. \quad (7.7)$$

In step (2) we would then add the variable that gives the lowest  $RSS$  (when added to the

	(1)	(2)	(3)	(4)
RV <sub>t-1</sub>	0.18 (2.11)			
RV <sub>t-2</sub>				
VIX <sub>t-1</sub>	0.95 (5.40)	1.12 (6.18)	1.14 (6.24)	0.88 (11.80)
VIX <sub>t-2</sub>	-0.27 (-1.99)	-0.24 (-1.74)	-0.28 (-1.91)	
R <sub>t-1</sub>			-0.22 (-2.28)	
R <sub>t-2</sub>			-0.14 (-1.47)	
constant	-0.66 (-0.71)	-1.85 (-1.55)	-1.16 (-1.22)	-1.59 (-1.34)
R <sup>2</sup>	0.55	0.54	0.55	0.54
BIC	3.80	3.80	3.81	3.81
obs	374	374	374	374

Table 7.2: Regression of monthly realized S&P 500 return volatility 1990:02-2022:12. Ordered from best (1) according to BIC to fourth best (4). Numbers in parentheses are t-stats, based on Newey-West with 4 lags.

previous selection). In step (3), it is often recommended that we stop adding regressors when

$$\frac{RSS(\hat{\beta}_{\text{old}}) - RSS(\hat{\beta}_{\text{new}})}{RSS(\hat{\beta}_{\text{new}})/(T - k - 1)} < c_{1,T-k-1}, \quad (7.8)$$

where  $k$  is the number of coefficients in  $\hat{\beta}_{\text{old}}$  (including the intercept) so there are  $k + 1$  coefficients in  $\hat{\beta}_{\text{new}}$  and  $c_{1,T-k-1}$  is the 90% or 95% critical value of an  $F_{1,T-k-1}$  distribution. For instance, the 90% critical value of  $F_{1,100}$  equals 2.76.

As an alternative to the  $RSS$  based rule in (7.7)–(7.8), we could instead use t-stats: in step (2) add the variable with the highest  $|t\text{-stat}|$  and in step (3) stop adding variables when that  $|t\text{-stat}|$  is lower than 1.64 (or 1.96).

**Empirical Example 7.3 (Forward stepwise selection)** Applying the forward step selection approach (based on t-stats) to the regression discussed in Example 7.1 gives a sequence of larger and larger models shown in Table 7.3.

	(1)	(2)	(3)
RV <sub>t-1</sub>		0.18 (2.11)	
RV <sub>t-2</sub>			
VIX <sub>t-1</sub>	0.93 (10.29)	1.12 (6.18)	0.95 (5.40)
VIX <sub>t-2</sub>		-0.24 (-1.74)	-0.27 (-1.99)
R <sub>t-1</sub>			
R <sub>t-2</sub>			
constant	-2.78 (-1.85)	-1.85 (-1.55)	-0.66 (-0.71)
R <sup>2</sup>	0.53	0.54	0.55
obs	374	374	374

Table 7.3: Best four regressions of monthly realized S&P 500 return volatility according to a forward step selection (based on t-stats), 1990:02-2022:12. Ordered from smallest model (1) to fourth smallest model (4). Numbers in parentheses are t-stats, based on Newey-West with 4 lags.

### 7.2.1 The Lasso Method\*

An alternative approach to model selection is the *Lasso method*, which minimizes the sum of squared residuals (just like OLS), but with a penalty on  $\sum_{i=1}^k |b_i|$ . In short, it solves the following optimization problem

$$\min_b \sum_{t=1}^T (y_t - \alpha - x'_t b)^2 + \gamma \sum_{i=1}^k |b_i|, \quad (7.9)$$

where the value of  $\gamma$  is chosen a priori, but where we typically consider different values of  $\gamma$ . Having the same penalty on all  $|b_i|$  makes perhaps most sense when the regressors have the same scale (for instance, zero mean and unit standard deviation). The *adaptive Lasso* instead uses weighted penalties,  $\gamma \sum_{i=1}^k w_i |b_i|$ , often with  $w_i = 1/|b_i^{OLS}|$ . This will clearly give a larger effective penalty on variables whose OLS coefficients are small (in absolute terms). It is sometimes an advantage to divide the first term in (7.9) by  $T$ , to make the interpretation of  $\gamma$  independent of the sample size (and sometimes also for numerical reasons).

	(1)	(2)	(3)	(4)
RV <sub>t-1</sub>		0.15 (2.11)	0.14 (1.82)	0.18 (2.21)
RV <sub>t-2</sub>				
VIX <sub>t-1</sub>	0.93 (10.29)	0.77 (7.58)	0.72 (7.05)	0.95 (3.53)
VIX <sub>t-2</sub>				-0.27 (-1.16)
R <sub>t-1</sub>			-0.21 (-2.11)	-0.00 (-0.01)
R <sub>t-2</sub>				
constant	-2.78 (-1.85)	-1.90 (-1.44)	-0.79 (-0.72)	-0.66 (-0.64)
R <sup>2</sup>	0.53	0.54	0.54	0.55
$\sum  b_i $	0.73	0.75	0.81	1.13
obs	374	374	374	374

Table 7.4: Best four regressions of monthly realized S&P 500 return volatility where the model are selected by lasso, but then estimated with OLS, 1990:02-2022:12. Ordered from smallest model (1) to fourth smallest model (4). Numbers in parentheses are t-stats, based on Newey-West with 4 lags. The  $\sum |b_i|$  is for regression using standardized variables.

**Remark 7.4** (*Alternative formulation*) *The same problem can also be written as a constrained optimisation problem*

$$\min_b \sum_{t=1}^T (y_t - \alpha - x_t' b)^2 \text{ subject to } \sum_{i=1}^k |b_i| \leq t,$$

where a small  $t$  corresponds to a high  $\gamma$ .

Clearly, when  $\gamma = 0$ , then the lasso approach reproduces the OLS estimates. For larger values of  $\gamma$ , the lasso will give smaller coefficients: some  $b_i$  will be zero and others tend to be closer to zero than OLS would suggest (similar to other “shrinkage” methods like a ridge estimation).

The lasso method can be used as a model selection technique by estimating a sequence of models with increasingly lower  $\gamma$  values. With a sufficiently high  $\gamma$ , only one coefficient is non-zero—for a somewhat lower  $\gamma$  value, two coefficients are non-zero and so on. See Figure 7.1. Once the  $L$  (five, say) smallest specifications are found, we could re-

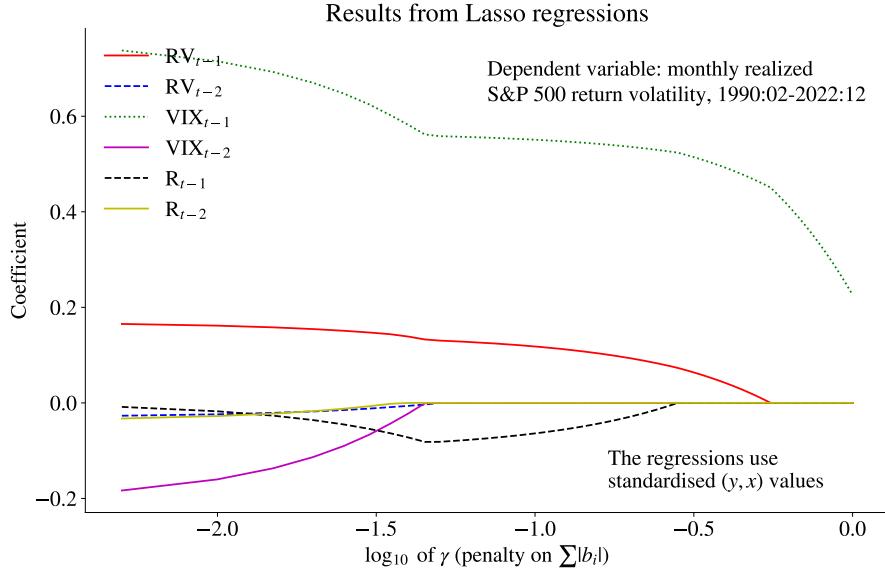


Figure 7.1: Lasso regressions

estimate each of them with OLS. (This is the lars-OLS hybrid discussed in Efron, Hastie, Johnstone, and Tibshirani (2004).)

**Empirical Example 7.5 (Lasso regression)** Applying the Lasso approach to the regression discussed in Example 7.1 gives a sequence of smaller and smaller models. Figure 7.1 shows how the coefficients of the normalised variables change as penalty parameter is increased. Re-estimating the four smallest of those models with OLS gives the results in Table 7.4.

**Remark 7.6 (Application of the lasso/lars algorithms)** These algorithms often standardize  $x_t$  to have zero means and unit standard deviations, and  $y_t$  to have zero means (and perhaps unit standard deviation).

### 7.2.2 Ridge Regressions\*

This section summarises some facts about ridge regressions.

**Remark 7.7 (Ridge regression)** The ridge regression solves  $\min_b \sum_{t=1}^T (y_t - \alpha - x_t' b)^2 + \lambda \sum_{i=1}^k b_i^2$ , where  $\lambda > 0$ , so it forms a compromise between OLS and zero coefficients. This is easiest to see if  $y_t$  and  $x_t$  are demeaned so  $\alpha = 0$ . Then, the first order conditions for minimization are  $\sum_{t=1}^T x_t (y_t - x_t' \hat{b}) - \lambda \hat{b} = \mathbf{0}$ , so  $\hat{b} = (\sum_{t=1}^T x_t x_t' + \lambda I)^{-1} \sum_{t=1}^T x_t y_t$ . Notice that  $\lambda = 0$  gives OLS, while  $\lambda = \infty$  gives  $\hat{b} = \mathbf{0}$ .

**Remark 7.8** (*Ridge regression with a target vector*) Let  $(y_t, x_t)$  be demeaned (so no intercept is needed) and let the target slope coefficients be the vector  $\beta_0$ .

$$\hat{b} = (\sum_{t=1}^T x_t x_t' + \lambda I)^{-1} (\sum_{t=1}^T x_t y_t + \lambda \beta_0).$$

This  $\hat{b}$  solves the problem  $\min_b \sum_{t=1}^T (y_t - x_t' b)^2 + \lambda \sum_{i=1}^k (b_i - \beta_{i0})^2$ . The first order conditions for minimization are  $\sum_{t=1}^T x_t (y_t - x_t' \hat{b}) - \lambda(\hat{b} - \beta_0) = 0$ , which has the solution above.

**Remark 7.9** (*Elastic net regression\**) An elastic net regression is a mix of a Lasso regression and a ridge regression. It solves  $\min_b \sum_{t=1}^T (y_t - x_t' b)^2 + \gamma \sum_{i=1}^k |b_i| + \lambda \sum_{i=1}^k b_i^2$ .

### 7.3 Weighted Least Squares\*

Suppose we want to put the weight  $w_t$  on observation  $(x_t, y_t)$  in a regression,  $y_t = x_t' \beta + u_t$ . That is, we want to minimize

$$\sum_{t=1}^T w_t (y_t - x_t' b)^2. \quad (7.10)$$

The first order conditions are

$$\mathbf{0}_{k \times 1} = \sum_{t=1}^T w_t x_t (y_t - x_t' \hat{\beta}), \quad (7.11)$$

so the solution is

$$\hat{\beta} = S_{wxx}^{-1} \sum_{t=1}^T w_t x_t y_t, \text{ where } S_{wxx} = \sum_{t=1}^T w_t x_t x_t' \quad (7.12)$$

It is straightforward to show that the variance-covariance matrix of  $\hat{\beta}$  is

$$\text{Var}(\hat{\beta}) = S_{wxx}^{-1} S S_{wxx}^{-1}, \text{ where } S = \text{Var}(\sum_{t=1}^T w_t x_t u_t). \quad (7.13)$$

We can estimate this by replacing  $u_t$  by the fitted residuals  $\hat{u}_t = y_t - x_t' \hat{\beta}$  and apply the usual methods on the  $T \times k$  matrix of “data”  $w_t x_t \hat{u}_t$ . For instance, we get a heteroskedasticity consistent (like White’s) estimate by simply estimating a traditional  $k \times k$  covariance matrix of  $w_t x_t \hat{u}_t$ .

**Proof.** (of (7.13)\*) Substitute for  $y_t = x_t' \beta + u_t$  in (7.12) to get (after simplification)

$$\hat{\beta} = \beta + S_{wxx}^{-1} \sum_{t=1}^T w_t x_t u_t.$$

The result in (7.13) follows directly. ■

**Remark 7.10** (*Alternative computation*) Let  $\tilde{x}_t = \sqrt{w_t}x_t$  and  $\tilde{y}_t = \sqrt{w_t}y_t$ . Then, regressing  $\tilde{y}_t$  on  $\tilde{x}_t$  gives the same result as in (7.12). Notice also that (a)  $\Sigma_{t=1}^T \tilde{x}_t \tilde{x}'_t$  is the same as  $S_{wxx}$ ; and (b)  $\Sigma_{t=1}^T \tilde{x}_t \tilde{u}_t$  (where  $\tilde{u}_t = \tilde{y}_t - \tilde{x}'_t \beta$ ) is the same as  $\Sigma_{t=1}^T w_t x_t u_t$ . This means that robust standard errors (for instance, White's) from the regression of  $\tilde{y}_t$  on  $\tilde{x}_t$  gives the same variance-covariance matrix as in (7.13). WLS can thus be implemented as OLS on  $(\tilde{y}_t, \tilde{x}_t)$ , and this applies to both point estimates and the variance-covariance matrix.

## 7.4 Comparing Non-Nested Models

Consider two competing models

$$\text{Model A: } y_t = x'_t \beta + \varepsilon_t \quad (7.14)$$

$$\text{Model B: } y_t = z'_t \gamma + v_t. \quad (7.15)$$

For instance, these models could represent alternative economic theories of the same phenomenon. They are *non-nested* if  $z$  is not a subset of  $x$  at the same time as  $x$  is not a subset of  $z$ . Comparing the fit of these models starts with the usual criteria:  $R^2$ ,  $\bar{R}^2$ , AIC, and BIC.

An alternative approach to compare the fit is to study *encompassing*. Model  $B$  is said to encompass model  $A$  if it can explain all that model  $A$  can (and more). This is clearly a good feature. To test this, run the regression

$$y_t = z'_t \gamma + x'_{2t} \delta_A + v_t, \quad (7.16)$$

where  $x_{2t}$  are those variables in  $x_t$  that are not also in  $z_t$ . Model  $B$  encompasses model  $A$  if  $\delta_A = 0$  (test this restriction). Clearly, we can repeat this to see if  $A$  encompasses  $B$ .

## 7.5 Non-Linear Models

Regression analysis typically starts with a linear model—which may or may not be a good approximation.

Notice that models that are *non-linear in variables*

$$y_t = \alpha + \delta x_t^{3.4} + \varepsilon_t, \quad (7.17)$$

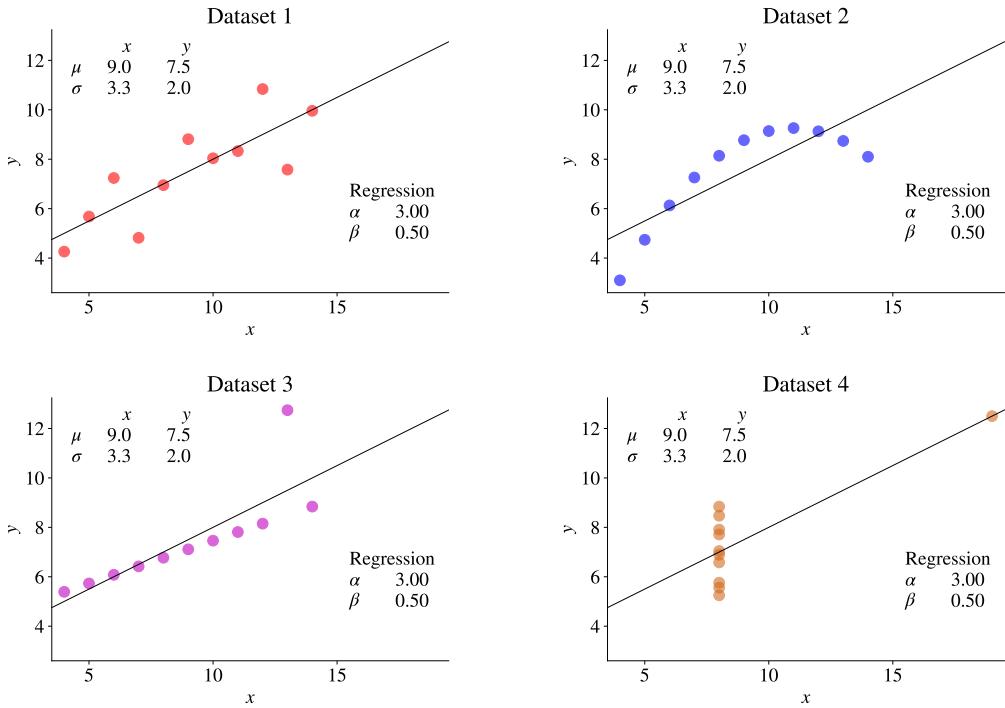


Figure 7.2: Model specification and descriptive statistics (Anscombe's quartet)

can be handled by OLS: just run OLS using  $x_t^{3.4}$  as a regressor.

In contrast, models that are *non-linear in parameters*

$$y_t = \beta_1 + \beta_2 x_t^{\beta_3} + u_t \quad (7.18)$$

cannot be estimated by OLS. Do nonlinear LS (NLS) instead. This requires the use of a numerical minimization routine to minimize the sum of squared residuals,  $\sum_{t=1}^T u_t^2$ .

To *test the functional form* (...is a linear specification really correct?), estimate non-linear extension and test if they are significant. Alternatively, do a RESET test

$$y_t = x_t' \beta + \alpha_2 \hat{y}_t^2 + v_t, \quad (7.19)$$

where  $\hat{y}_t = x_t' \hat{\gamma}$  (from a linear model,  $y_t = x_t' \gamma + \varepsilon_t$ ). If the null hypothesis  $\alpha_2 = 0$  cannot be rejected, then a linear model is good enough. Otherwise, we may need a non-linear specification.

## 7.6 Outliers

OLS is sensitive to extreme data points. The starting point (as always in empirical work) in detecting problems is to plot the data: time series plots and histograms—to see if there are extreme data points.

Since the loss function defining OLS is quadratic, a few outliers can easily have a very large influence on the estimated coefficients. For instance, suppose the true model is  $y_t = 0.75x_t + u_t$ , and that the residual is very large for some time period  $s$ .

Consider the loss function at a slope of 0.75 (the true value, actually): it would be large due to the  $u_t^2$  term. The loss function value will probably be lower if the coefficient is changed to pick up the  $y_s$  observation—even if this means that the errors for the other observations become larger (the sum of the square of many small errors can very well be less than the square of a single large error). See Figure 7.3.

There is of course nothing sacred about the quadratic loss function. Instead the sum of squared errors (as in OLS), one could, for instance, use a loss function in terms of the absolute value of the error  $\sum_{t=1}^T |y_t - b_0 - b_1 x_t|$ . This would produce the Least Absolute Deviation (LAD) estimator. It is typically less sensitive to outliers. This is illustrated in Figure 7.3.

However, LS is by far the most popular choice. There are two main reasons: LS is very easy to compute and it is fairly straightforward to construct standard errors and confidence intervals for the estimator. (From an econometric point of view you may want to add that LS coincides with maximum likelihood when the errors are normally distributed.) |

As complement, it is a good idea to try to identify outliers from the regression results. First, estimate on the whole sample to get the estimates of the coefficients  $\hat{\beta}$  and the fitted values  $\hat{y}_t$ . Second, estimate on the whole sample, except observation  $s$ , and record the estimate  $\hat{\beta}^{(s)}$  and the fitted value for period  $s$  (the one that was not used in the estimation)  $\hat{y}_s^{(s)} = x_s' \hat{\beta}^{(s)}$ . Repeat this for all data points ( $s$ ). Third, plot  $\hat{\beta}^{(s)} - \hat{\beta}$ ,  $\hat{y}_s^{(s)} - \hat{y}_s$  or  $\hat{u}_s^{(s)} / \hat{\sigma}$ . If these series make sudden jumps, then that data point is driving the results for the full sample. It then remains to determine whether this is good (a very informative data point) or bad (unrepresentative or even wrong data point). In particular, the *influence* of observation  $s$  (measured as  $|\hat{y}_s^{(s)} - \hat{y}_s|$ ) is often plotted and analysed. See Figure 7.4 for an illustration.

**Remark 7.11** (An alternative way to calculate  $\hat{\beta}^{(s)} - \hat{\beta}$  and  $\hat{y}_s^{(s)} - \hat{y}_s$ ) Let  $\hat{u}_t = y_t - x_t' \hat{\beta}$ , that is, the residuals from the regression using the whole sample. It is then straightforward

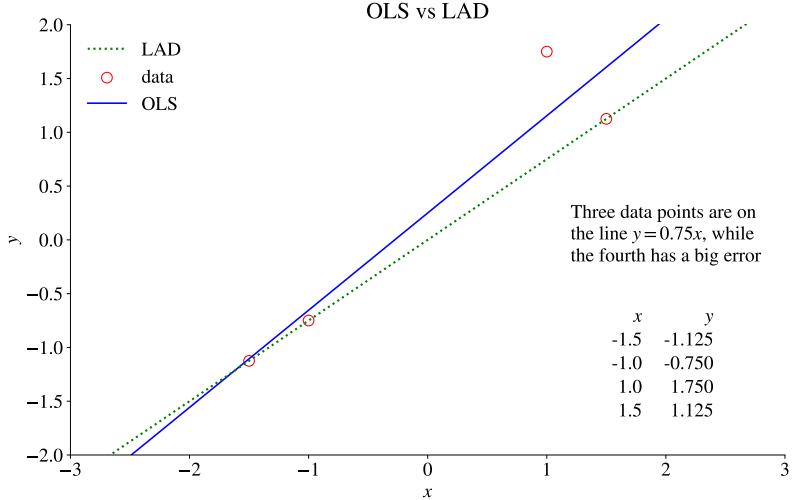


Figure 7.3: Data and regression line from OLS and LAD

to show (see, for instance, Hansen (forthcoming (2021) 3) that

$$\hat{\beta}^{(s)} - \hat{\beta} = -S_{xx}^{-1}x_s \frac{\hat{u}_s}{1 - h_s}, \text{ where } S_{xx} = \sum_{t=1}^T x_t x_t' \text{ and}$$

$$h_s = x_s' S_{xx}^{-1} x_s.$$

The  $h_s$  term is called the “leverage” since it will be a gauge of how important observation  $s$  is. This is perhaps best seen by rewriting the difference in the fitted values as

$$\begin{aligned} \hat{y}_s^{(s)} - \hat{y}_s &= x_s' (\hat{\beta}^{(s)} - \hat{\beta}) \\ &= -x_s' S_{xx}^{-1} x_s \frac{\hat{u}_s}{1 - h_s} = -\frac{h_s}{1 - h_s} \hat{u}_s. \end{aligned}$$

## 7.7 Estimation on Subsamples

To test for a structural break of (one or more) coefficients, add a dummy for a subsample and interact it with the those regressors that we suspect have structural breaks (denoted  $z_t$ , which is a subset of  $x_t$ )

$$y_t = x_t' \beta + g_t z_t' \delta + \varepsilon_t, \text{ where} \quad (7.20)$$

$$g_t = \begin{cases} 1 & \text{for some subsample} \\ 0 & \text{else} \end{cases} \quad (7.21)$$

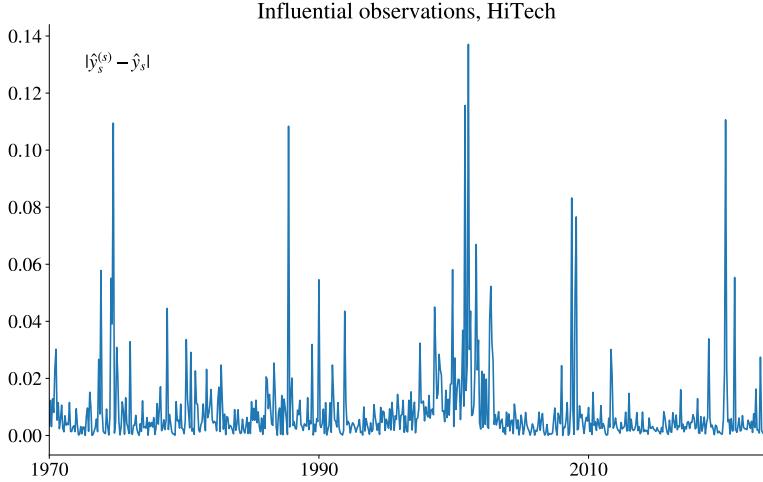


Figure 7.4: Influence of different observations

and test  $\delta = \mathbf{0}$  (a “Chow test”). Notice that  $\delta$  measures the change of the coefficients from one sub sample to another (since the elements in  $z_t$  are also included in  $x_t$ ).

To capture *time-variation in the regression coefficients*, it is fairly common to run the regression

$$y_t = x_t' \beta + \varepsilon_t \quad (7.22)$$

on a longer and longer data set (“recursive estimation”). In the standard recursive estimation, the first estimation is done on the sample  $t = 1, 2, \dots, \tau$ ; while the second estimation is done on  $t = 1, 2, \dots, \tau, \tau + 1$ ; and so forth until we use the entire sample  $t = 1, \dots, T$ . In the “backwards recursive estimate” we instead keep the end-point fixed and use more and more of old data. That is, the first sample could be  $T - \tau, \dots, T$ ; the second  $T - \tau - 1, \dots, T$ ; and so forth.

We could also apply an exponentially weighted moving average (EMA) estimator, which uses all data points since the beginning of the sample—but where recent observations carry larger weights. The weight for data in period  $t$  is  $\lambda^{T-t}$  where  $T$  is the latest observation and  $0 < \lambda < 1$ , where a smaller value of  $\lambda$  means that old data carries low weights. In practice, this means that we define

$$\tilde{x}_t = x_t \lambda^{T-t} \text{ and } \tilde{y}_t = y_t \lambda^{T-t} \quad (7.23)$$

and then estimate

$$\tilde{y}_t = \tilde{x}_t' \beta + \varepsilon_t. \quad (7.24)$$

Notice that also the constant (in  $x_t$ ) should be scaled in the same way. Again, see Figure 7.5 for an illustration.

Alternatively, a moving data window (“rolling samples”) could be used. In this case, the first sample is  $t = 1, 2, \dots, \tau$ ; but the second is on  $t = 2, \dots, \tau, \tau + 1$ . This means that we drop one observation at the start of the sample and add one at the end. This approach could also be reversed: use all the data except that in the window (this is similar to the approach for detecting outliers, except that we exclude a window, not a single data point).

**Empirical Example 7.12** (*Time-varying betas of the HiTech sector*) See Figure 7.5.

Estimation on subsamples is not only a way of getting a more recent/modern estimate, but also a way to gauge the historical range and volatility in the betas—which may be important for putting some discipline on judgemental forecasts.

**Empirical Example 7.13** (*Range of historical betas (different subsamples)*) See 7.6 for an illustration.

From the estimations on subsamples (irrespective of method), it might be informative to study plots of (a) residuals with confidence band ( $0 \pm 2$  standard errors) or standardized residuals with confidence band ( $0 \pm 2$ ) and (b) coefficients with confidence band ( $\pm 2$  standard errors). In these plots, the standard errors are typically from the subsamples.

The recursive estimates can be used to construct another formal test of structural breaks, the recursive *CUSUM test* (see, for instance, Enders (2004)). First, consider a regression on the sample of observation 1 to  $s - 1$  and use the estimated coefficients (denoted  $\hat{\beta}_{s-1}$ ) to calculate a forecast and an adjusted “forecast error” for  $s$  as

$$\hat{y}_s = x_s' \hat{\beta}_{s-1} \text{ and } v_s = \frac{y_s - \hat{y}_s}{\sqrt{1 + x_s' S_{xx,s-1}^{-1} x_s'}}, \quad (7.25)$$

where  $S_{xx,s-1} = \sum_{t=1}^{s-1} x_t x_t'$  (that is, the sum of outer products which is used in calculating  $\hat{\beta}_{s-1}$ ). Do this calculation for  $s = k + 1$  (where  $k$  is the number of regressors), then for  $s = k + 2$  etc. This means that the first estimation (that is, of  $\hat{\beta}_k$ ) uses the first  $k$  observations and so on. Second, estimate the standard deviation (denoted  $\sigma_v$  below) of the vector of  $v_s$  values. Third, calculate the sequence of cumulated errors

$$W_t = \sum_{s=k+1}^t \frac{v_s}{\sigma_v}, \text{ for } t = k + 1, \dots, T. \quad (7.26)$$

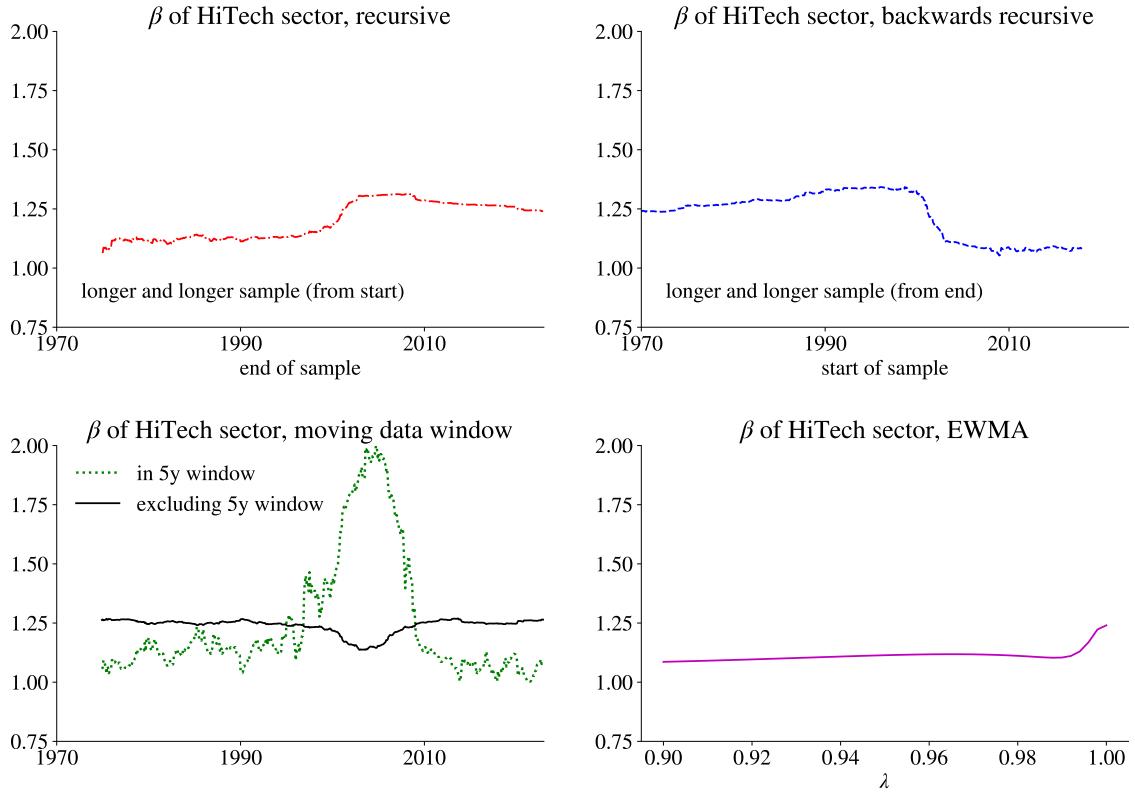


Figure 7.5: Betas of US industry portfolios

For instance,  $W_{k+1} = v_{k+1}/\sigma_v$  and  $W_{k+2} = (v_{k+1} + v_{k+2})/\sigma_v$ . Third, plot  $W_t$  (as a function of  $t$ ) along with confidence interval:  $\pm \lambda [\sqrt{T-k} + 2(t-k)/\sqrt{T-k}]$ , with  $\lambda = 0.948$  for a 95% confidence band and 0.85 for a 90% confidence interval. Reject stability if any observation  $W_t$  is outside. See Figure 7.7 for an example.

**Empirical Example 7.14** (*CUSUM test of a CAPM regression*) See Figure 7.8.

## 7.8 Robust Estimation\*

### 7.8.1 Robust Means, Variances and Correlations

Outliers and other extreme observations can have very decisive influence on the estimates of the key statistics needed for financial analysis, including mean returns, variances, covariances and also regression coefficients.

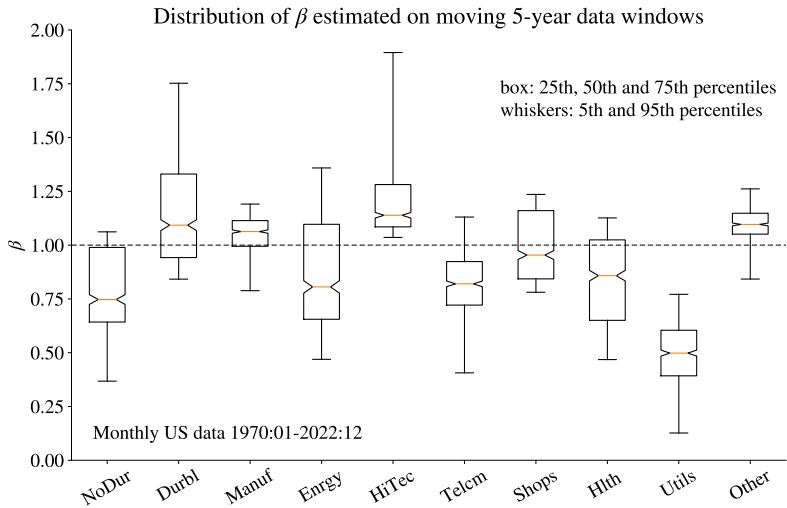


Figure 7.6: Distribution of betas of US industry portfolios (estimated on 5-year data windows)

The perhaps best way to solve these problems is to carefully analyse the data—and then decide which data points to exclude. Alternatively, robust estimators can be applied instead of the traditional ones.

To estimate the mean, the sample average can be replaced by the *median* or a *trimmed mean* (where the  $x\%$  lowest and highest observations are excluded).

Similarly, to estimate the variance, the sample standard deviation can be replaced by the *interquartile range* (the difference between the 75th and the 25th percentiles), divided by 1.35

$$\text{StdRobust} = [\text{quantile}(0.75) - \text{quantile}(0.25)]/1.35, \quad (7.27)$$

or by the *median absolute deviation*

$$\text{StdRobust} = \text{median}(|x_t - \mu|)/0.675. \quad (7.28)$$

Both these would coincide with the standard deviation if data was indeed drawn from a normal distribution without outliers.

**Remark 7.15** (\*Using other quantiles in (7.27)) To use another quantile, for instance, 0.9 and 0.1, change to

$$\text{StdRobust} = [\text{quantile}(0.9) - \text{quantile}(0.1)]/\gamma,$$

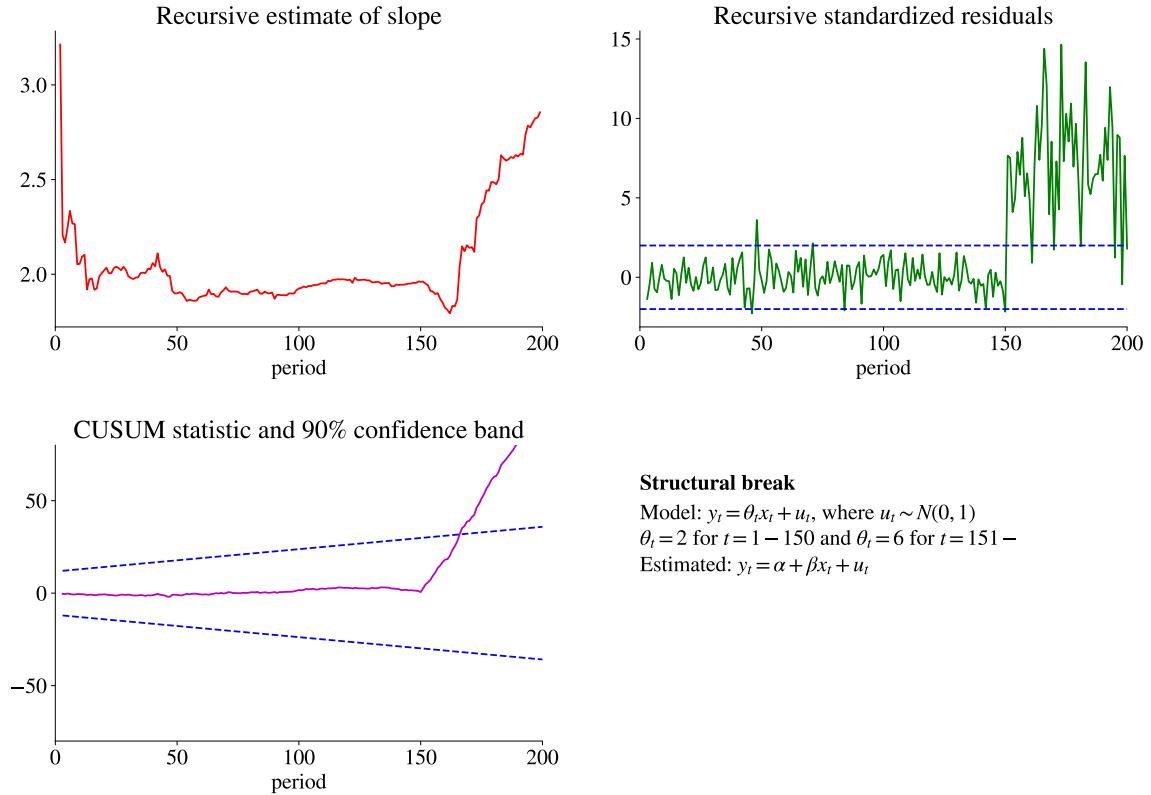


Figure 7.7: Example of a structural break

where  $\gamma$  is the difference between  $\text{quantile}(0.9)$  and  $\text{quantile}(0.1)$  according to a  $N(0, 1)$  distribution.

A robust covariance can be calculated by using the identity

$$\text{Cov}(x, y) = [\text{Var}(x + y) - \text{Var}(x - y)]/4 \quad (7.29)$$

and using a robust estimator of the variances—like the square of (7.27). A robust correlation is then created by dividing the robust covariance with the two robust standard deviations.

**Empirical Example 7.16** (*Robust estimates of means and standard deviations, U.S. industry portfolios*) See Figures 7.9–7.10 for empirical examples.

### 7.8.2 Robust Regression Coefficients

Reference: Amemiya (1985) 4.6

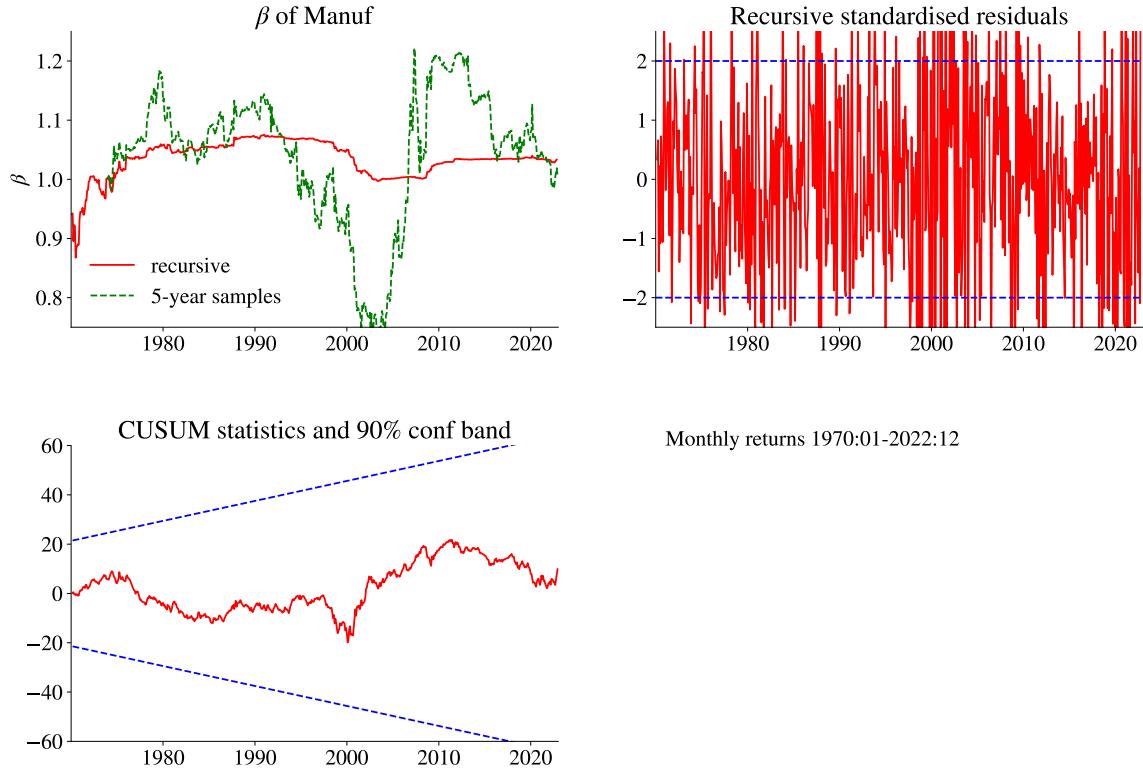


Figure 7.8: Stability test of a CAPM regression

The least absolute deviations (LAD) estimator minimizes the sum of absolute residuals (rather than the squared residuals)

$$\hat{\beta}_{LAD} = \arg \min_b \sum_{t=1}^T |y_t - x'_t b| \quad (7.30)$$

This estimator involves non-linearities, but a simple iteration works nicely. It is typically less sensitive to outliers than OLS. (There are also other ways to estimate robust regression coefficients.) This is illustrated in Figure 7.3.

**Empirical Example 7.17** (*Robust betas, U.S. industry portfolios*) See Figure 7.11.

If we assume that the median of the true residual,  $u_t$ , is zero, then we (typically) have

$$\sqrt{T}(\hat{\beta}_{LAD} - \beta_0) \xrightarrow{d} N[0, f(0)^{-2} \Sigma_{xx}^{-1}/4] \quad (7.31)$$

where  $\Sigma_{xx}$  is (the probability limit of)  $\sum_{t=1}^T x_t x'_t / T$  and where  $f(0)$  is the value of the pdf of the residual at zero. In practice,  $\Sigma_{xx}$  is estimated by data (as  $\sum_{t=1}^T x_t x'_t / T$ ).

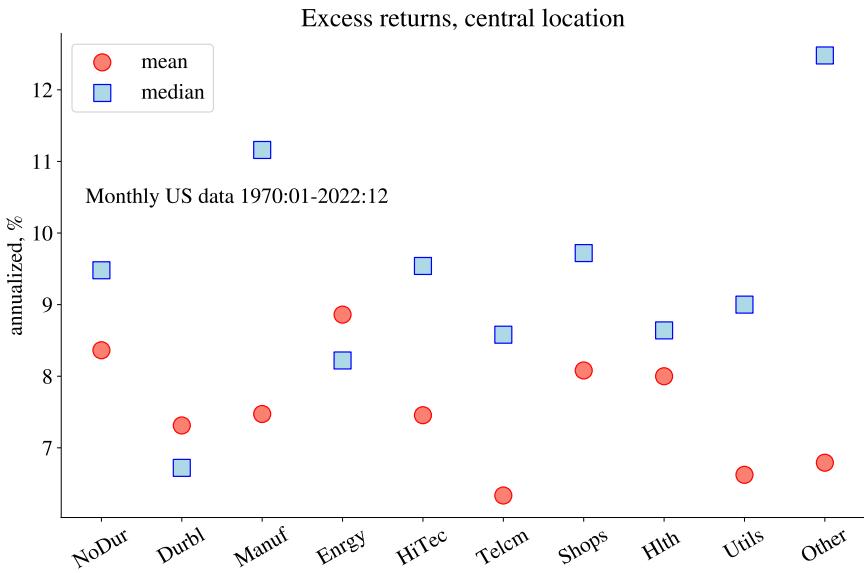


Figure 7.9: Mean excess returns of US industry portfolios

Unless we know density function  $f()$ , we need to estimate it—for instance with a kernel density method.

**Example 7.18** ( $N(0, \sigma^2)$ ) When  $u_t \sim N(0, \sigma^2)$ , then  $f(0) = 1/\sqrt{2\pi\sigma^2}$ , so the covariance matrix in (7.31) becomes  $\pi\sigma^2\Sigma_{xx}^{-1}/2$ . This is  $\pi/2$  times larger than when using LS.

**Remark 7.19** (Algorithm for LAD) The LAD estimator can be written

$$\hat{\beta}_{LAD} = \arg \min_{\beta} \sum_{t=1}^T w_t \hat{u}_t(b)^2, \quad w_t = 1/|\hat{u}_t(b)|, \text{ with } \hat{u}_t(b) = y_t - x'_t \hat{b}$$

so it is a weighted least squares where both  $y_t$  and  $x_t$  are multiplied by  $1/|\hat{u}_t(b)|$ . It can be shown that iterating on LS with the weights given by  $1/|\hat{u}_t(b)|$ , where the residuals are from the previous iteration, converges very quickly to the LAD estimator.

Some alternatives to LAD: least median squares (LMS), and least trimmed squares

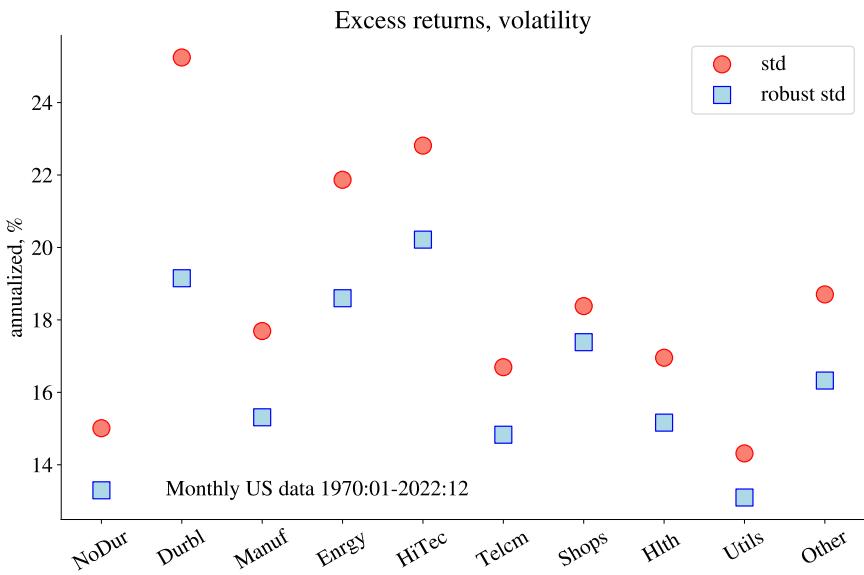


Figure 7.10: Volatility of US industry portfolios

(LTS) estimators which solve

$$\hat{\beta}_{LMS} = \arg \min_{\beta} [\text{median}(\hat{u}_t^2)], \text{ with } \hat{u}_t = y_t - x_t' \hat{b} \quad (7.32)$$

$$\hat{\beta}_{LTS} = \arg \min_{\beta} \sum_{i=1}^h \hat{u}_i^2, \hat{u}_1^2 \leq \hat{u}_2^2 \leq \dots \text{ and } h \leq T. \quad (7.33)$$

Note that the LTS estimator in (7.33) minimizes the sum of the  $h$  smallest squared residuals.



Figure 7.11: Betas of US industry portfolios

# Chapter 8

## Asymptotic Results on OLS\*

Reference: Verbeek (2012) 2 and 5

### 8.1 Motivation of Asymptotics

There are several problems when the standard assumptions about linear regressions are wrong. First, the result that  $E \hat{\beta} = \beta$  (unbiased) relies on the assumption that the regressors are fixed (or that we take expectations conditional on  $\{x_1, \dots, x_T\}$ ). Otherwise, it is probably not true (in a finite sample)—see Figure 8.1. Second, the result that  $\hat{\beta}$  is normally distributed relies on the assumption that residuals are normally distributed. Otherwise it is not true (in a finite sample). See Figure 8.2.

What *is* true when the standard assumptions are not satisfied? How should we test hypotheses? Two ways to find answers: (a) do computer (Monte Carlo or bootstrap) simulations; (b) find results for  $T \rightarrow \infty$  (“asymptotic properties”) and use them as approximations for large samples.

The results from asymptotic theory are more general (and perhaps prettier) than simulations—and can be used as approximations if the sample is large. The basic reason for why this works is that most estimators are sample averages and sample averages often have nice properties as  $T \rightarrow \infty$ . In particular, we can make use of the law of large numbers (LLN) and the central limit theorem (CLT). See Figure 8.9.

However, the asymptotic results are unlikely to be good approximations in small samples. In those cases we need simulations.

### 8.2 Asymptotics: Consistency

Reference: Greene (2018) 4.4; Hamilton (1994) 8.2; Davidson (2000) 3

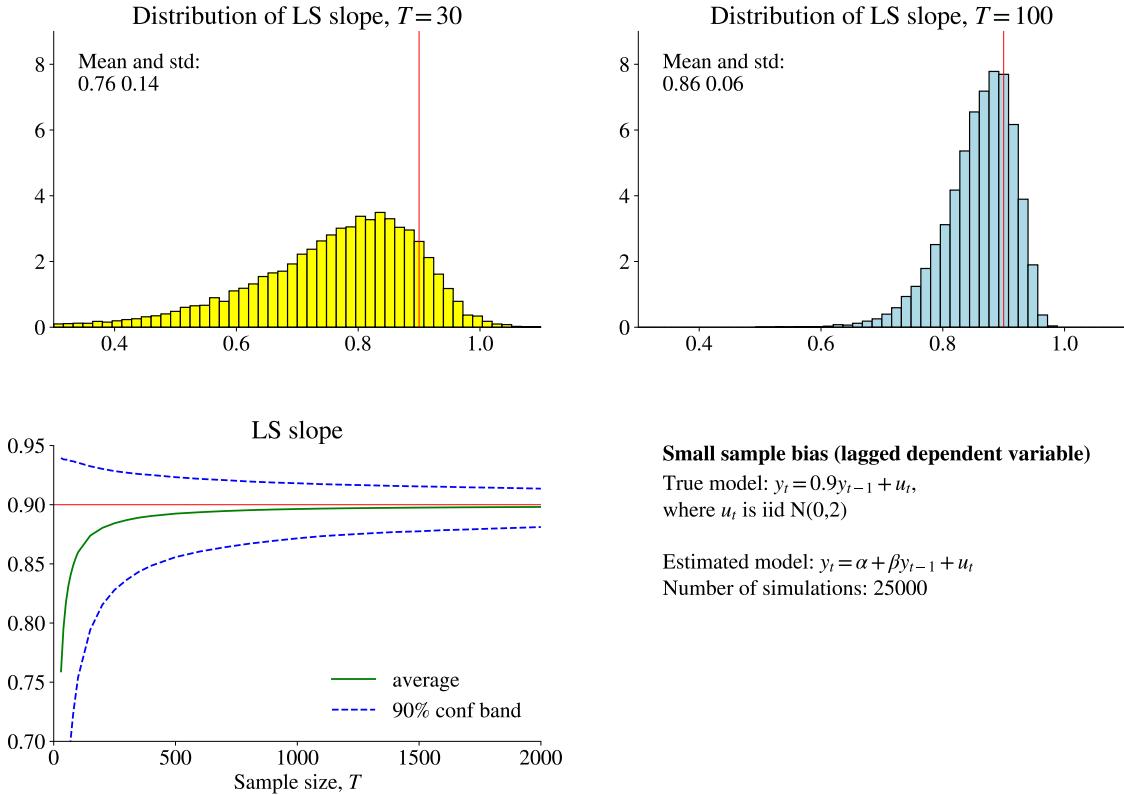


Figure 8.1: Distribution of LS estimator of autoregressive parameter

*Issue:* will our estimator come closer to the truth as the sample size increases? If not, use another estimator (method).

### 8.2.1 Probability Limits and the Law of Large Numbers

We need some basic facts about statistics (probability limits) for the discussion of consistency. These are summarized in the following remarks.

**Remark 8.1** (*Convergence in probability*)  $\hat{\beta}$  (which depends on the sample size  $T$ ) converges in probability to  $b$  if for every  $\varepsilon > 0$

$$\lim_{T \rightarrow \infty} \Pr(|\hat{\beta} - b| < \varepsilon) = 1.$$

Notation:  $\text{plim } \hat{\beta} = b$  or  $\hat{\beta} \rightarrow^p b$  where plim stands for the probability limit.

**Remark 8.2** (*Probability limits of a product and of a function*) If  $\text{plim } \hat{\alpha} = a$  and  $\text{plim } \hat{\beta} = b$ , then  $\text{plim } \hat{\alpha}\hat{\beta} = ab$ . (In contrast, this does not hold for expectations:  $E \hat{\alpha}\hat{\beta} \neq$

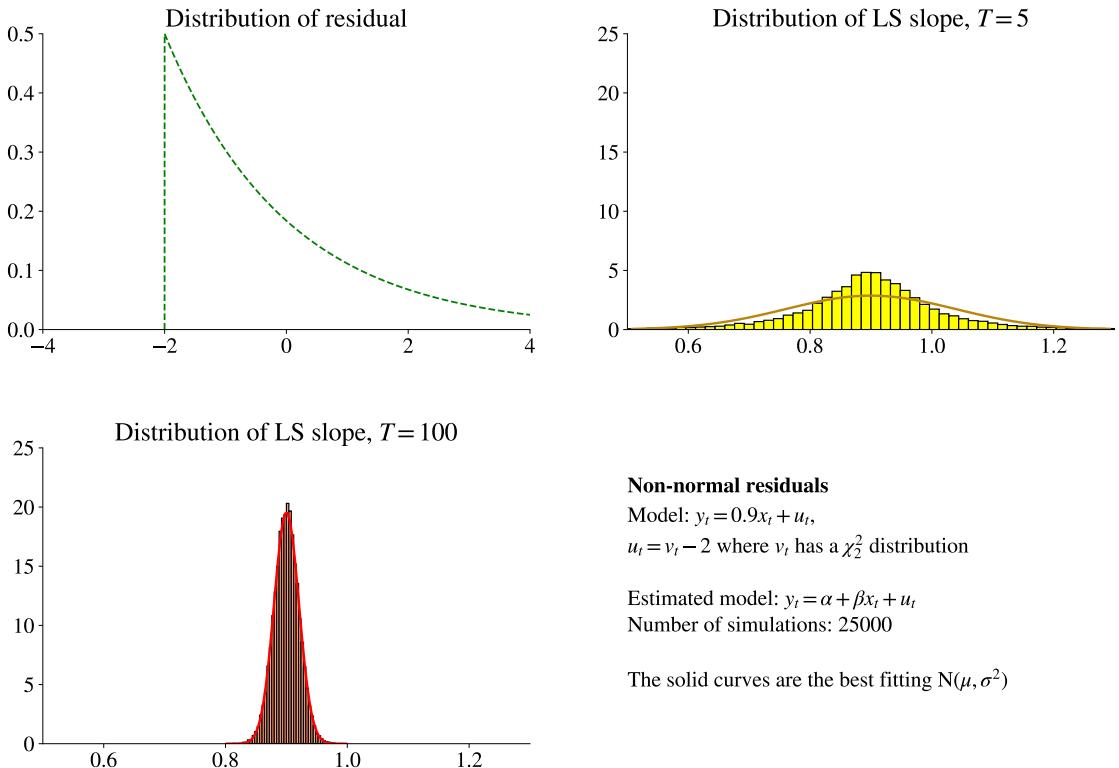


Figure 8.2: Results from a Monte Carlo experiment with thick-tailed errors.

$E\hat{\alpha} \neq E\hat{\beta}$  unless  $\hat{\alpha}$  and  $\hat{\beta}$  are uncorrelated.) More generally, Slutsky's theorem says that if  $g()$  is a continuous function, then  $\text{plim } g(\hat{\alpha}) = g(\text{plim } \hat{\alpha})$ .

**Remark 8.3** (Law of large numbers, simple version) A LLN says that the sample average converges to the population mean as the sample size increases (to infinity). Clearly, this means that the sample average is a consistent estimator of the population mean. Notation:  $\text{plim}(\bar{x}) = E(x)$ .

### 8.2.2 Consistency of OLS

**Remark 8.4** (Consistency) Consistency means that the estimate  $\hat{\beta}$  converges in probability to the true value as the sample size increases (to infinity).

The OLS estimate of a slope coefficient is (after dividing and multiplying by  $T$ )

$$\hat{\beta} = \beta + \underbrace{\left( \frac{1}{T} \sum_{t=1}^T x_t x_t' \right)^{-1}}_{\rightarrow \Sigma_{xx}^{-1}} \underbrace{\frac{1}{T} \sum_{t=1}^T x_t u_t}_{\rightarrow E(xu)} \quad (8.1)$$

where  $u_t$  are the residuals we could calculate if we knew the true slope coefficient (denoted  $\beta$ ), that is, the true residuals. The symbols below the equation indicate what the different terms converge to (according to a LLN) as the sample size increases. In particular, the inverse is a continuous function so the first term converges to the inverse of the second moment matrix of  $x_t$  ( $E(x_t x'_t)$ ) which is denoted  $\Sigma_{xx}$ . (This clearly assumes that  $x_t$  is such that the expectation is well defined.) Also, the two terms form a product so we can apply the rule that the probability limit is the product of the two (individual) probability limits.

In short, the probability limit is

$$\text{plim } \hat{\beta} = \beta + \Sigma_{xx}^{-1} E(x_t u_t), \quad (8.2)$$

where  $\Sigma_{xx}^{-1}$  is (asymptotically) a matrix of constants: there is nothing random about it. Clearly, for the estimate  $\hat{\beta}$  to converge to the true values ( $\beta$ ),  $E(x_t u_t) = 0$  is needed. If  $E u_t = 0$  (which is a basic assumption in most regression analysis), then  $E(x_t u_t) = \text{Cov}(x_t, u_t)$ , so consistency of  $\hat{\beta}$  requires the regressors and the (true) residuals to be uncorrelated.

Some observations:

1. We can not (easily) test this, since OLS *creates*  $\hat{\beta}$  and the fitted residuals  $\hat{u}_t$  such that  $\sum_{t=1}^T x_t \hat{u}_t / T = 0$ .
2. The standard regression assumption that  $u_t$  and  $x_t$  are independent implies that  $E(x_t u_t) = 0$ . This means that the standard regression assumptions take it for granted that OLS is consistent.
3. OLS can be biased (in a small sample), but still be consistent. This means that OLS is systematically wrong in any small sample, but the problem vanishes in large samples. See Figure 8.1. In these figures,  $\text{Cov}(u_{t-1}, x_t) \neq 0$  so OLS is biased since  $x_t$  is not independent of *all* residuals, but  $\text{Cov}(u_t, x_t) = 0$  so it is consistent since  $x_t$  is not correlated with the *contemporaneous* residual.
4. There are cases when  $E(x_t u_t) = 0$  doesn't make sense. Then OLS is inconsistent. More on this later.
5. See Figure 8.1 for an example of where OLS is consistent, and Figure 8.3 when it is not.

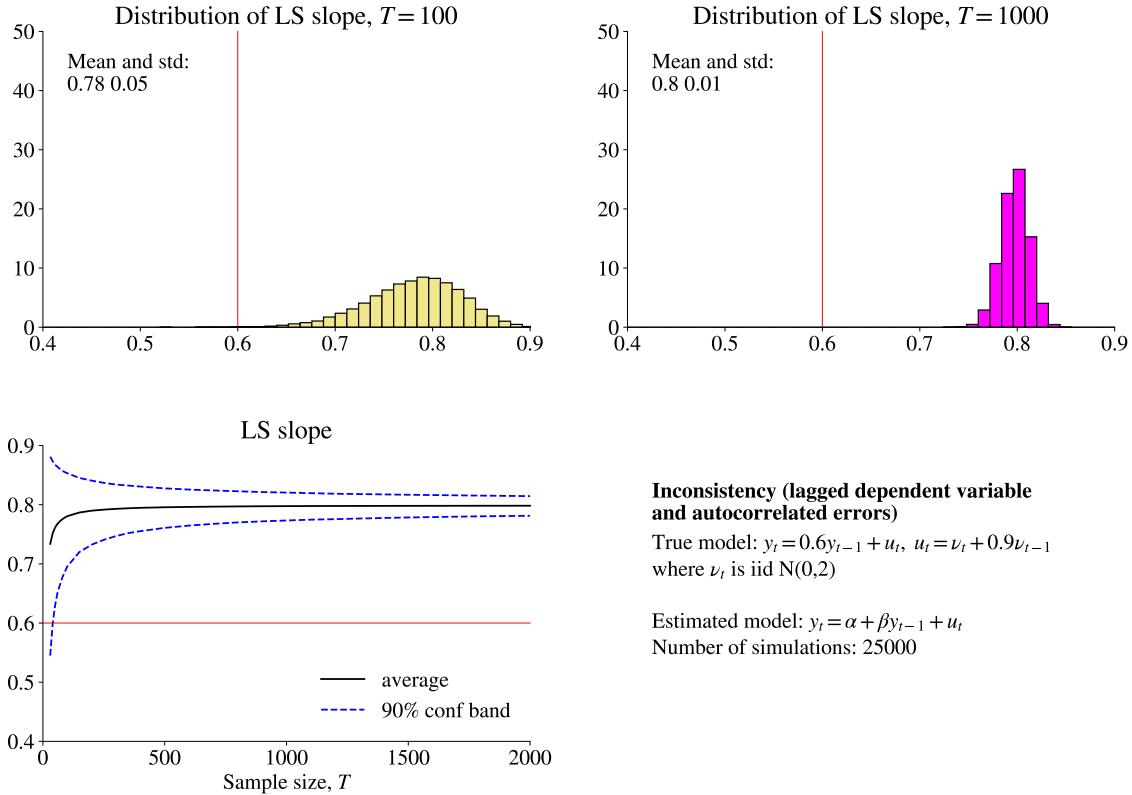


Figure 8.3: Results from a Monte Carlo experiment of LS estimation of the AR coefficient when data is from an ARMA process.

What have we learned? Well,...under what conditions ( $E(x_t u_t) = 0$ ) OLS comes closer to the correct value as  $T$  increases.

### 8.3 When OLS Is Inconsistent

This section discusses some typical cases where OLS is inconsistent, that is,  $E(x_t, u_t) \neq 0$ . These cases include (i) omitted variables; (ii) autocorrelated errors combined with lagged dependent variable; (iii) measurement errors in regressors; and (iv) endogenous regressors.

#### 8.3.1 Omitted Variables

Reference: Greene (2018) 4.3

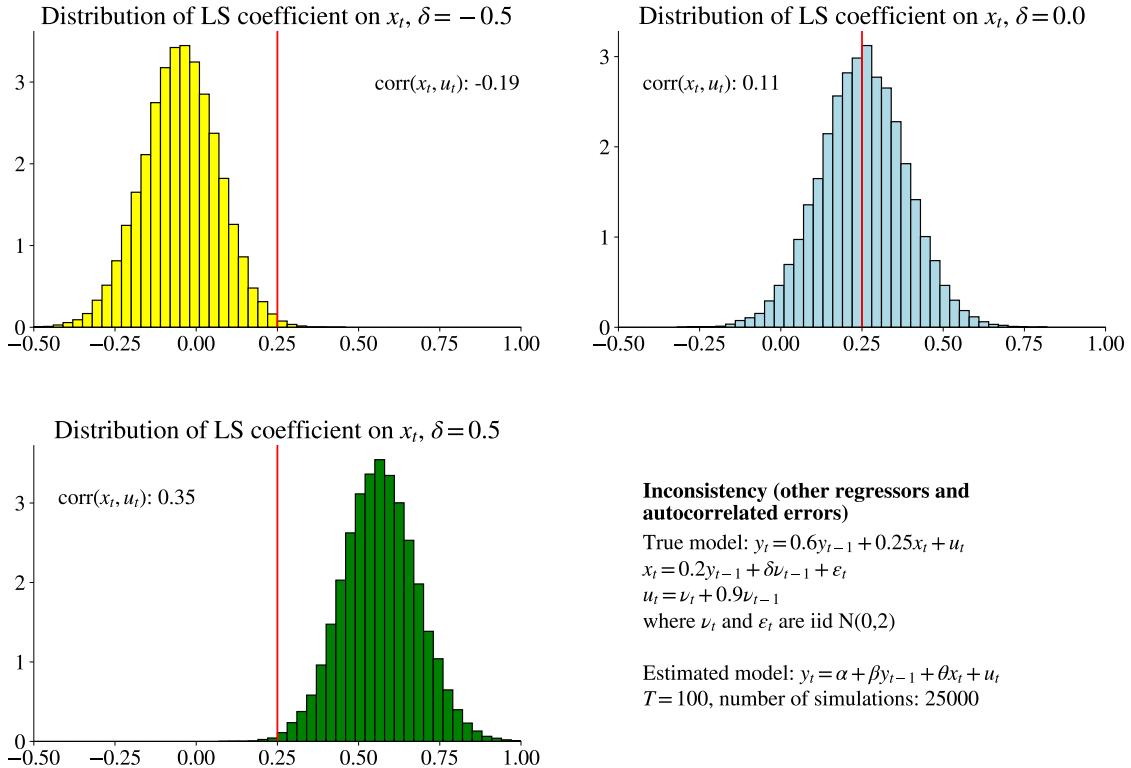


Figure 8.4: Results from a Monte Carlo experiment of LS estimation of the coefficient on  $x_t$  when the errors are autocorrelated.

Consider the regression

$$y_t = x_t' \beta + h_t' \gamma + \varepsilon_t, \quad (8.3)$$

where  $E(x_t \varepsilon_t) = 0$ .

Suppose we omit (exclude) the  $h_t$  variables and instead estimate

$$y_t = x_t' \beta + u_t. \quad (8.4)$$

This means that the residual from in the regression (8.4) is  $u_t = h_t' \gamma + \varepsilon_t$ , that is, it incorporates the effect of both the omitted variables and the “true” residual.

Recall that the OLS estimates are

$$\hat{\beta} = \beta + S_{xx}^{-1} \Sigma_{t=1}^T x_t u_t, \quad (8.5)$$

where  $S_{xx} = \Sigma_{t=1}^T x_t x_t'$ . Since  $u_t = h_t' \gamma + \varepsilon_t$ , we can write this as

$$\hat{\beta} = \beta + S_{xx}^{-1} \sum_{t=1}^T x_t h_t' \gamma + S_{xx}^{-1} \sum_{t=1}^T x_t \varepsilon_t. \quad (8.6)$$

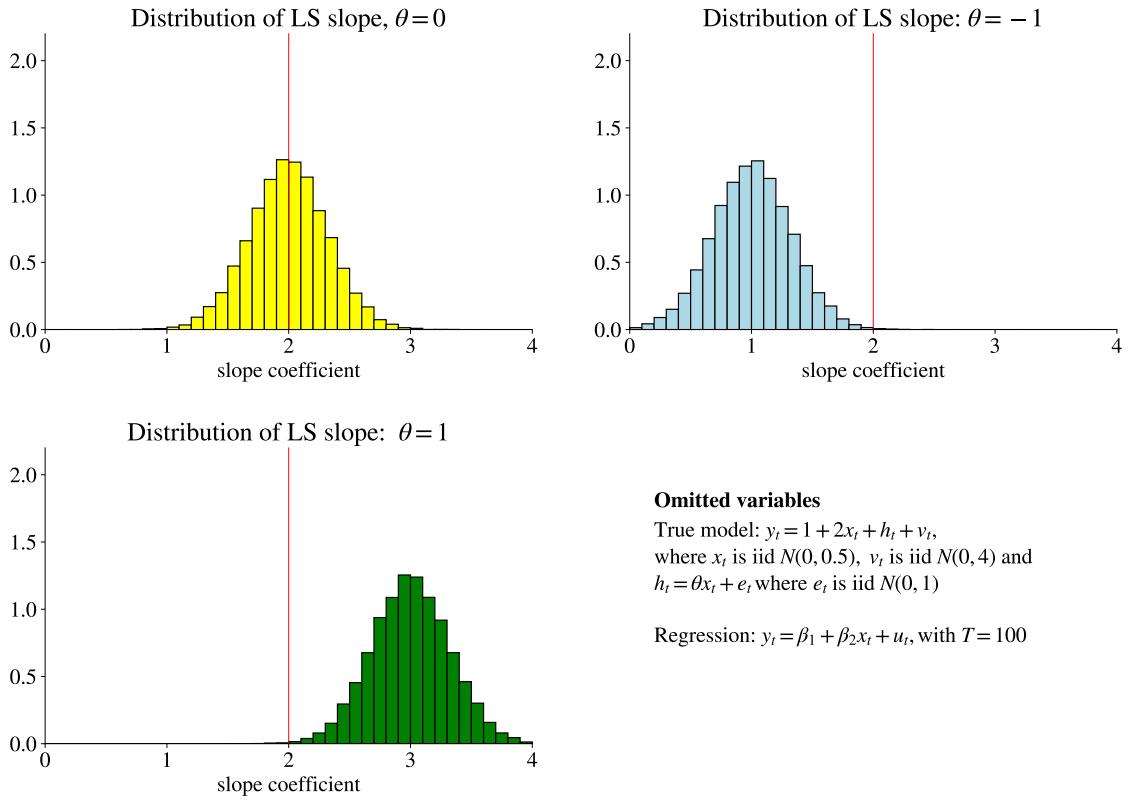


Figure 8.5: Effect of omitted variables

The last term should vanish as the sample size increases (the residual in (8.3) should not be correlated with any of the regressors), while the middle term can be written

$$[ \hat{\theta}_1 \dots \hat{\theta}_L ]\gamma \quad (8.7)$$

where  $\hat{\theta}_i$  is the (column) vector of coefficients obtained by regressing  $h_{it}$  on  $x_t$

$$\hat{\theta}_i = S_{xx}^{-1} \sum_{t=1}^T x_t h_{it}. \quad (8.8)$$

See Figure 8.5.

Together this shows that the probability limit of  $\hat{\beta}$  is

$$\text{plim } \hat{\beta} = \beta + [ \text{plim } \hat{\theta}_1 \dots \text{plim } \hat{\theta}_L ]\gamma. \quad (8.9)$$

This analysis shows that  $\hat{\beta}$  incorporates how  $x_t$  comoves with the  $h_t$ . In case they are uncorrelated ( $\theta_i = \mathbf{0}$ ), then omitting the  $h_t$  variables does not affect the point estimates

of  $\beta$ . However, if they are correlated, then the point estimates  $\hat{\beta}$  are inconsistent (and biased) in the sense of being systematically different from the true  $\beta$  values in (8.3).

Notice the following:

- $\hat{\beta}$  from (8.4) is actually the right number to use if we want to predict: “given  $x_t$ , what is the best guess of  $y_t$ ?” The reason is that  $\hat{\beta}$  factors in also how  $x_t$  predicts  $h_t$  (which affects  $y_t$ ).
- $\hat{\beta}$  from (8.4) is not the right number to use if we want to understand an economic mechanism: “if we increase  $x_{it}$ , by one unit (but holding all other variables constant), what is the likely effect on  $y_t$ ?” The reason is that we here need a consistent estimate of  $\beta$ . Even in this case, (8.9) and an economic theory might be useful in assessing (guessing) the sign of the bias.

### 8.3.2 Autocorrelated Errors Combined with Lagged Dependent Variable

As an example of how autocorrelated errors combined with a lagged dependent variable as regressor leads to inconsistent OLS estimates, consider

$$y_t = \beta_1 + \beta_2 x_t + \beta_3 y_{t-1} + u_t, \text{ where} \quad (8.10)$$

$$u_t = v_t + \theta v_{t-1}, v_t \text{ iid.} \quad (8.11)$$

As a special case,  $\beta_2 = 0$  gives an ARMA(1,1) model, which is a well known case which cannot be estimated by OLS. See Figure 8.3.

The issue is that  $y_{t-1}$  is correlated with the lagged shock ( $v_{t-1}$ ) and hence with the OLS residuals  $u_t$ :  $\text{Cov}(y_{t-1}, u_t) \neq 0$ . This is a common problem in dynamic models.

**Remark 8.5** (AR(1) with autocorrelated errors, theoretical result\*) Consider the case in (8.10)–(8.11) but where  $\beta_2 = 0$  so the regression is an AR(1) but the errors follow an MA(1) process. In the limit, the OLS estimate is  $\hat{\beta}_3 = \text{Cov}(y_t, y_{t-1}) / \text{Var}(y_{t-1})$ . Using (8.10) to replace  $y_t$  gives  $\hat{\beta}_3 = \beta_3 + \text{Cov}(v_t + \theta v_{t-1}, y_{t-1}) / \text{Var}(y_{t-1})$ . Since the 2nd term is non-zero (it is  $\theta \text{Var}(v_{t-1}) / \text{Var}(y_{t-1})$ ), this is not equal to  $\beta_3$ .

**Remark 8.6** (Autocorrelated errors and other regressors\*) Autocorrelated errors may affect the coefficient estimates also on other regressors ( $x_t$ ), but only if  $x_t$  is directly related to the residual. It (probably) is not enough that they are correlated with  $y_{t-1}$ . This might seem puzzling, since a correlation of a regressor with  $y_{t-1}$  will lead to a

*correlation with the residual, so  $E(x_t u_t) \neq 0$ . However, the bias in the coefficient on  $y_{t-1}$  will effectively create another residual that will be uncorrelated with  $x_t$ . (This could probably be proved by using the Frisch-Waugh theorem.) See Figure 8.4.*

### 8.3.3 Measurement Errors in a Regressor

As an example of how measurement errors in a regressor gives inconsistent OLS estimates, consider a simple (true) model like

$$y_t = \beta_1 + \beta_2 w_t + v_t. \quad (8.12)$$

However, we estimate with a proxy  $x_t$  for the regressor  $w_t$

$$y_t = \beta_1 + \beta_2 x_t + u_t, \text{ with} \quad (8.13)$$

$$x_t = w_t + e_t, \quad (8.14)$$

where  $e_t$  is a measurement error. This is a common problem in micro data, including corporate finance. This leads to  $\text{Cov}(x_t, u_t) \neq 0$  (since both  $x_t$  and  $u_t$  depend on the measurement error  $e_t$ ) so OLS is inconsistent for estimating  $\beta_2$ . See Figure 8.6.

To see the precise source of the inconsistency, solve for  $w_t = x_t - e_t$ , use in correct model (8.12) to get

$$\begin{aligned} y_t &= \beta_1 + \beta_2 (x_t - e_t) + v_t \\ &= \beta_1 + \beta_2 x_t - \underbrace{\beta_2 e_t + v_t}_{u_t}. \end{aligned} \quad (8.15)$$

From (8.14) we know that  $x_t$  is correlated with the measurement error ( $e_t$ ), which gives  $\text{Cov}(x_t, u_t) \neq 0$ . In fact, it can be shown that

$$\text{plim } \hat{\beta}_2 = \beta_2 \left( 1 - \frac{\sigma_e^2}{\sigma_w^2 + \sigma_e^2} \right). \quad (8.16)$$

Notice that  $\hat{\beta}_2 \rightarrow 0$  if the measurement error dominates ( $\sigma_e^2 \rightarrow \infty$ ), since  $y_t$  is not related to the measurement error. In contrast,  $\hat{\beta}_2 \rightarrow \beta_2$  as measurement vanishes ( $\sigma_e^2 \rightarrow 0$ ): no measurement error. Measurement errors will thus bias the coefficient towards zero. Any significant coefficient can therefore be seen as a conservative estimate.

**Proof.** (of (8.16)) To simplify, assume that  $x_t$  has a zero mean. From (8.2), we then have  $\text{plim } \hat{\beta}_2 = \beta_2 + \Sigma_{xx}^{-1} E(x_t u_t)$ . Here,  $\Sigma_{xx}^{-1} = 1 / \text{Var}(x_t)$ , but notice from (8.14) that

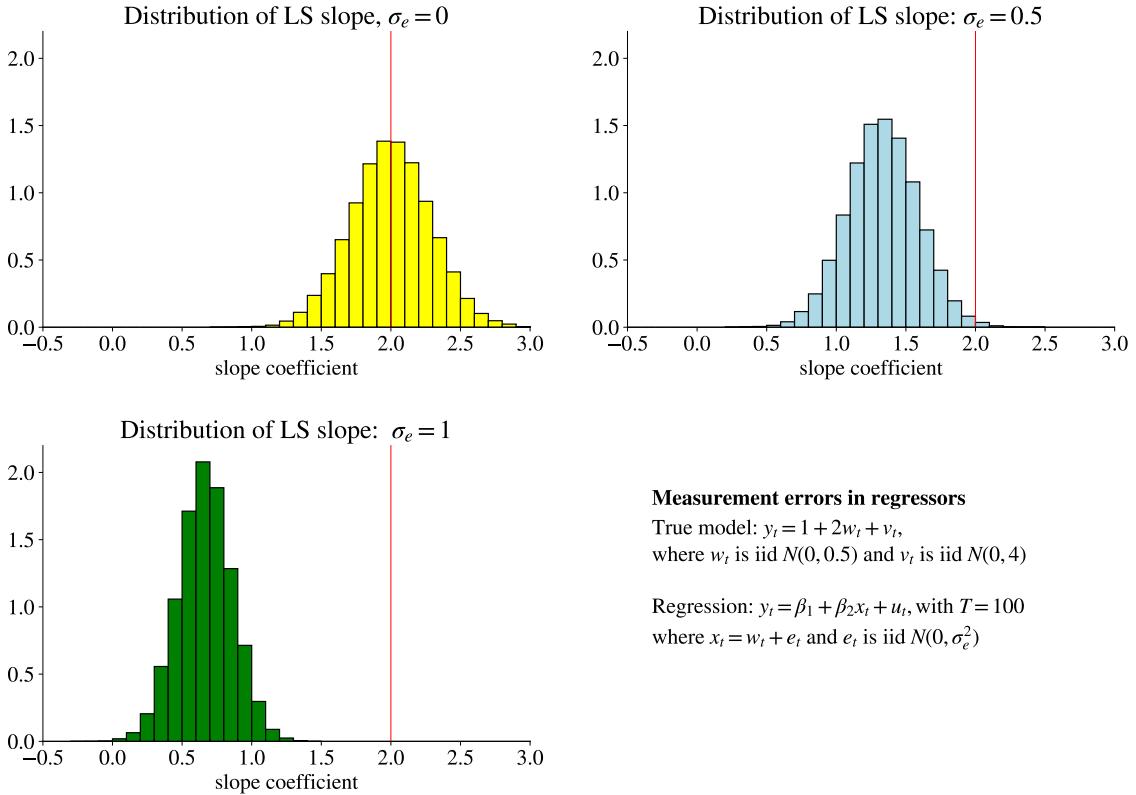


Figure 8.6: Effect of measurement error in regressor

$\text{Var}(x_t) = \sigma_w^2 + \sigma_e^2$  if  $w_t$  and  $e_t$  are uncorrelated. We also have  $E(x_t u_t) = \text{Cov}(x_t, u_t)$ , which from the definition of  $x_t$  in (8.14) and of  $u_t$  in (8.15) gives

$$\text{Cov}(x_t, u_t) = \text{Cov}(w_t + e_t, -\beta_2 e_t + v_t) = -\beta_2 \sigma_e^2.$$

Together we get

$$\text{plim } \hat{\beta}_2 = \beta_2 + \Sigma_{xx}^{-1} E(x_t u_t) = \beta_2 - \beta_2 \frac{\sigma_e^2}{\sigma_w^2 + \sigma_e^2},$$

which is (8.16). ■

### 8.3.4 Endogenous Regressors (System of Simultaneous Equations)

Consider the simplest simultaneous equations model for supply and demand on a market. Supply is

$$q_t = \gamma p_t + u_t^s, \quad \gamma > 0, \tag{8.17}$$

and demand is

$$q_t = \beta p_t + \alpha A_t + u_t^d, \quad \beta < 0, \quad (8.18)$$

where  $A_t$  is an observable demand shock (perhaps income).

**Example 8.7** (*Supply and Demand\**) The system (the “structural form”) is therefore

$$\begin{bmatrix} 1 & -\gamma \\ 1 & -\beta \end{bmatrix} \begin{bmatrix} q_t \\ p_t \end{bmatrix} + \begin{bmatrix} 0 \\ -\alpha \end{bmatrix} A_t = \begin{bmatrix} u_t^s \\ u_t^d \end{bmatrix}.$$

This can be solved in terms of the exogenous variables (the “reduced form”) as

$$\begin{bmatrix} q_t \\ p_t \end{bmatrix} = \begin{bmatrix} -\frac{\gamma}{\beta-\gamma}\alpha \\ -\frac{1}{\beta-\gamma}\alpha \end{bmatrix} A_t + \begin{bmatrix} \frac{\beta}{\beta-\gamma} & -\frac{\gamma}{\beta-\gamma} \\ \frac{1}{\beta-\gamma} & -\frac{1}{\beta-\gamma} \end{bmatrix} \begin{bmatrix} u_t^s \\ u_t^d \end{bmatrix}.$$

Suppose we try to estimate the supply equation (8.17) by LS. However,  $p_t$  is correlated with  $u_t^s$  (since  $u_t^s \rightarrow q_t \rightarrow p_t$ ), so we cannot hope that LS will be consistent. See 8.7 for an illustration (disregard the IV/2SLS subfigure for now). It is clear that the OLS estimate  $\hat{\gamma}_{OLS}$  will be a mixture of the true  $\gamma$  and  $\beta$  values (and other things), see Example 8.8 and Figure 8.8. It is sometimes possible to use economic theory to assess the sign of the bias. In some such cases, it can be argued that any significant coefficient is a conservative estimate.

**Example 8.8** (*Supply equation with LS\**) Using the reduced form from Example 8.7, it is straightforward to show that the probability limit of the OLS estimate of  $\gamma$  is (assuming that the supply and demand shocks are uncorrelated)

$$\begin{aligned} \text{plim } \hat{\gamma}_{OLS} &= \frac{\text{Cov}(q_t, p_t)}{\text{Var}(p_t)} \\ &= \frac{\gamma\alpha^2 \text{Var}(A_t) + \gamma \text{Var}(u_t^d) + \beta \text{Var}(u_t^s)}{\alpha^2 \text{Var}(A_t) + \text{Var}(u_t^d) + \text{Var}(u_t^s)}. \end{aligned}$$

First, suppose the supply shocks are zero,  $\text{Var}(u_t^s) = 0$ , then  $\text{plim } \hat{\gamma} = \gamma$ , so we indeed estimate the supply elasticity, as we wanted. Think of a fixed supply curve, and a demand curve which moves around. These point of  $p_t$  and  $q_t$  should trace out the supply curve. It is clearly  $u_t^s$  that causes a simultaneous equations problem in estimating the supply curve:  $u_t^s$  affects both  $q_t$  and  $p_t$  and the latter is the regressor in the supply equation. With no movements in  $u_t^s$  there is no correlation between the shock and the regressor. Second, now suppose instead that the both demand shocks are zero (both  $A_t = 0$  and  $\text{Var}(u_t^d) = 0$ ).

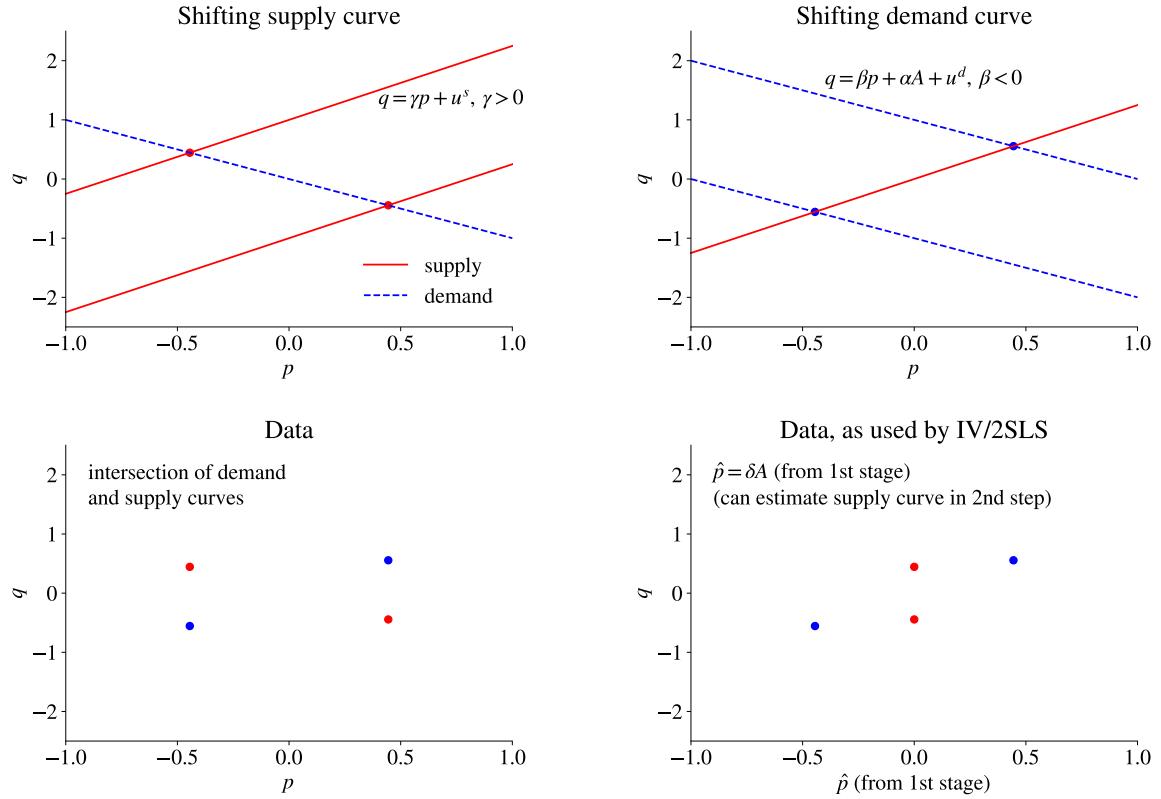


Figure 8.7: Illustration of demand and supply curves

*Then  $\text{plim } \hat{\gamma} = \beta$ , so the estimated value is not the supply, but the demand elasticity. Not good. This time, think of a fixed demand curve, and a supply curve which moves around.*

## 8.4 Asymptotic Normality

Reference: Greene (2018) 4.4; Hamilton (1994) 8.2; Davidson (2000) 3

*Issue:* what is the distribution of your estimator in large samples?

### 8.4.1 Central Limit Theorems

We need some basic facts about statistics (central limit theorems) for the discussion of asymptotic normality, summarized in the remarks below.

**Remark 8.9** (*Convergence in distribution*) Let  $\hat{z}$  be a random variable (which depends on the sample size  $T$ ) and let  $Z$  be another random variable that does not. If  $\lim_{T \rightarrow \infty} \Pr(\hat{z} <$

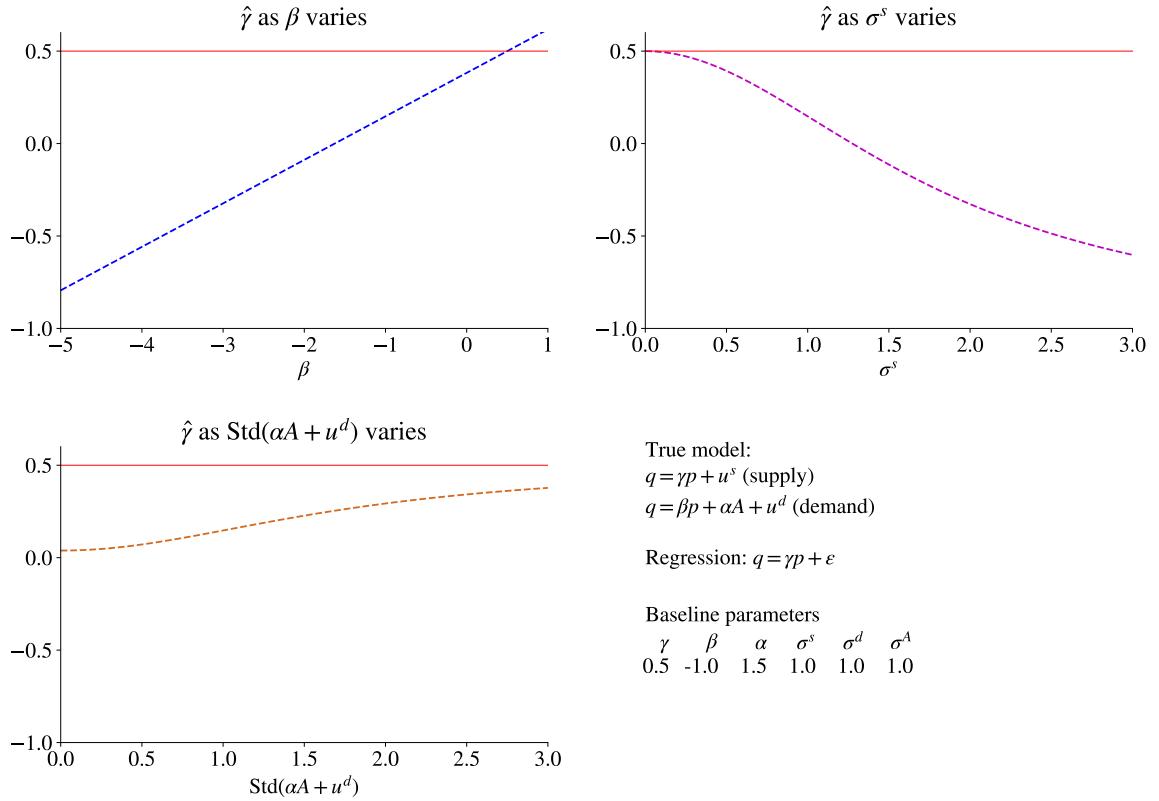


Figure 8.8: OLS estimate of  $\gamma$  in supply equation

$c) = \Pr(Z < c)$  for every  $c$ , then  $\hat{z}$  converges in distribution to the random variable  $Z$ . Notation  $\hat{z} \xrightarrow{d} Z$ .

**Remark 8.10** (Central limit theorem, simple version) A CLT says that  $\sqrt{T}\bar{x} \xrightarrow{d} N(0)$ , that is, becomes normally distributed when  $T$  becomes really large. This holds for many random variables (although exceptions exist). Notice that the distribution of  $\bar{x}$  converges to a spike as  $T$  increases (LLN), but the distribution of  $\sqrt{T}\bar{x}$  converges to a normal distribution. See Figure 8.9.

**Remark 8.11** (Continuous mapping theorem.) Let the random variables  $\hat{z}$  and  $\hat{q}$  and the non-random  $a_T$  be such that  $\hat{z} \xrightarrow{d} Z$ ,  $\hat{q} \xrightarrow{p} Q$  (a finite and positive definite matrix) and  $a_T \rightarrow a$  (a traditional limit). Also, let  $g(z, y, a)$  be a continuous function. Then  $g(\hat{z}, \hat{q}, a_T) \xrightarrow{d} g(Z, Q, a)$ .

**Example 8.12** For instance, the sequences in Remark 8.11 could be  $\hat{z} = \sqrt{T} \Sigma_{t=1}^T w_t / T$

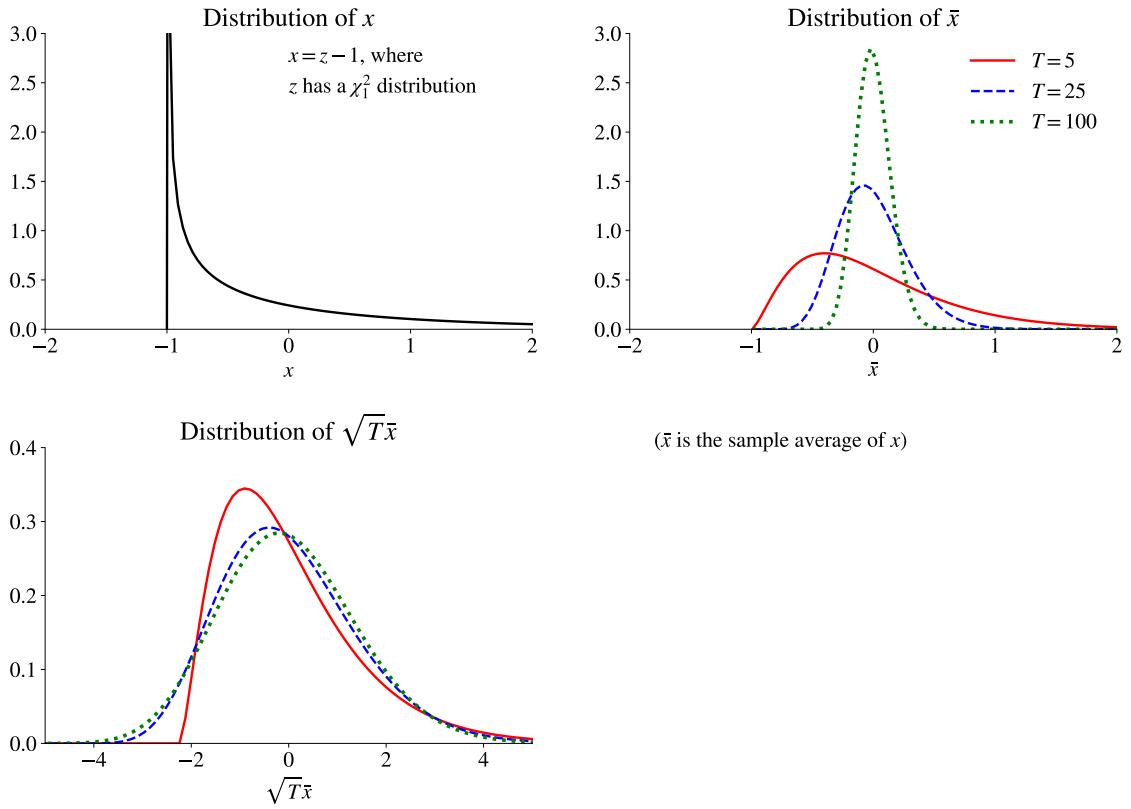


Figure 8.9: Distribution of sample averages

(the scaled sample average of a random variable  $w_t$ );  $\hat{q} = \sum_{t=1}^T w_t^2 / T$  (the sample second moment); and  $a = \sum_{t=1}^T 0.7^t$  (which converges to 2.333).

#### 8.4.2 Asymptotic Normality of OLS

Subtract  $\beta$  from both sides of (8.1), and multiply both sides by  $\sqrt{T}$  to get

$$\sqrt{T}(\hat{\beta} - \beta) = \underbrace{\left( \frac{1}{T} \sum_{t=1}^T x_t x_t' \right)^{-1}}_{\rightarrow \Sigma_{xx}^{-1}} \underbrace{\sqrt{T} \frac{1}{T} \sum_{t=1}^T x_t u_t}_{\sqrt{T} \times \text{sample average}} \quad (8.19)$$

The first term converges (by a LLN) in probability limit to  $\Sigma_{xx}^{-1}$ , assuming the  $x_t$  is such that the limit is well defined. (This is like the  $\hat{q} \xrightarrow{P} Q$  variables in Remark 8.11.) The second term is  $\sqrt{T} \times \text{sample average (of } x_t u_t)$ , which (by a CLT) will (typically) converge in distribution to a normally distributed variable. According to Remark 8.11, we should therefore expect  $\sqrt{T} \hat{\beta}$  to be normally distributed in *large* samples—even if the residual

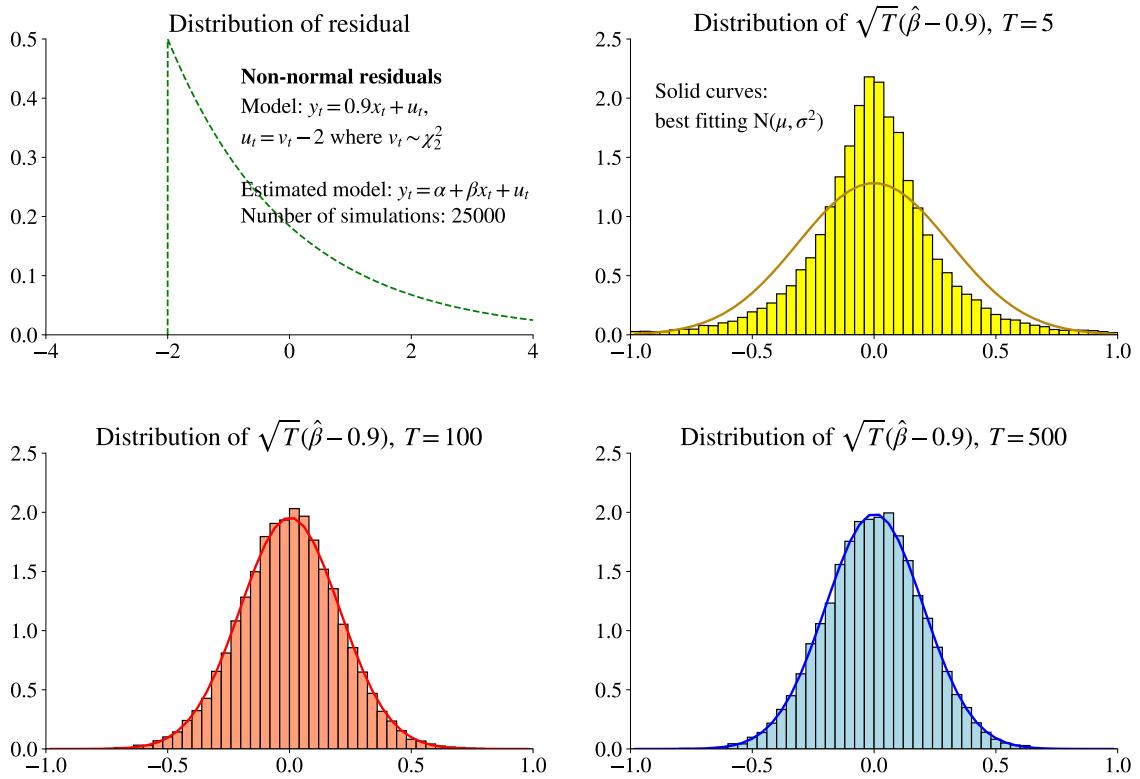


Figure 8.10: Results from a Monte Carlo experiment with thick-tailed errors.

doesn't have a normal distribution. See Figure 8.10 for an example.

According to Remark 8.11 and (8.19)  $\sqrt{T}(\hat{\beta} - \beta)$  converges in distribution to  $\Sigma_{xx}^{-1}$  times a normally distributed variable (vector). If OLS is consistent, then the normal distribution has a zero mean ( $E x_t u_t = 0$ ). Let  $\Sigma$  denote the variance-covariance matrix of  $\sum_{t=1}^T x_t u_t / \sqrt{T}$

$$\Sigma = \text{Var} \left( \sum_{t=1}^T x_t u_t / \sqrt{T} \right). \quad (8.20)$$

Together, we then have

$$\sqrt{T}(\hat{\beta} - \beta) \xrightarrow{d} N(0, \Sigma_{xx}^{-1} \Sigma \Sigma_{xx}^{-1}) \quad (8.21)$$

We sometimes rewrite this as

$$\hat{\beta} \xrightarrow{a} N(\beta, \Sigma_{xx}^{-1} \Sigma \Sigma_{xx}^{-1} / T), \quad (8.22)$$

where  $\xrightarrow{a}$  means “is asymptotically distributed as”. (This transformation is (a) divide the

LHS of (8.21) by  $\sqrt{T}$  and thus the covariance matrix by  $T$ ; (b) add  $\beta$  to the LHS and thus shift the mean fromn 0 to  $\beta$ .)

Recall that we can write the variance-covariance matrix in (8.22) as

$$\text{Var}(\hat{\beta}) = \left( \frac{S_{xx}^*}{T} \right)^{-1} \frac{S}{T} \left( \frac{S_{xx}^*}{T} \right)^{-1} \frac{1}{T}, \quad (8.23)$$

where  $S_{xx}^*/T$  is the limit of  $\sum_{t=1}^T x_t x_t' / T$  as  $T \rightarrow \infty$  and  $S/T$  is the variance-covariance matrix of  $\sum_{t=1}^T x_t u_t / \sqrt{T}$ . Cancelling  $T$  terms and plugging in the estimate  $S_{xx} = \sum_{t=1}^T x_t x_t'$  of  $S_{xx}^*$  and also an estimate of  $S$  gives

$$\widehat{\text{Var}}(\hat{\beta}) = S_{xx}^{-1} \hat{S} S_{xx}^{-1}. \quad (8.24)$$

This is an *estimate* of the variance-covariance matrix, but it has the same form as (an estimate of) the variance-covariance matrix derived under the assumption of fixed regressors.

## 8.5 Spurious Regressions

This section contains an informal discussion of what happens when the data contains trends of have unit root behaviour. (A correct formal discussion is rather involved and beyond the scope of these notes.)

Strong trends often causes problems in econometric models where  $y_t$  and  $x_t$  both have trending behaviour, but where an explicit trend is missing from the set of regressors: this may then make a regressor look significant just because it is a proxy for the missing trend (a missing variable bias). The same holds for non-stationary processes, even if they have no deterministic trends. The reason is that the innovations accumulate and the series therefore tend to be trending in small samples. Asymptotic results are typically of *little use* here, since the non-stationarity means that the asymptotic results are degenerate (for instance, infinite variance). A warning sign of a spurious regression is when  $R^2 > DW$  statistic.

**Empirical Example 8.13** (*Regressing the price level on GDP*) See Figure 8.11 for results from regressing the U.S. price level (GDP deflator) on output (GDP level). The results indicate a very significant regression slope, but extreme autocorrelation. This is likely to be a spurious regression. Also, economics would suggest that nominal (price level) and real variables (output) variables are driven by completely different factors.

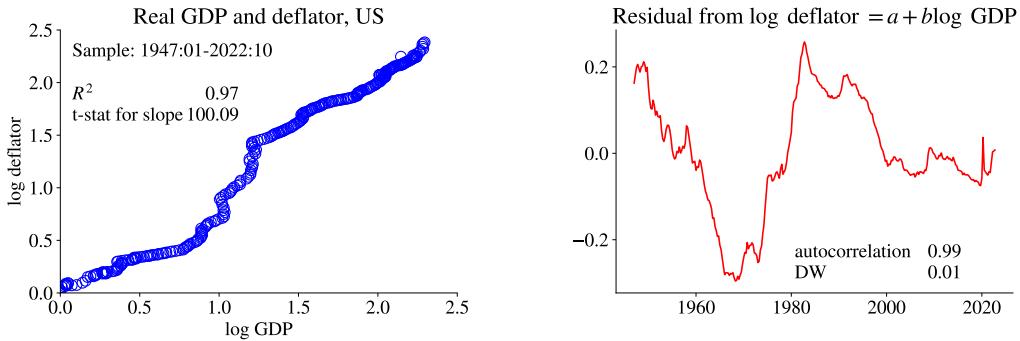


Figure 8.11: Example of a spurious regression

See Figures 8.12 –8.15 for a Monte Carlo simulation. Figure 8.12 shows how the uncertainty about a slope coefficient becomes very large (for a fixed sample size) in a unit root case. That, in itself, is perhaps no big surprise. Figure 8.13 is more worrying since it suggests that (with a unit root) a larger sample size might not help. Figure 8.14 shows how the distribution of the t-stat (of a true null hypothesis) has a very wide distribution—far from being  $N(0,1)$ . This holds also when Newey-West standard errors are used. Finally, Figure 8.15 show that the  $R^2$  gets a strange distribution and that the autocorrelation of the residuals is typically very high.

For trend-stationary data, this problem is easily solved by detrending with a linear trend (before estimating or just adding a trend variable to the set of regressors).

However, this is usually a poor method for a unit root processes. What is needed is a first difference. For instance, a first difference of the random walk with drift is

$$\begin{aligned}\Delta y_t &= y_t - y_{t-1} \\ &= \mu + \varepsilon_t,\end{aligned}\tag{8.25}$$

which is white noise (any finite difference, like  $y_t - y_{t-s}$ , will give a stationary series), so we could proceed by applying standard econometric tools to  $\Delta y_t$ .

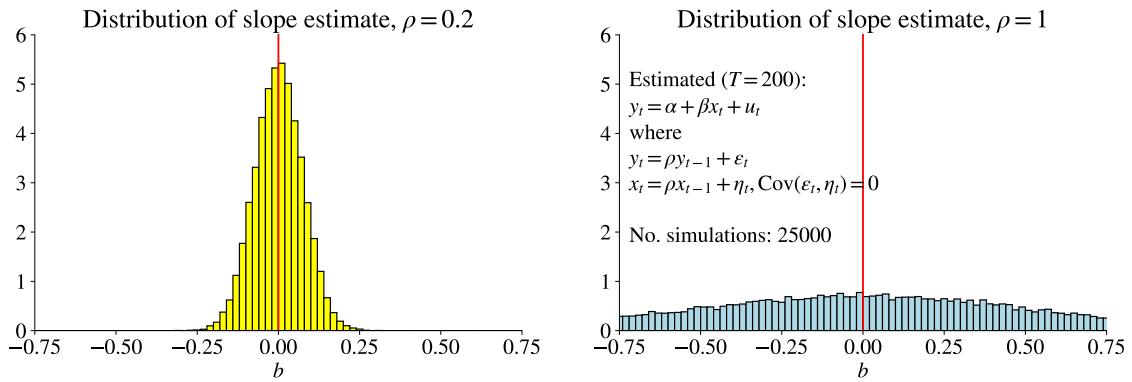


Figure 8.12: Distribution of slope coefficient when  $y_t$  and  $x_t$  are independent AR(1) processes

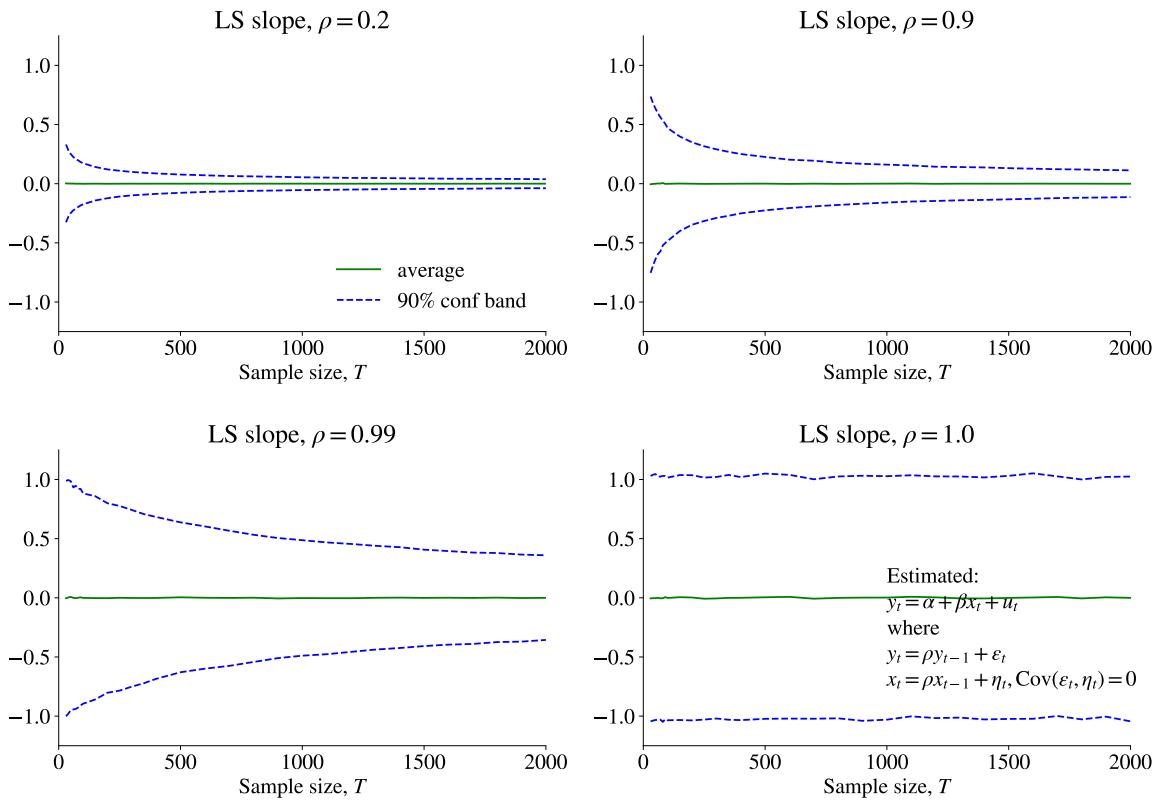


Figure 8.13: Distribution of slope coefficient when  $y_t$  and  $x_t$  are independent AR(1) processes

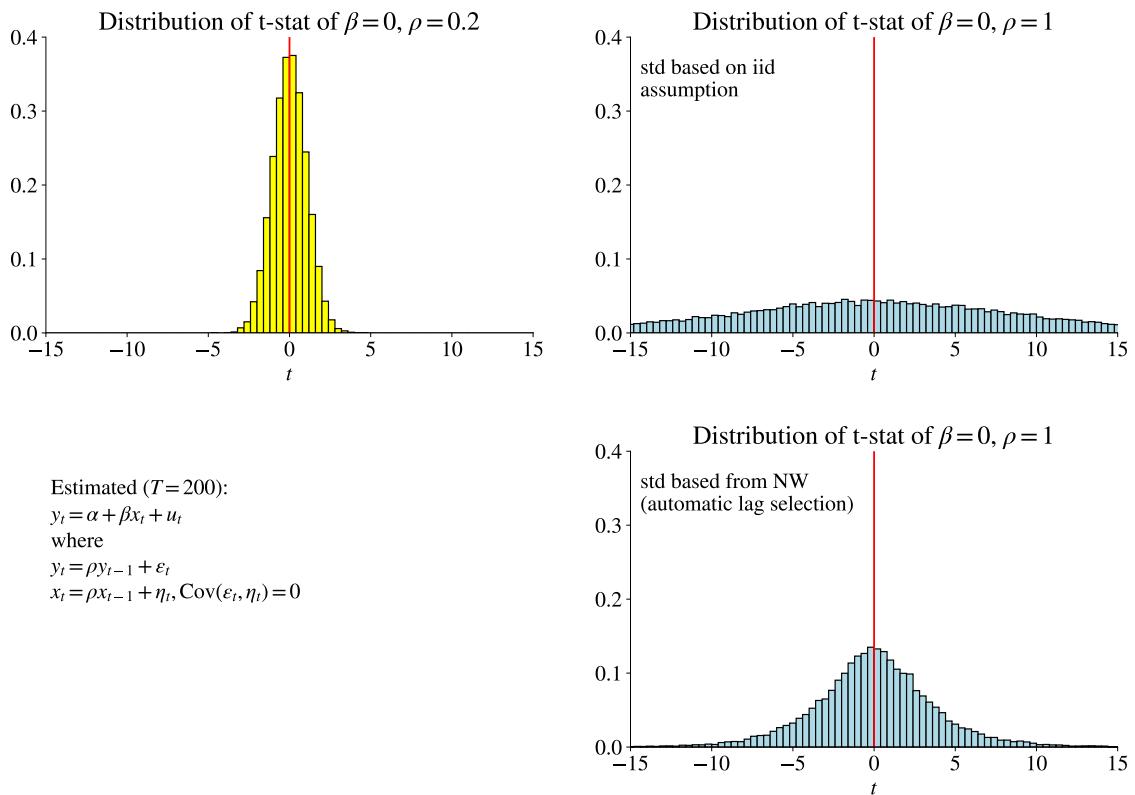


Figure 8.14: Distribution of the t-statistic when  $y_t$  and  $x_t$  are independent AR(1) processes. See Figure 8.12.

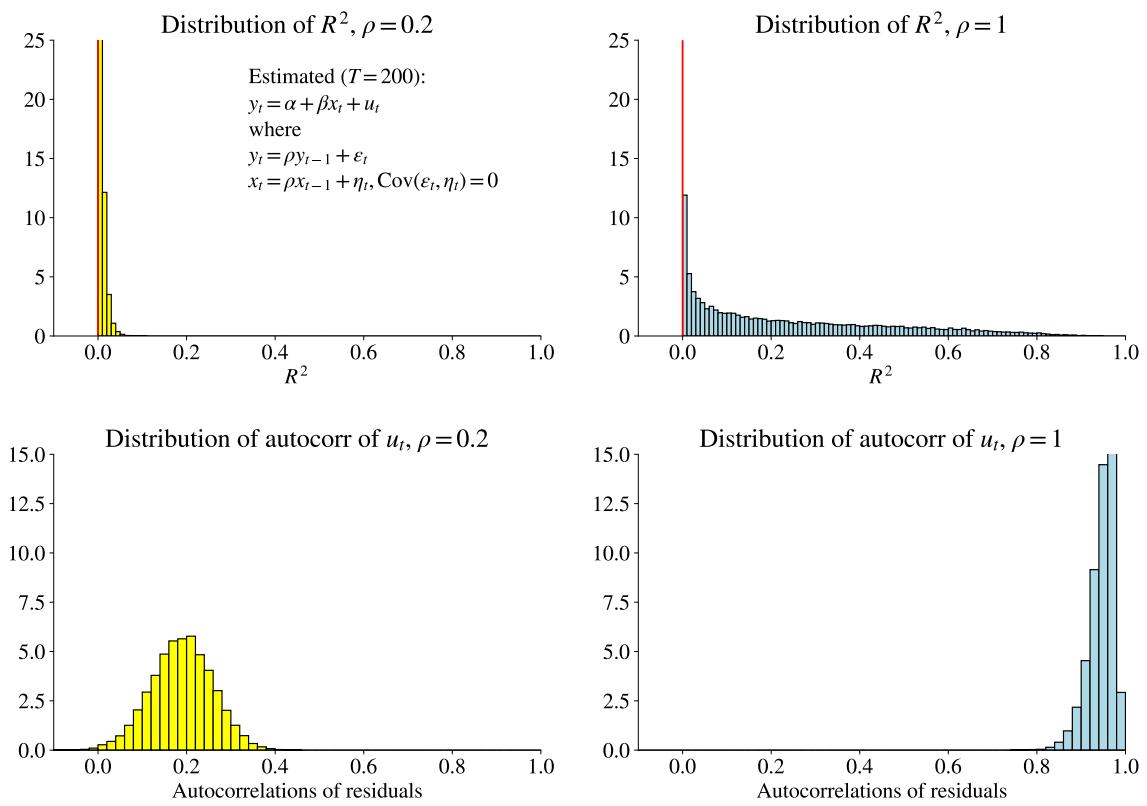


Figure 8.15: Distribution of  $R^2$  and autocorrelation of residuals. See Figure 8.12.

# Chapter 9

## Simulating the Finite Sample Properties

Reference: Greene (2018) 15 and Horowitz (2001)

Additional references: Cochrane (2001) 15.2; Davidson and MacKinnon (1993) 21; Davidson and Hinkley (1997); Efron and Tibshirani (1993) (bootstrapping, chap 9 in particular); and Berkowitz and Kilian (2000) (bootstrapping in time series models)

### 9.1 Introduction

We know the small sample properties of regression coefficients in linear models with fixed regressors and iid normal error terms. When these conditions are not satisfied, then we may either rely on asymptotic (large sample) results or use Monte Carlo simulations and bootstrapping to understand the small sample properties.

How such simulations should be implemented depends crucially on the properties of the model and data: if the residuals are autocorrelated, heteroskedastic, or perhaps correlated across regressions equations. These notes summarize a few typical cases.

**Empirical Example 9.1** (*The empirical importance of simulated standard errors*) *The need for using Monte Carlos or bootstraps varies across applications and data sets. For a case where it does not matter much, see Table 9.1, and for a case where it matters, compare the traditional and bootstrapped t-stats in Tables 9.2–9.3.*

### 9.2 Monte Carlo Simulations

#### 9.2.1 Monte Carlo Simulations in the Simplest Case

Monte Carlo simulations is essentially a way to generate many artificial (small) samples from a parameterised model and then estimate the statistic (for instance, a slope coeffi-

	$\alpha$	$t$ (LS)	$t$ (NW)	$t$ (boot)
A (NoDur)	3.12	2.60	2.43	2.15
B (Durbl)	-1.11	-0.51	-0.52	-0.51
C (Manuf)	0.41	0.46	0.44	0.43
D (Enrgy)	2.89	1.24	1.20	1.10
E (HiTec)	-1.04	-0.67	-0.68	-0.61
F (Telcm)	0.88	0.59	0.57	0.51
G (Shops)	1.24	0.99	0.94	0.90
H (Hlth )	2.46	1.63	1.66	1.63
I (Utils)	3.09	1.91	1.87	1.94
J (Other)	-0.65	-0.68	-0.65	-0.57

Table 9.1: Estimates of CAPM on US industry portfolios 1970:01-2022:12. NW uses 1 lag. The bootstrap samples  $(y_t, x_t)$  pairs, in blocks of 10 observations and has 3000 simulations.

	2y	3y	4y	5y
factor	1.00 (6.74)	1.83 (6.67)	2.58 (6.69)	3.28 (6.75)
constant	-0.00 (-0.00)	-0.00 (-0.20)	-0.00 (-0.39)	-0.00 (-0.60)
$R^2$	0.13	0.13	0.13	0.14
obs	696	696	696	696

Table 9.2: Regression of different excess (1-year) holding period returns (in columns, indicating the maturity of the respective bond) on a single forecasting factor and a constant. Numbers in parentheses are t-stats. U.S. data for 1964:01-2022:12.

cient) on each of those samples. The distribution of the statistic is then used as the small sample distribution of the estimator.

The following is an example of how Monte Carlo simulations could be done in the special case of a linear model

$$y_t = x_t' \beta + u_t, \quad (9.1)$$

where  $u_t$  is iid  $N(0, \sigma^2)$  and  $x_t$  is stochastic but independent of  $u_{t \pm s}$  for all  $s$ . This means that  $x_t$  cannot include lags of  $y_t$ .

Suppose we want to find the small sample distribution of a function of the estimate,  $g(\hat{\beta})$ . To do a Monte Carlo experiment, we need information on (i) the coefficients  $\beta$ ; (ii) the variance of  $u_t$ ,  $\sigma^2$ ; (iii) and a process for  $x_t$ .

The process for  $x_t$  is typically estimated from the data on  $x_t$  (for instance, a VAR

	2y	3y	4y	5y
factor	1.00 (4.06)	1.83 (4.08)	2.58 (4.13)	3.28 (4.20)
constant	-0.00 (-0.00)	-0.00 (-0.10)	-0.00 (-0.19)	-0.00 (-0.29)
$R^2$	0.13	0.13	0.13	0.14
obs	696	696	696	696

Table 9.3: Regression of different excess (1-year) holding period returns (in columns, indicating the maturity of the respective bond) on a single forecasting factor and a constant. U.S. data for 1964:01-2022:12. Numbers in parentheses are t-stats. Bootstrapped standard errors, with blocks of 10 observations.

system  $x_t = A_1x_{t-1} + A_2x_{t-2} + e_t$ ). Alternatively, we could simply use the actual sample of  $x_t$  and repeat it.

The values of  $\beta$  and  $\sigma^2$  are often a mix of estimation results and theory. In some case, we simply take the point estimates. In other cases, we adjust the point estimates so that  $g(\beta) = 0$  holds, that is, so you *simulate the model under the null hypothesis* in order to study the size of tests and to find valid critical values for small samples. Alternatively, you may *simulate the model under an alternative hypothesis* in order to study the power of the test using either critical values from either the asymptotic distribution or from a (perhaps simulated) small sample distribution.

To make it a bit concrete, suppose you want to use these simulations to get a 5% critical value for testing the null hypothesis  $g(\beta) = 0$ . The Monte Carlo experiment follows these steps.

1. Construct an artificial sample of the regressors (see above),  $\tilde{x}_t$  for  $t = 1, \dots, T$ .

Draw random numbers  $\tilde{u}_t$  for  $t = 1, \dots, T$  from a prespecified distribution (for instance, normal) and use those together with the artificial sample of  $\tilde{x}_t$  to calculate an artificial sample  $\tilde{y}_t$  for  $t = 1, \dots, T$  from

$$\tilde{y}_t = \tilde{x}'_t \beta + \tilde{u}_t, \quad (9.2)$$

by using the prespecified values of the coefficients  $\beta$  (perhaps your point estimates or a tweaked version of the point estimates so  $g(\beta) = 0$  holds).

2. Calculate an estimate  $\tilde{\beta}$  and record it along with the value of  $g(\tilde{\beta})$  and perhaps also the test statistic of the hypothesis that  $g(\beta) = 0$ .

3. Repeat the previous steps  $N$  (3000, say) times. The more times you repeat, the better is the approximation of the small sample distribution.
4. Sort your simulated  $\tilde{\beta}$ ,  $g(\tilde{\beta})$ , and the test statistic in ascending order. For a one-sided test (for instance, a chi-square test), take the  $(0.95N)$ th observations in these sorted vector as your 5% critical values. For a two-sided test (for instance, a t-test), take the  $(0.025N)$ th and  $(0.975N)$ th observations as the 5% critical values. You may also record how many times the 5% critical values from the asymptotic distribution would reject a true null hypothesis.
5. You may also want to plot a histogram of  $\tilde{\beta}$ ,  $g(\tilde{\beta})$ , and the test statistic to see if there is a small sample bias, and how the distribution looks like. Is it close to normal? How wide is it? You could also estimate the variance-covariance matrix of  $\tilde{\beta}$  by treating each estimate (from each simulation) as an observation—and then estimate the covariance matrix across these observations.

We have the same basic procedure when  $y_t$  is a vector, except that we might have to consider correlations across the elements of the vector of residuals  $u_t$ . For instance, we might want to generate the vector  $\tilde{u}_t$  from a  $N(\mathbf{0}, \Sigma)$  distribution—where  $\Sigma$  is the variance-covariance matrix of  $u_t$ .

**Remark 9.2** (*Generating  $N(\mu, \Sigma)$  random numbers\**) Suppose you want to draw an  $n \times 1$  vector  $\varepsilon_t$  of  $N(\mu, \Sigma)$  variables. Use the Cholesky decomposition of  $\Sigma$  to calculate the lower triangular  $P$  such that  $\Sigma = PP'$ . Draw  $u_t$  from an  $N(0, I_n)$  distribution, and define  $\varepsilon_t = \mu + Pu_t$ . Note that  $\text{Var}(\varepsilon_t) = E Pu_t u_t' P' = PIP' = \Sigma$ .

It is straightforward to sample the errors from other distributions than the normal, for instance, a student- $t$  distribution. Equipped with uniformly distributed random numbers, you can always (numerically) invert the cumulative distribution function (cdf) of any distribution to generate random variables from any distribution by using the probability transformation method. See *Figure 9.1* for an example.

**Remark 9.3** (*The probability transformation method\**) A random variable  $Y$  has the cdf  $u = \Pr(Y \leq y) = F(y)$ , where  $y$  is a number. Clearly,  $u$  is a probability and thus between 0 and 1. Draw random numbers  $u_i$  from a uniform distribution over  $(0, 1)$ . Then, calculate  $y_i = F^{-1}(u_i)$ , where  $F^{-1}()$  is the inverse of  $F()$ . A sample of  $y_i$  will have the cdf  $F$ .

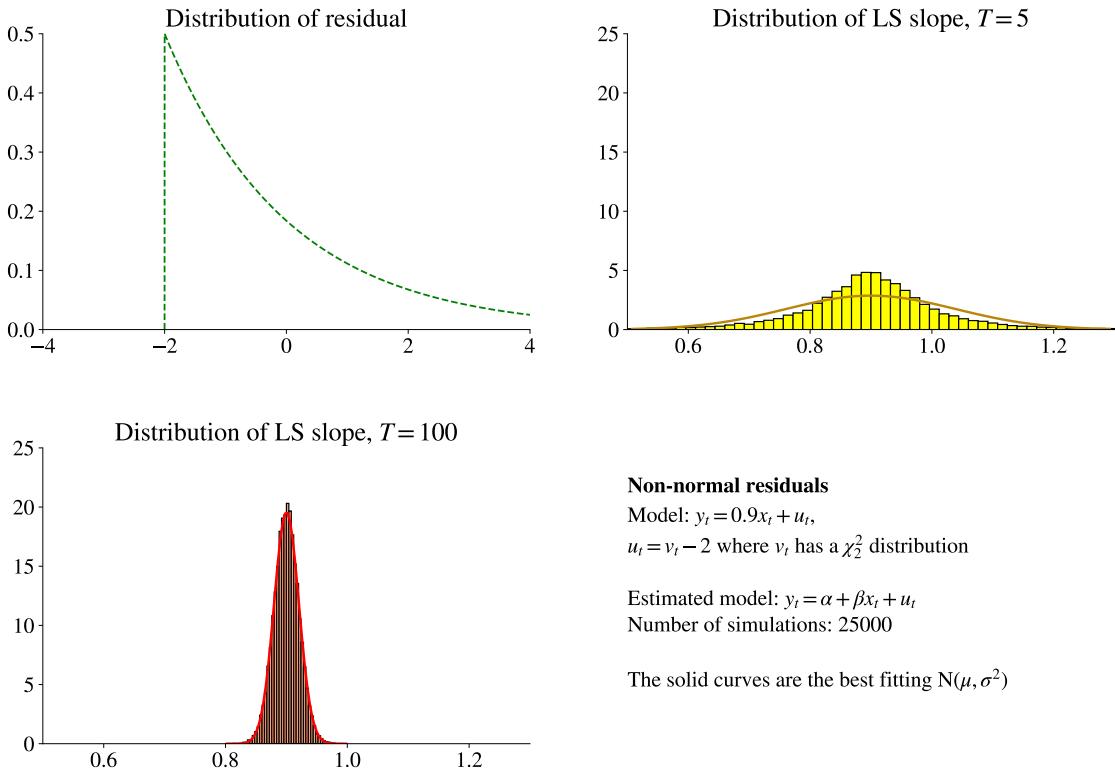


Figure 9.1: Results from a Monte Carlo experiment with thick-tailed errors.

**Example 9.4** (*The probability transformation method\**) *The exponential cdf is  $u = 1 - \exp(-\theta y)$  with inverse  $y = -\ln(1-u)/\theta$ . Draw  $u_i$  from  $U(0, 1)$  and transform to  $y_i$  to get an exponentially distributed variable.*

### 9.2.2 \*Monte Carlo Simulations when $x_t$ Includes Lags of $y_t$

If  $x_t$  contains lags of  $y_t$ , then we must set up the simulations so that temporal link is preserved in every artificial sample which we create. For instance, suppose  $x_t$  includes  $y_{t-1}$  and another vector  $z_t$  of variables which are independent of  $u_{t \pm s}$  for all  $s$

$$\begin{aligned} y_t &= x_t' \beta + u_t \\ &= \gamma y_{t-1} + \phi' z_t + u_t \end{aligned} \tag{9.3}$$

We can then generate an artificial sample as follows. First, create a sample  $\tilde{z}_t$  for  $t = 1, \dots, T$  by some time series model (for instance, a VAR) or by taking the observed

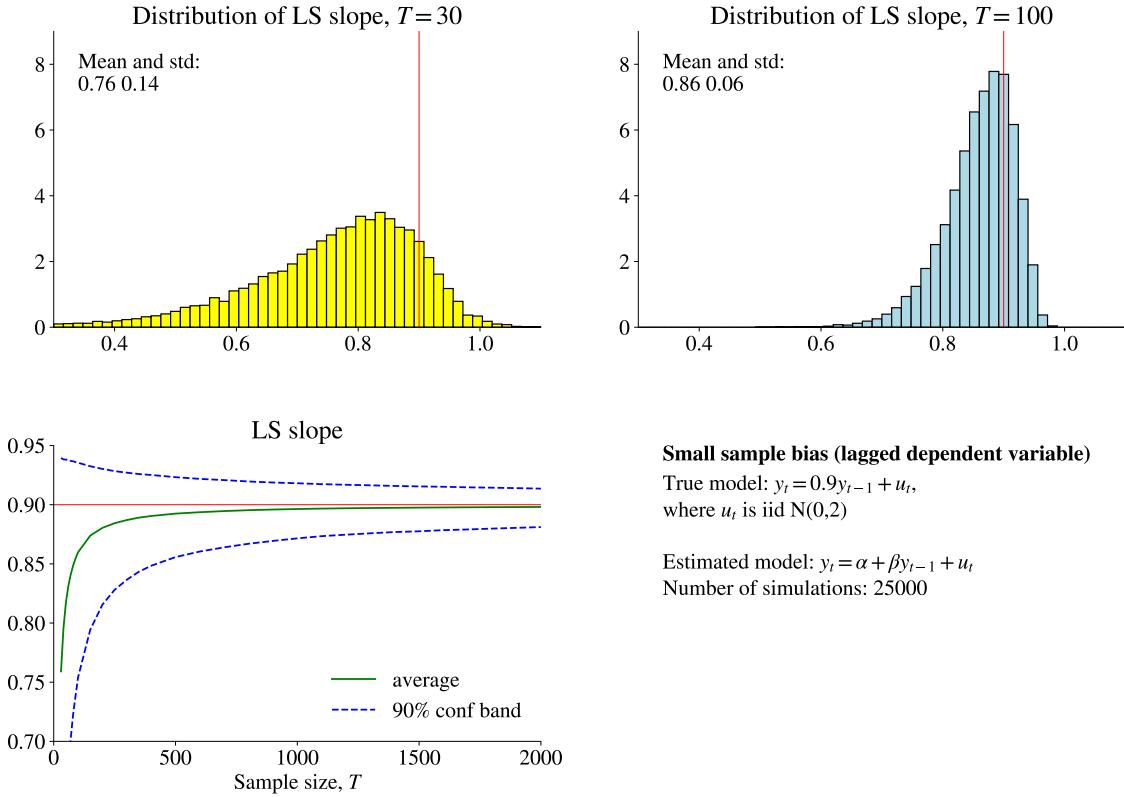


Figure 9.2: Results from a Monte Carlo experiment of LS estimation of the AR coefficient.

sample itself. Second, observation  $t$  of is generated recursively as

$$\tilde{y}_t = \gamma \tilde{y}_{t-1} + \phi' z_t + \tilde{u}_t \text{ for } t = 1, \dots, T \quad (9.4)$$

We clearly need the initial value  $\tilde{y}_0$  to start up the artificial sample—and then the rest of the sample ( $t = 1, 2, \dots$ ) is calculated recursively. See Figures 9.2–9.2 for an example.

**Example 9.5 (Simulating VAR models)** A VAR model is similar to (9.3), but includes no  $z_t$  variable but may have more lags. For instance, a VAR(2)

$$y_t = A_1 y_{t-1} + A_2 y_{t-2} + u_t,$$

where  $y_t$  could be a vector of variables. The simulation procedure is straightforward. First, estimate the model on data and record the estimates ( $A_1, A_2, \text{Var}(u_t)$ ). Second, draw a new time series of residuals,  $\tilde{u}_t$  for  $t = 1, \dots, T$  and construct an artificial

sample recursively (first  $t = 1$ , then  $t = 2$  and so forth) as

$$\tilde{y}_t = A_1 \tilde{y}_{t-1} + A_2 \tilde{y}_{t-2} + \tilde{u}_t.$$

(This requires some starting values for  $y_{-1}$  and  $y_0$ .) Third, re-estimate the model on the artificial sample,  $\tilde{y}_t$  for  $t = 1, \dots, T$ .

### 9.2.3 Monte Carlo Simulations with non-iid Errors

It is more difficult to handle non-iid errors, like those with autocorrelation and heteroskedasticity. We then need to model the error process and generate the errors from that model.

If the errors are *autocorrelated*, then we could estimate a time series process from the fitted errors and then generate artificial samples of errors. For instance, with an AR(2) we get

$$\tilde{u}_t = a_1 \tilde{u}_{t-1} + a_2 \tilde{u}_{t-2} + \tilde{\varepsilon}_t. \quad (9.5)$$

See Figure 9.3 for an illustration.

Alternatively, *heteroskedastic errors* can be generated by, for instance, a GARCH(1,1) model

$$u_t \sim N(0, \sigma_t^2), \text{ where } \sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta \sigma_{t-1}^2. \quad (9.6)$$

However, this specification does not account for any link between the volatility and the regressors (squared)—as tested for by White’s test. This would invalidate the usual OLS standard errors and therefore deserves to be taken seriously. A simple, but crude, approach is to generate residuals from a  $N(0, \sigma_t^2)$  process, but where  $\sigma_t^2$  is approximated by the absolute values of fitted values ( $\sigma_t^2 = |\hat{\varepsilon}_t^2|$ ) from

$$\hat{\varepsilon}_t^2 = c' w_t + \eta_t, \quad (9.7)$$

where  $w_t$  include the squares and cross product of all the regressors.

## 9.3 Bootstrapping

### 9.3.1 Bootstrapping in the Simplest Case

Bootstrapping is another way to do simulations, where we construct artificial samples by sampling from the actual data. The advantage of the bootstrap is then that we do not

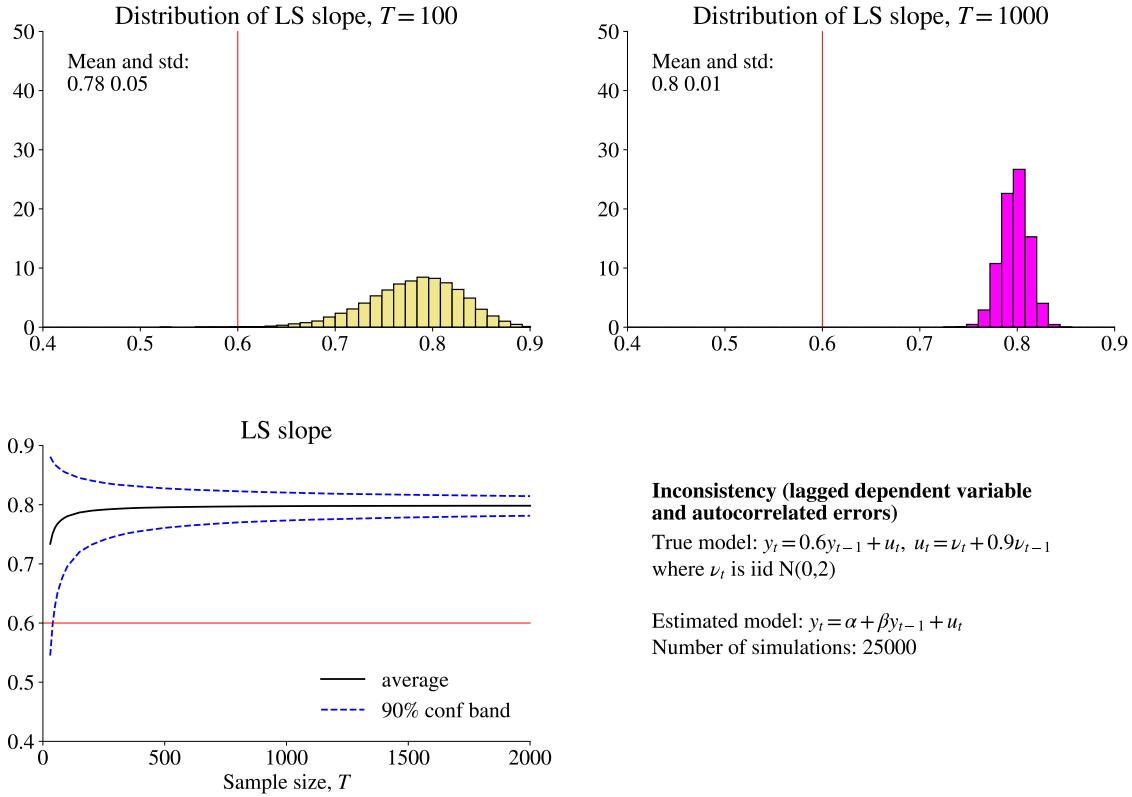


Figure 9.3: Results from a Monte Carlo experiment of LS estimation of the AR coefficient when data is from an ARMA process.

have to try to estimate the process of the errors and regressors (as we do in a Monte Carlo experiment). The real benefit of this is that we do not have to make any strong assumption about the distribution of the errors.

The bootstrap approach works particularly well when the errors are iid and independent of  $x_{t-s}$  for all  $s$ . (This means that  $x_t$  cannot include lags of  $y_t$ .) We here consider bootstrapping the linear model (9.1), for which we have point estimates (perhaps from LS) and fitted residuals. The procedure is similar to the Monte Carlo approach, except that the artificial sample is generated differently. In particular, Step 1 in the Monte Carlo simulation is replaced by the following:

1. Construct an artificial sample  $\tilde{y}_t$  for  $t = 1, \dots, T$  by

$$\tilde{y}_t = x'_t \beta + \tilde{u}_t, \quad (9.8)$$

where  $\tilde{u}_t$  is drawn (with replacement) from the *fitted residual* (“residual resam-

$\alpha :$	$\underline{\gamma = 0}$		$\underline{\gamma = 1}$	
	0	1	0	1
Simulated	7.1	18.8	13.5	25.1
OLS formula	7.1	13.3	13.4	19.3
White's	7.0	18.5	13.3	24.3
Bootstrap	7.1	18.5	13.4	24.3
Bootstrap 2	7.0	18.5	13.3	24.3
Jackknife	7.1	18.9	13.5	24.8
FGLS	7.5	17.3	14.0	24.2

Table 9.4: Standard error of OLS slope (%) under heteroskedasticity (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t \sim N(0, \sigma_t^2)$ , with  $\sigma_t^2 = (1 + \gamma|z_t| + \alpha|x_t|)^2$ , where  $z_t$  is iid  $N(0, 1)$  and independent of  $x_t$ . Sample length: 200. Number of simulations: 25000. The bootstrap draws pairs  $(y_s, x_s)$  with replacement while bootstrap 2 is a wild bootstrap.

pling") and where  $\beta$  is the point estimate from the original sample.

**Example 9.6** With  $T = 3$ , the artificial sample could be

$$\begin{bmatrix} (\tilde{y}_1, \tilde{x}_1) \\ (\tilde{y}_2, \tilde{x}_2) \\ (\tilde{y}_3, \tilde{x}_3) \end{bmatrix} = \begin{bmatrix} (x_1' \beta + u_2, x_1) \\ (x_2' \beta + u_1, x_2) \\ (x_3' \beta + u_2, x_3) \end{bmatrix}.$$

The approach in (9.8) works also when  $y_t$  is a vector of dependent variables—and will then help retain the cross-sectional correlation of the residuals.

### 9.3.2 \*Bootstrapping when $x_t$ Includes Lags of $y_t$

When  $x_t$  contains lagged values of  $y_t$ , then we have to modify the approach in (9.8) since  $\tilde{u}_t$  can become correlated with  $x_t$ . For instance, if  $x_t$  includes  $y_{t-1}$  and we happen to sample  $\tilde{u}_t = u_{t-1}$ , then we get a non-zero correlation. The easiest way to handle this is as in the Monte Carlo simulations in (9.4), but where  $\tilde{u}_t$  are drawn (with replacement) from the sample of fitted residuals.

### 9.3.3 Bootstrapping when Errors Are Heteroskedastic

Suppose now that the errors are heteroskedastic, but serially uncorrelated. If the heteroskedasticity is unrelated to the regressors, then we can still use (9.8).

In contrast, if the heteroskedasticity is related to the regressors, then the traditional LS covariance matrix is not correct (this is the case that White's test for heteroskedasticity tries to identify). It would then be wrong to pair  $x_t$  with just any  $\tilde{u}_t = u_s$  since that destroys the relation between  $x_t$  and the variance of the residual.

An alternative way of bootstrapping can then be used: generate the artificial sample by drawing (with replacement) *pairs*  $(y_s, x_s)$ , that is, we let the artificial pair in  $t$  be  $(\tilde{y}_t, \tilde{x}_t) = (y_s, x_s) = (x'_s \beta + u_s, x_s)$  for some random draw of  $s$  so we are always pairing the residual,  $u_s$ , with the contemporaneous regressors,  $x_s$ . This approach is also called “case resampling.” Note that we are always sampling with replacement—otherwise the approach of drawing pairs would be to just re-create the original data set.

This approach works also when  $y_t$  is a vector of dependent variables.

See Table 9.4 for results from a simulation.

**Example 9.7** With  $T = 3$ , the artificial sample could be

$$\begin{bmatrix} (\tilde{y}_1, \tilde{x}_1) \\ (\tilde{y}_2, \tilde{x}_2) \\ (\tilde{y}_3, \tilde{x}_3) \end{bmatrix} = \begin{bmatrix} (y_2, x_2) \\ (y_3, x_3) \\ (y_3, x_3) \end{bmatrix} = \begin{bmatrix} (x'_2 \beta + u_2, x_2) \\ (x'_3 \beta + u_3, x_3) \\ (x'_3 \beta + u_3, x_3) \end{bmatrix}$$

It could be argued (see, for instance, Davidson and MacKinnon (1993)) that bootstrapping the pairs  $(y_s, x_s)$  makes little sense when  $x_s$  contains lags of  $y_s$ , since the random sampling of the pair  $(y_s, x_s)$  destroys the autocorrelation pattern on the regressors.

### 9.3.4 Bootstrapping when Errors Are Autocorrelated

It is quite hard to handle the case when the errors are serially dependent, since we must the sample in such a way that we do not destroy the autocorrelation structure of the data. A common approach is to fit a time series model for the residuals, for instance, an AR(1), and then bootstrap the (hopefully iid) innovations to that process.

Another approach amounts to *resampling blocks* of residuals. For instance, suppose the sample has 10 observations, and we decide to create blocks of 3 observations. The first block is  $(\hat{u}_1, \hat{u}_2, \hat{u}_3)$ , the second block is  $(\hat{u}_2, \hat{u}_3, \hat{u}_4)$ , and so forth until the last block,  $(\hat{u}_8, \hat{u}_9, \hat{u}_{10})$ . If we need a sample of length  $3\tau$ , say, then we simply draw  $\tau$  of those block randomly (with replacement) and stack them to form a longer series. To handle end point effects (so that all data points have the same probability to be drawn), we also create blocks by “wrapping” the data around a circle. In practice, this means that we add a the following blocks:  $(\hat{u}_{10}, \hat{u}_1, \hat{u}_2)$  and  $(\hat{u}_9, \hat{u}_{10}, \hat{u}_1)$ . The length of the blocks should clearly

depend on the degree of autocorrelation, but  $T^{1/3}$  is sometimes recommended as a rough guide. An alternative approach is to have non-overlapping blocks. See Berkowitz and Kilian (2000) for some other approaches.

**Example 9.8** With  $T = 9$  and a block size of 3, the artificial sample could be

$$\underbrace{u_2, u_3, u_4}_{block\ 2}, \underbrace{u_7, u_8, u_9}_{block\ 7}, \underbrace{u_4, u_5, u_6}_{block\ 4}.$$

See Table 9.5 for results from a simulation.

$\rho :$	0.0	0.75
Simulated	5.9	23.0
OLS formula	5.8	8.7
Newey-West	5.7	16.3
VARHAC	5.7	22.4
Bootstrapped	5.5	19.6
FGLS	5.9	23.0

Table 9.5: Standard error of OLS intercept (%) under autocorrelation (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t = \rho\epsilon_{t-1} + \xi_t$ ,  $\xi_t$  is iid  $N()$ . NW uses 5 lags. VARHAC uses 5 lags and a VAR(1). The bootstrap uses blocks of size 20. Sample length: 300. Number of simulations: 25000.

# Chapter 10

## Instrumental Variables Method (IV)\*

Reference: Verbeek (2012) 5, Greene (2018) 8.3; Hamilton (1994) 9.2; and Pindyck and Rubinfeld (1998) 7.

### 10.1 Instrumental Variables Method

When OLS is inconsistent (see Figure 10.1 for an example), then we typically apply MLE or the instrumental variables (IV) or 2SLS methods. This section describes the latter.

We want to estimate  $\beta$  in

$$y_t = x'_t \beta + u_t, \quad (10.1)$$

where  $x_t$  and  $\beta$  are vectors with  $k$  elements. Recall that OLS is defined by making the fitted residuals orthogonal (uncorrelated) with the regressors

$$\mathbf{0}_{kx1} = \sum_{t=1}^T x_t (y_t - x'_t \hat{\beta}). \quad (10.2)$$

**Example 10.1** (ARMA(1,1)) Consider the time series process  $y_t = 0.9y_{t-1} + \varepsilon_t$  where  $\varepsilon_t = v_t + 0.5v_{t-1}$ . Notice that the regressor ( $y_{t-1}$ ) is correlated with the residual (especially the  $v_{t-1}$  part), so OLS is inconsistent.

The IV method replaces (10.2) by

$$\mathbf{0}_{kx1} = \sum_{t=1}^T z_t (y_t - x'_t \hat{\beta}_{iv}), \quad (10.3)$$

where  $z_t$  is a vector of  $k$  elements that have two key properties: (1)  $z_t$  is uncorrelated with the true residual ( $u_t$ ) so  $z_t$  are *valid instruments*; but (2) correlated with the regressors ( $x_t$ ) so  $z_t$  are *relevant instruments*. The first property cannot be directly checked since we never observe the true residuals. Instead, theoretical arguments must be used, but the

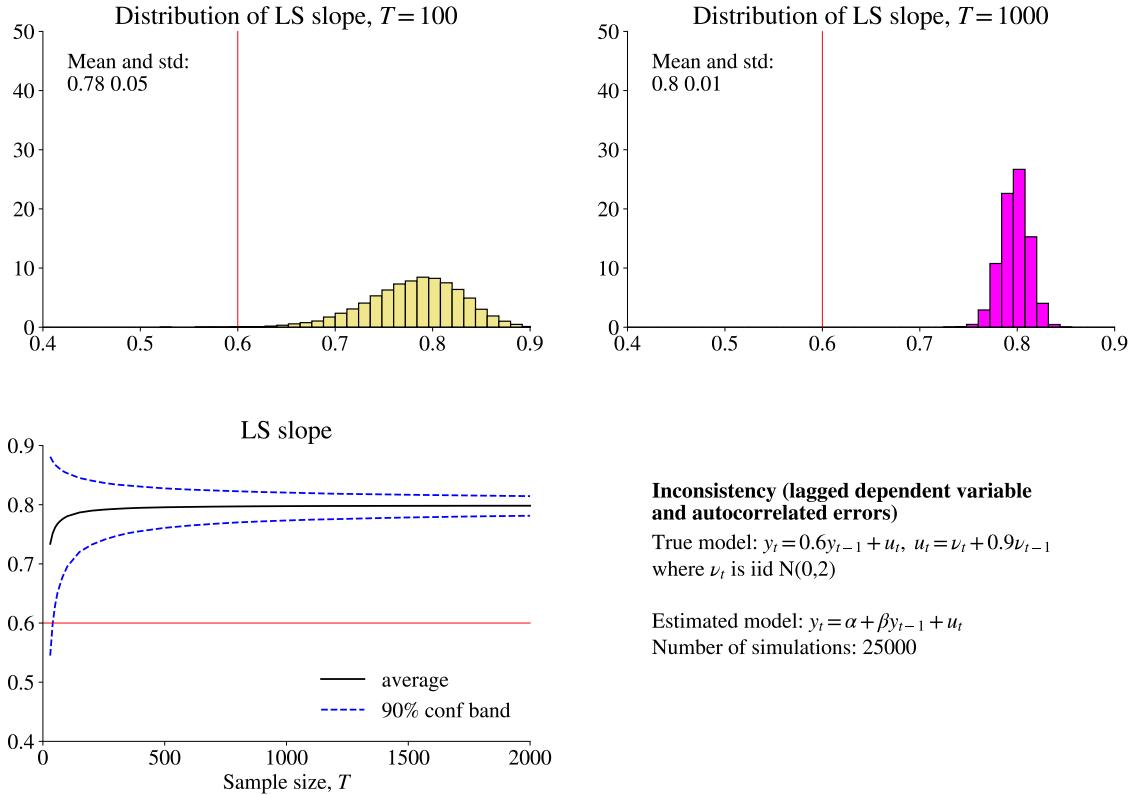


Figure 10.1: Results from a Monte Carlo experiment of LS estimation of the AR coefficient when data is from an ARMA process.

Hausman test can be of some help (see below). In particular, a valid instrument *cannot be endogenous* with respect to (that is, caused by)  $y_t$  and it *cannot be an erroneously excluded regressor*, because both cases would lead to  $\text{Cov}(z_t, u_t) \neq 0$ . A good application of the IV method must argue why that is not the case.

In contrast, the second property is easily checked by, for instance, regressing  $x_t$  on  $z_t$  and studying the t-statistics. (A perhaps more intuitive discussion of what the IV estimator does is found in the section on 2SLS.)

**Example 10.2 (ARMA(1,1) continued)** Continuing Example 10.1, notice that  $y_{t-2}$  (or earlier lags) are not correlated with the residual so they could be used as instruments.

Notice that some regressors (elements of  $x_t$ ) may also be used as instruments ( $z_t$ ). For instance, if just one of the regressors is an endogenous variable then we need (at least one) new instrument for that regressor, while the other regressors can be instruments for themselves.

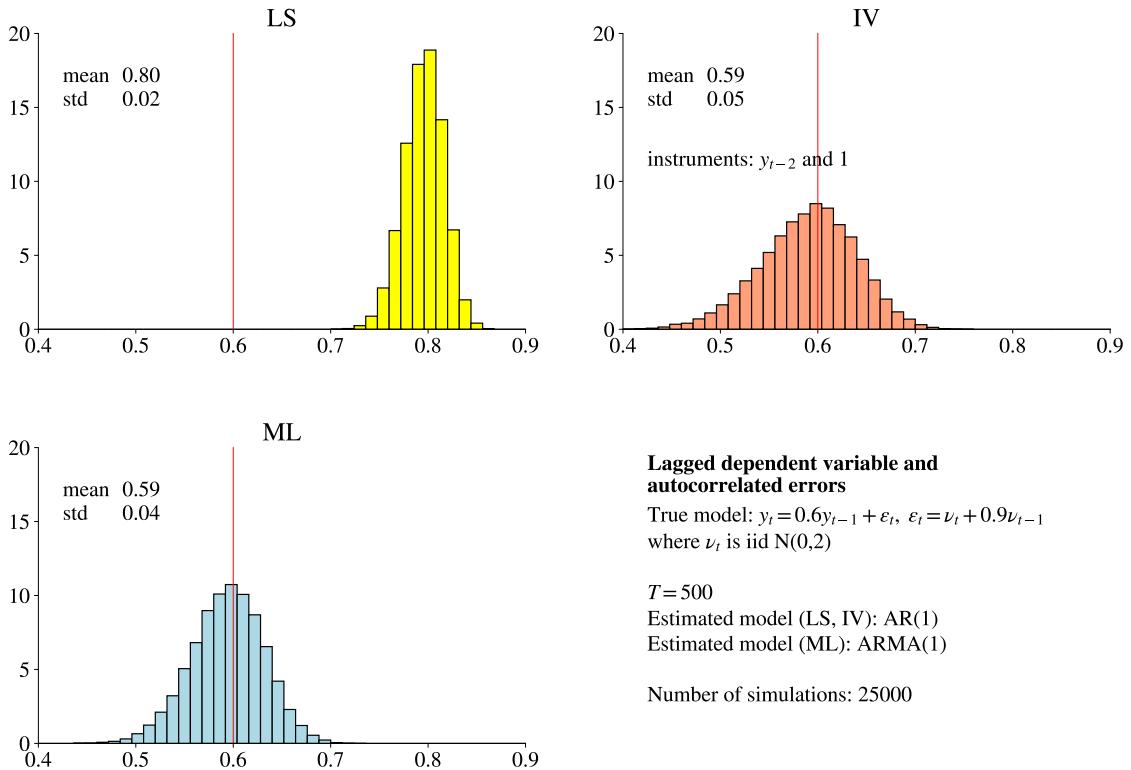


Figure 10.2: Results from a Monte Carlo experiment when data is from an ARMA process.

**Example 10.3 (Supply and Demand)** Consider the simplest simultaneous equations model for supply and demand on a market are

$$\begin{aligned} q_t &= \gamma p_t + u_t^s, \quad \gamma > 0 \text{ (supply)} \\ q_t &= \beta p_t + \alpha A_t + u_t^d, \quad \beta < 0 \text{ (demand)}, \end{aligned}$$

where  $A_t$  is an observable demand shock (perhaps income). To estimate the supply curve, the observable demand shocks  $A_t$  can be used as an instrument. See Figure 10.3 for an illustration.

Solving (10.3) gives the IV estimator

$$\hat{\beta}_{iv} = \left( \sum_{t=1}^T z_t x_t' \right)^{-1} \sum_{t=1}^T z_t y_t. \quad (10.4)$$

Clearly, this is the same as OLS when  $z_t = x_t$ . Notice that  $\Sigma z_t x_t'$  must be invertible (have full rank) for this to work, that is,  $z_t$  and  $x_t$  must be correlated (or else  $z_t$  are not valid

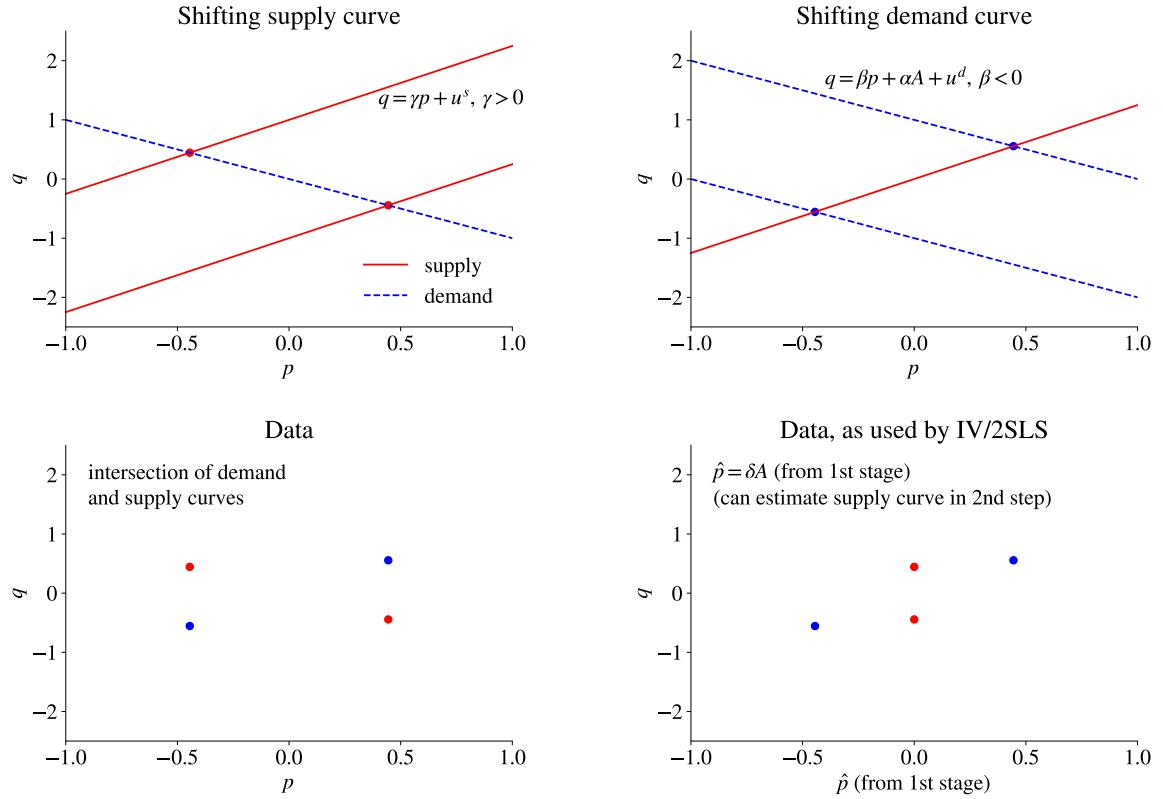


Figure 10.3: Illustration of demand and supply curves

instruments). We need as many instruments as regressors, but some can be instruments for themselves (if it can be argued that this regressor is not correlated with the true residual). There are few results on the small sample properties, although it is often found that there is a small sample bias.

**Remark 10.4 (Matrix notation)** Let  $z'_t$  be the  $t^{th}$  row of  $Z$  and similarly for  $X$ . We then have  $\hat{\beta}_{iv} = (Z'X)^{-1}(Z'Y)$ .

Figure 10.2 shows an example with an  $ARMA(1,1)$  process. The regressor ( $y_{t-1}$ ) is correlated with the residual ( $v_{t-1}$ ), so OLS is inconsistent. The IV method uses  $(1, y_{t-2})$  as instruments for  $(1, y_{t-1})$ . Notice that  $(1, y_{t-2})$  are indeed uncorrelated with the residual (which include shocks in  $t$  and  $t - 1$  but not earlier), but correlated with the regressors (because of the persistence of the  $y_t$  series).

$\hat{\beta}_{iv}$  is (asymptotically) normally distributed so

$$\begin{aligned}\hat{\beta}_{iv} &\stackrel{a}{\sim} N(\beta, V), \text{ with} \\ V &= S_{zx}^{-1} S S_{xz}^{-1} \text{ where } S = \text{Var}(\sum_{t=1}^T z_t u_t)\end{aligned}\tag{10.5}$$

and  $S_{zx} = \Sigma_{t=1}^T z_t x'_t$ . (See Appendix 10.4 for details.) This general expression is valid for both autocorrelated and heteroskedastic residuals—all such features are loaded into the  $S$  matrix.

**Remark 10.5** (Background to (10.5)) As discussed in earlier chapters, the variance-covariance matrix (10.5) can be motivated by either (a) assuming that  $(x_t, z_t)$  are fixed regressors/instruments or (b) by asymptotic results. In the latter case, the more precise statement is that  $S_{zx}^{-1} \hat{S} S_{xz}^{-1}$  is an estimate of the variance-covariance matrix.

**Remark 10.6** In practice, the same expression emerges from both approaches.

We can estimate  $S$  by replacing  $u_t$  by fitted residuals

$$\hat{u}_t = y_t - x'_t \hat{\beta}_{iv}.\tag{10.6}$$

If the residuals are iid and independent of  $z_t$  (so  $S = \sigma^2 S_{zz}$ ), then

$$V = \sigma^2 S_{zx}^{-1} S_{zz} S_{xz}^{-1}, \text{ if } u_t \text{ are iid.}\tag{10.7}$$

The IV estimator has often large standard deviations, especially with “weak instruments” (weak correlation with regressors). This is illustrated in Figure 10.4.

**Example 10.7** ( $\text{Var}(\hat{\beta}_{iv})$  in the simplest case) Assume  $y_t$ ,  $x_t$  and  $z_t$  are zero mean variables and that  $z_t$  and  $u_t$  are independent. Equation (10.7) for a simple regression can then be written

$$\begin{aligned}\text{Var}(\hat{\beta}_{iv}) &= \frac{\sigma^2 \text{Var}(z_t)/T}{\text{Cov}(x, z)^2} \\ &= \frac{\sigma^2/T}{\text{Var}(x_t)} \frac{1}{\text{Corr}(x_t, z_t)^2}.\end{aligned}$$

If  $\text{Corr}(x_t, z_t) = 1$  or  $-1$ , then this is the same as with OLS (but the consistency can be questioned in this case). Instead, with a low  $\text{Corr}(x_t, z_t)^2$  value (weak instruments), then the uncertainty increases.

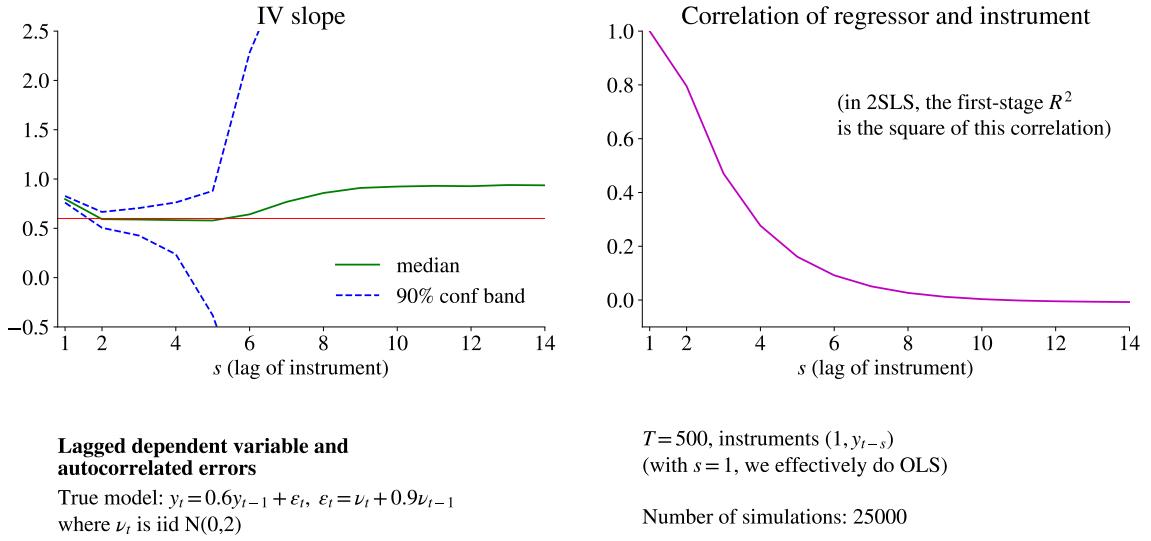


Figure 10.4: Results from a Monte Carlo experiment when data is from an ARMA process.

## 10.2 Two-stages-least squares (2SLS)

2SLS is the same as IV when there are as many instruments ( $L$ ) as there are regressors ( $k$ ). When there are more instruments than regressors ( $L > k$ ), then 2SLS can produce more precise (efficient) estimates than IV. It proceeds in two steps.

*First*, regress each of the elements in  $x_t$  on

$$x_{it} = \delta_i' z_t + \varepsilon_t, \text{ for } i = 1 \text{ to } k. \quad (10.8)$$

where  $\delta_i$  is a vector with  $L$  elements and let  $\hat{x}_{it}$  be the fitted values

$$\hat{x}_{it} = \delta_i' z_t. \quad (10.9)$$

We can stack the equations as

$$\hat{x}_t = \delta' z_t, \quad (10.10)$$

where  $\delta$  is an  $L \times k$  matrix with  $\delta_i$  in column  $i$ . The fit (or t-stats) of these regressions are often used to assess if the instruments are relevant, but we typically require very high  $|t\text{-stats}|$ , see the discussion of weak instruments.

*Second*, regress  $y_t$  on the fitted values  $\hat{x}_t$

$$y_t = \beta' \hat{x}_t + v_t. \quad (10.11)$$

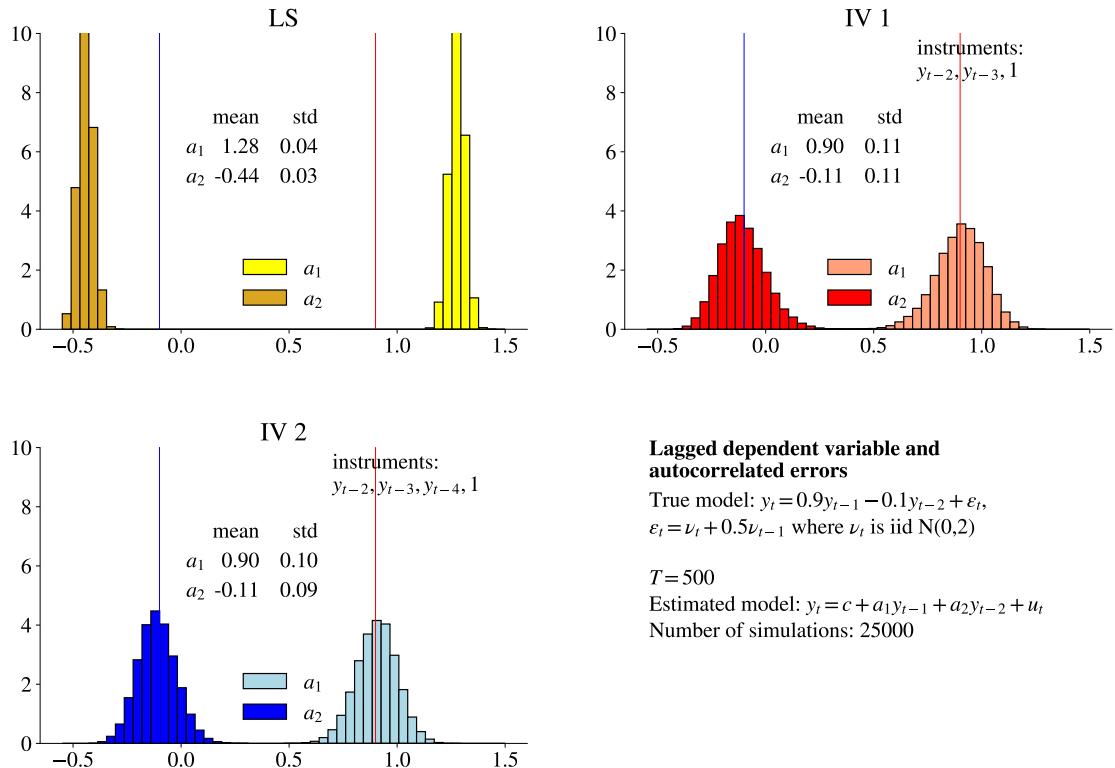


Figure 10.5: Results from a Monte Carlo experiment when data is from an ARMA process.

**Remark 10.8** (Alternative to (10.11)\*) We could equally well use  $\hat{x}_t$  instead of  $z_t$  in the IV estimator (10.4). This gives the same result as (10.11), provided that the instruments in the first stage estimation (10.8) include all “non-problematic” regressors.

Similarly to IV, the small sample properties are poor if the first-stage regression has a low  $R^2$  (“weak instruments”), but also when  $R^2$  is extremely high, since then the orthogonality conditions are likely to be violated — see Figure 10.4.

The 2SLS approach highlights the key idea of IV (and 2SLS): in the regression (10.11) we only consider those movements in the regressors that are correlated with  $z_t$  (as captured by  $\hat{x}_t$ ). Since  $z_t$  is chosen to be uncorrelated with the residuals, but correlated with  $x_t$ , we are only using the “clean” co-movements of  $x_t$  and  $y_t$  to estimate the coefficients. See Figure 10.3 for an illustration.

See Figure 10.5 for a case where using more instruments gives more precise estimates.

It can be shown (see Appendix 10.4 for details) that the (asymptotically valid) variance-

covariance matrix for  $\hat{\beta}_{SLS}$  is

$$V = B S B', \text{ where} \\ B = (S_{xz} S_{zz}^{-1} S_{zx})^{-1} S_{xz} S_{zz}^{-1} \text{ and } S = \text{Var}(\sum_{t=1}^T z_t u_t).$$
(10.12)

This general expression is valid for both autocorrelated and heteroskedastic residuals since those features are loaded into the  $S$  matrix. We can estimate  $S$  as in the IV case: by replacing  $u_t$  by the fitted residuals

$$\hat{u}_t = y_t - x'_t \beta_{iv}. \quad (10.13)$$

Notice that these are *not* the same as the fitted residuals from the 2nd stage regression. If the residuals are iid and independent of  $z_t$  (so  $S = \sigma^2 S_{zz}$ ), then  $V$  simplifies to

$$V = \sigma^2 (S_{xz} S_{zz}^{-1} S_{zx})^{-1} \text{ if } u_t \text{ are iid.} \quad (10.14)$$

**Example 10.9** (ARMA(2,1))  $y_t = 0.6y_{t-1} + 0.3y_{t-2} + \varepsilon_t$  where  $\varepsilon_t = v_t + 0.5v_{t-1}$ . Notice that  $y_{t-1}$  is correlated with  $v_{t-1}$  but  $y_{t-2}$  is not. We could therefore use  $y_{t-2}, y_{t-3}, \dots$  as instruments for the two regressors.

**Example 10.10** (Supply and Demand) Continuing Example 10.3 ,it can be shown that regressing  $q_t$  on  $\hat{p}_t$  (where  $\hat{p}_t = \delta A_t$ ) will give a consistent estimate of  $\gamma$ : see Figure 10.3 for an illustration. (Example 10.13) calculates the probability limit of  $\hat{\delta}$ ).

**Empirical Example 10.11** (Wage equation) Tables 10.1 –10.2 shows results from an example in Hill, Griffiths, and Lim (2008) 10.3.3. The purpose is to estimate how log wages depend on education, experience and experience<sup>2</sup>, while treating education as an endogenous variable. The instruments are experience, experience<sup>2</sup> and the education of the mother: see the first stage regression in 10.1. The result is fairly different from the OLS regression: see Table 10.2.

**Remark 10.12** (Overidentifying restrictions in 2SLS\*) When we use 2SLS, then we can test if instruments affect the dependent variable only via their correlation with the regressors. If not, something is wrong with the model since some relevant variables are excluded from the regression. A simple test is to first estimate with 2SLS to get the fitted residuals  $\hat{u}_t$ , then regress those on  $z_t$ . The  $TR^2$  from this second regression is (under the null hypothesis)  $\chi^2_{df}$  with  $df$  being the number of overidentifying restrictions.

	1st stage
c	9.775 (23.753)
exper	0.049 (1.152)
exper <sup>2</sup>	−0.001 (−0.959)
mothereduc	0.268 (8.481)
T	428

Table 10.1: First stage estimation of the 'educ' variable. Example of IV estimation, Hill et al (2008), section 10.3.3. Instruments: c, exper, exper<sup>2</sup>, and mothereduc. Numbers in parentheses are t-stats (from White's method).

### 10.3 Hausman's Specification Test

Reference: Greene (2018) 8.6

This test is constructed to test if an efficient estimator (like LS) gives (approximately) the same estimate as a consistent estimator (like IV). If not, the efficient estimator is most likely inconsistent. It is therefore a way to test for the presence of endogeneity and/or measurement errors.

Let  $\hat{\beta}_e$  be an estimator that is consistent and asymptotically efficient when the null hypothesis,  $H_0$ , is true, but inconsistent when  $H_0$  is false. Let  $\hat{\beta}_c$  be an estimator that is consistent under both  $H_0$  and the alternative hypothesis. When  $H_0$  is true, the asymptotic distribution is such that

$$\text{Cov}(\hat{\beta}_e, \hat{\beta}_c) = \text{Var}(\hat{\beta}_e). \quad (10.15)$$

**Proof.** (of 10.15, univariate version\*) Consider the estimator  $\lambda\hat{\beta}_c + (1 - \lambda)\hat{\beta}_e$ , which is clearly consistent under  $H_0$  since both  $\hat{\beta}_c$  and  $\hat{\beta}_e$  are. The asymptotic variance of this estimator is

$$\lambda^2 \text{Var}(\hat{\beta}_c) + (1 - \lambda)^2 \text{Var}(\hat{\beta}_e) + 2\lambda(1 - \lambda) \text{Cov}(\hat{\beta}_c, \hat{\beta}_e),$$

which is minimized at  $\lambda = 0$  (since  $\hat{\beta}_e$  is asymptotically efficient). The first order condition with respect to  $\lambda$

$$2\lambda \text{Var}(\hat{\beta}_c) - 2(1 - \lambda) \text{Var}(\hat{\beta}_e) + 2(1 - 2\lambda) \text{Cov}(\hat{\beta}_c, \hat{\beta}_e) = 0$$

	OLS	IV/2SLS
c	-0.522 (-2.641)	0.198 (0.407)
educ	0.107 (7.634)	0.049 (1.301)
exper	0.042 (3.170)	0.045 (2.888)
exper <sup>2</sup>	-0.001 (-2.073)	-0.001 (-2.145)
T	428	428

Table 10.2: IV estimation of wage equation. Example of IV estimation, Hill et al (2008), section 10.3.3. Instruments: c, exper, exper<sup>2</sup>, and mothereduc. Numbers in parentheses are t-stats (from White's method).

should therefore be zero at  $\lambda = 0$  so

$$\text{Var}(\hat{\beta}_e) = \text{Cov}(\hat{\beta}_c, \hat{\beta}_e).$$

(See Davidson (2000) 8.1) ■

This means that we can write

$$\begin{aligned}\text{Var}(\hat{\beta}_e - \hat{\beta}_c) &= \text{Var}(\hat{\beta}_e) + \text{Var}(\hat{\beta}_c) - 2\text{Cov}(\hat{\beta}_e, \hat{\beta}_c) \\ &= \text{Var}(\hat{\beta}_c) - \text{Var}(\hat{\beta}_e).\end{aligned}\tag{10.16}$$

We can use this to test, for instance, if the estimates from least squares ( $\hat{\beta}_e$ , since LS is efficient if errors are iid normally distributed) and instrumental variable method ( $\hat{\beta}_c$ , since consistent even if the true residuals are correlated with the regressors) are the same. In this case,  $H_0$  is that the true residuals are uncorrelated with the regressors.

All we need for this test are the point estimates and consistent estimates of the variance-covariance matrices. Testing one of the coefficient can be done by a  $t$  test, and testing all the parameters by a  $\chi^2$  test

$$(\hat{\beta}_e - \hat{\beta}_c)' \text{Var}(\hat{\beta}_e - \hat{\beta}_c)^{-1} (\hat{\beta}_e - \hat{\beta}_c) \sim \chi_j^2,\tag{10.17}$$

where the covariance matrix is from (10.16) and where  $j$  equals the number of regressors that are potentially endogenous or measured with error. Note that the covariance matrix is likely to have a reduced rank, so the inverse needs to be calculated as a generalized

(pseudo) inverse.

## 10.4 Appendix: Consistency and Asymptotic Distributions of the IV and 2SLS Estimators\*

This section gives some details of the asymptotic properties of IV and 2SLS.

### 10.4.1 Asymptotic Results on the IV Estimator\*

There are few results on small sample properties, but IV is often imprecise and even biased. In large samples, we typically get consistency and a normal distribution.

Use (10.1) to substitute for  $y_t$  in (10.4), multiply both sides by  $\sqrt{T}$  and rearrange as

$$\begin{aligned}\sqrt{T}(\hat{\beta}_{iv} - \beta) &= \hat{\Sigma}_{zx}^{-1} \sqrt{T} \sum_{t=1}^T z_t u_t / T, \text{ where} \\ \hat{\Sigma}_{zx} &= \sum_{t=1}^T z_t x'_t / T.\end{aligned}\quad (10.18)$$

Since we have strong beliefs that  $\text{Cov}(z_t, u_t) = 0$ , this expression shows that  $\hat{\beta}_{iv}$  should be consistent.

**Example 10.13 (Supply and Demand)** Continuing Example 10.3, we can solve for the two endogenous variables (the “reduced form”) as

$$\begin{bmatrix} q_t \\ p_t \end{bmatrix} = \begin{bmatrix} \frac{\gamma\alpha}{\gamma-\beta} \\ \frac{\alpha}{\gamma-\beta} \end{bmatrix} A_t + \begin{bmatrix} \frac{\beta}{\beta-\gamma} & -\frac{\gamma}{\beta-\gamma} \\ \frac{1}{\beta-\gamma} & -\frac{1}{\beta-\gamma} \end{bmatrix} \begin{bmatrix} u_t^s \\ u_t^d \end{bmatrix}.$$

Suppose we estimate the supply curve by using  $A_t$  as the instrument. For simplicity, assume all variables have zero means. Then the probability limit of (10.4) is

$$\text{plim } \hat{\gamma}_{iv} = \text{Cov}(p_t, A_t)^{-1} \text{Cov}(q_t, A_t).$$

From the reduced form we have (assuming  $A_t, u_t^d$  and  $u_t^s$  are uncorrelated)  $\text{Cov}(p_t, A_t) = \frac{\alpha}{\gamma-\beta} \text{Var}(A_t)$  and  $\text{Cov}(q_t, A_t) = \frac{\gamma\alpha}{\gamma-\beta} \text{Var}(A_t)$ . Combining gives  $\text{plim } \hat{\gamma}_{iv} = \gamma$ . Also notice that  $\text{plim } \hat{\delta} = \text{Cov}(p_t, A_t) / \text{Var}(A_t) = \alpha / (\gamma - \beta)$ .

**Example 10.14 (Supply and Demand)** Continuing Examples 10.3 and 10.13, we have  $\text{plim } \hat{\delta} = \alpha / (\gamma - \beta)$ . Thus, regressing  $q_t$  on  $\hat{p}_t = \delta A_t$  has a probability limit of  $\text{Cov}(q_t, \delta A_t) / \text{Var}(\delta A_t)$ , which (using Example 10.13) can be simplified to  $\frac{\gamma\alpha}{\gamma-\beta} / \delta = \gamma$ .

Since  $\sqrt{T} \Sigma_{t=1}^T z_t u_t / T$  in (10.18) is  $\sqrt{T}$  times a sample average, it is plausible that a CLT applies so the asymptotic distribution  $\sqrt{T}(\hat{\beta}_{iv} - \beta)$  might be normal with a zero mean and a variance-covariance matrix

$$\text{Var}(\sqrt{T} \hat{\beta}_{iv}) = \Sigma_{zx}^{-1} \Sigma \Sigma_{xz}^{-1}, \text{ where } \Sigma = \text{Var}\left(\sum_{t=1}^T z_t u_t / \sqrt{T}\right). \quad (10.19)$$

and where  $\Sigma_{zx}$  is the probability limit of  $\hat{\Sigma}_{zx}$ . The last matrix in the covariance matrix follows from  $(\Sigma_{zx}^{-1})' = (\Sigma_{zx}')^{-1} = \Sigma_{xz}^{-1}$ . Dividing both sides by  $T$  and rewriting gives (10.5). (Details:  $\Sigma_{zx}$  is the probability limit of  $S_{zx}/T$  and  $\Sigma = S/T$ . Use this in (10.19) and simplify to get the probability limit of  $TS_{zx}^{-1}SS_{xz}^{-1}$ . Divide both sides by  $T$  to get  $\text{Var}(\hat{\beta}_{iv})$  which then equals (10.5).)

#### 10.4.2 Asymptotic Results on 2SLS\*

From (10.8)–(10.9) we have

$$\begin{aligned} \hat{\delta} &= \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zx}, \\ \hat{\beta} &= \hat{\Sigma}_{\hat{x}\hat{x}}^{-1} \hat{\Sigma}_{\hat{x}y} \end{aligned} \quad (10.20)$$

where  $\hat{\Sigma}_{zz} = \sum_{t=1}^T z_t z_t' / T$ , and so forth. Notice that  $\hat{\Sigma}_{zz}^{-1}$  is an  $L \times L$  matrix and  $\hat{\Sigma}_{zx}$  is an  $L \times k$  matrix, so  $\hat{\delta}$  is  $L \times k$  as mentioned around (10.10). The fitted values in (10.10) can then be written

$$\begin{aligned} \hat{x}_t &= \hat{\delta}' z_t \\ &= \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} z_t, \end{aligned} \quad (10.21)$$

so

$$\begin{aligned} \hat{\Sigma}_{\hat{x}\hat{x}} &= \sum_{t=1}^T \hat{x}_t \hat{x}_t' / T = \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zx} \text{ and} \\ \hat{\Sigma}_{\hat{x}y} &= \sum_{t=1}^T \hat{x}_t y_t / T = \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zy}. \end{aligned} \quad (10.22)$$

(Substitute for  $\hat{x}$  from (10.21) and simplify to derive this.)

Using these results in the equations of  $\hat{\delta}$  and  $\hat{\beta}$  (10.20) gives

$$\hat{\beta} = (\hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zx})^{-1} \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zy} \quad (10.23)$$

Substituting for  $y_t$  by using (10.1) and expanding gives

$$\begin{aligned}\hat{\beta} &= (\hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zx})^{-1} \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \sum_{t=1}^T z_t (x'_t \beta + u_t) / T \\ &= \beta + \underbrace{(\hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1} \hat{\Sigma}_{zx})^{-1} \hat{\Sigma}_{xz} \hat{\Sigma}_{zz}^{-1}}_A \sum_{t=1}^T z_t u_t.\end{aligned}\quad (10.24)$$

Consistency follows from  $\text{plim} \sum_{t=1}^T z_t u_t / T = 0$  and asymptotic normality from a CLT applied to  $\sqrt{T} \sum_{t=1}^T z_t u_t / T$  and the asymptotic variance-covariance matrix is

$$\text{Var}(\sqrt{T} \hat{\beta}_{iv}) = A \Sigma A', \text{ where } \Sigma = \text{Var}(\Sigma_{t=1}^T z_t u_t / \sqrt{T}) \quad (10.25)$$

This can be rewritten as (10.12). (Details:  $\Sigma_{zx}$  is the probability limit of  $S_{zx} / T$  etc and  $\Sigma = S / T$ . Divide both sides by  $T$ .)

**Remark 10.15** (\*Alternative expression for  $A$ ) By using (10.20),  $A$  in (10.24) can also be written  $A = (\hat{\delta}' \Sigma_{zz} \hat{\delta})^{-1} \hat{\delta}'$ .

# Chapter 11

## Portfolio Sorts

### 11.1 Overview

Reference: Bali, Engle, and Murray (2016)

Portfolio sorts are used to construct portfolios (groups) based on some characteristic, for instance, firm size. Once the portfolios have been defined (to which group/portfolio does  $i$  belong?) we often compute the (possible weighted) average with each (group or) portfolio

$$R_{gt} = \sum_{i \in \text{Group}_g} w_{it} R_{it}, \quad (11.1)$$

where  $w_{it}$  is the relative portfolio weight of asset  $i$  in the portfolio ( $\sum w_{it} = 1$ ). We often use an unweighted average where  $w_{it} = 1/(\text{number of members of the group})$ .

A common way (since Jensen, updated in Huberman and Kandel (1987)) is to study the performance of a portfolio by running the following regression

$$\begin{aligned} R_{gt}^e &= \alpha + \beta R_{mt}^e + \varepsilon_t, \text{ with} \\ \mathbb{E} \varepsilon_t &= 0 \text{ and } \text{Cov}(R_{mt}^e, \varepsilon_t) = 0, \end{aligned} \quad (11.2)$$

where  $R_{gt}^e$  is the excess return on the portfolio being studied and  $R_{mt}^e$  the excess returns of a vector of benchmark portfolios (for instance, only the market portfolio if we want to rely on CAPM). Neutral performance requires  $\alpha = 0$ , which can be tested with a  $t$  test.

### 11.2 Univariate Sorts

A simple and commonly applied method for studying how an asset characteristic ( $x_i$ ) is related to returns (or some other performance measure) is to do a *univariate sort*. For instance, we could sort the assets  $i = 1, \dots, n$  according to  $x_i$  and then construct three

portfolios: (1) for those  $i$  whose  $x_i$  belong to the lowest 1/3; (2) those in the mid 1/3 and (3) those in the highest 1/3. Then, we measure the return on equally weighted portfolios—and perhaps analyse the return of portfolio 3 minus the return on portfolio 1. The sorting and portfolio construction is typically repeated at regular intervals. For instance, the Fama-French size portfolios are based on the market capitalization and are rebalanced every June. For a daily momentum strategy, we would rather redo the sort every day based on recent performance.

**Empirical Example 11.1** (*Sorting on recent returns*) See Table 11.1 for an empirical example where the 25 FF portfolios are sorted into low/low recent 22-day returns, with 5 portfolios in each. The results indicate strong momentum.

Low 22-day return	3.81
	(0.19)
High 22-day return	13.96
	(0.76)
Difference	10.15
	(0.91)

Table 11.1: Average excess returns and (Sharpe ratios) for 3 portfolios from a univariate sort on recent (22-day) returns (5/5 assets). Daily data on 25 FF portfolios 1979:01-2022:12

**Example 11.2** (*Simplified version of “Betting against beta” by Frazzini and Pedersen\**) First, find those assets with  $\beta_{i,t-1} < \text{median}(\beta_{i,t-1})$  where  $\beta_{i,t-1}$  is the CAPM beta estimated on data up to and including  $t - 1$ . (The median is across the assets.) This is the low beta group. Second, calculate the equally weighted portfolio return in  $t$ . Third, repeat for all periods. Fourth, do points 1–3 also for the high beta assets,  $\beta_{i,t-1} \geq \text{median}(\beta_{i,t-1})$ . Fifth, form the excess return as the difference between the two portfolios.

### 11.3 Bivariate Sorts

Bivariate sorts (also called double sorts) are used when there are two important characteristics (here called  $x$  and  $z$ ) and you want to study how  $z$  affects returns—controlling for  $x$  (that is, holding  $x$  “constant”). This may well be important if  $x$  and  $z$  are correlated.

Bivariate sorts can be done in several ways. An *independent bivariate sort* first does a univariate sort of  $x_i$  (say, forming 3 categories: growth, neutral or value), then it makes another univariate sort according to another sorting variable  $z_i$  (say, forming two categories: small or big). Then we find the intersections of the two sorts—think of a matrix

	<u>Low <math>x_i</math></u>	<u>Medium <math>x_i</math></u>	<u>High <math>x_i</math></u>	
Low $z_i$ :	$(x_L, z_L)$	$(x_M, z_L)$	$(x_H, z_L)$	
High $z_i$ :	$(x_L, z_H)$	$(x_M, z_H)$	$(x_H, z_H)$	

(11.3)

where, for instance,  $(x_M, z_H)$  denote the set of assets that belong to the medium  $x$  category and high  $z$  category. Notice that this matrix has a different structure than a traditional scatter plot with  $x$  on the horizontal axis and  $z$  on the vertical axis: in this (and all other tables) we put low  $z_i$  on the first line and high  $z_i$  on the second.

In an independent bivariate sort we cannot directly control how many assets there will be in each group—and some groups might be empty (see Example 11.3 and Figure 11.1).

Once the portfolio sort is done, we typically calculate the average return (or some other variable of interest) of each portfolio. In the independent sort, you can either compare across rows or across columns.

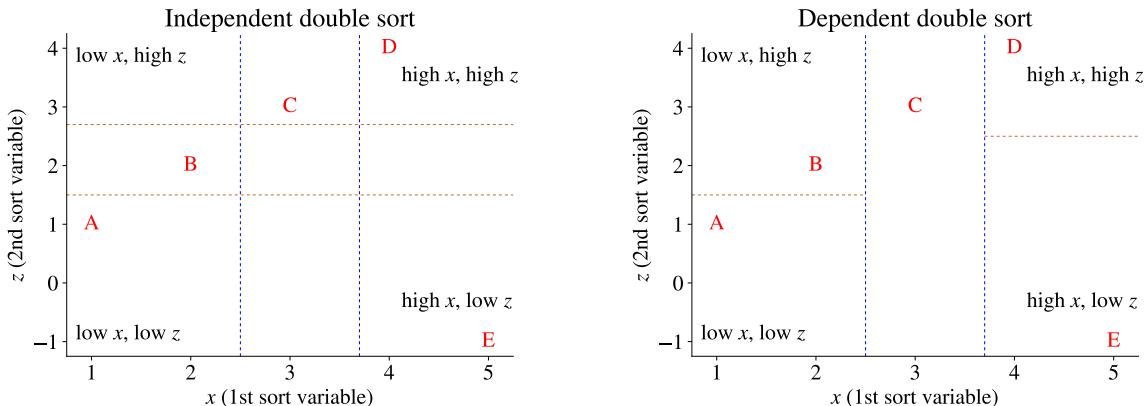


Figure 11.1: Example of bivariate sorts. The data is indicated by letters.

**Example 11.3 (Independent double sort)** Suppose there are 5 assets (labelled A, B,...)

and that the values of  $x$  and  $z$  are

	$\underline{x_i}$	$\underline{z_i}$
Asset A	1	1
Asset B	2	2
Asset C	3	3
Asset D	4	4
Asset E	5	-1

We form low/high groups with 2 elements in each

	<u>Assets</u>
Low $x$ :	A, B
High $x$ :	D, E
Low $z$ :	E, A
High $z$ :	C, D

The independent double sort then gives

	<u>Low <math>x</math></u>	<u>High <math>x</math></u>
Low $z$ :	A	E
High $z$ :		D

Notice that there are no assets in the (low  $x$ , high  $z$ ) group. See also Figure 11.1 for an illustration, but notice that the scatter plot has a different structure: low  $z$  values are plotted below high  $z$  values.

**Empirical Example 11.4** (*Independent sorting on recent volatility and returns*) We first sort the 25 FF portfolios according to recent volatility, putting 10 into the low group and 10 into the high group. Then we sort on recent returns, also putting 10 into a low group and 10 into a high group. Finally, we form intersections. Figure 11.2 illustrates (for a short subsample) how the number of portfolios in the “low vol, low return” group varies over time. Typically, there are 4–5 portfolios in the group, but it varies considerably over time. The subsequent analysis is therefore focused on the dependent sort (see below).

In *dependent bivariate sort* we first sort according to  $x_i$  as before. Then, *within* an  $x$  category we sort according to  $z_i$ . This allows us to control the number of assets in each group. Notice that the ordering matters in the dependent sort: letting  $x$  represent

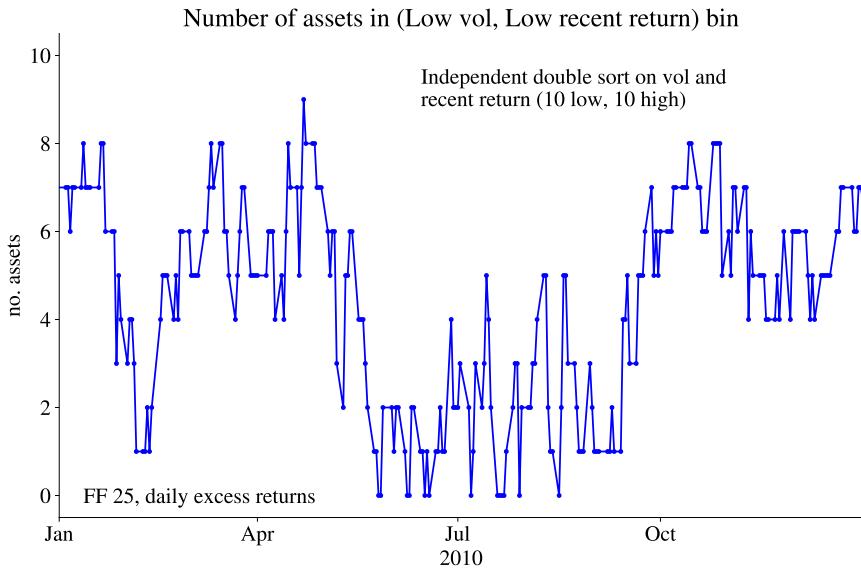


Figure 11.2: Independent bivariate portfolio sort, 25 FF portfolios

growth/neutral/value and  $z$  small/big will not give the same results as switching the labels. In the dependent sort, we compare across the  $z$  categories, that is, *across rows* in (11.3), for instance, the return of  $(x_L, z_H)$  minus the return of  $(x_L, z_L)$  and so forth. In (11.3) this gives three numbers—which are sometimes averaged: the interpretation is that you are studying the effect of  $z$  (here: small/large), but controlling for  $x$  (here: one of growth/neutral/value). See Figure 11.1 for an example.

**Example 11.5 (Dependent double sort)** Continuing the previous example, the dependent double sort (with one asset in each portfolio) gives

	<u>Low <math>x</math></u>	<u>High <math>x</math></u>
<i>Low <math>z</math>:</i>	A	E
<i>High <math>z</math>:</i>	B	D

For instance, among the “high  $x$ ” assets  $D$  and  $E$ , asset  $E$  has a lower  $z$  value so it is allocated to the (high  $x$ , low  $z$ ) portfolio, while asset  $D$  has a higher  $z$  value so it is allocated to the (high  $x$ , high  $z$ ) portfolio. Notice that all portfolios are populated. See also Figure 11.1 for an illustration.

**Empirical Example 11.6 (Dependent sorting on recent volatility and returns)** We first sort the 25 FF portfolios according to recent volatility, putting 10 into the low group and

10 into the high group. Within the “low vol” group, we then sort according to recent returns, putting 5 into to the “low vol, low return” group and 5 into the “low vol, high return” group. We do the same within the “high volatility” group. This means that there are always 5 FF portfolios in each of the 4 groups. See Figure 11.3 for some (unconditional) background information about the 25 FF portfolios and Figure 11.4 for how often the different FF portfolios are in each of the four groups. Table 11.2 reports the average excess returns and the Sharpe ratios for the four groups.

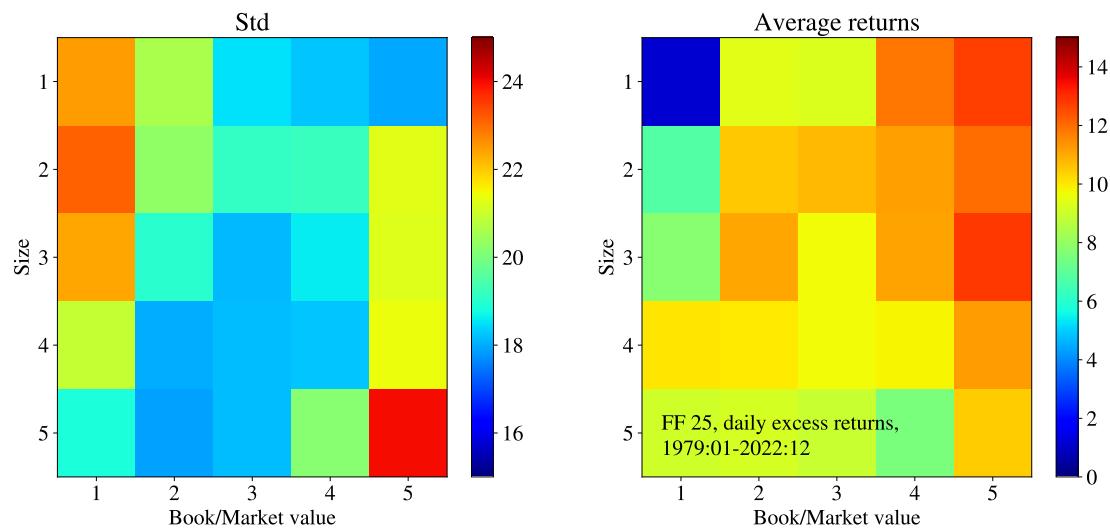


Figure 11.3: Average returns and volatility of the 25 FF portfolios

	Low 22-day vol	High 22-day vol
Low 22-day return	8.28 (0.51)	4.44 (0.20)
High 22-day return	12.77 (0.82)	11.98 (0.57)
High - low	4.48 (0.89)	7.54 (0.94)
High - low, average	6.01 (1.12)	

Table 11.2: Average excess returns and (Sharpe ratios) for 4 portfolios from a dependent bivariate sort. The first sort is on volatility (10/10 assets), the second sort (within each volatility bin) is on recent returns (5/5 assets). Daily data on 25 FF portfolios 1979:01-2022:12

The bivariate sort is designed to handle some *correlation* between  $x$  and  $z$ . If there is no correlation, then a single sort is enough. However, the bivariate sort will break down if the correlation is too strong. In the independent sort, it can lead to few (or even zero) assets in the off-diagonal portfolios if the correlation is positive (and vice versa if the correlation is negative). In the dependent sort, it may simply leads to results that cannot be trusted, see Figure 11.5 for an example. The figure illustrates how the “high  $z$ ” portfolios have clearly higher  $x$  values than the “low  $z$ ” portfolios have, so the approach is only moderately successful in controlling for  $x$ . This could be solved by having smaller  $x$  bins (which may require many assets), so that the variation in  $x$  within each bin is small compared to the variation in  $z$ . For instance, the low  $x$  bin could contain 20% of the assets, the high  $x$  also 20%, leaving out the 60% in the middle. As an alternative, we could consider an orthogonalisation (see below).

**Remark 11.7** (*When  $x$  and  $z$  are perfectly correlated\**) If we change Example 11.3 so  $z$  equals  $x$ , then the independent double sort gives

	<u>Low <math>x</math></u>	<u>High <math>x</math></u>
<i>Low <math>z</math>:</i>		D, E
<i>High <math>z</math>:</i>	A, B	

This has the problem that the off-diagonal portfolios are empty. In contrast, the dependent sort gives

	<u>Low <math>x</math></u>	<u>High <math>x</math></u>
<i>Low <math>z</math>:</i>	A	D
<i>High <math>z</math>:</i>	B	E

The latter has the problem that comparing across rows does not control for  $x$ . For instance, asset B has a higher  $x$  (and  $z$ ) value than asset A.

**Remark 11.8** (*The Fama-French factors\**) The SMB and HML are created by an independent bivariate sort. First, classify firms according to the book/market value: low (growth stocks, using 30th percentile as cutoff), neutral or high (value stocks, using 70th percentile as cutoff). Second, classify firms according to size: small or big, using the median as a cutoff. Create six value weighted portfolios from the intersection of those

categories

	<u>Low book/market</u>	<u>Medium book/market</u>	<u>High book/market</u>
Small:	Small Growth (SG)	Small Neutral (SN)	Small Value (SV)
Big:	Big Growth (BG)	Big Neutral (BN)	Big Value (BV)

The *SMB* is the average of the small portfolios minus the average of the big portfolios:  $SMB = 1/3(SG + SN + SV) - 1/3(BG + BN + BV)$ . Rearranging gives  $SMB = 1/3(SG - BG) + 1/3(SN - BN) + SV + 1/3(SV - BV)$ , which shows that it represents the return on small stocks (for a given book/market) minus the return on big stocks (for same book/market). The *HML* is the average of the value stocks minus the growth stocks,  $HML = 1/2(SV + BV) - 1/2(SG + BG)$ , which can be rearranged as  $HML = 1/2(SV - SG) + 1/2(BV - BG)$ , which shows that it represents the return on value stocks (for a given size) minus the return on growth stocks (for the same size).

## 11.4 Orthogonalisation

Single sort on orthogonalised data is an alternative to a double sort and may be better at handling strong (linear) correlation of  $x$  and  $z$ . It involves two steps. First, run a regression of ( $z$  on  $x$  and a constant) to get coefficients  $(a, b)$ . Second, do a single sort on the residual

$$\varepsilon_i = z_i - (a + bx_i). \quad (11.4)$$

The regression can be done in several different ways: (1) a cross-sectional regression as in Figure 11.6 ; (2) time series regressions; (3) a panel regression. In cases (1) and (2) there is also a choice between using the full sample or just data up to  $t - 1$ .

## 11.5 Trading Strategies

*Dynamic trading strategies* are similar (and sometimes identical) to portfolio sorts. The basic idea is to create a portfolio based on some kind of sorting of a trading signal.

**Empirical Example 11.9** (*Momentum for daily returns on the 25 FF portfolios*) Figure 14.13 suggests that there is considerable momentum in the cross-section of the 25 FF portfolios. Investing in past winners earns high returns.

**Empirical Example 11.10** (*Mean reversion of daily S&P 500 returns*) Figure 14.14 shows that extreme S&P 500 returns are followed by mean-reverting movements the following

*day (negative autocorrelation)—which suggests that a trading strategy should sell after a high return and buy after a low return.*

**Empirical Example 11.11** (*Mean reversion of daily returns for different size categories*) *Figure 14.15 compares the results for daily returns on different size categories—and illustrates that there is more predictability (indicating positive autocorrelation) for small stocks.*

**Empirical Example 11.12** (*Long run S&P 500 after different p/e values*) *Figure 14.16 shows average one-year return on S&P 500 for different bins of the p/e ratio (at the beginning of the year). The figure illustrates that buying when the market is undervalued (low p/e) might be a winning strategy.*

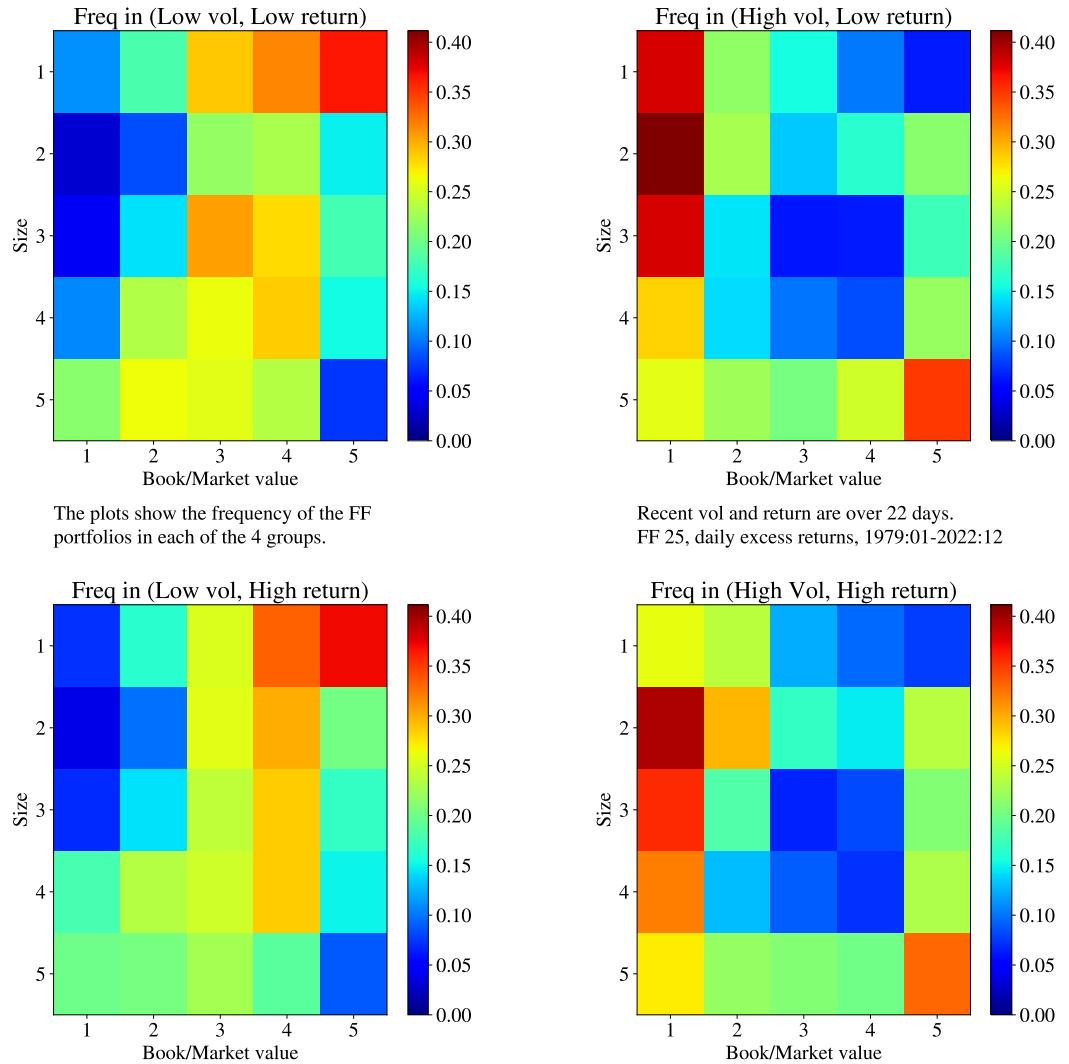


Figure 11.4: Dependent bivariate portfolio sort, 25 FF portfolios

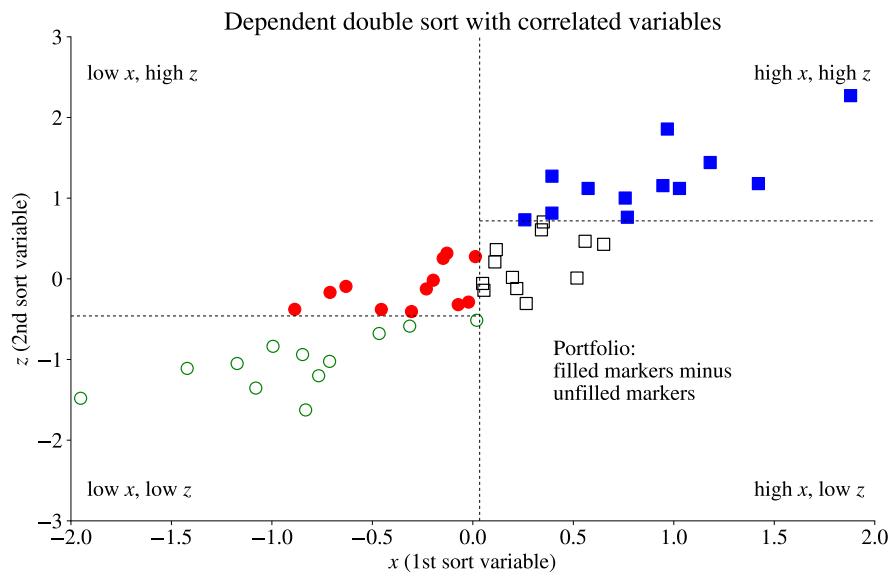


Figure 11.5: Example of dependent bivariate sort with correlated variables

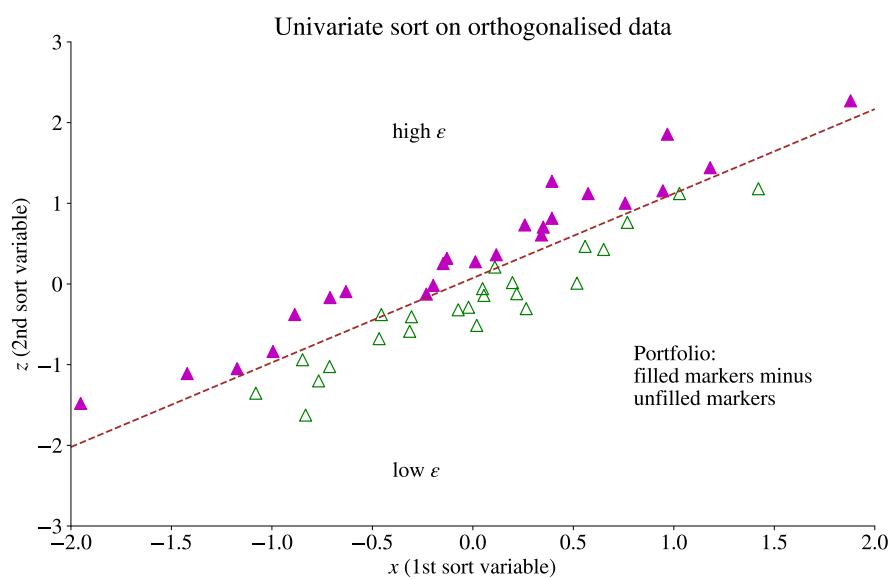


Figure 11.6: Example of univariate sort on orthogonalised data

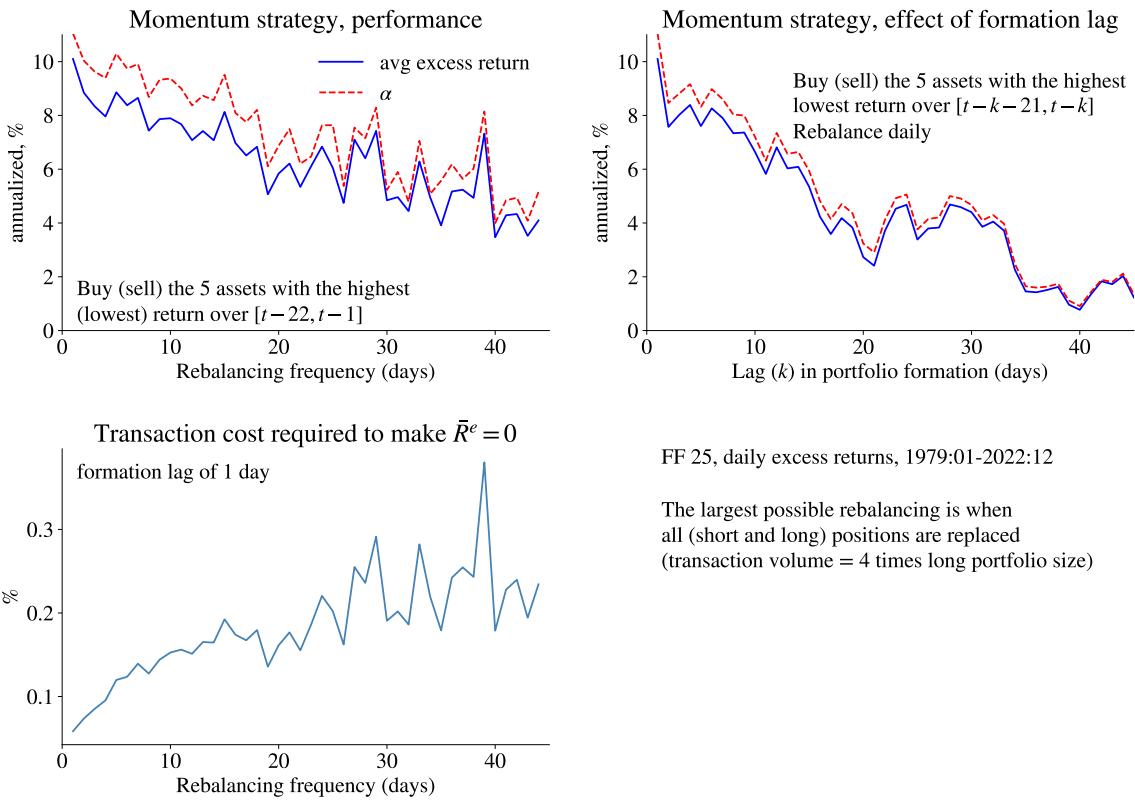


Figure 11.7: Predictability of daily US stock returns, momentum strategy

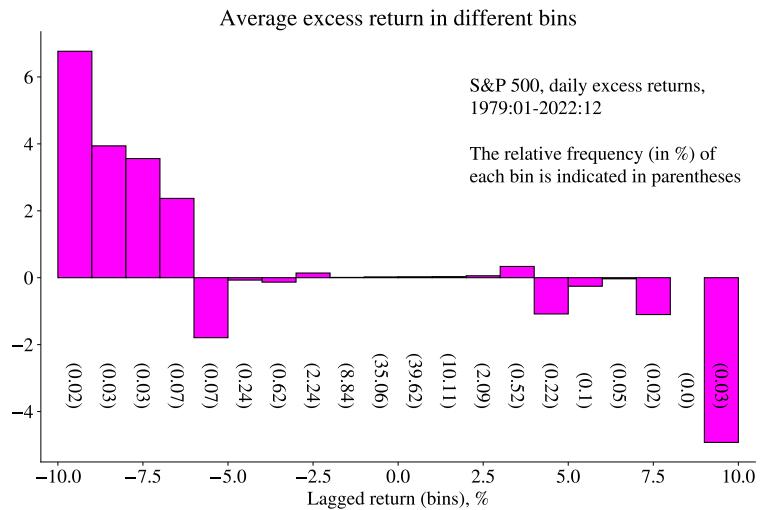


Figure 11.8: Predictability of daily US stock returns, out-of-sample

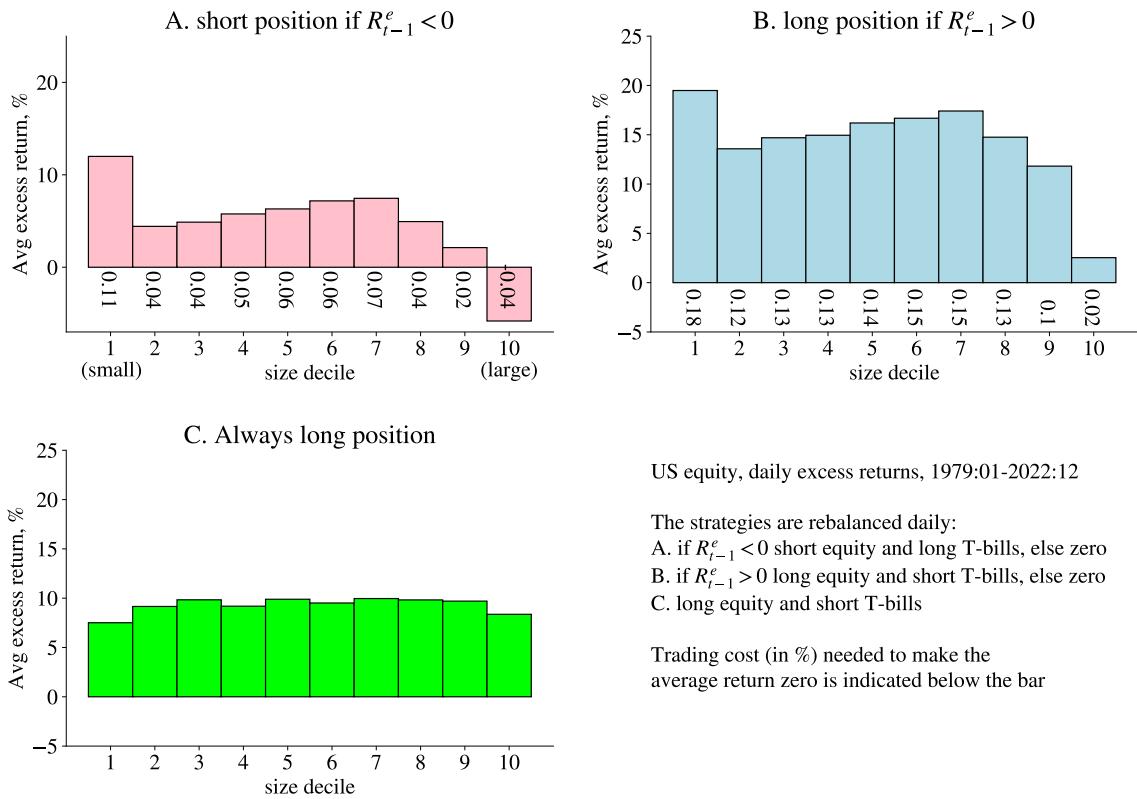


Figure 11.9: Predictability of daily US stock returns, out-of-sample

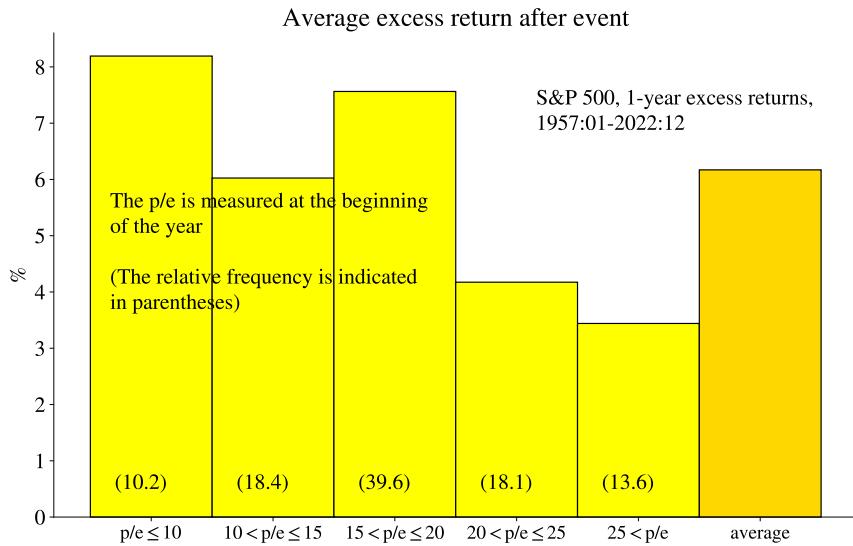


Figure 11.10: Predictability of annual US stock returns, out-of-sample

# Chapter 12

## Financial Panel Data

References: Verbeek (2012) 10; Baltagi (2008); Greene (2018) 6.3 and 11.

### 12.1 Introduction to Panel Data

A panel data set (also called a longitudinal data set) has data on a cross-section ( $i = 1, 2, \dots, N$ , individuals or firms) over many time periods ( $t = 1, 2, \dots, T$ ). Our aim is to estimate a linear relation between the dependent variable and the regressors

$$y_{it} = \alpha_i + x'_{it}\beta_i + u_{it}, \quad (12.1)$$

where the coefficients  $(\alpha_i, \beta_i)$  may or may not be different for different individuals (this is discussed in detail below). As examples of such applications, we may want to evaluate if alphas or betas of different mutual funds are related to fund characteristics, for instance, age or trading activity. Alternatively, we want to investigate whether firms with different types of board compositions perform differently.

Data on the dependent variable has this structure

$$\begin{array}{cccccc} & \underline{i=1} & \underline{i=2} & \cdots & \underline{i=N} \\ t=1: & y_{11} & y_{21} & & y_{N1} \\ t=2: & y_{12} & y_{22} & & y_{N2} \\ & \vdots & & & \\ t=T: & y_{1T} & y_{2T} & & y_{NT} \end{array} \quad (12.2)$$

The structure for each of the regressors is similar, although it can also be the case that (some of) the regressors are the same for all  $N$  investors (for instance, when the regressors are pricing factors like the market excess return). When needed for clarity we will use the

$y_{i,t}$  notation instead of  $y_{it}$ .

The structure in (12.2) implicitly assumes that we have a *balanced panel*, that is, have data for all the cells. However, it is often the case that the panel is *unbalanced* in the sense that some data is missing. For instance, we may not have data on regressor 3 for  $i = 7$  and  $t = 3$ . If data is *missing in a random way*, then we can simply exclude  $(y_{it}, x_{it})$  for the missing  $(i, t)$ . (Practical tips on how to do that is discussed later.) In our example that means just excluding  $(y_{7,3}, x_{7,3})$  but keeping all other data. In contrast, if data is missing in a non-random way (for instance, depending on the value of  $y_{it}$ ), then we have to apply more sophisticated sample-selection models (not discussed in this chapter).

## 12.2 Portfolio Sorts

Reference: Bali, Engle, and Murray (2016)

Portfolio sorts are used to construct portfolios (groups) based on some characteristic, for instance, firm size. Once the portfolios have been defined (to which group/portfolio does  $i$  belong?) we often compute the (possibly weighted) average with each (group or) portfolio

$$y_{gt} = \sum_{i \in \text{Group}_g} w_{it} y_{it}, \quad (12.3)$$

where  $w_{it}$  is the relative portfolio weight of asset  $i$  in the portfolio ( $\sum w_{it} = 1$ ). We often use an unweighted average where  $w_{it} = 1/(\text{number of members of the group})$ .

More details on portfolio sorts are given in a separate chapter.

## 12.3 Calendar Time Regressions and SURE

Once we have defined portfolios and computed their average excess returns as in (12.3), we may want to regress the portfolio returns on risk factors (the market excess return or the three Fama-French factors) to estimate the portfolio alpha. This section discusses how to do that—in such a way that we can test differences (in alphas) across portfolios.

### 12.3.1 SURE

Consider a model where each asset ( $i$ ) has its own intercept and slope coefficients as in (12.1). For convenience, write the model as

$$y_{it} = z_t' \gamma_i + u_{it}, \quad (12.4)$$

where  $z_t$  contains both the constant and the other regressors ( $x_t$ ). Notice that SURE is about the case when all regressors are the same, so we drop the  $i$  subscript on  $z_t$ .

Previous chapters of the lecture notes have shown how to test such a system of regressions.

### 12.3.2 Calendar Time Regressions

To investigate how the performance (alpha) or exposure (betas) of different investors/funds are related to investor/fund characteristics, we often use the *calendar time* (CalTime) approach. First define  $M$  discrete asset groups by a portfolio sort (for instance, construct ten portfolios for different firm size deciles) and calculate their respective excess returns as in (12.3) by letting  $y_{it}$  represent the excess return of asset  $i$ .

Then, we run a factor model

$$R_{gt}^e = z_t' \gamma_g + u_{gt}, \text{ for } g = 1, 2, \dots, M \quad (12.5)$$

where  $z_t$  typically includes a constant and various return factors (for instance, the three Fama-French factors). By estimating these  $M$  equations as a SURE system with White's (or Newey-West's) covariance estimator, it is straightforward to test various hypotheses, for instance, that the intercept (the “alpha”) is the same for all portfolios.

**Example 12.1** (*CalTime with two asset groups*) *With two asset groups, estimate the following SURE system*

$$\begin{aligned} R_{1t}^e &= z_t' \gamma_1 + u_{1t}, \\ R_{2t}^e &= z_t' \gamma_2 + u_{2t}. \end{aligned}$$

The CalTime approach is straightforward and the cross-sectional correlations are handled. However, it forces us to define discrete asset groups—which makes it hard to handle several different types of characteristics at the same time. We therefore consider panel data models.

**Empirical Example 12.2** (*Investor activity vs performance*) *See Table 12.1 for results on a ten-year panel of some 60,000 Swedish pension savers from Dahlquist, Martinez, and Söderlind (2016). In this case, the dependent variable is the return of a pension investment portfolio (on day  $t$ , individual  $i$ ). The regressors include a constant, 7 risk factors (global and Swedish market, SMB, HML as a well as a bond factor) on  $\pm 2$  days ( $1 + 7 \times 5$  regressors).*

	Inactive	Active	Higly Active
coef	-0.76	3.08	8.65
t-tstat NW	-0.69	1.77	2.73

Table 12.1: Calendar time regressions. Annualised coefficients and t-stats from Table 10, in Dahlquist et al (RFS 2017). For Inactive the coefficient is the annualised alpha, but for the other two categories it is the difference in alpha to the Inactive. Three EW portfolios based on 62640 individuals, 2116 days. The dependent variables are the returns of the EW portfolio based on the activity indicators. The regressions also control for 7 risk factors over 5 days (2 lags, 2 leads).

## 12.4 An Overview of Different Panel Data Models

A *pooled model* assumes that all individuals have the same coefficients (no subscript on  $\beta$ ), so (12.1) becomes

$$y_{it} = \alpha + x'_{it}\beta + u_{it}. \quad (12.6)$$

This model can be estimated by pooled OLS (see below).

A *fixed effects model* assumes that all individuals have the same slope coefficients, but that their intercepts might differ

$$y_{it} = \alpha_i + x'_{it}\beta + u_{it}. \quad (12.7)$$

An extension of the fixed effects model is to also allow for *time fixed effects*

$$y_{it} = \lambda_t + \alpha_i + x'_{it}\beta + u_{it}. \quad (12.8)$$

Estimation of these models is discussed below. One way of handling the fixed effects are a first-difference model

$$\Delta y_{it} = \Delta \lambda_t + \Delta x'_{it}\beta + u_{it}^*, \quad (12.9)$$

where  $\Delta y_{it} = y_{it} - y_{i,t-1}$  denotes a first difference (in the time dimension).

A *random effects model* is similar to a fixed effects model, except that the individual “mean”  $\alpha_i$  now contains a common component ( $\alpha$ ) and a random individual component ( $\mu_i$ ). We can then write the model as

$$y_{it} = \alpha + x'_{it}\beta + u_{it} \text{ where } u_{it} = \mu_i + \varepsilon_{it}. \quad (12.10)$$

The  $\varepsilon_{it}$  is typically assumed to be uncorrelated across time and individuals, but the  $\mu_i$  terms make the  $u_{it}$  residuals correlated over time (for the same individual). The estima-

tion of this model is discussed later.

The *unrestricted model* allows all individuals to have different coefficients (hence a subscript  $i$  on  $\beta_i$ ). These regressions could be estimated by OLS for each individual separately (see SURE for the case when the regressor values are common among the assets).

## 12.5 Pooled OLS

Consider the regression model

$$y_{it} = z'_{it}\gamma + u_{it}, \quad (12.11)$$

where  $z_{it}$  is an  $k \times 1$  vector. For notational convenience, this section assumes that any constant is included in the  $z_{it}$  vector along with the other regressors ( $x_{it}$ ). Notice that the coefficients are the same across individuals (and time), but that the regressors may vary along both the time series and cross-sectional dimensions. We assume that  $u_{jt}$  is uncorrelated with  $z_{it}$  (across all  $i$  and  $j$ ).

Define the matrices

$$S_{zz} = \sum_{t=1}^T \sum_{i=1}^N z_{it}z'_{it} \text{ (a } k \times k \text{ matrix)} \quad (12.12)$$

$$S_{zy} = \sum_{t=1}^T \sum_{i=1}^N z_{it}y_{it} \text{ (a } k \times 1 \text{ vector).} \quad (12.13)$$

The LS estimator (stacking all  $TN$  observations) is then

$$\hat{\gamma} = S_{zz}^{-1}S_{zy}. \quad (12.14)$$

In case  $u_{it}$  is uncorrelated across time and also across individuals, then the usual expressions for  $\text{Std}(\hat{\gamma})$  apply. However, it is often the case that there are *clusters* of individuals (all small firms, say) that have correlated residuals. This would require handling those correlations.

Recall that we can (conceptually) decompose the point estimate  $\hat{\gamma}$  by using (12.11) to substitute for  $y_{it}$  in  $S_{zy}$  (12.13) and then in (12.14). The result is

$$\hat{\gamma} = \gamma + S_{zz}^{-1} \sum_{t=1}^T \sum_{i=1}^N z_{it}u_{it}. \quad (12.15)$$

The variance-covariance matrix can then be written

$$\text{Var}(\hat{\gamma}) = S_{zz}^{-1} S S_{zz}^{-1}, \text{ where} \quad (12.16)$$

$$S = \text{Var}\left(\sum_{t=1}^T \sum_{i=1}^N h_{it}\right), \quad (12.17)$$

where  $h_{it} = z_{it} u_{it}$  is used as short hand notation.

**Remark 12.3** (*Background to (12.16)*) As discussed in earlier chapters, the variance-covariance matrix (12.16) can be motivated by either (a) assuming that  $x_t$  are fixed regressors or (b) by asymptotic results. A more precise statement is thus that  $S_{zz}^{-1} \hat{S} S_{zz}^{-1}$  is an estimate of the variance-covariance matrix. In practice, this gives the same estimate of the variance-covariance matrix as under assumption (a).

**Remark 12.4** (*Unbalanced panels\**) With missing values in  $(y_{it}, z_{it})$  we want to exclude that observation. This can be done in several ways. For instance, by changing the summations in (12.12), (12.13) and (12.17) to skip over such data points. Alternatively, we can set  $(y_{it}, z_{it}) = (0, \mathbf{0}_k)$  so all variables related to  $(t, i)$  are set to zero—but then keep the standard summation.

When we assume that the residuals in (12.17) are iid and also independent of the regressors, then  $\text{Var}(\hat{\gamma})$  simplifies to the usual OLS expression. Instead, with heteroskedasticity (but still no cross-sectional correlations) we can apply the usual White's approach, and with autocorrelation the Newey-West approach. Instead, with cross-sectional correlations we need to make further adjustments (see below for a discussion).

**Remark 12.5** (\**Panel regression vs average coefficient in the case of common regressors*) Consider the regression for investor  $i$

$$y_{it} = z_t' \gamma_i + u_{it}, \quad i = 1 \dots N,$$

where the regressors are the same in all regressions—but where the coefficients might be different across investors. Clearly, we have for each  $i$

$$\hat{\gamma}_i = \tilde{S}_{zz}^{-1} \tilde{S}_{zy_i},$$

where  $\tilde{S}_{zz} = \sum_{t=1}^T z_t z_t'$  and  $\tilde{S}_{zy_i} = \sum_{t=1}^T z_t y_{it}$ .

The cross-sectional average of the regression coefficients is therefore

$$\frac{1}{N} \sum_{i=1}^N \gamma_i = (N \tilde{S}_{zz})^{-1} \sum_{i=1}^N \tilde{S}_{zy_i}.$$

Notice that  $N\tilde{S}_{zz} = S_{zz}$  in (12.12) and that  $\Sigma\tilde{S}_{zy_i} = S_{zy}$  in (12.13), which shows that  $\frac{1}{N}\sum_{i=1}^N \gamma_i = \gamma$ , where the latter is from the pooled panel regression (12.14).

### 12.5.1 Panel Regression with Clustering of Residuals

Different *cluster methods* account for a non-zero covariance within the same period (for instance, between  $u_{it}$  and  $u_{jt}$ ). If there is no autocorrelation ( $\text{Cov}(h_{i,t}, h_{j,t+s}) = 0$  for  $s \neq 0$ ), then we can write 12.17) as

$$S = \sum_{t=1}^T \text{Var} \left( \sum_{i=1}^N h_{it} \right). \quad (12.18)$$

Positive correlations in the cross-section ( $h_{it}$  is correlated with  $h_{jt}$ ) increases the right hand side of (12.18).

**Example 12.6** ( $N = 4$ ) To save space, let  $V()$  denote a variance (possibly a variance-covariance matrix) and  $C(, )$  a covariance (possibly a matrix). For  $N = 4$ , the  $\text{Var}()$  term in (12.18) can then be written (dropping the time subscripts to save even more space)

$$\begin{aligned} \text{Var}(\sum_{i=1}^4 h_i) &= V(h_1) + V(h_2) + V(h_3) + V(h_4) + \\ &\quad 2C(h_1, h_2) + 2C(h_1, h_3) + 2C(h_1, h_4) + 2C(h_2, h_3) + 2C(h_2, h_4) + 2C(h_3, h_4). \end{aligned}$$

Cross-sectional correlations mean that some  $C(, )$  terms are non-zero. The interpretation is easiest when there is a single regressor so  $h_i$  is a scalar. (In case there are several regressors, then  $V(h_i)$  is a variance-covariance matrix, and  $C(h_1, h_2)$  is a covariance matrix.)

A cluster method makes assumptions about which cross-sectional units ( $i$  and  $j$ ) can be correlated—and then uses the time-series data to estimate those.

**Example 12.7** (Cluster method on  $N = 4$ ) Assume that individuals 1 and 2 form cluster A and that individuals 3 and 4 form cluster B—and disregard correlations across clusters. This means setting the covariances across clusters to zero,

$$\begin{aligned} \text{Var}(\sum_{i=1}^4 h_i) &= V(h_1) + V(h_2) + V(h_3) + V(h_4) + \\ &\quad 2C(h_1, h_2) + \underbrace{2C(h_1, h_3)}_0 + \underbrace{2C(h_1, h_4)}_0 + \underbrace{2C(h_2, h_3)}_0 + \underbrace{2C(h_2, h_4)}_0 + 2C(h_3, h_4). \end{aligned}$$

Notice that this can be written

$$\text{Var}(\sum_{i=1}^4 h_i) = \text{Var}(h_1 + h_2) + \text{Var}(h_3 + h_4),$$

which hints at how this is typically estimated.

To estimate the  $S$  matrix in (12.18), we first define  $C$  clusters ( $c = 1, \dots, C$ ) and then calculate

$$\hat{S} = \sum_{t=1}^T \sum_{c=1}^C h_t^c (h_t^c)' \text{, where } h_t^c = \sum_{i \in \text{cluster } c} h_{it}. \quad (12.19)$$

The iid case is when each  $i$  is her/his own cluster. The Driscoll-Kraay approach puts everyone in one cluster.

**Remark 12.8** (*The logic of (12.19)\**) To make a trivial case, let  $N = 1$ . According to (12.18) and the previous examples  $S = T \text{Var}(h_1)$ . The traditional estimate of  $\text{Var}(h_1)$  is  $\sum_{t=1}^T h_{1t}^2 / T$ . Multiply by  $T$  to get the estimate of  $S$  as  $\sum_{t=1}^T h_{1t}^2$ .

**Remark 12.9** ( $T = 1^*$ ) When we have a pure cross-sectional data set, so  $T = 1$ , then we can still apply (12.19). However, it is common to replace  $h_i$  by  $h_i C / (C - 1)$  to improve the small sample properties of  $S$ . Also, notice that the Driscoll-Kraay approach (letting everyone be in one big cluster) does not work when  $T = 1$  since  $\sum_{i=1}^N h_i = 0$ .

	coef	t-tstat W	tstat DK
Inactive	-0.76	-56.89	-0.69
Active	3.08	37.48	1.77
Higly Active	8.65	28.73	2.73

Table 12.2: Annualised regression coefficients and different t-stats from Table 10, regressions I and II in Dahlquist et al (RFS 2017). For Inactive the coefficient is the annualised alpha, but for the other two categories it is the difference in alpha to the Inactive. Panel regressions, 62640 individuals, 2116 days. The dependent variable is the return of the individual portfolio (day  $t$ , individual  $i$ ). The regressions also control for 7 risk factors over 5 days (2 lags, 2 leads).

**Empirical Example 12.10** (*Investor activity vs performance*) For an empirical illustration, see Table 12.2 where White's t-stats look massively inflated. In contrast, the Driscoll-Kraay (DK) t-stats are actually the same as in the calendar time approach in Table 12.1. Table 12.3 extends the panel estimation in Table 12.2, but it includes more regressors (age, gender and pension rights). This would be difficult to handle in a calendar time approach, and thus illustrates that a panel regression can handle more general cases. Notice that the investor characteristics are here allowed to change across time. For instance, an investor can be active during the early years and then become inactive.

	coef	t-tstat W	tstat DK
Inactive	-1.10	-1.63	-0.69
Active	3.10	34.61	1.79
Higly Active	8.69	28.44	2.74
Age	0.00	0.19	0.11
Male	0.62	2.94	2.22
Pension rights	-0.03	-0.39	-0.33

Table 12.3: Annualised regression coefficients and different t-stats from Table 10, regressions I and II in Dahlquist et al (RFS 2017). Panel regressions, 62640 individuals, 2116 days. The dependent variable is the return of the individual portfolio (day  $t$ , individual  $i$ ). The regressions also control for 7 risk factors over 5 days (2 lags, 2 leads).

## 12.6 The Within Estimator (“Fixed Effects Estimator”)

In the fixed effects model, we allow for different individual intercepts

$$y_{it} = \alpha_i + x'_{it}\beta + u_{it}, \quad (12.20)$$

where  $u_{it}$  is iid with zero mean and variance  $\sigma_u^2$ .

There are several ways to estimate this model. The conceptually most straightforward is to include individual dummies ( $N$ ) where dummy  $i$  takes the value of one if the data refers to individual  $i$  and zero otherwise and estimate the model with pooled OLS. (Clearly, the regression can then not include any intercept. Alternatively, include an intercept but only  $N - 1$  dummies, for  $i = 2 - N$ .) However, this approach can be difficult to implement since it may involve a very large number of regressors.

As an alternative (which gives the same point estimates as pooled OLS with dummies) consider the following approach. First, take average across time (for a given  $i$ ) of  $y_{it}$  and  $x_{it}$  in (12.20). That is, think (but do not run any estimation yet...) of forming the cross-sectional regression

$$\bar{y}_i = \alpha_i + \bar{x}'_i\beta + \bar{u}_i, \text{ where} \quad (12.21)$$

$$\bar{y}_i = \frac{1}{T} \sum_{t=1}^T y_{it} \text{ and } \bar{x}_i = \frac{1}{T} \sum_{t=1}^T x_{it}. \quad (12.22)$$

Second, transform the data as

$$y_{it}^* = y_{it} - \bar{y}_i \quad (12.23)$$

$$x_{it}^* = x_{it} - \bar{x}_i. \quad (12.24)$$

Use this to express the difference between (12.20) and (12.21) as

$$y_{it}^* = x_{it}^{*\prime} \beta + u_{it}^*. \quad (12.25)$$

At this stage, estimate  $\beta$  by running pooled OLS on all observations of (12.25). There is no intercept in this regression, but adding an intercept should not affect the slope coefficients (since  $y_{it}^*$  and  $x_{it}^*$  have zero means).

We denote the estimate from (12.25) by  $\hat{\beta}_{FE}$  (FE stands for fixed effects) and it is also often called the *within estimator*. The interpretation of this approach is that we estimate the slope coefficients by using only the movements around individual means (not how the individual means differ). Notice that it gives the same results as OLS with dummies. Third and finally, get estimates of individual intercepts as

$$\alpha_i = \bar{y}_i - \bar{x}_i' \hat{\beta}_{FE}. \quad (12.26)$$

Clearly, the within estimator wipes out all regressors that are constant across time for a given individual (say, gender and schooling): they are effectively merged with the individual means ( $\mu_i$ ). In practice, such variables must be excluded from the  $x_{it}$  vector since otherwise there will be some transformed variables,  $x_{it} - \bar{x}_i$ , that are always zero—causing numerical problems. See Table 12.4 for an example (see "south").

**Remark 12.11** (*The within estimator and the Frisch-Waugh-Lovell theorem\**) Regressing  $y_t$  and  $x_t$  on a set of dummies gives  $\bar{y}_i$  and  $\bar{x}_i$ . The FWL theorem says that then regressing  $y_{it}^*$  on  $x_{it}^*$  gives the same slope coefficients as regressing  $y_{it}$  on  $x_{it}$  and the dummies.

We can apply the usual tests (including accounting for heteroskedasticity) on the pooled OLS results from (12.25)—provided the residuals are uncorrelated across time and individuals. Otherwise, we need to apply a cluster method.

Measures of fit ( $R^2$ ) are often calculated as the squared correlation between the dependent variable and the fitted value. The  $R^2$  from (12.25),  $\text{Corr}(y_{it}^*, \hat{y}_{it}^*)^2$ , is called the within- $R^2$ . Instead, if we add back the individual means and calculate  $\text{Corr}(y_{it}, \hat{y}_{it}^* + \bar{y}_i)^2$ , then we have the “overall  $R^2$ ”.

**Remark 12.12** (*Fixed effects in unbalanced panels*) When  $(y_{it}, x_{it})$  include one or more missing values, then we typically exclude that observation from the estimation. For that reason, they should also be excluded from calculating  $\bar{y}_i$  and  $\bar{x}_i$ . In this way,  $(y_{it}^*, x_{it}^*)$  will have zero means in the sample that is used in the estimation.

**Remark 12.13** (*Lagged dependent variable as regressor\**) If  $y_{i,t-1}$  is among the regressors  $x_{it}$ , then the within estimator (12.25) is biased in short samples (that is, when  $T$  is small)—and increasing the cross-section (that is,  $N$ ) does not help. To see the problem, suppose that the lagged dependent variable is the only regressor ( $x_{it} = y_{i,t-1}$ ). The within estimator (12.25) is then

$$y_{it} - \sum_{t=1}^T y_{it}/T = \left( y_{i,t-1} - \sum_{t=2}^T y_{i,t-1}/(T-1) \right) \beta + \left( u_{it} - \sum_{t=1}^T u_{it}/T \right).$$

The problem is that  $y_{i,t-1}$  is correlated with  $\Sigma u_{it}$  since the latter contains  $u_{i,t-1}$  which affects  $y_{i,t-1}$  directly. In addition,  $\Sigma y_{i,t-1}$  contains  $y_{i,t}$  which is correlated with  $u_{it}$ . It can be shown that this bias can be substantial for panels with small  $T$ .

	LS	Fixed eff	Between	GLS	1st diff
exper/100	7.84 (8.25)	4.11 (6.21)	10.64 (4.05)	4.57 (7.12)	3.55 (2.33)
exper <sup>2</sup> /100	-0.20 (-5.04)	-0.04 (-1.50)	-0.32 (-2.83)	-0.06 (-2.37)	-0.05 (-0.93)
tenure/100	1.21 (2.47)	1.39 (4.25)	1.25 (0.90)	1.38 (4.32)	1.29 (2.98)
tenure <sup>2</sup> /100	-0.02 (-0.85)	-0.09 (-4.36)	-0.02 (-0.20)	-0.07 (-3.77)	-0.08 (-2.45)
south	-0.20 (-13.51)	-0.02 (-0.45)	-0.20 (-6.67)	-0.13 (-5.70)	-0.02 (-0.56)
union	0.11 (6.72)	0.06 (4.47)	0.12 (3.09)	0.07 (5.57)	0.04 (3.31)

Table 12.4: Panel estimation of log wages for women,  $T = 5$  and  $N = 716$  from NLS (1982,1983,1985,1987,1988). Example of fixed and random effects models, Hill et al (2008), Table 15.9. Numbers in parentheses are t-stats.

### 12.6.1 The Within Estimator with Time Fixed Effects

When we allow for both time fixed effects and individual fixed effects

$$y_{it} = \lambda_t + \alpha_i + x'_{it}\beta + u_{it}, \quad (12.27)$$

then we could once again introduce dummies (now for both time periods and individuals) and apply pooled OLS.

As before, it is often easier to transform the data before estimating with pooled OLS. In this case, we run the regression on transformed variables

$$y_{it}^* = x_{it}'\beta + u_{it}^*. \quad (12.28)$$

The transformations are

$$y_{it}^* = y_{it} - \bar{y}_i - \bar{y}_t + \bar{y} \quad (12.29)$$

$$x_{it}^* = x_{it} - \bar{x}_i - \bar{x}_t + \bar{x}, \quad (12.30)$$

where  $\bar{x}_i$  is defined in (12.22) and

$$\begin{aligned} \bar{x}_t &= \sum_{i=1}^N x_{it}/N \text{ for each } t, \text{ and} \\ \bar{x} &= \sum_{t=1}^T \sum_{i=1}^N x_{it}/(TN). \end{aligned}$$

(Similarly for the transformation of  $y_{it}$ .) The last terms ( $\bar{y}, \bar{x}$ ) makes sure that the grand mean of the transformed variable is zero. (If we instead add an intercept to (12.28), then it should not affect the slope coefficients.)

The estimation and testing of (12.28) is the same as for the standard within estimator (see above).

**Remark 12.14** (\*Only time fixed effects) When we allow for time fixed effects but no individual fixed effect, then the transformations are

$$\begin{aligned} y_{it}^* &= y_{it} - \bar{y}_t \\ x_{it}^* &= x_{it} - \bar{x}_t. \end{aligned}$$

**Remark 12.15** (\*Fixed effects in unbalanced panels) As with individual fixed effects, the averages should only be calculated from those data points that will be used in the estimation.

**Proof.** (\*of (12.28)) First, take averages over time (for each individual,  $i = 1$  to  $N$ ) of (12.27) to get

$$\bar{y}_i = \bar{\lambda} + \alpha_i + \bar{x}_i'\beta + \bar{u}_i.$$

Second, take averages over the cross section (in each time period,  $t = 1$  to  $T$ )

$$\bar{y}_t = \lambda_t + \bar{\alpha} + \bar{x}_t'\beta + \bar{u}_t.$$

Third, take averages across both time and the cross-section

$$\bar{y} = \bar{\lambda} + \bar{\alpha} + \bar{x}'\beta.$$

Finally, subtract all three from (12.27) to get (12.28). ■

## 12.7 The First-Difference Estimator

An another way of estimating the fixed effects model is to difference away the  $\alpha_i$  by taking *first-differences* (in time)

$$\Delta y_{it} = \Delta \lambda_t + \Delta x'_{it}\beta + u_{it}^*, \quad (12.31)$$

where  $\Delta y_{it} = y_{it} - y_{i,t-1}$  and similarly for the regressors. Quite often, we interpret  $\Delta \lambda_t$  as just a constant. Notice that

$$u_{it}^* = u_{it} - u_{i,t-1}, \quad (12.32)$$

so there are reasons to suspect that  $u_{it}^*$  is (negatively) autocorrelated.

Notice that the first-difference approach focuses on how changes in the regressors (over time, for the same individual) affect changes in the dependent variable. Also this method wipes out all regressors that are constant across time (for a given individual).

Regression (12.31) can be estimated by pooled OLS. However, unadjusted standard errors are likely to overstate the uncertainty. This suggests that using the unadjusted standard errors is a conservative approach (harder to reject the null hypothesis).

**Example 12.16** (\*Negative autocorrelation of  $u_{it}^*$ ) If  $u_{it}$  in (12.32) is iid, then  $\text{Cov}(u_{it}^*, u_{it-1}^*) = \text{Cov}(u_{it} - u_{i,t-1}, u_{it-1} - u_{i,t-2}) = -\sigma_u^2$ .

**Remark 12.17** (Lagged dependent variable as regressor\*) If  $y_{i,t-1}$  is among the regressors  $x_{it}$ , then the first-difference method (12.31) does not work (OLS is inconsistent and a larger sample does not help). The reason is that the (autocorrelated) residual is then correlated with the lagged dependent variable. This model cannot be estimated by OLS (the instrumental variable method might work).

## 12.8 Differences-in-Differences Estimator

Consider the model (12.31) when one of the regressors is a dummy variable indicating whether individual  $i$  was “treated” (for instance, received investment advise) in period  $t$ .

We can estimate this as before—and interpret the coefficient as the effect of the “treatment” (conditional on all other variables)

In the classical difference-in-difference estimator there are only two periods ( $T = 2$ ): before and after the treatment. *If there are no other regressors*, then (12.31) can be written

$$\Delta y_{it} = \Delta \lambda_t + \beta Q_{it} + u_{it}^*, \quad (12.33)$$

where  $Q_{it}$  is the dummy variable. (The restriction that all individuals have the same  $\Delta \lambda_t$  term is the so called “parallel trend assumption.”) In this case  $\beta$  can be estimated by the difference between the average  $\Delta y_{it}$  among the treated ( $\Delta \bar{y}_{B2}$ ) and the average  $\Delta y_{it}$  among the non-treated ( $\Delta \bar{y}_{A2}$ )

$$\hat{\beta} = \Delta \bar{y}_{B2} - \Delta \bar{y}_{A2}. \quad (12.34)$$

(Notice that the change of the average is the same as the average of the change.)

## 12.9 Random Effects Model\*

The random effects model allows for *random* individual “intercepts” ( $\mu_i$ )

$$y_{it} = \alpha + x'_{it}\beta + \mu_i + \varepsilon_{it}, \text{ where} \quad (12.35)$$

$$\varepsilon_{it} \text{ is iid } N(0, \sigma_\varepsilon^2) \text{ and } \mu_i \text{ is iid } N(0, \sigma_\mu^2). \quad (12.36)$$

Notice that  $\mu_i$  is random (across agents) but constant across time, while  $\varepsilon_{it}$  is just random noise. Hence,  $\mu_i$  can be interpreted as the permanent “luck” of individual  $i$ .

It is sometimes argued that the random effect only makes sense if the data is a sample from a larger population—and then captures the peculiar (relative to the population) features of the individuals that end up in the sample. It is then convenient to merge  $\mu_i$  with  $\varepsilon_{it}$ , because it gives fewer parameters to estimate (and thus, saves degrees of freedom). In contrast, if the cross-section effectively contains the population (all mutual funds on a market, say), then a fixed effect is perhaps more reasonable.

Clearly, if we regard  $\mu_i$  as non-random, then we are back in the fixed-effects model. (The choice between the two models is not always easy, so it may be wise to try both—and compare the results.)

We could write the regression as

$$y_{it} = \alpha + x'_{it}\beta + u_{it}, \text{ where } u_{it} = \mu_i + \varepsilon_{it}, \quad (12.37)$$

and we typically assume that  $u_{it}$  is uncorrelated across individuals, but correlated across time (only because of  $\mu_i$ ). In addition, we assume that  $\varepsilon_{jt}$  and  $\mu_i$  are not correlated with each other or with  $x_{it}$ .

There are several ways to estimate the random effects model. First, the methods for fixed effects (the within and first-difference estimators) all work—so the “fixed effect” can actually be a random effect. Second, the *between estimator* using only individual time averages (from (12.22))

$$\bar{y}_i = \alpha + \bar{x}'_i \beta + \underbrace{\mu_i + \bar{\varepsilon}_i}_{\text{residual}_i}, \quad (12.38)$$

is also consistent, but discards all time-series information. Third, LS on

$$y_{it} = \alpha + x'_{it} \beta + \underbrace{\mu_i + \varepsilon_{it}}_{\text{residual}_{it}} \quad (12.39)$$

is consistent (but not really efficient). However, in this case we may need to adjust  $\text{Var}(\hat{\beta})$  since the covariance matrix of the residuals is not diagonal.

In the random effects model, the  $\mu_i$  variable can be thought of as an *excluded variable*. Excluded variables typically give a bias in the coefficients of all included variables—unless the excluded variable is uncorrelated with all of them. This is the assumption in the random effects model (recall: we assumed that  $\mu_i$  is uncorrelated with  $x_{jt}$ ). If this assumption is wrong, then we cannot estimate the RE model by either OLS or GLS, but the within-estimator (compare with the FE model) works, since it effectively eliminates the excluded variable from the system.

**Example 12.18**  $N = 2, T = 2$ . If we stack the data for individual  $i = 1$  first and those for individual  $i = N$  second

$$\text{Var} \left( \begin{bmatrix} u_{1,T-1} \\ u_{1T} \\ u_{N,T-1} \\ u_{NT} \end{bmatrix} \right) = \begin{bmatrix} \sigma_\mu^2 + \sigma_\varepsilon^2 & \sigma_\mu^2 & 0 & 0 \\ \sigma_\mu^2 & \sigma_\mu^2 + \sigma_\varepsilon^2 & 0 & 0 \\ 0 & 0 & \sigma_\mu^2 + \sigma_\varepsilon^2 & \sigma_\mu^2 \\ 0 & 0 & \sigma_\mu^2 & \sigma_\mu^2 + \sigma_\varepsilon^2 \end{bmatrix},$$

which has elements off the main diagonal.

**Remark 12.19** (*Generalized least squares\**) GLS is an alternative estimation method that exploits correlation structure of residuals to increase the efficiency. In this case,

it can be implemented by running OLS on

$$y_{it} - \vartheta \bar{y}_i = \alpha(1 - \vartheta) + (x_{it} - \vartheta \bar{x}_i)' \beta + v_{it}, \text{ where}$$

$$\vartheta = 1 - \sqrt{\sigma_u^2 / (\sigma_u^2 + T\sigma_\mu^2)}.$$

In this equation,  $\sigma_u^2$  is the variance of the residuals in the “within regression” as estimated in (12.25) and  $\sigma_\mu^2 = \sigma_B^2 - \sigma_u^2 / T$ , where  $\sigma_B^2$  is the variance of the residuals in the “between regression” (12.38). Here,  $\sigma_\mu^2$  can be interpreted as the variance of the random effect  $\mu_i$ . However, watch out for negative values of  $\sigma_\mu^2$  and notice that when  $\vartheta \approx 1$ , then GLS is similar to the “within estimator” from (12.25). This happens when  $\sigma_\mu^2 \gg \sigma_u^2$  or when  $T$  is large. The intuition is that when  $\sigma_\mu^2$  is large, then it is smart to get rid of that source of noise by using the within estimator, which disregards the information in the differences between individual means.

## 12.10 Fama-MacBeth

The Fama and MacBeth (1973) approach (called FMB below) is a different method for handling panel data. The method has two main steps, described below.

*First*, estimate  $\lambda_t$  and  $\beta_t$

$$y_{it} = \lambda_t + x'_{it} \beta_t + u_{it} \quad (12.40)$$

period by period (using the cross section  $i = 1 - N$ ). The FMB has the nice properties of easily handling unbalanced data sets (the cross-sectional regressions (12.40) are run the available cross section for each time period).

*Second*, estimate the time averages

$$\hat{\beta} = \frac{1}{T} \sum_{t=1}^T \hat{\beta}_t. \quad (12.41)$$

**Remark 12.20** (*Step 0\**) The FMB can also be used to test CAPM (or other linear factor models). In this case,  $y_{it}$  in (12.40) are the excess returns on asset  $i$  in period  $t$  ( $R_{it}^e$ ) and  $x_{it}$  are the loadings ( $\gamma_{it}$ ) of the excess return on the market excess return (or other factors) according to the regression  $R_{it}^e = \alpha + f_t' \gamma_{it} + \varepsilon_{it}$ . In many cases, the  $\gamma_{it}$  values used as  $x_{it}$  are estimated during a previous sample, for instance, during the five years up to and including  $t - 1$ . In other cases, the  $\gamma_{it}$  values are estimated from the full sample,

and are thus constant across periods. The latter has the advantage of being more precise estimates, provided the assumption of constant loadings is correct.

Fama and MacBeth (1973) suggest that the standard deviation should be found by studying the time-variation in  $\hat{\beta}_t$ . In particular, they suggest that the variance of  $\hat{\beta}_t$  (notice, not  $\hat{\beta}$ ) can be estimated by the (average) squared variation around its mean

$$\widehat{\text{Var}}(\hat{\beta}_t) = \frac{1}{T} \sum_{t=1}^T (\hat{\beta}_t - \hat{\beta})^2. \quad (12.42)$$

Since  $\hat{\beta}$  is the sample average of  $\hat{\beta}_t$ , the variance of the former is the variance of the latter divided by  $T$  (the sample size)—provided  $\hat{\beta}_t$  is iid. That is,

$$\widehat{\text{Var}}(\hat{\beta}) = \frac{1}{T} \text{Var}(\hat{\beta}_t) = \frac{1}{T^2} \sum_{t=1}^T (\hat{\beta}_t - \hat{\beta})^2. \quad (12.43)$$

When  $x_{it}$  are common risk factors ( $x_{it} = x_t$ ), then FMB and pooled OLS give the same point estimates (provided (12.40) is estimated without an intercept, effectively setting  $\lambda_t = 0$ ). However, FMB's variance-covariance matrix automatically handles the cross sectional correlations between residuals, while the pooled OLS would require applying a cluster method.

**Empirical Example 12.21** (*Estimated factor risk premia from different methods*) Table 12.5 shows estimates of the factor risk premia from several methods based on the 25 FF portfolios.

	Data	CR	FMB1	FMB2
Market	6.85 (2.20)	6.43 (2.28)	6.43 (2.23)	-7.31 (3.96)
SMB	1.41 (1.46)	1.29 (1.54)	1.29 (1.50)	0.90 (1.50)
HML	3.91 (1.46)	4.58 (1.62)	4.58 (1.50)	4.22 (1.50)

Table 12.5: Different estimates of factor risk premia, annualized %. Numbers in (parentheses) are standard deviations. The 25 FF portfolios 1970:01-2022:12. Data are the mean excess returns of the factors; CR are estimates of the factor risk premia from a cross-sectional regression; FMB1 are from Fama-MacBeth without intercept in the cross-sectional regression; FMB2 are from Fama-MacBeth with intercept in the cross-sectional regression. In both FMB regressions, the betas are estimated from the full sample.

# Chapter 13

## Time Series Analysis

Reference: Newbold (1995) 17 or Pindyck and Rubinfeld (1998) 13.5, 16.1–2, and 17.2; Greene (2018) 20

More advanced material is denoted by a star (\*). It is not required reading.

### 13.1 Descriptive Statistics

The  $s$ th *autocovariance* of  $y_t$  is estimated by

$$\widehat{\text{Cov}}(y_t, y_{t-s}) = \sum_{t=1}^T (y_t - \bar{y})(y_{t-s} - \bar{y}) / T, \text{ where } \bar{y} = \sum_{t=1}^T y_t / T. \quad (13.1)$$

The convention in time series analysis is that we use the same estimated (using all data) mean in both places and that we divide by  $T$ .

The  $s$ th *autocorrelation* is estimated as

$$\hat{\rho}_s = \frac{\widehat{\text{Cov}}(y_t, y_{t-s})}{\widehat{\text{Std}}(y_t)^2}. \quad (13.2)$$

Compared with a traditional estimate of a correlation we here impose that the standard deviation of  $y_t$  and  $y_{t-s}$  are the same (which typically does not make much of a difference).

The sampling properties of  $\hat{\rho}_s$  are complicated, but there are several useful large sample results for Gaussian processes (these results often carry over to processes which are similar to a Gaussian process—a homoskedastic process with finite 6th moment is typically enough, see Priestley (1981) 5.3 or Brockwell and Davis (1991) 7.2–7.3). When the true autocorrelations are all zero (not  $\rho_0$ , of course), then for any  $i$  and  $j$  different from

zero

$$\sqrt{T} \begin{bmatrix} \hat{\rho}_i \\ \hat{\rho}_j \end{bmatrix} \xrightarrow{d} N \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right). \quad (13.3)$$

This result can be used to construct tests for both single autocorrelations (t-test or  $\chi^2$  test) and several autocorrelations at once ( $\chi^2$  test). In particular,

$$\sqrt{T} \hat{\rho}_s \xrightarrow{d} N(0, 1), \quad (13.4)$$

so  $\sqrt{T} \hat{\rho}_s$  can be used as a t-stat. We can then define a 90% confidence band for  $\hat{\rho}$  as  $\pm 1.64/\sqrt{T}$  around the point estimate  $\hat{\rho}$  or around the null hypothesis (0).

**Empirical Example 13.1** (*Autocorrelations of returns and absolute values of returns, different lags*) See Figure 13.1 for results on S&P 500.

**Example 13.2** (*t-test*) We want to test the hypothesis that  $\rho_1 = 0$ . Since the  $N(0, 1)$  distribution has 5% of the probability mass below -1.64 and another 5% above 1.64, we can reject the null hypothesis at the 10% level if  $\sqrt{T}|\hat{\rho}_1| > 1.64$ . With  $T = 100$ , we therefore need  $|\hat{\rho}_1| > 1.64/\sqrt{100} = 0.165$  for rejection, and with  $T = 1000$  we need  $|\hat{\rho}_1| > 1.64/\sqrt{1000} \approx 0.052$ .

The Box-Pierce test follows directly from the result in (13.3), since it shows that  $\sqrt{T} \hat{\rho}_i$  and  $\sqrt{T} \hat{\rho}_j$  are independent  $N(0, 1)$  variables. Therefore, the sum of the square of them is distributed as a  $\chi^2$  variable. The test statistic is

$$Q_L = T \sum_{s=1}^L \hat{\rho}_s^2 \xrightarrow{d} \chi_L^2. \quad (13.5)$$

However, you could also test  $T(\rho_2^2 + \rho_5^2)$ , and it would have a  $\chi_2^2$  distribution.

**Example 13.3** (*Box-Pierce*) Let  $\hat{\rho}_1 = 0.165$ , and  $T = 100$ , so  $Q_1 = 100 \times 0.165^2 = 2.72$ . The 10% critical value of the  $\chi_1^2$  distribution is 2.71, so the null hypothesis of no autocorrelation is rejected.

The choice of lag order in (13.5),  $L$ , should be guided by theoretical considerations, but it may also be wise to try different values. There is clearly a trade off: too few lags may miss a significant high-order autocorrelation, but too many lags can destroy the power of the test (as the test statistic is not affected much by increasing  $L$ , but the critical values increase).

Partial autocorrelations are discussed in Section 13.5.1.

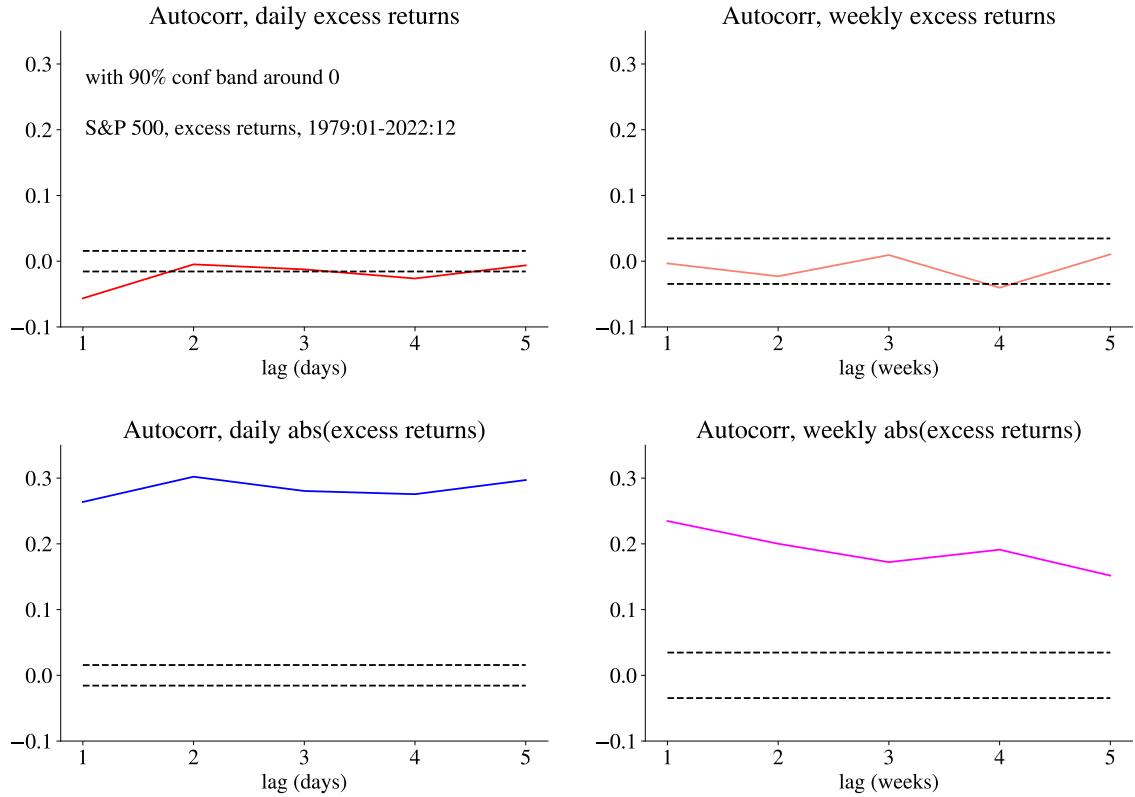


Figure 13.1: Predictability of US stock returns

**Remark 13.4** (*Runs test\**) A “runs test” is a non-parametric test of randomness. Let  $x_t$  be an indicator variable

$$x_t = \begin{cases} 0 & \text{if } y_t \leq q \\ 1 & \text{if } y_t > q \end{cases}$$

where  $q$  typically (but not necessarily) is the mean of  $y_t$ . Let  $T_1 = \sum_{t=1}^T x_t$ , that is the number of occasions when  $y_t > q$ , and  $T_2 = T - T_1$  (the number of occasions when  $y_t \leq q$ ). Also define the numbers of runs, that is, the number of changes in the  $x_t$  series (where the first observation is counted as a change). That is define

$$r = 1 + \sum_{t=2}^T |x_t - x_{t-1}|.$$

*It is straightforward (but tedious) to show that, under the null hypothesis of randomness,*

$$\begin{aligned}\mathbb{E} r &= 2 \frac{T_1 T_2}{T} + 1 \text{ and} \\ \text{Var}(r) &= \frac{(\mathbb{E} r - 1)(\mathbb{E} r - 2)}{T - 1}.\end{aligned}$$

*We can therefore test the null hypothesis of randomness by a t-stat*

$$\frac{r - \mathbb{E} r}{\sqrt{\text{Var}(r)}} \xrightarrow{d} N(0, 1).$$

*The basic intuition of the test is that a positive autocorrelation would lead to too few runs ( $r < \mathbb{E} r$ ): the  $y_t$  variable would stay on one side of the threshold  $q$  for long spells of time—and hence there would be few changes in  $x_t$ . Negative autocorrelation is just the opposite, since it tends to give a zigzag pattern around the mean. See Figure 13.2 for an example.*

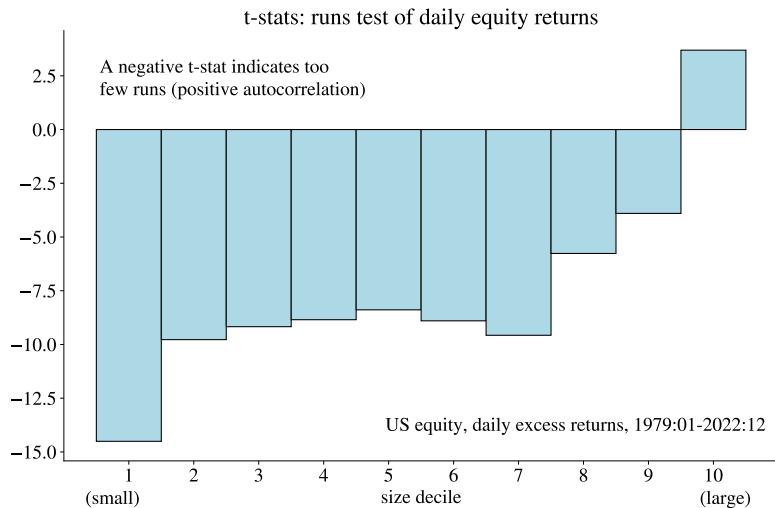


Figure 13.2: Runs test

## 13.2 Stationarity

The process  $y_t$  is (weakly) stationary if the mean, variance, and covariances are finite and constant across time

$$\mathbb{E} y_t = \mu < \infty \quad (13.6)$$

$$\text{Var}(y_t) = \gamma_0 < \infty \quad (13.7)$$

$$\text{Cov}(y_t, y_{t-s}) = \gamma_s < \infty \quad (13.8)$$

The *autocorrelation function* is just the autocorrelation coefficient  $\rho_s$  as a function of  $s$ . Notice that

$$\lim_{|s| \rightarrow \infty} \rho_s = 0 \text{ for any stationary series.} \quad (13.9)$$

See Figure 13.3 for an example.

The autocorrelation function is strongly related to the *impulse response function* (IRF) which shows the dynamic response of  $y_{t+s}$  ( $s = 0, 1, 2, \dots$ ) to a shock in  $t$ . For any stationary series, the IRF converges to zero as the horizon ( $s$ ) is increased. See Figure 13.4 for an example.

## 13.3 White Noise

The *white noise* process is the basic building block used in most other time series models. It is characterized by a zero mean, a constant variance, and no autocorrelation

$$\begin{aligned} \mathbb{E} \varepsilon_t &= 0 \\ \text{Var}(\varepsilon_t) &= \sigma^2, \text{ and} \\ \text{Cov}(\varepsilon_{t-s}, \varepsilon_t) &= 0 \text{ if } s \neq 0. \end{aligned} \quad (13.10)$$

This process can clearly not be forecasted. If, in addition,  $\varepsilon_t$  is normally distributed, then it is said to be Gaussian white noise.

To construct a variable that has a non-zero mean, we can form

$$y_t = \mu + \varepsilon_t, \quad (13.11)$$

where  $\mu$  is a constant. This process is most easily estimated by the sample mean and variance or by OLS with a constant as the only regressor.

The *impulse response function* of a white noise process is just a blip.

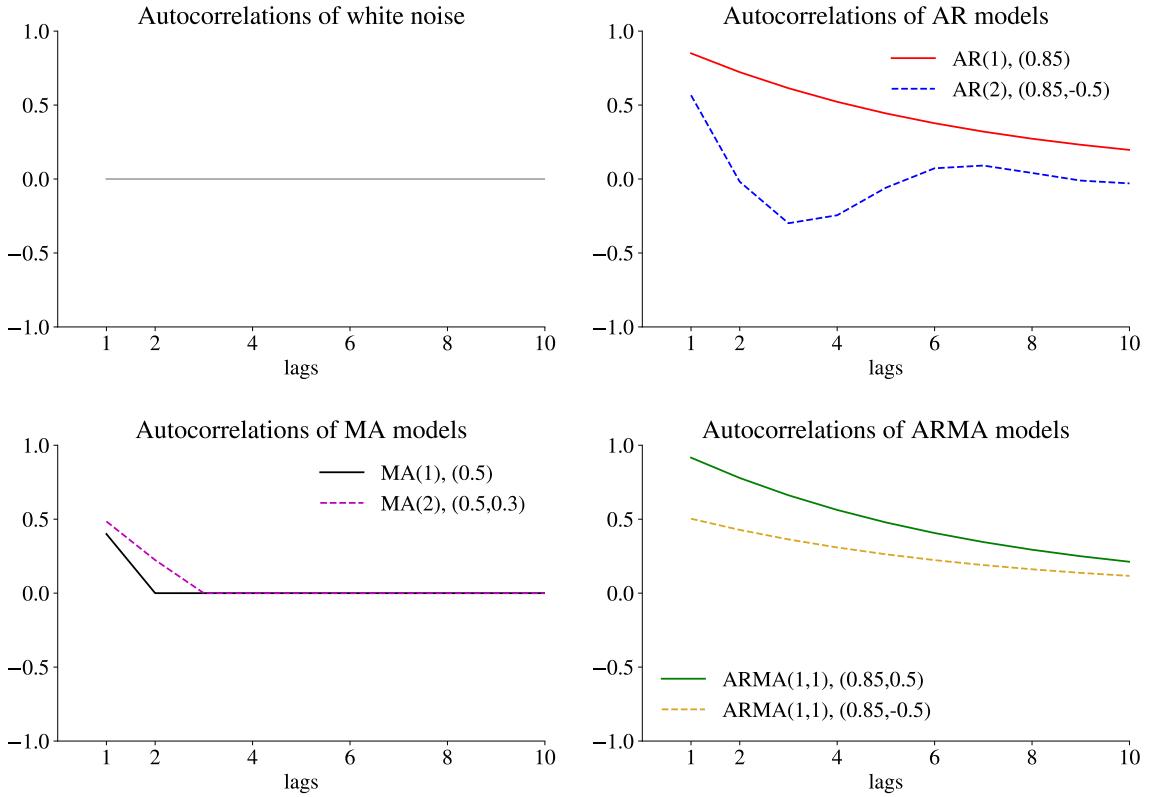


Figure 13.3: Example of autocorrelation functions

## 13.4 AR(1)

In this section we study the *first-order autoregressive* process, AR(1), in some detail in order to understand the basic concepts of autoregressive processes. The process is assumed to have a zero mean (or is demeaned: the original variable minus its mean,  $y_t = x_t - \bar{x}$ ), but it is straightforward to put in any mean or trend.

An AR(1) is

$$y_t = ay_{t-1} + \varepsilon_t, \text{ with } \text{Var}(\varepsilon_t) = \sigma^2, \quad (13.12)$$

where  $\varepsilon_t$  is the white noise process in (13.10) which is uncorrelated with  $y_{t-1}$ . If  $|a| < 1$ , then the effect of a shock eventually dies out:  $y_t$  is stationary.

The *impulse response function* of an AR(1) with  $a > 0$  shows an exponentially decaying response and with  $a < 0$  it is zigzag response that decreases in amplitude. See Figure 13.4 for an illustration.

The AR(1) model can be *estimated with OLS* (since  $\varepsilon_t$  and  $y_{t-1}$  are uncorrelated) and

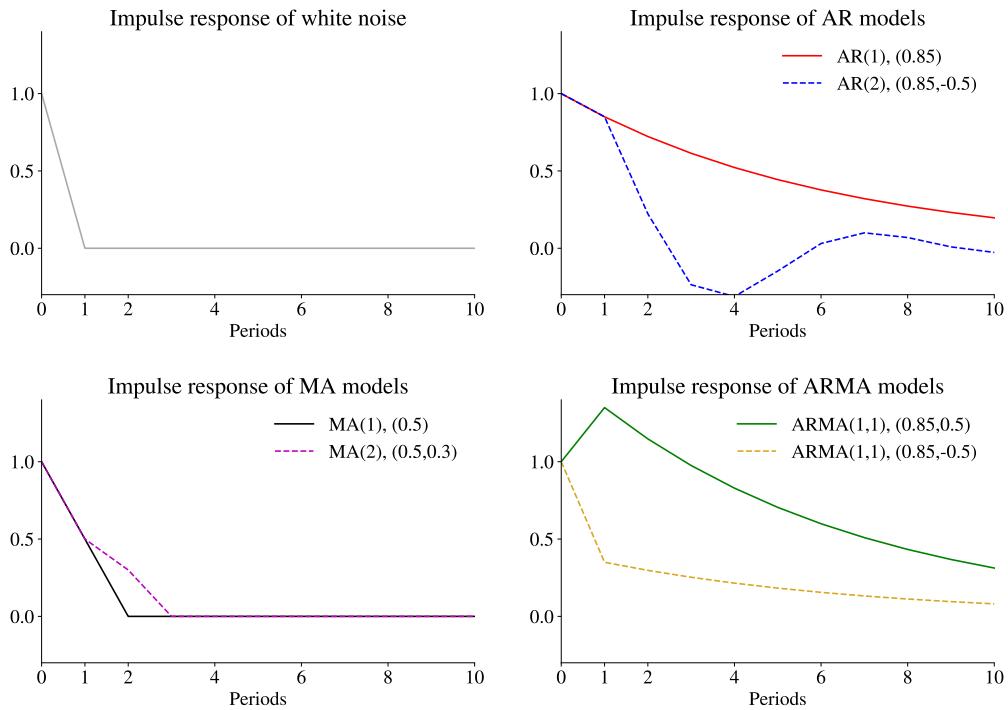


Figure 13.4: Impulse responses

the usual tools for testing significance of coefficients and estimating the variance of the residual all apply.

The basic properties of an AR(1) process are (provided  $|a| < 1$ )

$$\text{Var}(y_t) = \sigma^2 / (1 - a^2) \quad (13.13)$$

$$\text{Corr}(y_t, y_{t-s}) = a^s, \quad (13.14)$$

so the variance and autocorrelation are increasing in  $a$  (assuming  $a > 0$ ). When  $|a| \geq 1$ , then the process is non-stationary, which means that the impulse response does not converge to zero as the horizon increases (see below for a discussion of such models: they are tricky).

See Figure 13.4 for an illustration.

**Remark 13.5** (*Autocorrelation and autoregression*). Notice that the OLS estimate of  $a$  in (13.12) is essentially the same as the sample autocorrelation coefficient in (13.2). This follows from the fact that the slope coefficient is  $\text{Cov}(y_t, y_{t-1}) / \text{Var}(y_{t-1})$ . The denominator can be a bit different since a few data points are left out in the OLS estimation, but the difference is likely to be small.

**Example 13.6** With  $a = 0.85$  and  $\sigma^2 = 0.5^2$ , we have  $\text{Var}(y_t) = 0.25/(1 - 0.85^2) \approx 0.9$ , which is much larger than the variance of the residual since the uncertainty is accumulating when  $a > 0$ .

If  $a = 1$  in (13.12), then we get a *random walk*. It is clear from the previous analysis that a random walk is non-stationary—that is, the effect of a shock never dies out. This implies that the variance is infinite and that the standard tools for testing coefficients are invalid. The solution is to study changes in  $y$  instead:  $y_t - y_{t-1}$ . In general, processes with the property that the effect of a shock never dies out are called non-stationary or unit root or integrated processes. Try to avoid them.

**Empirical Example 13.7 (AR(1) for different investment horizons)** See Figure 13.5 for AR(1) results for different investment horizons.

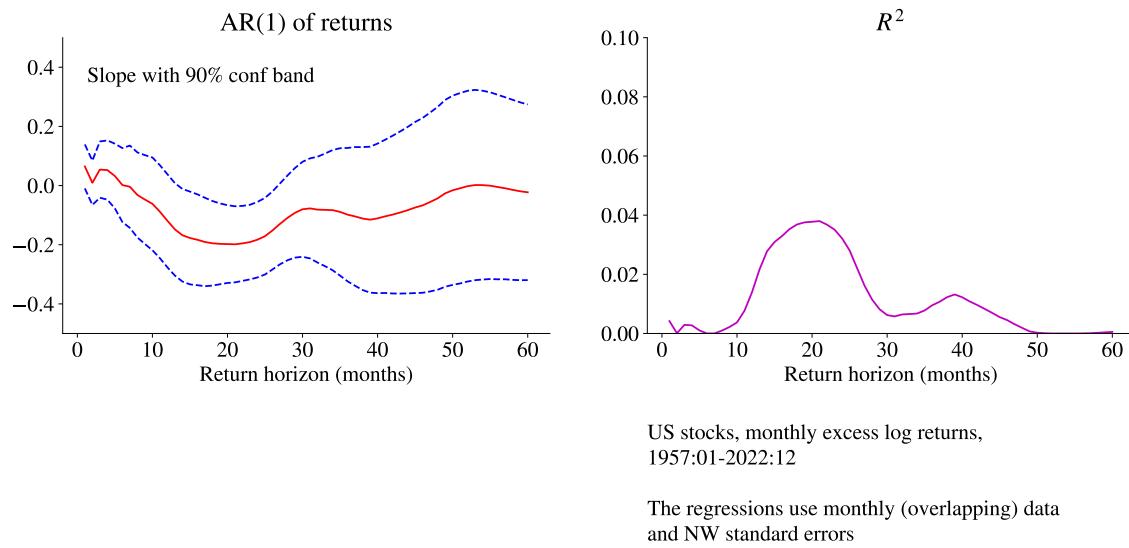


Figure 13.5: Predicting long run US stock returns

### 13.4.1 More on the Properties of an AR(1) Process\*

Solve (13.12) backwards by repeated substitution

$$y_t = a \underbrace{(ay_{t-2} + \varepsilon_{t-1})}_{y_{t-1}} + \varepsilon_t \quad (13.15)$$

$$= a^2 y_{t-2} + a \varepsilon_{t-1} + \varepsilon_t \quad (13.16)$$

$$\vdots \quad (13.17)$$

$$= a^{K+1} y_{t-K-1} + \sum_{s=0}^K a^s \varepsilon_{t-s}. \quad (13.18)$$

The factor  $a^{K+1} y_{t-K-1}$  declines monotonically to zero if  $0 < a < 1$  as  $K$  increases, and declines in an oscillating fashion if  $-1 < a < 0$ . In either case, the AR(1) process is covariance *stationary* and we can then take the limit as  $K \rightarrow \infty$  to get

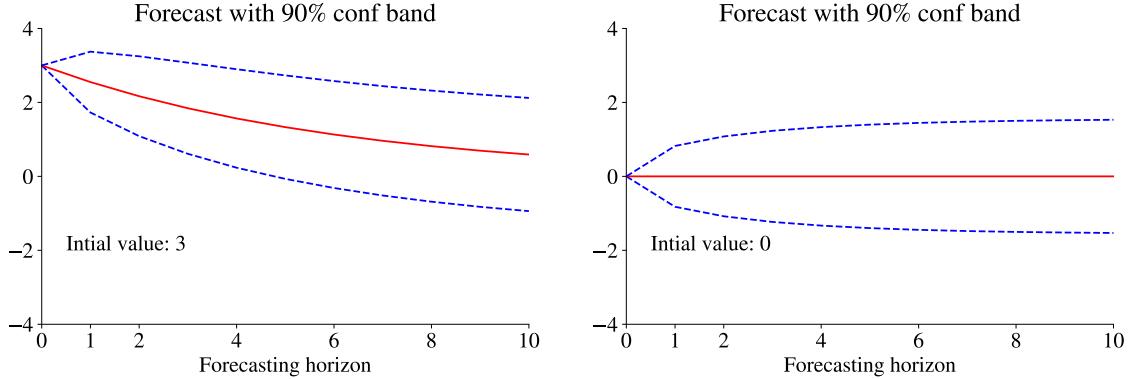
$$\begin{aligned} y_t &= \varepsilon_t + a \varepsilon_{t-1} + a^2 \varepsilon_{t-2} + \dots \\ &= \sum_{s=0}^{\infty} a^s \varepsilon_{t-s}. \end{aligned} \quad (13.19)$$

Since  $\varepsilon_t$  is uncorrelated over time,  $y_{t-1}$  and  $\varepsilon_t$  are uncorrelated. We can therefore calculate the variance of  $y_t$  in (13.12) as the sum of the variances of the two components on the right hand side

$$\begin{aligned} \text{Var}(y_t) &= \text{Var}(ay_{t-1}) + \text{Var}(\varepsilon_t) \\ &= a^2 \text{Var}(y_{t-1}) + \text{Var}(\varepsilon_t) \\ &= \text{Var}(\varepsilon_t) / (1 - a^2), \text{ since } \text{Var}(y_{t-1}) = \text{Var}(y_t). \end{aligned} \quad (13.20)$$

In this calculation, we use the fact that  $\text{Var}(y_{t-1})$  and  $\text{Var}(y_t)$  are equal. Formally, this follows from that they are both linear functions of current and past  $\varepsilon_s$  terms (see (13.19)), which have the same variance over time ( $\varepsilon_t$  is assumed to be white noise).

Note from (13.20) that the variance of  $y_t$  is increasing in the absolute value of  $a$ , which is illustrated in Figure 13.6. The intuition is that a large  $|a|$  implies that a shock have effect over many time periods and thereby create movements (volatility) in  $y_t$ .



AR(1) model:  $y_{t+1} = 0.85y_t + \varepsilon_{t+1}$ , with  $\sigma = 0.5$

Figure 13.6: Properties of AR(1) process

Similarly, the covariance of  $y_t$  and  $y_{t-1}$  is

$$\begin{aligned}\text{Cov}(y_t, y_{t-1}) &= \text{Cov}(ay_{t-1} + \varepsilon_t, y_{t-1}) \\ &= a \text{Cov}(y_{t-1}, y_{t-1}) \\ &= a \text{Var}(y_t).\end{aligned}\tag{13.21}$$

We can then calculate the first-order autocorrelation as

$$\begin{aligned}\text{Corr}(y_t, y_{t-1}) &= \frac{\text{Cov}(y_t, y_{t-1})}{\text{Std}(y_t) \text{Std}(y_{t-1})} \\ &= a.\end{aligned}\tag{13.22}$$

It is straightforward to show that

$$\text{Corr}(y_t, y_{t-s}) = \text{Corr}(y_{t+s}, y_t) = a^s.\tag{13.23}$$

### 13.4.2 Forecasting with an AR(1)

Suppose we have estimated an AR(1). To simplify the exposition, we assume that we actually know  $a$  and  $\text{Var}(\varepsilon_t)$ , which might be a reasonable approximation if they were estimated on a long sample.

We want to *forecast*  $y_{t+1}$  using information available in  $t$ . From (13.12) we get

$$y_{t+1} = ay_t + \varepsilon_{t+1}.\tag{13.24}$$

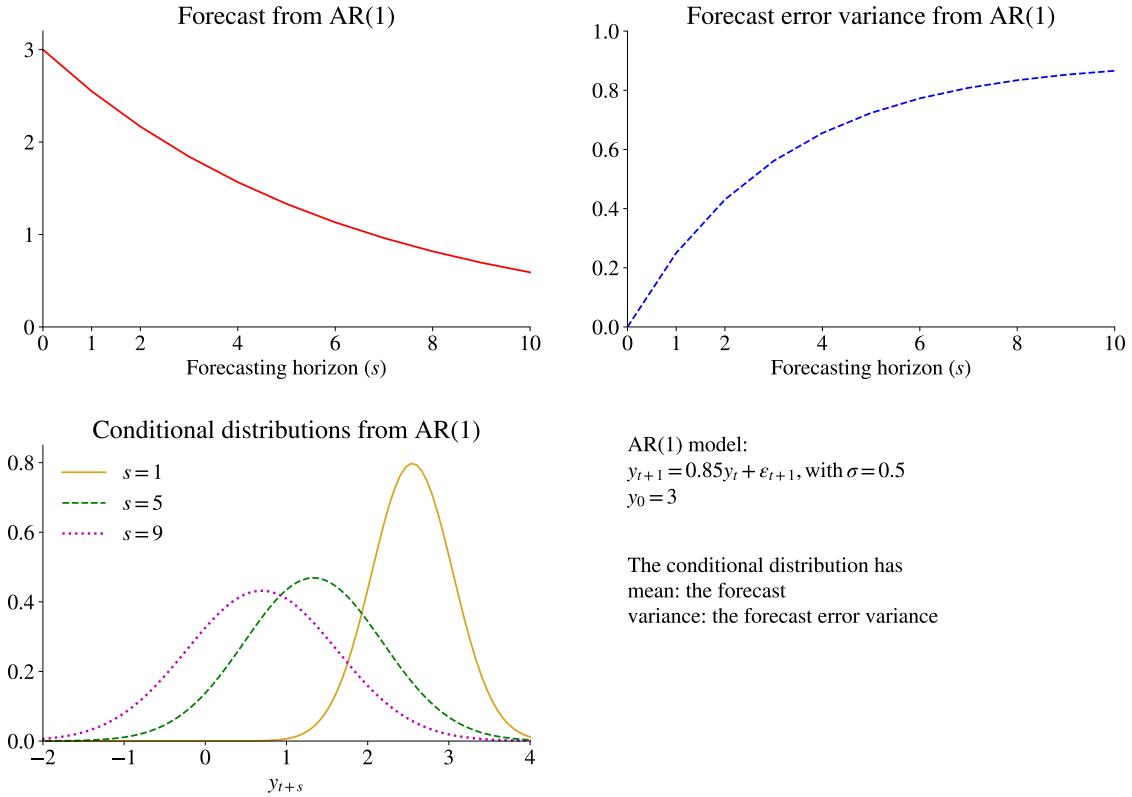


Figure 13.7: Properties of forecasts from AR(1) process

Since the best guess of  $\varepsilon_{t+1}$  is that it is zero, the best forecast and the associated forecast error are

$$E_t y_{t+1} = ay_t, \text{ and} \quad (13.25)$$

$$y_{t+1} - E_t y_{t+1} = \varepsilon_{t+1} \text{ with variance } \sigma^2. \quad (13.26)$$

We may also want to forecast  $y_{t+2}$  using the information in  $t$ . To do that note that (13.12) gives

$$\begin{aligned} y_{t+2} &= ay_{t+1} + \varepsilon_{t+2} \\ &= a(\underbrace{ay_t + \varepsilon_{t+1}}_{y_{t+1}}) + \varepsilon_{t+2} \\ &= a^2 y_t + a\varepsilon_{t+1} + \varepsilon_{t+2}. \end{aligned} \quad (13.27)$$

Since the  $E_t \varepsilon_{t+1}$  and  $E_t \varepsilon_{t+2}$  are both zero and  $\text{Cov}(\varepsilon_{t+1}, \varepsilon_{t+2}) = 0$  we get that

$$E_t y_{t+2} = a^2 y_t, \text{ and} \quad (13.28)$$

$$y_{t+2} - E_t y_{t+2} = a\varepsilon_{t+1} + \varepsilon_{t+2} \text{ with variance } a^2\sigma^2 + \sigma^2. \quad (13.29)$$

More generally, we have

$$E_t y_{t+s} = a^s y_t, \quad (13.30)$$

$$\text{Var}(y_{t+s} - E_t y_{t+s}) = (1 + a^2 + a^4 + \dots + a^{2(s-1)})\sigma^2 \quad (13.31)$$

$$= \frac{a^{2s} - 1}{a^2 - 1}\sigma^2. \quad (13.32)$$

Notice that the point forecast converges towards zero and the variance of the forecast error variance to the unconditional variance (see Example 13.6).

**Example 13.8** If  $y_t = 3$ ,  $a = 0.85$  and  $\sigma = 0.5$ , then the forecasts and the forecast error variances become

Horizon $s$	$E_t y_{t+s}$	$\text{Var}(y_{t+s} - E_t y_{t+s})$
1	$0.85 \times 3 = 2.55$	0.25
2	$0.85^2 \times 3 = 2.17$	$(0.85^2 + 1) \times 0.5^2 = 0.43$
25	$0.85^{25} \times 3 = 0.05$	$\frac{0.85^{50}-1}{0.85^2-1} \times 0.5^2 = 0.90$

To calculate the forecasts, you could alternatively apply a simple *recursive approach* like

$$E_t y_{t+1} = a y_t \quad (13.33)$$

$$E_t y_{t+2} = a E_t y_{t+1} \quad (13.34)$$

and so forth. We will later use the same principle for more complicated AR models.

If the shocks  $\varepsilon_t$  are normally distributed, then we can calculate 90% confidence intervals around the point forecasts in (13.25) and (13.28) as

$$90\% \text{ confidence band of } E_t y_{t+1} : a y_t \pm 1.64 \times \sigma \quad (13.35)$$

$$90\% \text{ confidence band of } E_t y_{t+2} : a^2 y_t \pm 1.64 \times \sqrt{a^2\sigma^2 + \sigma^2}. \quad (13.36)$$

(Recall that 90% of the probability mass is within the interval  $-1.64$  to  $1.64$  in the  $N(0,1)$  distribution). To get 95% confidence bands, replace 1.64 by 1.96. See Figures 13.6–13.7 for illustrations.

**Example 13.9** Continuing Example 13.8, we get the following 90% confidence bands

<u>Horizon <math>s</math></u>	
1	$2.55 \pm 1.64 \times \sqrt{0.25} \approx [1.7, 3.4]$
2	$2.17 \pm 1.64 \times \sqrt{0.43} \approx [1.1, 3.2]$
25	$0.05 \pm 1.64 \times \sqrt{0.90} \approx [-1.5, 1.6]$

**Remark 13.10** (White noise as special case of AR(1).) When  $a = 0$  in (13.12), then the AR(1) collapses to a white noise process. The forecast is then a constant (zero) for all forecasting horizons, see (13.30), and the forecast error variance is also the same for all horizons, see (13.32).

### 13.4.3 Adding a Constant to the AR(1)

The discussion of the AR(1) worked with a zero mean variable, but that was just for convenience (to make the equations shorter). One way to work with a variable  $x_t$  with a non-zero mean, is to first estimate its sample mean  $\bar{x}$  and then let the  $y_t$  in the AR(1) model (13.12) be a demeaned variable  $y_t = x_t - \bar{x}$ .

To include a mean,  $\mu$ , in the theoretical expressions, we just need to substitute  $x_t - \mu$  for  $y_t$  everywhere. For instance, in (13.12) we would get

$$\begin{aligned} x_t - \mu &= a(x_{t-1} - \mu) + \varepsilon_t \text{ or} \\ x_t &= (1 - a)\mu + ax_{t-1} + \varepsilon_t. \end{aligned} \tag{13.37}$$

Estimation by LS will therefore give an intercept that equals  $(1 - a)\mu$  and a slope coefficient that equals  $a$ .

## 13.5 AR(p)

The  $p$ th-order autoregressive process, AR(p), is a straightforward extension of the AR(1)

$$y_t = a_1 y_{t-1} + a_2 y_{t-2} + \dots + a_p y_{t-p} + \varepsilon_t. \tag{13.38}$$

The AR(p) can capture richer dynamics than the AR(1). See Figure 13.4 for an illustration of impulse response functions.

This process can also be estimated with OLS since  $\varepsilon_t$  is uncorrelated with lags of  $y_t$ . Adding a constant to the theoretical expressions is straightforward: substitute  $x_t - \mu$  for  $y_t$  everywhere.

**Remark 13.11** (*Stationarity of an AR( $p$ ) model\**) To investigate if the AR( $p$ ) model is stationary (the impulse responses converge to zero), rewrite it on vector form (also called “companion form”) as

$$\begin{bmatrix} y_t \\ y_{t-1} \\ \vdots \\ y_{t-p} \end{bmatrix} = \begin{bmatrix} a_1 & a_2 & \cdots & a_p \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} y_{t-1} \\ y_{t-2} \\ \vdots \\ y_{t-p-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_t \\ 0 \\ 0 \\ 0 \end{bmatrix}.$$

Calculate the eigenvalues ( $\lambda_i$  for  $i = 1, \dots, p$ ) of the (companion) matrix on the right hand side. If  $|\lambda_i| < 1$  for all  $i$ , then the model is stationary. Basically, this means that the model is “stable” in the sense that the effect of a shock eventually dies out.

### 13.5.1 Partial Autocorrelations

The  $p$ th partial autocorrelation tries to measure the direct relation between  $y_t$  and  $y_{t-p}$ , where the indirect effects of  $y_{t-1}, \dots, y_{t-p+1}$  are eliminated. That is,

$$\text{partial autocorrelation}(s) = \text{Corr}(y_t - \hat{y}_t, y_{t-s} - \hat{y}_{t-s}), \quad (13.39)$$

where  $\hat{y}_t$  and  $\hat{y}_{t-s}$  are the best (linear) estimates of  $y_t$  and  $y_{t-s}$  based on  $(y_{t-1}, \dots, y_{t-s+1})$ . Yes, the “regressors” are the same in both regressions.

**Example 13.12** (*The 3rd partial autocorrelation coefficient*) Regress

$$\begin{aligned} y_t &= a_0 + a_1 y_{t-1} + a_2 y_{t-2} + \varepsilon_t \\ y_{t-3} &= b_0 + b_1 y_{t-1} + b_2 y_{t-2} + u_{t-3}. \end{aligned}$$

The third partial autocorrelation coefficient is then  $\text{Corr}(\hat{\varepsilon}_t, \hat{u}_{t-3})$ .

For instance, if  $y_t$  is generated by an AR(1) model, then the 2nd autocorrelation is  $a^2$ , whereas the 2nd partial autocorrelation is zero (since  $y_{t-2}$  does not have any direct effect on  $y_t$  once you have controlled for  $y_{t-1}$ ). The partial autocorrelation is therefore a way to gauge how many lags that are needed in an AR( $p$ ) model.

In practice, the first partial autocorrelation is estimated by  $a$  in an AR(1)

$$y_t = \underline{a} y_{t-1} + \varepsilon_t. \quad (13.40)$$

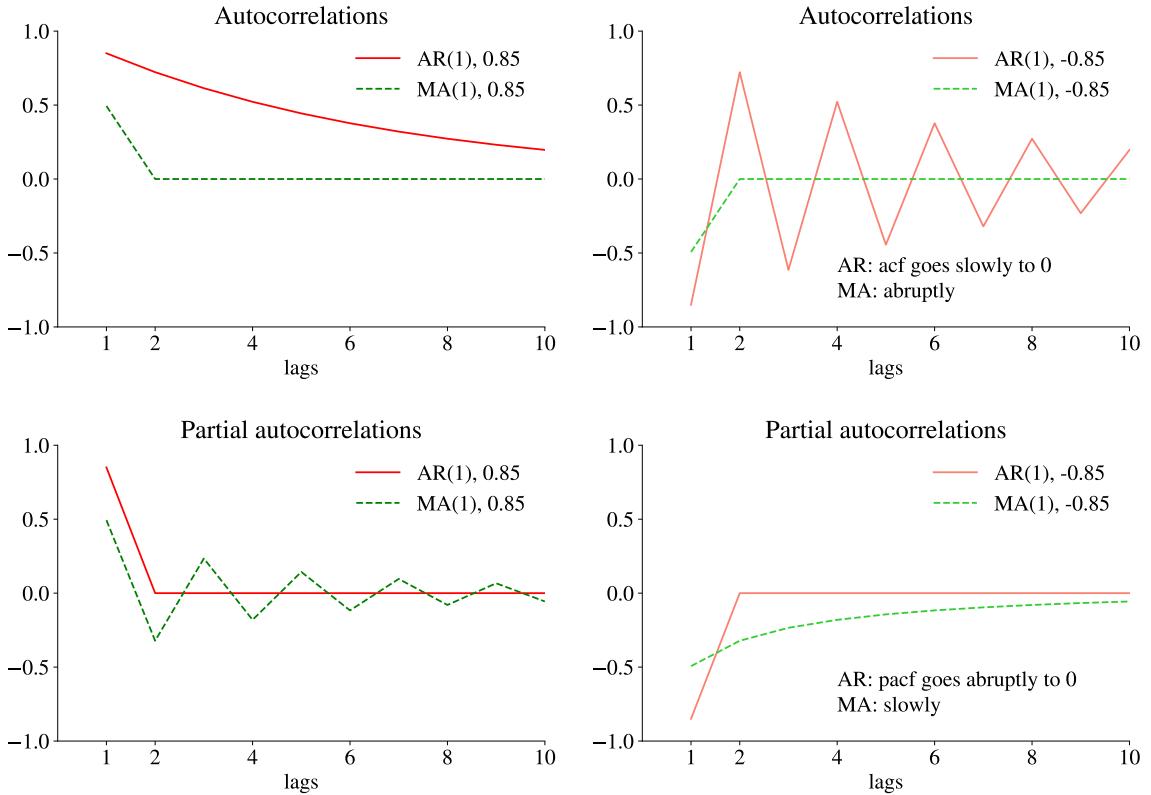


Figure 13.8: Autocorrelations and partial autocorrelations

This gives the same result as following the definition in (13.39). The second partial autocorrelation is estimated by the second slope coefficient ( $a_2$ ) in an AR(2)

$$y_t = a_1 y_{t-1} + \underline{a_2} y_{t-2} + \varepsilon_t, \quad (13.41)$$

and so forth. The general pattern is that the  $p$ th partial autocorrelation is estimated by the slope coefficient of the  $p$ th lag in an AR( $p$ ), where we let  $p$  first be 1, then 2, and then 3, and so forth. See Figure 13.8 for an illustration.

To choose a model, study the ACF and PACF—and check that residual are close to white noise (or at least not strongly autocorrelated). To avoid overfitting, try “punishing” models with many parameters. Akaike’s Information Criterion (AIC) and the Bayesian

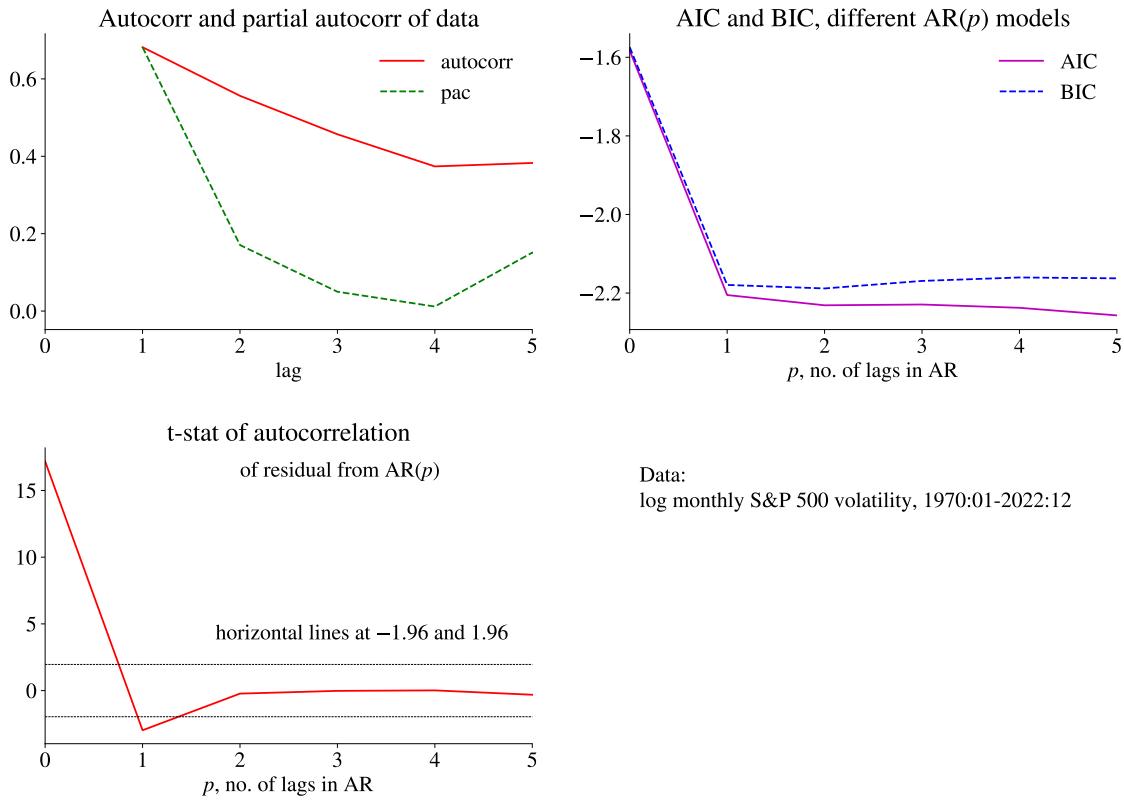


Figure 13.9: Example of choosing lag length in an AR model

information criterion (BIC) are

$$AIC = \ln \hat{\sigma}^2 + 2 \frac{p+1}{T} \quad (13.42)$$

$$BIC = \ln \hat{\sigma}^2 + \frac{p+1}{T} \ln T, \quad (13.43)$$

where  $\hat{\sigma}^2$  is the variance of the fitted residuals. Choose the model with the lowest AIC or BIC. (Notice, however, that AIC often exaggerates the lag length.) This provides a trade-off between fit (low  $\hat{\sigma}^2$ ) and number of parameters ( $p+1$ ). See Figure 13.9 for an empirical illustration.

### 13.5.2 Forecasting with an AR( $p$ )

As an example, consider making a forecast of  $y_{t+1}$  based on the information in  $t$  by using an AR(2)

$$y_{t+1} = a_1 y_t + a_2 y_{t-1} + \varepsilon_{t+1}. \quad (13.44)$$

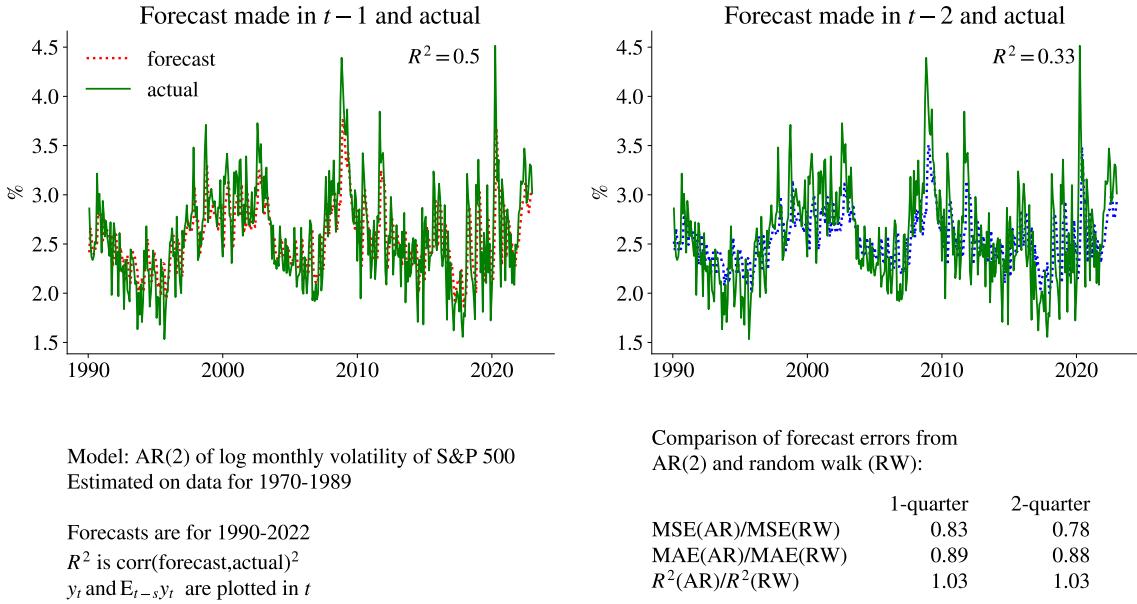


Figure 13.10: Forecasting with an AR(2)

This immediately gives the one-period point forecast

$$E_t y_{t+1} = a_1 y_t + a_2 y_{t-1}. \quad (13.45)$$

The two-period forecast is then calculated recursively as

$$E_t y_{t+2} = a_1 E_t y_{t+1} + a_2 y_t. \quad (13.46)$$

**Empirical Example 13.13** (*AR(2) results for realized volatility of S&P 500 returns*) Figure 13.10 shows results for monthly volatility of the S&P 500.

**Example 13.14** (*Forecasts*) With  $(a_1, a_2) = (0.85, -0.5)$  and  $(y_t, y_{t-1}) = (3, 1)$  we get

$$E_t y_{t+1} = 0.85 \times 3 - 0.5 \times 1 = 2.05,$$

$$E_t y_{t+2} = 0.85 \times 2.05 - 0.5 \times 3 = 0.24.$$

The calculations of the forecasting error variance is straightforward, but somewhat messy. However, both the one-period and two-period forecasts are linear functions of  $y_t$  and  $y_{t-1}$ . We could therefore estimate the following two equations with OLS

$$y_{t+1} = a_1 y_t + a_2 y_{t-1} + \varepsilon_{t+1}$$

$$y_{t+2} = b_1 y_t + b_2 y_{t-1} + v_{t+2}.$$

This will give results that are very similar to (13.45)–(13.46). (Asymptotically, the results will be the same.) The variances of  $\varepsilon_{t+1}$  and  $v_{t+2}$  are also very similar to the theoretical results.

### 13.5.3 Autoregressions versus Autocorrelations\*

It is straightforward to see the relation between autocorrelations and the AR model. This relation is given by the *Yule-Walker equations*. For instance, for an AR(1), the autoregression coefficient is simply the first autocorrelation coefficient. For higher-order process, the transformation is non-linear, but testing if all the autocorrelations are zero is essentially the same as testing if all the autoregressive coefficients are zero.

To illustrate the Yule-Walker equations, consider an AR(2)

$$y_t = a_1 y_{t-1} + a_2 y_{t-2} + \varepsilon_t. \quad (13.47)$$

Clearly, the covariance of  $y_t$  and  $y_{t-s}$  must be the same as the covariance between the right hand side of (13.47) and  $y_{t-s}$

$$\begin{aligned} \text{Cov}(y_t, y_{t-s}) &= \text{Cov}(a_1 y_{t-1} + a_2 y_{t-2} + \varepsilon_t, y_{t-s}) \\ &= a_1 \text{Cov}(y_{t-1}, y_{t-s}) + a_2 \text{Cov}(y_{t-2}, y_{t-s}) + \text{Cov}(\varepsilon_t, y_{t-s}). \end{aligned}$$

Applying this on  $s = 1, 2$  (and replacing  $\text{Cov}(y_t, y_{t-s})$  and  $\text{Cov}(y_{t-s}, y_t)$  by  $\gamma_s$  etc) gives

$$\begin{aligned} \gamma_1 &= a_1 \gamma_0 + a_2 \gamma_1 \\ \gamma_2 &= a_1 \gamma_1 + a_2 \gamma_0, \end{aligned} \quad (13.48)$$

provided  $\text{Cov}(\varepsilon_t, y_{t-1}) = 0$  and  $\text{Cov}(\varepsilon_t, y_{t-2}) = 0$ . This holds in (at least) two settings: when  $y_t$  is truly an AR(2) process *or* when we have estimated (13.47) by OLS (since it creates fitted residuals that uncorrelated with the regressors).

With information on the autocovariances ( $\gamma_0, \gamma_1, \gamma_2$ ) we can solve these equations for the autoregression parameters ( $a_1, a_2$ ). To see how, rewrite (13.48) as

$$\begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix} = \begin{bmatrix} \gamma_0 & \gamma_1 \\ \gamma_1 & \gamma_0 \end{bmatrix} \begin{bmatrix} a_1 \\ a_2 \end{bmatrix}, \quad (13.49)$$

which we can solve for  $(a_1, a_2)$  as

$$\begin{bmatrix} a_1 \\ a_2 \end{bmatrix} = \begin{bmatrix} \gamma_0 & \gamma_1 \\ \gamma_1 & \gamma_0 \end{bmatrix}^{-1} \begin{bmatrix} \gamma_1 \\ \gamma_2 \end{bmatrix}. \quad (13.50)$$

Notice that dividing both sides of (13.49) by  $\gamma_0$  would not change the solution of  $(a_1, a_2)$ . This means that  $\gamma_i$  could effectively be either autocovariances or autocorrelations (in the latter case,  $\gamma_0 = 1$ ).

With  $p$  autocovariances (instead of 2) we get

$$\begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_p \end{bmatrix} = \begin{bmatrix} \gamma_0 & \gamma_1 & \cdots & \gamma_{p-1} \\ \gamma_1 & \gamma_0 & \cdots & \gamma_{p-2} \\ \vdots & \vdots & \ddots & \vdots \\ \gamma_{p-1} & \gamma_{p-2} & \cdots & \gamma_0 \end{bmatrix}^{-1} \begin{bmatrix} \gamma_1 \\ \gamma_2 \\ \vdots \\ \gamma_p \end{bmatrix}. \quad (13.51)$$

This also provides a mechanism for calculating the partial autocorrelations ( $a_p$  for  $p = 1, 2, 3, \dots$ ) from the autocovariances. First, set  $p = 1$  in (13.51) to find the AR(1) coefficient (which will be  $a_1 = \gamma_1/\gamma_0$ ). Second, set  $p = 2$  and solve to find  $a_2$ . Third, set  $p = 3$  and solve to find  $a_3$  and so forth.

## 13.6 Moving Average (MA)

A  $q^{th}$ -order moving average process MA( $q$ ) is

$$y_t = \varepsilon_t + \theta_1 \varepsilon_{t-1} + \dots + \theta_q \varepsilon_{t-q}, \quad (13.52)$$

where the innovation  $\varepsilon_t$  is white noise (usually Gaussian). It is straightforward to add a constant to capture a non-zero mean. If the order of the MA is finite ( $q < \infty$ ), then the MA model is stationary.

The *impulse response function* of an MA( $q$ ) is simply the MA coefficients  $(1, \theta_1, \dots, \theta_q)$ . It can show many different patterns, but they are all 0 at horizons beyond  $q$ . See Figure 13.4 for an illustration.

**Remark 13.15** (*Impulse response function\**) For instance, write out (13.52) for  $y_t, y_{t+1}, \dots$

$$\begin{aligned}y_t &= \underline{\varepsilon}_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2} + \dots \\y_{t+1} &= \varepsilon_{t+1} + \theta_1 \underline{\varepsilon}_t + \theta_2 \varepsilon_{t-1} + \dots \\y_{t+2} &= \varepsilon_{t+2} + \theta_1 \varepsilon_{t+1} + \theta_2 \underline{\varepsilon}_t + \dots,\end{aligned}$$

which shows that the dynamic effect of  $\varepsilon_t = 1$  is  $(1, \theta_1, \theta_2, \dots)$ .

Estimation of an MA processes is typically done by *maximum likelihood*. LS does not work at all since the right hand side variables are unobservable. This is one reason why MA models play a limited role in applied work. Moreover, most MA models can be well approximated by an AR model of low order.

**Remark 13.16** (*MLE of an MA(1)*) The MA(1) is  $y_t = \varepsilon_t + \theta \varepsilon_{t-1}$ . Assume that  $\varepsilon_0 = 0$ , so you can calculate  $\varepsilon_1 = y_1$  and  $\varepsilon_t = y_t - \theta \varepsilon_{t-1}$  for  $t \geq 2$ . If  $\varepsilon_t \sim N(0, \sigma^2)$ , then the log-likelihood function for  $T$  observations is  $-\ln(2\pi)T/2 - \ln(\sigma^2)T/2 - \sum_{t=1}^T \varepsilon_t^2/(2\sigma^2)$ . This is maximized with respect to  $\theta$  and  $\sigma^2$  (or  $\sigma$ ). Clearly, the  $\varepsilon_t$  series must be recalculated in each iteration (as  $\theta$  changes).

**Remark 13.17** (*MLE of an MA(2)\**) The MA(2) is  $y_t = \varepsilon_t + \theta_1 \varepsilon_{t-1} + \theta_2 \varepsilon_{t-2}$ . Assume that  $(\varepsilon_{-1}, \varepsilon_0) = (0, 0)$ . Calculate  $\varepsilon_1 = y_1$ ,  $\varepsilon_2 = y_2 - \theta_1 \varepsilon_1$ , and  $\varepsilon_t = y_t - \theta_1 \varepsilon_{t-1} - \theta_2 \varepsilon_{t-2}$  for  $t \geq 3$ . It can be noticed that  $\varepsilon_t$  is an AR(2) where  $y_t$  is the “shock” and the autoregressive coefficients are  $(-\theta_1, -\theta_2)$ . Once we have a series of fitted residuals, use them in the likelihood function as for an MA(1). Consequently, this estimation approach only works if  $(-\theta_1, -\theta_2)$  defines a stationary AR(2). Otherwise, more sophisticated methods are needed.

Equation (13.53) shows that when  $\theta > 0$ , then autoregression coefficients converge in a zigzag way to zero. In contrast, when  $\theta < 0$ , the convergence is monotonic. This pattern can help us to distinguish a true AR process from an MA process. The autocorrelations and partial autocorrelations (for different lags) can help us gauge if the time series *looks more like an AR or an MA*. In an AR( $p$ ) model, the autocorrelations decay to zero for long lags, while the  $p + 1$  partial autocorrelation (and beyond) goes abruptly to zero. The reverse is true for an MA model. See Figure 13.8 for an illustration.

This distinction between AR and MA is most clear for low-order models (for instance, an AR(2) and an MA(3)), but it can be blurred for high-order models. The reason is that

we can often rewrite (“invert”) an  $\text{MA}(q)$  as an  $\text{AR}(\infty)$ , and vice versa. For instance, if  $|\theta| < 1$  then the  $\text{MA}(1)$  can be written

$$y_t = \theta y_{t-1} - \theta^2 y_{t-2} + \theta^3 y_{t-3} + \dots + \varepsilon_t. \quad (13.53)$$

**Proof.** (\*of (13.53)) Notice that  $\varepsilon_t = y_t - \theta \varepsilon_{t-1}$ . Substitute for  $\varepsilon_{t-1}$  by using  $y_{t-1} - \theta \varepsilon_{t-2}$ , to get  $\varepsilon_t = y_t - \theta y_{t-1} + \theta^2 \varepsilon_{t-2}$ . Keep substituting and notice that the  $\theta^s \varepsilon_{t-s}$  goes to zero as  $s$  goes to infinity (provided  $|\theta| < 1$ ). Rearrange as (13.53). ■

## 13.7 ARMA(p,q)

When the autocorrelations and partial autocorrelations show mixed patterns, then a combination of AR and MA models might be appropriate.

Autoregressive-moving average (ARMA) models add a moving average structure to an AR model. For instance, an  $\text{ARMA}(2,1)$  is

$$y_t = a_1 y_{t-1} + a_2 y_{t-2} + \varepsilon_t + \theta \varepsilon_{t-1}, \quad (13.54)$$

where  $\varepsilon_t$  is white noise. (It is straightforward to add a constant to capture a non-zero mean.) If the AR part of the ARMA is stationary, then the whole ARMA model is (since MA models are stationary). In an ARMA model, both the autocorrelations and partial autocorrelations decay to slowly zero. ARMA models can generate complicated dynamics. See Figure 13.4 for impulse response functions.

ARMA are harder to estimate than the autoregressive model, and we typically use *MLE*. The appropriate specification of the model (number of lags of  $y_t$  and  $\varepsilon_t$ ) is often unknown. The Box-Jenkins methodology is a set of guidelines for arriving at the correct specification by starting with some model, study the autocorrelation structure of the fitted residuals and then changing the model.

**Remark 13.18** (*MLE of an ARMA(2,1)\**) Assume  $\varepsilon_0 = 0$  and calculate  $\varepsilon_1 = y_1 - a_1 y_0 - a_2 y_{-1}$  and  $\varepsilon_t = y_t - a_1 y_{t-1} - a_2 y_{t-2} - \theta \varepsilon_{t-1}$  for  $t \geq 2$ . Use in the likelihood function  $-\ln(2\pi)T/2 - \ln(\sigma^2)T/2 - \sum_{t=1}^T \varepsilon_t^2/(2\sigma^2)$  and maximize with respect to  $(a_1, a_2, \theta, \sigma^2)$ . As usual, the  $\varepsilon_t$  series must be recalculated for every new guess of the parameter vector.

Most ARMA models can be well approximated by an AR model—provided we add some extra lags. Since AR models are so simple to estimate, this approximation approach is often used.

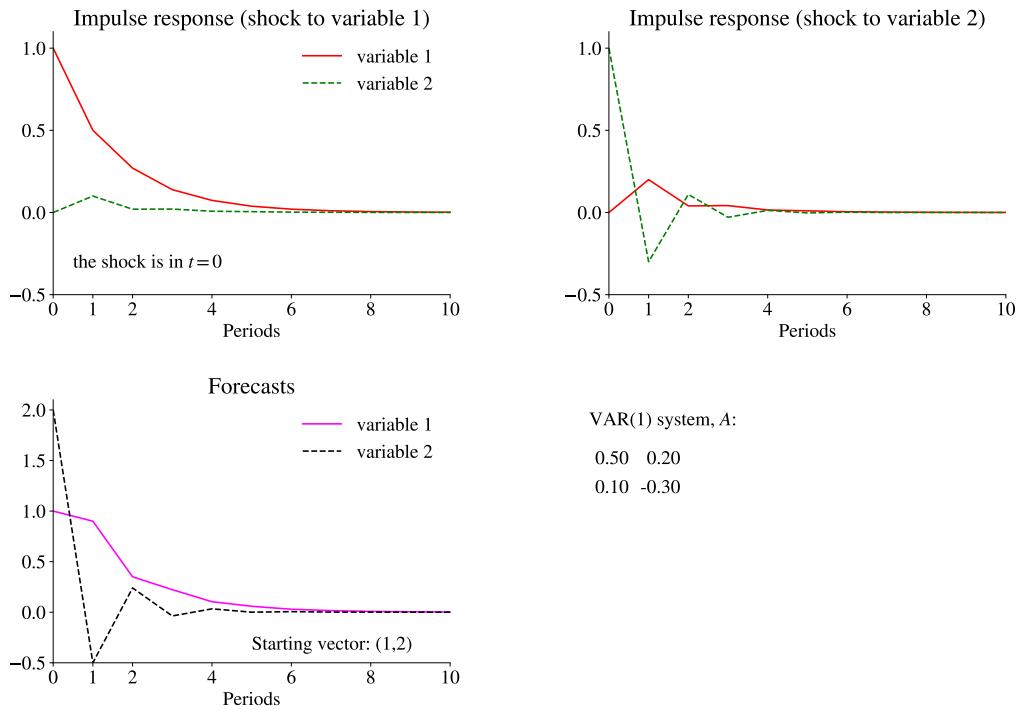


Figure 13.11: Properties of a VAR(1) model

### 13.8 VAR( $p$ )

Let  $y_t$  be an  $n \times 1$  vector of variables. The VAR( $p$ ) is

$$y_t = \mu + A_1 y_{t-1} + \dots + A_p y_{t-p} + \varepsilon_t, \quad (13.55)$$

where  $A_1, \dots, A_p$  are  $n \times n$  matrices and  $\varepsilon_t$  is an  $n \times 1$  vector of shocks. The vector autoregression is a multivariate version of an AR process: we can think of  $y_t$  and  $\varepsilon_t$  in (13.38) as vectors and the  $a_i$  as matrices.

To gauge the dynamics we can calculate the *impulse response function* of (all the  $n$  elements of)  $y_t$  to a shock to the 1st element of the  $n \times 1$  vector  $\varepsilon_0$  (set element 1 of  $\varepsilon_0$  equal to one, but all other elements equal to zero). Then, we redo the same exercise, but now with respect to the 2nd element of  $\varepsilon_0$ , and so on. In this way we get the response of each element of  $y_t$  with respect to each element of  $\varepsilon_0$ . See Figure 13.11 for an illustration. It suggests that a low-order VAR model (here a VAR(1)) can create more complicated dynamics than a low-order AR model.

For instance the VAR(1) of two variables ( $x_t$  and  $z_t$ ) is (in matrix form)

$$\begin{bmatrix} x_t \\ z_t \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} x_{t-1} \\ z_{t-1} \end{bmatrix} + \begin{bmatrix} \varepsilon_{xt} \\ \varepsilon_{zt} \end{bmatrix}, \quad (13.56)$$

or equivalently

$$x_t = A_{11}x_{t-1} + A_{12}z_{t-1} + \varepsilon_{xt}, \text{ and} \quad (13.57)$$

$$z_t = A_{21}x_{t-1} + A_{22}z_{t-1} + \varepsilon_{zt}. \quad (13.58)$$

Both (13.57) and (13.58) are regression equations, which can be *estimated with OLS* (since  $\varepsilon_{xt}$  and  $\varepsilon_{zt}$  are uncorrelated with  $x_{t-1}$  and  $z_{t-1}$ ).

**Example 13.19** (VAR(1) of 2 variables). Let the  $A$  matrix in (13.56) be

$$A = \begin{bmatrix} 0.5 & 0.2 \\ 0.1 & -0.3 \end{bmatrix}.$$

**Remark 13.20** (Stationarity\*) The VAR(1) is stationary if the  $a$  matrix in (13.56) has  $|\lambda_i| < 1$  where  $\lambda_i$  are the eigenvalues. For instance, for the 2-variable VAR(1) in Example 13.19 we get  $(|\lambda_1|, |\lambda_2|) \approx (0.52, 0.32)$ .

With the information available in  $t$ , that is, information about  $x_t$  and  $z_t$ , (13.57) and (13.58) can be used to forecast one- and two-step ahead as

$$\begin{bmatrix} E_t x_{t+1} \\ E_t z_{t+1} \end{bmatrix} = A \begin{bmatrix} x_t \\ z_t \end{bmatrix} \text{ and} \quad (13.59)$$

$$\begin{bmatrix} E_t x_{t+2} \\ E_t z_{t+2} \end{bmatrix} = A \begin{bmatrix} E_t x_{t+1} \\ E_t z_{t+1} \end{bmatrix} = AA \begin{bmatrix} x_t \\ z_t \end{bmatrix}, \quad (13.60)$$

where  $AA$  is the matrix product of  $A$  and  $A$ .

The two-period forecast has the same form as the one-period forecast, but with other coefficients. Note that all we need to make the forecasts (for both  $t + 1$  and  $t + 2$ ) are the values in period  $t$  ( $x_t$  and  $z_t$ ). This follows from that (13.56) is a first-order system where the values of  $x_t$  and  $z_t$  summarize all relevant information about the future that is available in  $t$ .

**Example 13.21** (Forecasts from a VAR(1)) With the 2-variable VAR(1) in Example 13.19

and the initial values  $(x_0, z_0) = (1, 2)$  we get

$$\begin{bmatrix} E_0 x_1 \\ E_0 z_1 \end{bmatrix} = \begin{bmatrix} 0.5 & 0.2 \\ 0.1 & -0.3 \end{bmatrix} \begin{bmatrix} 1 \\ 2 \end{bmatrix} = \begin{bmatrix} 0.9 \\ -0.5 \end{bmatrix} \text{ and}$$

$$\begin{bmatrix} E_0 x_2 \\ E_0 z_2 \end{bmatrix} = \begin{bmatrix} 0.5 & 0.2 \\ 0.1 & -0.3 \end{bmatrix} \begin{bmatrix} 0.9 \\ -0.5 \end{bmatrix} = \begin{bmatrix} 0.35 \\ 0.24 \end{bmatrix}.$$

The forecast uncertainty about the one-period forecast is simple: the forecast error  $x_{t+1} - E_t x_{t+1} = \varepsilon_{xt+1}$ . The two-period forecast error,  $x_{t+2} - E_t x_{t+2}$ , is a linear combination of  $\varepsilon_{xt+1}$ ,  $\varepsilon_{zt+1}$ , and  $\varepsilon_{xt+2}$ . The calculations of the forecasting error variance (as well as for the forecasts themselves) quickly get messy. This is even more true when the VAR system is of a higher order.

As for the AR( $p$ ) model, a practical way to get around the problem with complicated calculations is to estimate a separate model for each forecasting horizon. In a large sample, the difference between the two ways is trivial. For instance, suppose the correct model is the VAR(1) in (13.56) and that we want to forecast  $x$  one and two periods ahead. From (13.59) and (13.60) we see that the regression equations should be of the form

$$x_{t+1} = \delta_1 x_t + \delta_2 z_t + u_{t+1}, \text{ and} \quad (13.61)$$

$$x_{t+2} = \gamma_1 x_t + \gamma_2 z_t + w_{t+s}. \quad (13.62)$$

With estimated coefficients (OLS can be used), it is straightforward to calculate forecasts and forecast error variances.

**Remark 13.22** (*Local projections\**) Similar to the logic of different regressions for different forecasting horizons (for instance, (13.62)) we could also estimate the impulse response function by “local projections.” In practice, it means estimating

$$x_{t+s} = a + B_{1,s} x_t + \dots + B_{p,s} x_{t-s+1} + u_{t+s}$$

repeatedly (for  $s = 1, 2, \dots$ ) and recording the  $B_{1,s}$  estimates. The impulse response matrices are  $B_{1,1}$ ,  $B_{1,2}$ , etc.

**Example 13.23** (VAR(2) of  $2 \times 1$  vector.) Let  $y_t = (x_t, y_t)$ . Then a VAR(2) is

$$\begin{bmatrix} x_t \\ z_t \end{bmatrix} = \begin{bmatrix} A_{1,11} & A_{1,12} \\ A_{1,21} & A_{1,22} \end{bmatrix} \begin{bmatrix} x_{t-1} \\ z_{t-1} \end{bmatrix} + \begin{bmatrix} A_{2,11} & A_{2,12} \\ A_{2,21} & A_{2,22} \end{bmatrix} \begin{bmatrix} x_{t-2} \\ z_{t-2} \end{bmatrix} + \begin{bmatrix} \varepsilon_{xt} \\ \varepsilon_{zt} \end{bmatrix}.$$

**Remark 13.24** (*Stationarity of a VAR( $p$ ) model\**) Construct the companion matrix as for the AR( $p$ ), but recall that  $a_i$  are matrices and replace the ones (1) with  $I_n$  where  $n$  indicates the number of variables in the VAR system. Then, the model is stationary if  $|\lambda_i| < 1$  where  $\lambda_i$  are the eigenvalues of the companion matrix. For instance, for 2-variable VAR(2) in Remark 13.23 we get ) Continuing on the previous example, we get

$$\begin{bmatrix} A_{1,11} & A_{1,11} & A_{2,11} & A_{2,12} \\ A_{1,21} & A_{1,22} & A_{2,21} & A_{2,22} \\ 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

### 13.8.1 Granger Causality

If  $z_t$  can help predict future  $x$ , over and above what lags of  $x$  itself can, then  $z$  is said to *Granger Cause*  $x$ . This is a statistical notion of causality, and may not necessarily have much to do with true causality (for instance, Christmas cards may Granger cause Christmas). In (13.61)  $z$  does Granger cause  $x$  if  $\delta_2 \neq 0$ , which is easily tested. More generally, there may be more lags of both  $x$  and  $z$  in the equation, so we need to test if all coefficients on different lags of  $z$  are zero.

## 13.9 Non-stationary Processes

### 13.9.1 Introduction

A *trend-stationary process* has a (deterministic) trend. The simplest example is

$$y_t = \mu + \beta t + \varepsilon_t \quad (13.63)$$

where  $\varepsilon_t$  is white noise. It can be made stationary by subtracting the linear trend

$$y_t - \beta t = \mu + \varepsilon_t. \quad (13.64)$$

We can typically apply all standard econometric methods on this de-trended data. This can be done in two steps: first estimate the trend and then use  $y_t - \hat{\beta}t$  in the subsequent analysis. Alternatively, we can work also with the  $y_t$  series directly, provided we explicitly include a trend variable in the analysis (say, in the regression model).

A *unit root process* has a (random) trend. The simplest example is the *random walk*

with drift

$$y_t = \mu + y_{t-1} + \varepsilon_t, \quad (13.65)$$

where  $\varepsilon_t$  is white noise. The name “unit root process” comes from the fact that the largest eigenvalues of the companion form (the VAR(1) form of the AR( $p$ )) is one. Such a process is said to be integrated of order one, denoted I(1). Most standard statistical econometric methods fail on such data. However, the process can be made stationary by taking first differences

$$y_t - y_{t-1} = \mu + \varepsilon_t. \quad (13.66)$$

Standard methods can readily be applied to  $y_t - y_{t-1}$ . This is one (of several) reasons why financial econometrics study asset returns (not prices).

**Example 13.25** (*Non-stationary AR(2)*) *The process  $y_t = 1.5y_{t-1} - 0.5y_{t-2} + \varepsilon_t$  can be written*

$$\begin{bmatrix} y_t \\ y_{t-1} \end{bmatrix} = \begin{bmatrix} 1.5 & -0.5 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} y_{t-1} \\ y_{t-2} \end{bmatrix} + \begin{bmatrix} \varepsilon_t \\ 0 \end{bmatrix},$$

where the matrix has the eigenvalues 1 and 0.5 and is therefore non-stationary. Note that subtracting  $y_{t-1}$  from both sides gives  $y_t - y_{t-1} = 0.5(y_{t-1} - y_{t-2}) + \varepsilon_t$ , so the variable  $x_t = y_t - y_{t-1}$  is stationary.

The distinguishing feature of unit root processes is that the effect of a shock never vanishes, that is, the impulse response function does not converge to zero. This is most easily seen for the random walk. Substitute repeatedly in (13.65) to get

$$\begin{aligned} y_t &= \mu + (\mu + y_{t-2} + \varepsilon_{t-1}) + \varepsilon_t \\ &\vdots \\ &= t\mu + y_0 + \sum_{s=1}^t \varepsilon_s. \end{aligned} \quad (13.67)$$

The effect of  $\varepsilon_t$  never dies out: a non-zero value of  $\varepsilon_t$  gives a permanent shift of the level of  $y_t$ . This process is clearly non-stationary. See Figure 13.12 for an illustration.

A consequence of the permanent effect of a shock is that the variance of the forecast error grows without bound as the forecasting horizon is extended. For instance, for the random walk with drift, (13.67), the distribution conditional on the information in  $t = 0$  is  $N(y_0 + t\mu, s\sigma^2)$  if the innovations are normally distributed. This means that the expected change is  $t\mu$  and that the conditional variance grows linearly with the forecasting horizon.

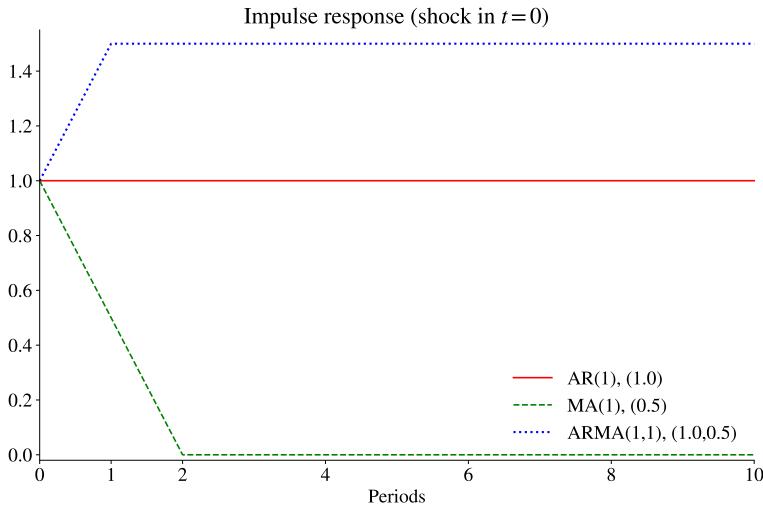


Figure 13.12: Impulse responses

The unconditional variance is therefore infinite and the standard results on inference are not applicable. See Figure 13.13.

A process could have two unit roots (integrated of order 2: I(2)). In this case, we need to difference twice to make it stationary. Alternatively, a process can also be explosive, that is, have eigenvalues outside the unit circle. In this case, the impulse response function diverges—and this type of data is very difficult to analyse with traditional statistical methods.

**Example 13.26** (*Two unit roots\**) Suppose  $y_t$  in Example (13.25) is actually the first difference of some other series,  $y_t = z_t - z_{t-1}$ . We then have

$$\begin{aligned} z_t - z_{t-1} &= 1.5(z_{t-1} - z_{t-2}) - 0.5(z_{t-2} - z_{t-3}) + \varepsilon_t \\ z_t &= 2.5z_{t-1} - 2z_{t-2} + 0.5z_{t-3} + \varepsilon_t, \end{aligned}$$

which is an AR(3) with the following canonical form

$$\begin{bmatrix} z_t \\ z_{t-1} \\ z_{t-2} \end{bmatrix} = \begin{bmatrix} 2.5 & -2 & 0.5 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} \begin{bmatrix} z_{t-1} \\ z_{t-2} \\ z_{t-3} \end{bmatrix} + \begin{bmatrix} \varepsilon_t \\ 0 \\ 0 \end{bmatrix}.$$

The eigenvalues are 1, 1, and 0.5, so  $z_t$  has two unit roots (integrated of order 2: I(2) and needs to be differenced twice to become stationary).

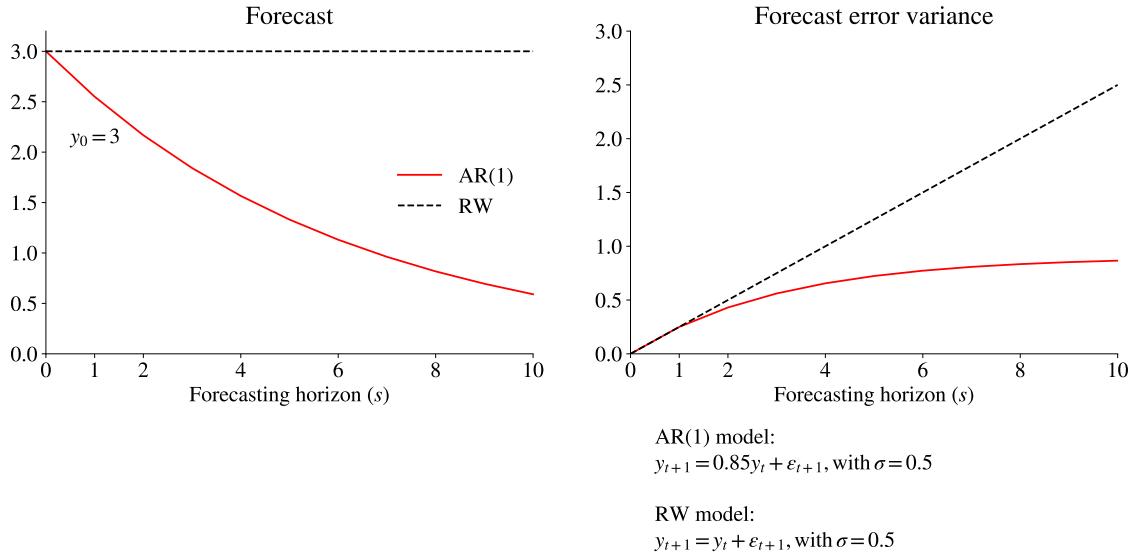


Figure 13.13: Properties of forecasts from random walk process

**Example 13.27** (Explosive AR(1).) Consider the process  $y_t = 1.5y_{t-1} + \varepsilon_t$ . The eigenvalue is then outside the unit circle, so the process is explosive. This means that the impulse response to a shock to  $\varepsilon_t$  diverges (it is  $1.5^s$  for  $s$  periods ahead).

**Remark 13.28** (Lag operator\*) A common and convenient way of dealing with leads and lags is the lag operator,  $L$ . It is such that

$$L^s y_t = y_{t-s}$$

For instance, the AR(1) model

$$\begin{aligned} y_t &= \theta \underbrace{y_{t-1}}_{Ly_t} + \varepsilon_t, \text{ or} \\ (1 - \theta L) y_t &= \varepsilon_t, \text{ or} \\ \theta(L) y_t &= \varepsilon_t, \end{aligned}$$

where  $\theta(L) = (1 - \theta L)$  is a lag polynomial. Similarly, an ARMA(2,1) can be written

$$\begin{aligned} y_t - \theta_1 y_{t-1} - \theta_2 y_{t-2} &= \varepsilon_t + \alpha_1 \varepsilon_{t-1} \\ (1 - \theta_1 L - \theta_2 L^2) y_t &= (1 + \alpha_1 L) \varepsilon_t. \end{aligned}$$

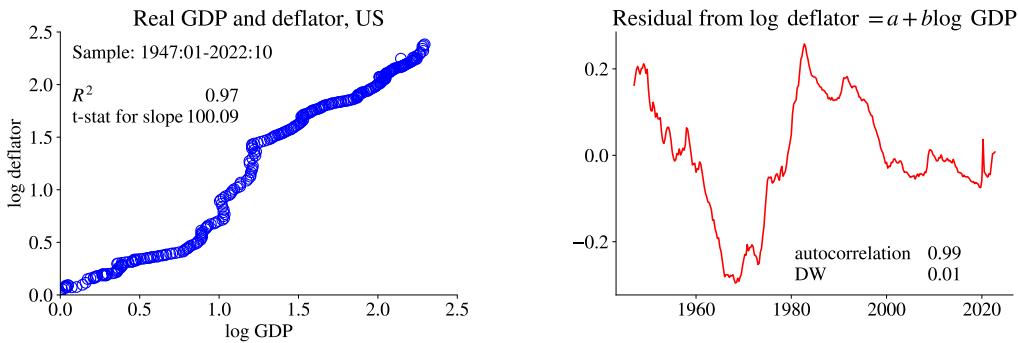


Figure 13.14: Example of a spurious regression

### 13.9.2 Spurious Regressions

Strong trends often causes problems in econometric models where  $y_t$  is regressed on  $x_t$ . In essence, if no trend is included in the regression, then  $x_t$  will appear to be significant, just because it is a proxy for that trend. The same holds for unit root processes, even if they have no deterministic trends. The reason is that the innovations accumulate and the series therefore tend to be trending in small samples. A warning sign of a spurious regression is when  $R^2 > DW$  statistic.

**Empirical Example 13.29** (*Regressing the price level on GDP*) See Figure 13.14 for results from regressing the U.S. price level (GDP deflator) on output (GDP level). The results indicate a very significant regression slope, but extreme autocorrelation. This is likely to be a spurious regression. Also, economics would suggest that nominal (price level) and real variables (output) variables are driven by completely different factors.

See Figures 13.15–13.18 for a Monte Carlo simulation.

For trend-stationary data, this problem is easily solved by detrending with a linear trend (before estimating or just adding a trend to the regression).

However, this is usually a poor method for a unit root processes. What is needed is a first difference. For instance, a first difference of the random walk with drift is

$$\begin{aligned}\Delta y_t &= y_t - y_{t-1} \\ &= \mu + \varepsilon_t,\end{aligned}\tag{13.68}$$

which is white noise (any finite difference, like  $y_t - y_{t-s}$ , will give a stationary series), so we could proceed by applying standard econometric tools to  $\Delta y_t$ .

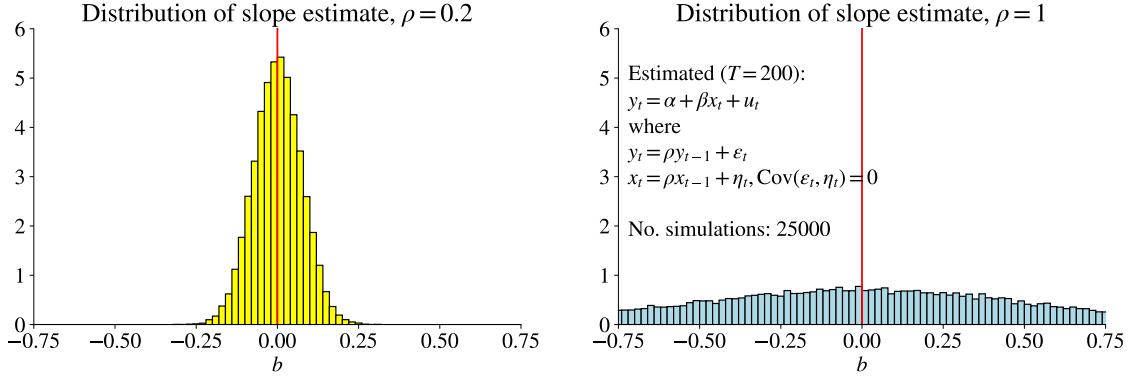


Figure 13.15: Distribution of slope coefficient when  $y_t$  and  $x_t$  are independent AR(1) processes

One may then be tempted to try first-differencing all non-stationary series, since it may be hard to tell if they are unit root process or just trend-stationary. For instance, a first difference of the trend stationary process, (13.63), gives

$$y_t - y_{t-1} = \beta + \varepsilon_t - \varepsilon_{t-1}. \quad (13.69)$$

Its unclear if this is an improvement: the trend is gone, but the errors are now of MA(1) type, which means that they are autocorrelated.

### 13.9.3 Testing for a Unit Root

Suppose we run an OLS regression of

$$y_t = ay_{t-1} + \varepsilon_t, \quad (13.70)$$

where the true value of  $|a| < 1$ . The asymptotic distribution of the LS estimator is

$$\sqrt{T}(\hat{a} - a) \sim N(0, 1 - a^2). \quad (13.71)$$

(The variance follows from the standard OLS formula where the variance of the estimator is  $\sigma^2 (\Sigma_{t=1}^T x_t x_t' / T)^{-1}$ . Here  $\text{plim } \Sigma_{t=1}^T x_t x_t' / T = \text{Var}(y_t)$  which we know is  $\sigma^2 / (1 - a^2)$ ).

It is well known (but not easy to show) that when  $a = 1$ , then  $\hat{a}$  is biased towards zero in small samples. In addition, the asymptotic distribution is no longer (13.71). In fact, there is a discontinuity in the limiting distribution as we move from a stationary to

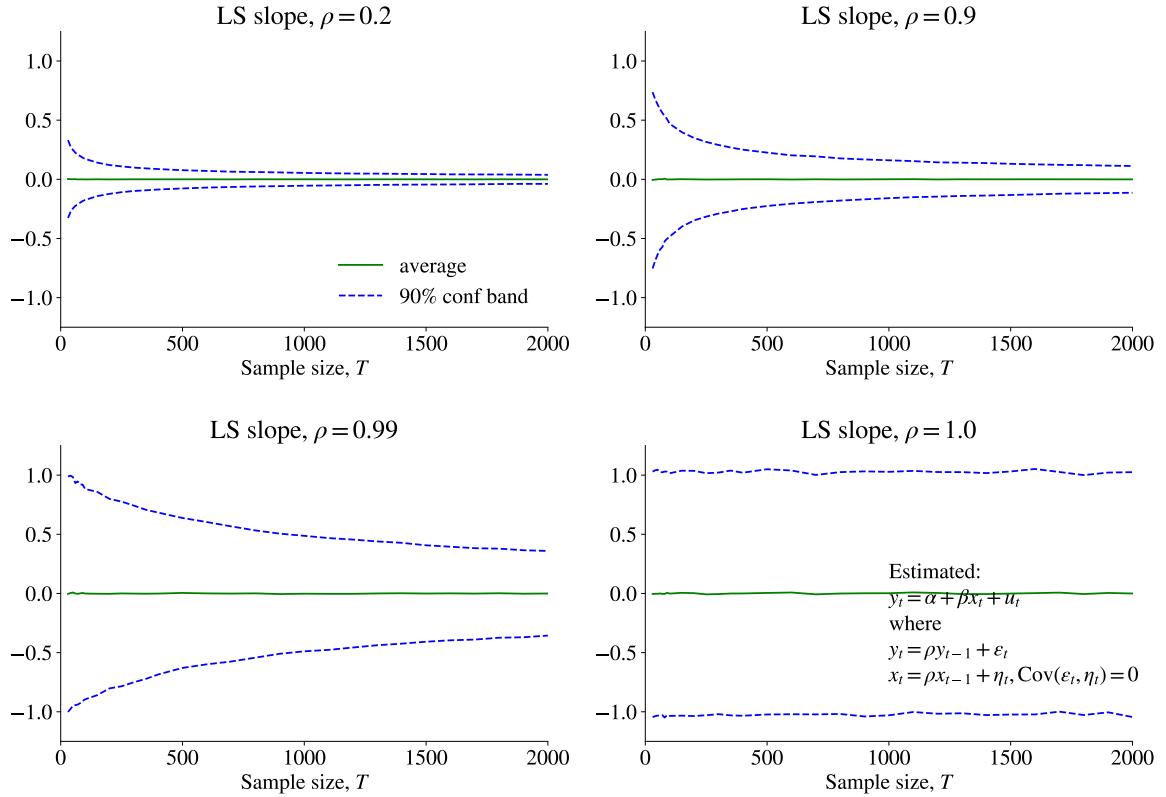


Figure 13.16: Distribution of slope coefficient when  $y_t$  and  $x_t$  are independent AR(1) processes

a non-stationary variable. This, together with the small sample bias means that we have to use simulated critical values for testing the null hypothesis of  $a = 1$  based on the OLS estimate from (13.70).

In practice, the approach is to run the regression (13.70) with a constant (and perhaps even a time trend), calculate the test statistic

$$DF = \frac{\hat{a} - 1}{\text{Std}(\hat{a})}, \quad (13.72)$$

and reject *the null of non-stationarity* if  $DF$  is less than the critical values published by Dickey and Fuller (-2.86 at the 5% level if the regression has a constant, and -3.41 if the regression includes a trend).

With more dynamics (to capture any serial correlation in  $\varepsilon_t$  in (13.70)), do an *aug-*

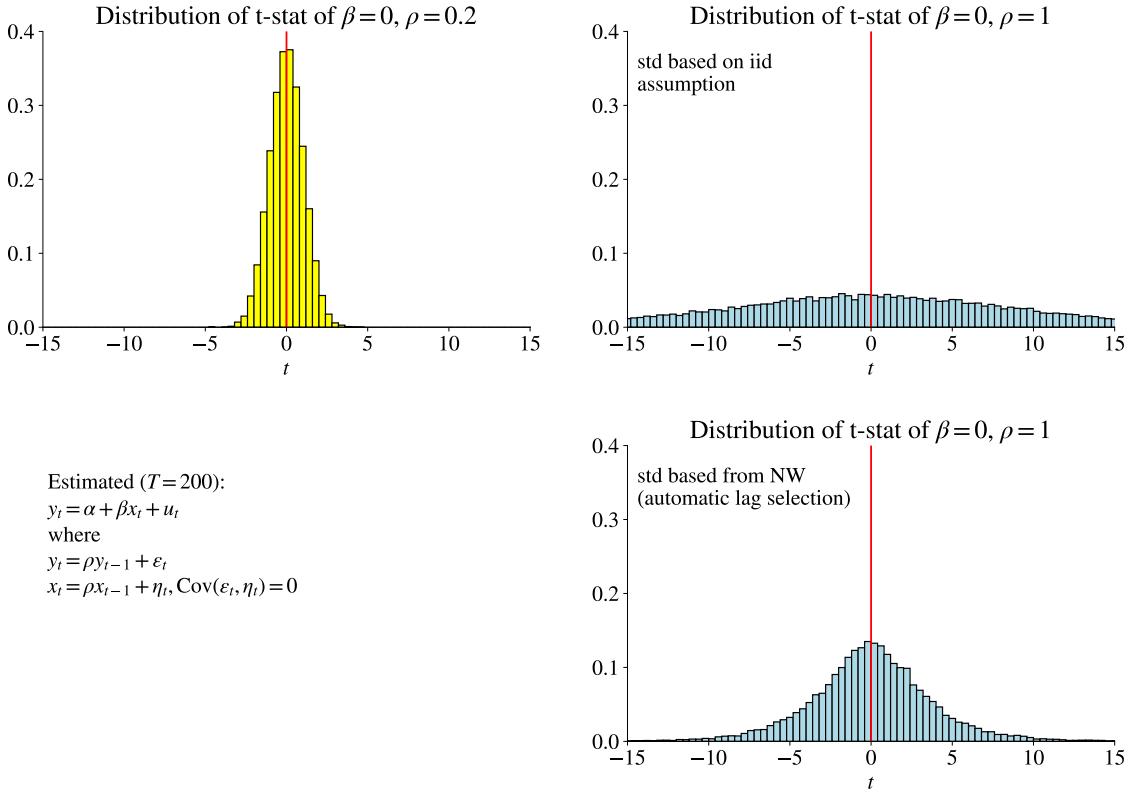


Figure 13.17: Distribution of the t-statistic when  $y_t$  and  $x_t$  are independent AR(1) processes. See Figure 13.15.

mented Dickey-Fuller test (ADF)

$$y_t = \delta + \theta_1 y_{t-1} + \theta_2 y_{t-2} + \varepsilon_{2t}, \text{ or}$$

$$\Delta y_t = \delta + (\theta_1 + \theta_2 - 1) y_{t-1} - \theta_2 \Delta y_{t-1} + \varepsilon_{2t}, \quad (13.73)$$

and test the coefficient on  $y_{t-1}$  in (13.73) (which should equal  $\theta_1 + \theta_2 - 1$ ) against the alternative that it is less than zero. The critical values are as for the DF test. If  $\varepsilon_{2t}$  is autocorrelated, then add further lags of  $\Delta y$ .

The KPSS test has stationarity as the null hypothesis (in contrast to the DF and ADF tests that have non-stationarity as the null hypothesis). It has three steps. First, regress

$$y_t = a + \varepsilon_t. \quad (13.74)$$

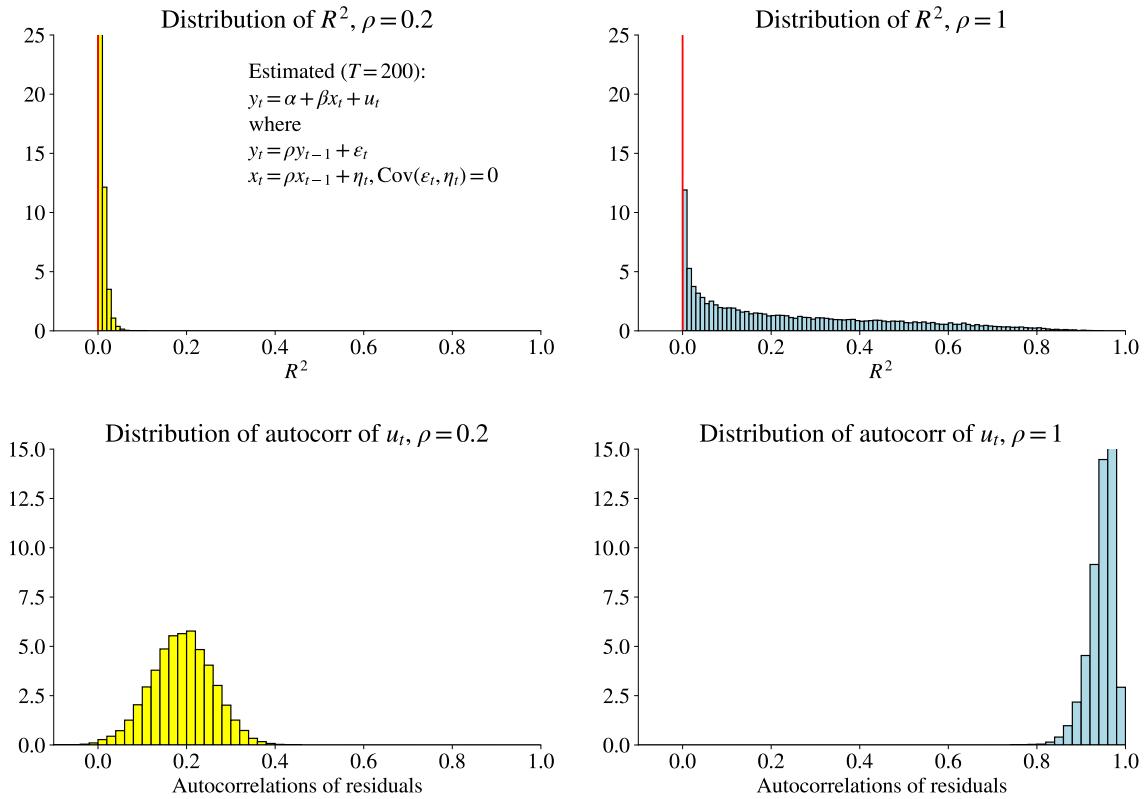


Figure 13.18: Distribution of  $R^2$  and autocorrelation of residuals. See Figure 13.15.

Second, define

$$S_t = \sum_{s=1}^t \hat{\varepsilon}_s \text{ for } t = 1, \dots, T \text{ and} \quad (13.75)$$

$$\hat{\sigma}^2 = \text{Var}(\hat{\varepsilon}_t). \quad (13.76)$$

Third, the test statistic is

$$KPSS = \frac{1}{T^2} \sum_{t=1}^T S_t^2 / \hat{\sigma}^2 \quad (13.77)$$

Reject stationarity if  $KPSS > 0.463$  (a 5% critical value). We could also include a linear trend in (13.74). The 5% critical value is then 0.146.

In principle, distinguishing between a stationary and a non-stationary series is very difficult (and impossible unless we restrict the class of processes, for instance, to an AR(2)), since any sample from a non-stationary process can be arbitrary well approximated by *some* stationary process et vice versa. The lesson to be learned, from a practical point of view, is that *strong persistence in the data generating process* (stationary or not)

*invalidates the usual results on inference.* We are usually on safer ground to apply the unit root results in this case, even if the process is actually stationary.

### 13.9.4 Cointegration\*

An exception to the “spurious regression” result:  $Y_t$  and  $X_t$  are I(1) but share a common stochastic trend such that

$$y_t - \alpha - \beta x_t \text{ is I}(0). \quad (13.78)$$

In this case, OLS works fine: it is actually very good (super consistent),  $\hat{\beta}$  converges to true value  $\beta$  faster than in standard theory. The intuition is that if  $\hat{\beta} \neq \beta$ , then  $\varepsilon_t$  are I(1) and therefore have high sample variance: OLS will pick  $\hat{\beta}$  close to  $\beta$ .

In (13.78), we call  $(1, -\beta)$  the *cointegrating vector*, since

$$\begin{bmatrix} 1 & -\beta \end{bmatrix} \begin{bmatrix} y_t \\ x_t \end{bmatrix} \text{ is I}(0) \quad (13.79)$$

**Example 13.30**  $Y_t$  is GDP,  $x_t$  is private consumption. Suppose both are driven by the non-stationary productivity of the economy,  $A_t$ , plus other stationary stuff ( $z_t, w_t$ )

$$\begin{aligned} y_t &= \gamma A_t + z_t \\ x_t &= \delta A_t + w_t \end{aligned}$$

From the second equation  $A_t = (x_t - w_t)/\delta$ , use in first equation

$$\underbrace{y_t}_{I(1)} = \frac{\gamma}{\delta} \underbrace{x_t}_{I(1)} + z_t - \underbrace{\frac{\gamma}{\delta} w_t}_{I(0)}$$

To test if  $y_t$  and  $x_t$  are cointegrated, we need to study three things. First, does it make sense? Look at data, and consider the (economic) theory. Second, are both  $x_t$  and  $y_t$  I(I)? Do Dickey-Fuller tests, etc. Third, are  $(\hat{a}, \hat{b})$  in from the regression

$$y_t = a + b x_t + \varepsilon_t \quad (13.80)$$

such that  $\hat{\varepsilon}_t$  is I(0)? To determine the latter, do an ADF test on  $\hat{\varepsilon}_t$ , but use special critical values— $H_0$ : no cointegration (so  $\varepsilon_t$  is I(1)). 5% critical values:  $-3.34$  (if  $x_t$  is a scalar).

One way to incorporate the cointegration in a model of the short-run dynamics is to

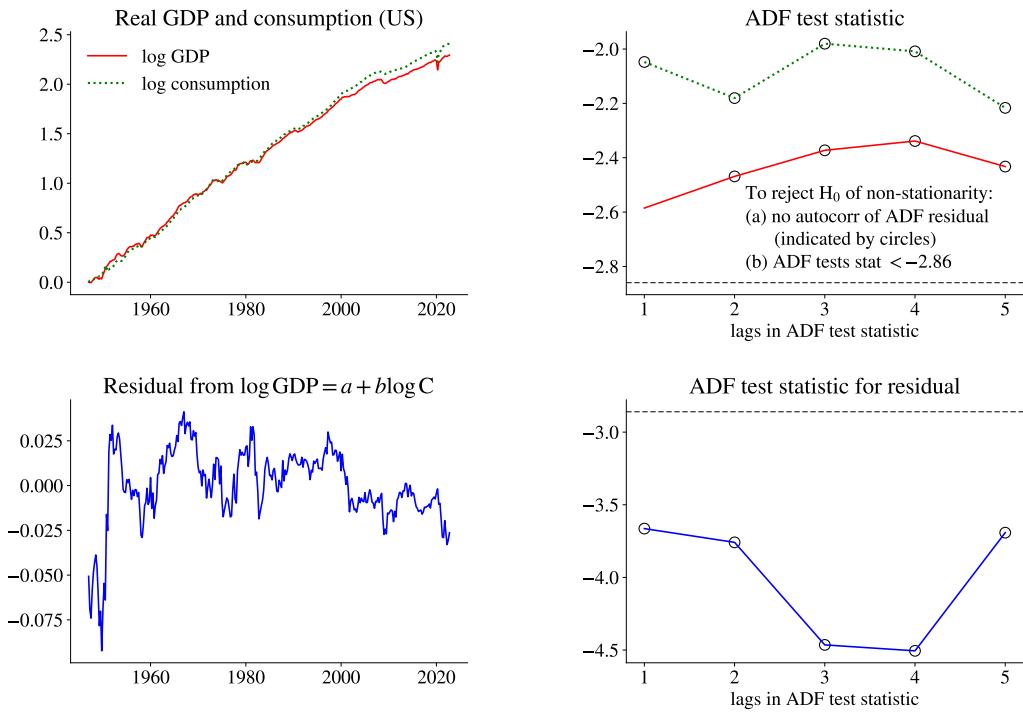


Figure 13.19: Unit root tests, US quarterly macro data

use a *Error-Correction Model*, for instance,

$$\begin{aligned}\Delta y_t &= \delta - \gamma (y_{t-1} - \beta x_{t-1}) + \phi_1 \Delta x_{t-1} + \varepsilon_t \text{ or perhaps} \\ &= \delta - \gamma (y_{t-1} - \beta x_{t-1}) + \phi_1 \Delta x_{t-1} + \theta_1 \Delta y_{t-1} + \varepsilon_t\end{aligned}\quad (13.81)$$

Recall:  $(y_t, x_t)$  are I(1), but  $y_{t-1} - \beta x_{t-1}$  is I(0), so all terms in (13.81) are I(0). We typically do not put the intercept into the cointegrating relation (as there is already another intercept in the equation).

If  $\gamma > 0$  (notice the sign convention in (13.81)), then the system is driven back to a stationary path for  $y - \beta x$ : the “error correction mechanism.” If  $\varepsilon_t$  is autocorrelated, then we add more lags of both  $\Delta y$  and  $\Delta x$ .

Estimation is fairly straightforward (Engle-Granger’s 2-step method). First, estimate the cointegrating vector. Second, use it in (13.81) and estimate the rest of the parameters. Standard tests can be applied to them.

**Empirical Example 13.31** (*Cointegration and error correction model of output and consumption*) See Figure 13.19 and Table 13.1.

	(1)
constant	0.01 (1.86)
Coint res <sub>t-1</sub>	-0.08 (-2.17)
$\Delta \text{gdp}_{t-1}$	0.07 (0.75)
$\Delta c_{t-1}$	0.05 (0.23)
$\Delta \text{gdp}_{t-2}$	0.10 (1.11)
$\Delta c_{t-2}$	0.05 (0.44)
$R^2$	0.05
obs	301

Table 13.1: Error-correction model for log real US GDP growth, 1947:01-2022:10. Numbers in parentheses are t-stats. The Coint res is the residual from regressing the log GDP level on the log consumption level.

# Chapter 14

## Predicting Asset Returns

Reference (medium): Elton, Gruber, Brown, and Goetzmann (2010) 17 (efficient markets) and 26 (earnings estimation)

Additional references: Campbell, Lo, and MacKinlay (1997) 2 and 7; Cochrane (2001) 20.1

More advanced material is denoted by a star (\*). It is not required reading.

### 14.1 Autocorrelations and Autoregressions

#### 14.1.1 Autocorrelation Coefficients

When the true autocorrelations are all zero (not  $\rho_0$ , of course), then for any  $i$  and  $j$  different from zero

$$\sqrt{T} \begin{bmatrix} \hat{\rho}_i \\ \hat{\rho}_j \end{bmatrix} \xrightarrow{d} N \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \right). \quad (14.1)$$

This result can be used to construct tests for both single autocorrelations (t-test or  $\chi^2$  test) and several autocorrelations at once ( $\chi^2$  test).

**Empirical Example 14.1** (*Autocorrelations for different lags, daily equity returns*) See Figure 14.1 for autocorrelations (different lags) of S&P 500 returns. The figure suggests little autocorrelation in returns ( $R_t^e$ ), but considerable autocorrelation for the absolute value ( $|R_t^e|$ ). Since,  $R_t^e = \text{sign}(R_t^e)|R_t^e|$ , this suggests that it is very difficult to predict the sign of the returns. Also, see Figure 14.2 for ten size-sorted equity portfolios which suggests that most size categories have more autocorrelations than large cap (which are fairly closer to S&P 500).

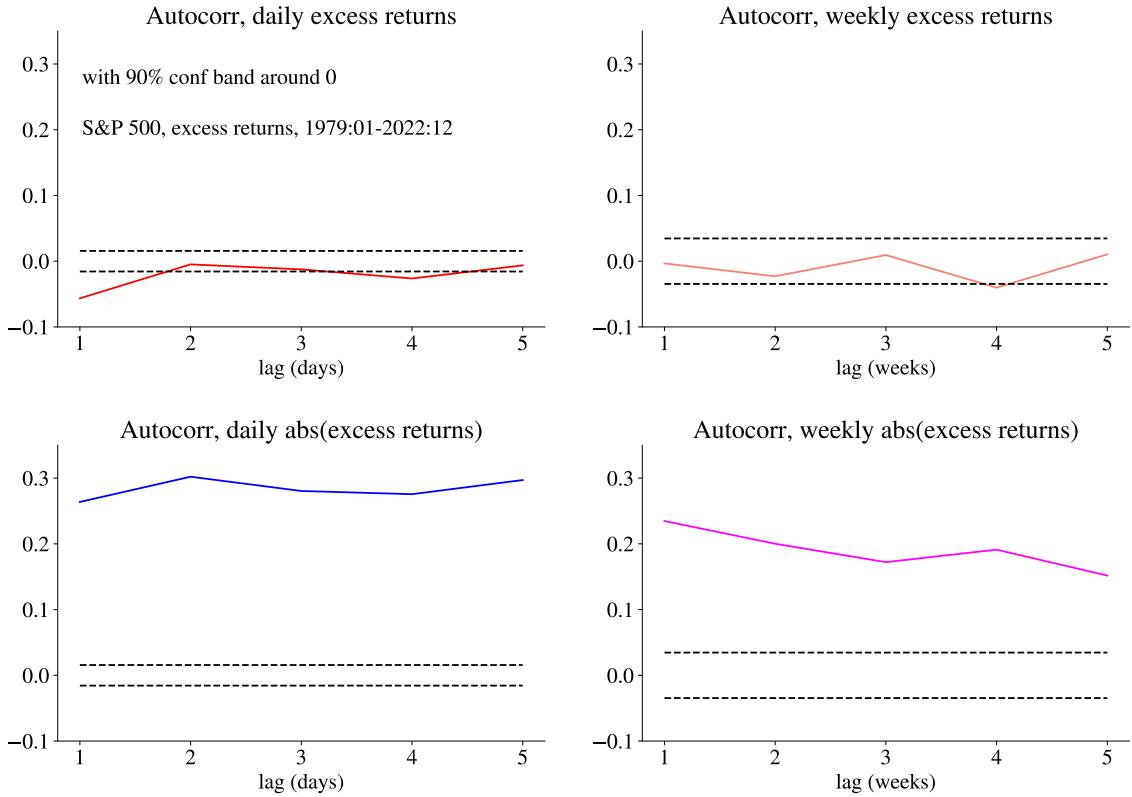


Figure 14.1: Predictability of daily US stock returns

#### 14.1.2 Autoregressions

An alternative way of testing autocorrelations is to estimate an AR model

$$y_t = c + a_1 y_{t-1} + a_2 y_{t-2} + \dots + a_p y_{t-p} + \varepsilon_t, \quad (14.2)$$

and then test if all slope coefficients ( $a_1, a_2, \dots, a_p$ ) are zero with a  $\chi^2$  or  $F$  test. This approach is somewhat less general than the Box-Pierce test, but most stationary time series processes can be well approximated by an AR of relatively low order.

**Empirical Example 14.2** (*AR(1) and asymmetric AR(1) for daily S&P 500 returns*) See [Figure 14.3](#).

**Empirical Example 14.3** (*AR(1) for long run equity returns*) See [Figure 14.4](#) for AR(1) results for different (long) investment horizons.

The autoregression can also allow for the coefficients to depend on the market situation. For instance, consider an AR(1), but where the autoregression coefficient may be

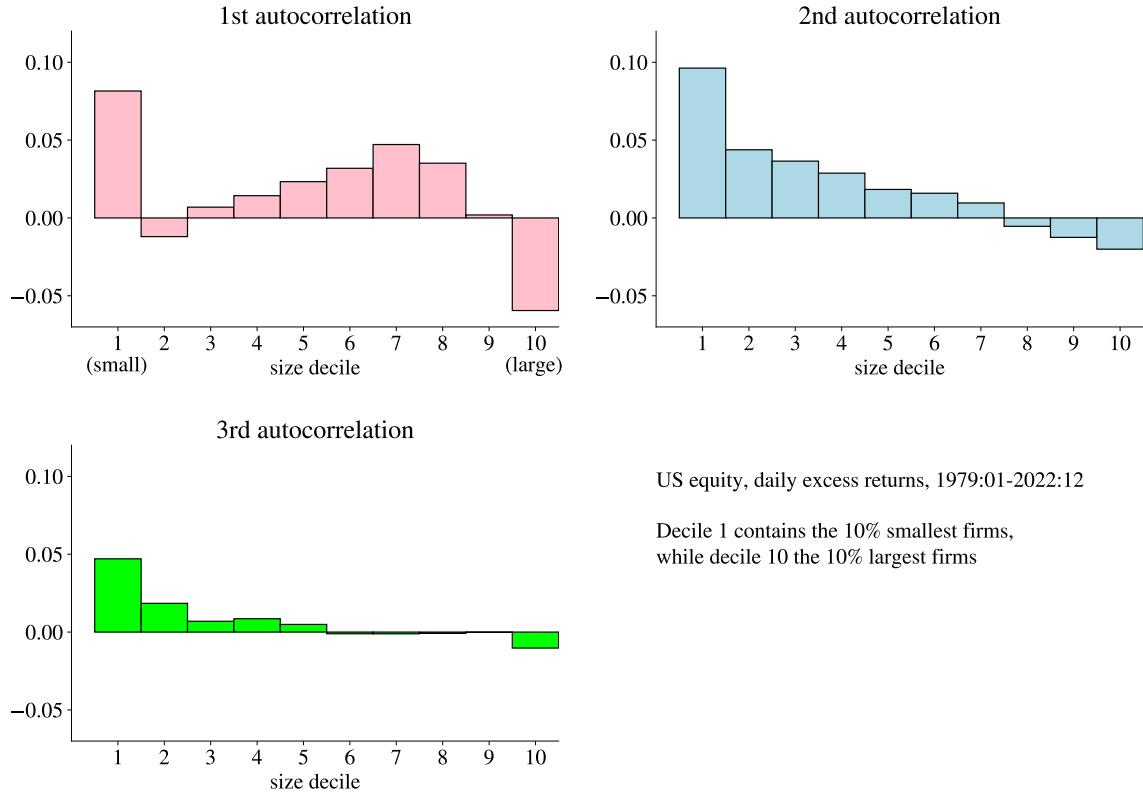


Figure 14.2: Predictability of daily US stock returns, size deciles

different depending on the sign of last period's return

$$y_t = \alpha + \beta Q_{t-1} y_{t-1} + \gamma(1 - Q_{t-1}) y_{t-1} + \varepsilon_t, \text{ where} \quad (14.3)$$

$$Q_{t-1} = \begin{cases} 1 & \text{if } y_{t-1} < 0 \\ 0 & \text{else.} \end{cases}$$

See Figure 14.3 for an illustration.

Inference of the slope coefficient in autoregressions on returns for longer data horizons than the data frequency (for instance, analysis of weekly returns in a data set consisting of daily observations) must be done with care. If only non-overlapping returns are used (for instance, the weekly returns recorded on Wednesdays only), the standard LS expression for the standard deviation of the autoregressive parameter is likely to be reasonable. This is not the case if overlapping returns (all daily data on weekly returns) are used.

**Remark 14.4** (*Overlapping returns\**) Consider an AR(1) for the two-period return,  $y_{t-1} +$

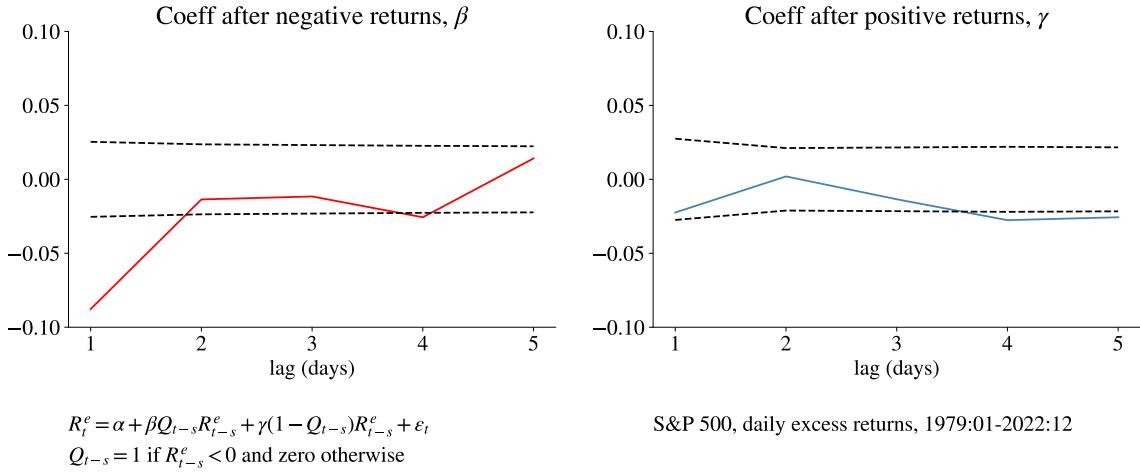


Figure 14.3: Predictability of daily US stock returns, symmetric and asymmetric AR(1)

$y_t$

$$y_{t+1} + y_{t+2} = a + b_2 (y_{t-1} + y_t) + \varepsilon_{t+2}.$$

Two successive observations with non-overlapping returns are then

$$\begin{aligned} y_{t+1} + y_{t+2} &= a + b_2 (y_{t-1} + y_t) + \varepsilon_{t+2} \\ y_{t+3} + y_{t+4} &= a + b_2 (y_{t+1} + y_{t+2}) + \varepsilon_{t+4}. \end{aligned}$$

Suppose that  $y_t$  is not autocorrelated, so the slope coefficient  $b_2 = 0$ . We can then write the residuals as

$$\begin{aligned} \varepsilon_{t+2} &= -a + y_{t+1} + y_{t+2} \\ \varepsilon_{t+4} &= -a + y_{t+3} + y_{t+4}, \end{aligned}$$

which are uncorrelated. Compare this to the case where we use overlapping data. Two successive observations are then

$$\begin{aligned} y_{t+1} + y_{t+2} &= a + b_2 (y_{t-1} + y_t) + \varepsilon_{t+2} \\ y_{t+2} + y_{t+3} &= a + b_2 (y_t + y_{t+1}) + \varepsilon_{t+3}. \end{aligned}$$

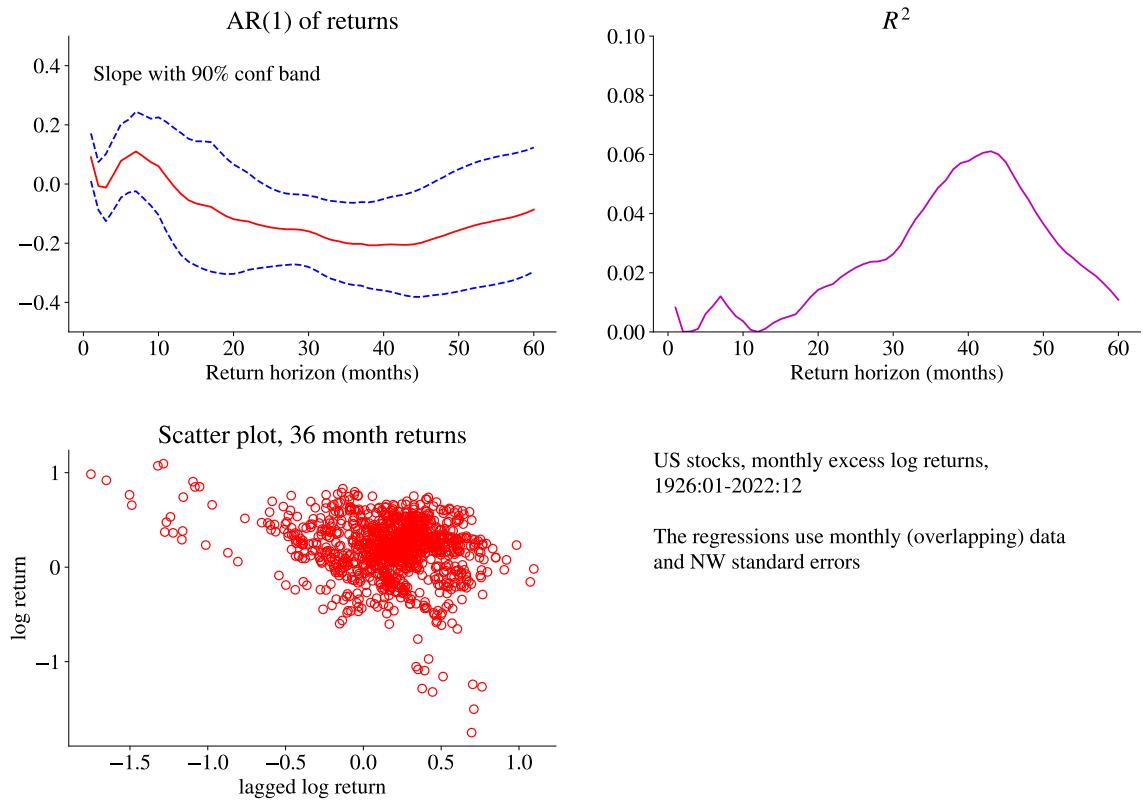


Figure 14.4: Predictability of long run US stock returns

As before,  $b_2 = 0$  if  $y_t$  has no autocorrelation, so the residuals become

$$\begin{aligned}\varepsilon_{t+2} &= -a + y_{t+1} + y_{t+2} \\ \varepsilon_{t+3} &= -a + y_{t+2} + y_{t+3},\end{aligned}$$

which are correlated since  $y_{t+2}$  shows up in both. This demonstrates that overlapping return data introduces autocorrelation of the residuals—which has to be handled in order to make correct inference.

### 14.1.3 Variance Ratios

A variance ratio is another way to measure predictability. It is defined as the variance of a  $q$ -period return divided by  $q$  times the variance of a 1-period return

$$VR_q = \frac{\text{Var}\left(\sum_{s=0}^{q-1} y_{t-s}\right)}{q \text{Var}(y_t)}. \quad (14.4)$$

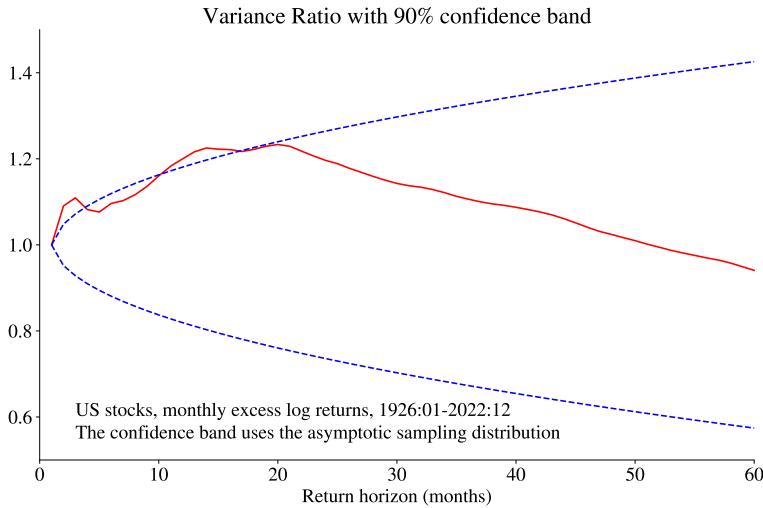


Figure 14.5: Variance ratios, long run US excess stock returns

To see that this is related to predictability, consider the 2-period variance ratio.

$$VR_2 = \frac{\text{Var}(y_t + y_{t-1})}{2 \text{Var}(y_t)} \quad (14.5)$$

$$\begin{aligned} &= \frac{\text{Var}(y_t) + \text{Var}(y_{t-1}) + 2 \text{Cov}(y_t, y_{t-1})}{2 \text{Var}(y_t)} \\ &= 1 + \frac{\text{Cov}(y_t, y_{t-1})}{\text{Var}(y_t)} \\ &= 1 + \rho_1. \end{aligned} \quad (14.6)$$

It is clear from (14.6) that if  $y_t$  is not serially correlated, then the variance ratio is unity; a value above one indicates positive serial correlation and a value below one indicates negative serial correlation. The same applies to longer horizons.

The estimation of  $VR_q$  is typically *not* done by replacing the population variances in (14.4) with the sample variances, since this would require using non-overlapping long returns—which wastes a lot of data points. For instance, if we have 24 years of data and we want to study the variance ratio for the 5-year horizon, then 4 years of data are wasted.

Instead, we typically rely on a transformation of (14.4)

$$\begin{aligned}
VR_q &= \frac{\text{Var}\left(\sum_{s=0}^{q-1} y_{t-s}\right)}{q \text{Var}(y_t)} \\
&= \sum_{s=-(q-1)}^{q-1} \left(1 - \frac{|s|}{q}\right) \rho_s \text{ or} \\
&= 1 + 2 \sum_{s=1}^{q-1} \left(1 - \frac{s}{q}\right) \rho_s.
\end{aligned} \tag{14.7}$$

To estimate  $VR_q$ , we first estimate the autocorrelation coefficients (using all available data points for each estimation) and then calculate (14.7).

**Empirical Example 14.5** (*Variance ratio for long run U.S. equity returns*) See Figure 14.5.

**Remark 14.6** (\*Sampling distribution of  $\widehat{VR}_q$ ) Under the null hypothesis that there is no autocorrelation, (14.1) and (14.7) give

$$\sqrt{T} \left( \widehat{VR}_q - 1 \right) \xrightarrow{d} N \left[ 0, \sum_{s=1}^{q-1} 4 \left(1 - \frac{s}{q}\right)^2 \right].$$

**Example 14.7** (*Sampling distributions of  $\widehat{VR}_2$  and  $\widehat{VR}_3$* )

$$\begin{aligned}
\sqrt{T} \left( \widehat{VR}_2 - 1 \right) &\xrightarrow{d} N(0, 1) \text{ or } \widehat{VR}_2 \xrightarrow{d} N(1, 1/T) \\
\text{and } \sqrt{T} \left( \widehat{VR}_3 - 1 \right) &\xrightarrow{d} N(0, 20/9) \text{ or } \widehat{VR}_3 \xrightarrow{d} N[1, (20/9)/T].
\end{aligned}$$

**Remark 14.8** The results in CLM Table 2.5 and 2.6 (weekly CRSP stock index returns, early 1960s to mid 1990s) show variance ratios above one and increasing with the number of lags,  $q$ . The results for individual stocks in CLM Table 2.7 show variance ratios close to, or even below, unity. Cochrane Tables 20.5–6 report weak evidence for more mean reversion in multi-year returns (annual NYSE stock index, 1926 to mid 1990s).

## 14.2 Other Predictors and Methods

There are many other possible predictors of future stock returns. For instance, both the dividend-price ratio and nominal interest rates have been used to predict long-run returns, and lagged short-run returns on other assets have been used to predict short-run returns.

### 14.2.1 Lead-Lags

Stock indices have more positive autocorrelation than (most) individual stocks: there should therefore be fairly strong cross-autocorrelations across individual stocks. (See Campbell, Lo, and MacKinlay (1997) Tables 2.7 and 2.8.) Indeed, this is also what is found in US data where weekly returns of large size stocks forecast weekly returns of small size stocks.

**Empirical Example 14.9** (*Correlations of  $R_{i,t}$  and  $R_{j,t-s}$* ) See Figure 14.6 for cross-autocovariances of the daily 25 FF portfolios. For instance, cell  $(i,j)$  shows the correlation of  $R_{i,t}$  and  $R_{j,t-1}$ . Figure 14.7 shows results from augmented AR(1) estimations for each of the ten size-sorted equity portfolios: the lagged return of the largest firms (decile 10) is added as a regressor.

### 14.2.2 Dividend-Price Ratio as a Predictor

One of the most successful attempts to forecast long-run returns is a regression of future returns on the current earnings-price ratio (here in logs)

$$R_{t+s} = \alpha + \beta_s \ln(E_t/P_t) + \varepsilon_{t+s}, \quad (14.8)$$

where  $R_{t+s}$  is the return from  $t$  to  $t + s$ . This is illustrated in Figure 14.8.

For instance, CLM Table 7.1, report  $R^2$  values from this regression which are close to zero for monthly returns, but they increase to 0.4 for 4-year returns (US, value weighted index, mid 1920s to mid 1990s).

**Empirical Example 14.10** (*Predicting long run equity returns with E/P*) See Figure 14.9.

### 14.2.3 Predictability but No Autocorrelation

The evidence for US stock returns is that long-run returns may perhaps be predicted by the dividend-price ratio or interest rates, but that the long-run autocorrelations are weak (long-run US stock returns appear to be “weak-form efficient” but not “semi-strong efficient”). This should remind us of the fact that predictability and autocorrelation need not be the same thing: although autocorrelation implies predictability, we can have predictability without autocorrelation.

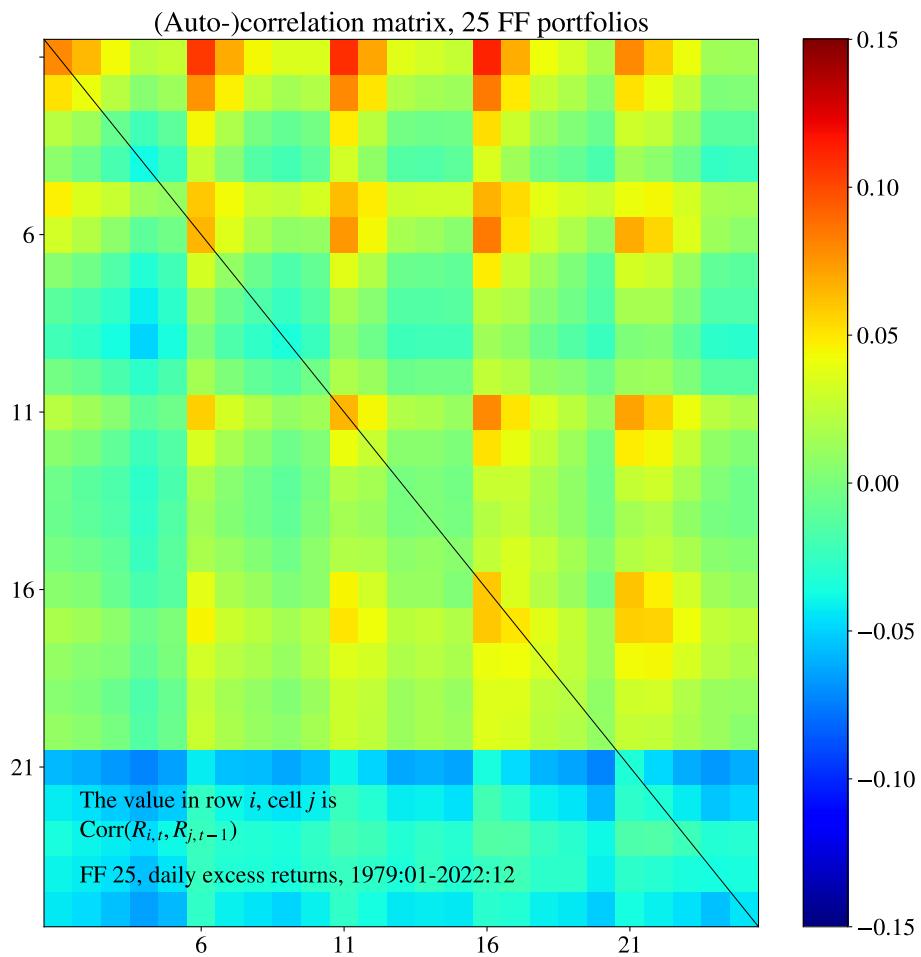


Figure 14.6: Illustration of the cross-autocorrelations,  $\text{Corr}(R_t, R_{t-k})$ , daily FF data. Dark colours indicate high correlations, light colours indicate low correlations.

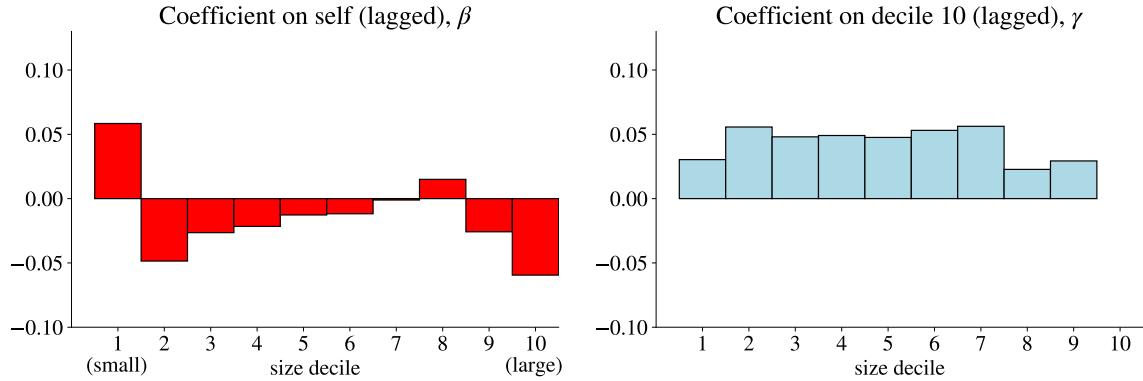
## 14.3 Out-of-Sample Forecasting Performance

### 14.3.1 In-Sample versus Out-of-Sample Forecasting

References: Goyal and Welch (2008), and Campbell and Thompson (2008)

In-sample evidence on predictability may suffer from several problems. First, the link between the predictor and future returns may be unstable (so the model has “breaks”). Second, if the estimated (in-sample) model includes many predictors, then it is likely to give poor predictions due to in-sample “overfitting.”

To gauge the out-of-sample predictability, we estimate the prediction equation using data up to and including  $t - 1$ , and then make a forecast for period  $t$ . See Figure 14.10



$$R_{i,t}^e = \alpha + \beta R_{i,t-1}^e + \gamma R_{10,t-1}^e + \varepsilon_t$$

US equity, daily excess returns, 1979:01-2022:12

Decile 1 contains the 10% smallest firms,  
while decile 10 the 10% largest firms

Figure 14.7: Spillover effects, daily data

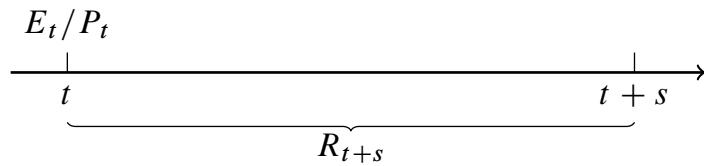


Figure 14.8: Using  $E/P$  or  $D/P$  to predict returns

for an illustration.

The forecasting performance of the equation is then compared with a benchmark prediction model (for instance, using the historical average as the predictor). Notice that this benchmark model is also estimated on data up to and including  $t - 1$ , so it changes over time. Effectively, they are comparing the forecast performance of two models estimated in a recursive way (long and longer sample). The comparison can be done in terms of the RMSE and an “out-of-sample  $R^2$ ”

$$R_{OS}^2 = 1 - \frac{1}{T} \sum_{t=s}^T (y_t - \hat{y}_t)^2 / \frac{1}{T} \sum_{t=s}^T (y_t - \tilde{y}_t)^2, \quad (14.9)$$

where  $s$  is the first period with an out-of-sample forecast,  $\hat{y}_t$  is the forecast based on the prediction model (estimated on data up to and including  $t-1$ ) and  $\tilde{y}_t$  is the prediction from some benchmark model (also estimated on data up to and including  $t-1$ ). In practice, the paper uses the historical average as the benchmark prediction model.

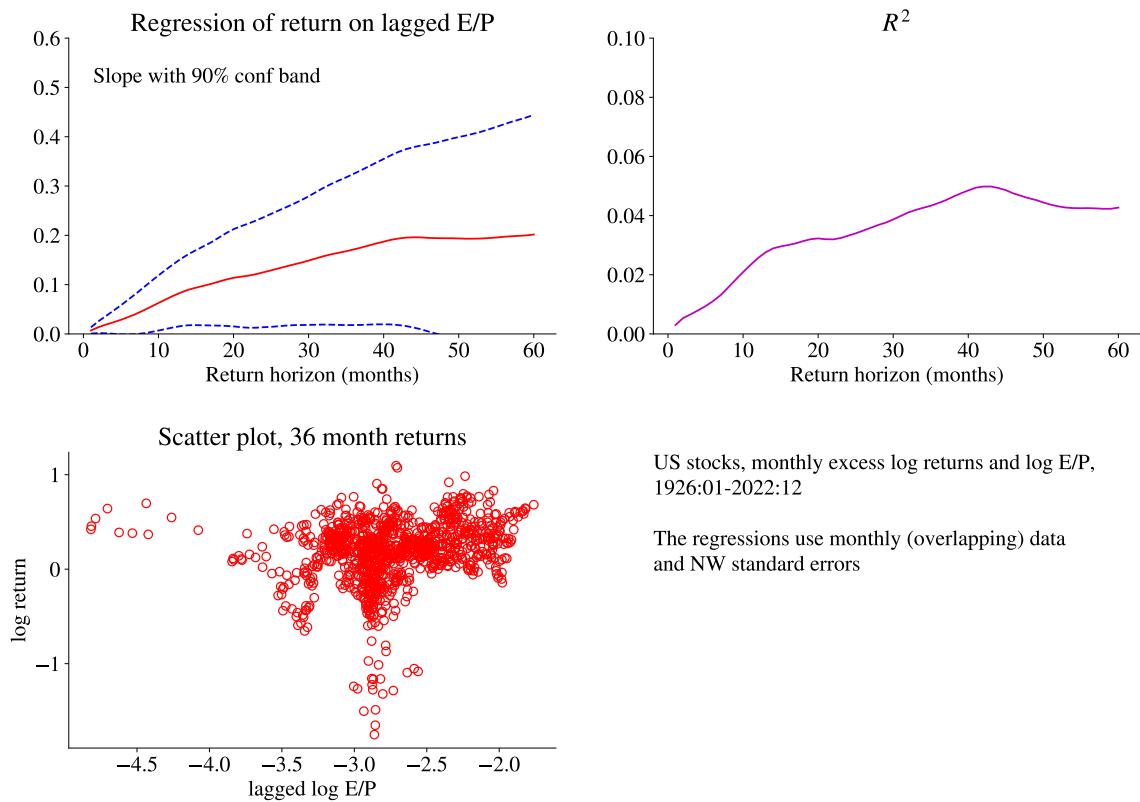


Figure 14.9: Forecast regressions, long run US stock returns

### Example 14.11 ( $R^2_{OS}$ )

$$R^2_{OS} = 1 - \frac{0.4}{0.5} = 0.2 \text{ (your model is better)}$$

$$R^2_{OS} = 1 - \frac{0.5}{0.4} = -0.25 \text{ (your model is worse)}$$

**Empirical Example 14.12** (*Out-of-sample prediction of equity returns*) Figure 14.11 shows results for daily size-sorted equity returns. There is some short-run predictability for small firm returns also out-of-sample. Figure 14.12 shows results on predicting long run equity returns with E/P. The evidence suggests that the in-sample long-run predictability vanishes out-of-sample.

### 14.3.2 Trading Strategies

Another way to measure predictability and to illustrate its economic importance is to calculate the return of a *dynamic trading strategy*, and then measure the “performance”

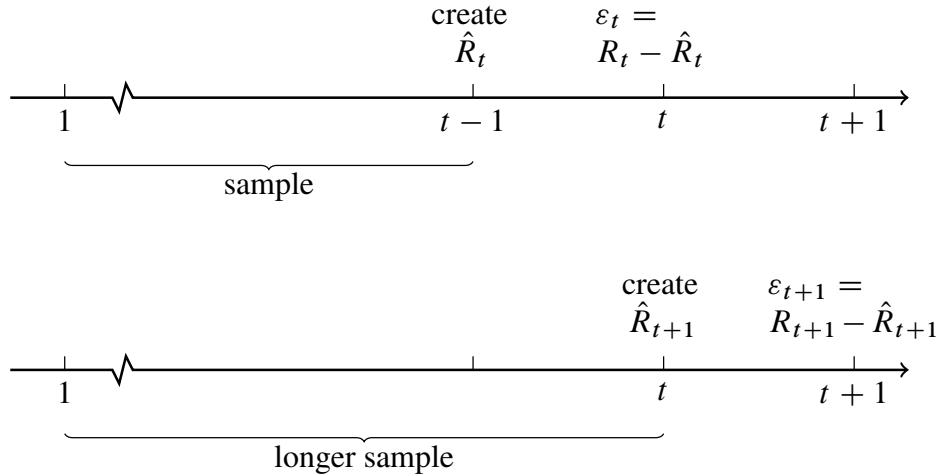


Figure 14.10: Out-of-sample forecasting

of this strategy in relation to some benchmark portfolios. The trading strategy should, of course, be based on the variable that is supposed to forecast returns.

A common way (since Jensen, updated in Huberman and Kandel (1987)) is to study the performance of a portfolio by running the following regression

$$R_{pt}^e = \alpha + \beta R_{mt}^e + \varepsilon_t, \text{ with} \quad (14.10)$$

$$\mathbb{E} \varepsilon_t = 0 \text{ and } \text{Cov}(R_{mt}^e, \varepsilon_t) = 0,$$

where  $R_{pt}^e$  is the excess return on the portfolio being studied and  $R_{mt}^e$  the excess returns of a vector of benchmark portfolios (for instance, only the market portfolio if we want to rely on CAPM). Neutral performance requires  $\alpha = 0$ , which can be tested with a  $t$  test.

**Empirical Example 14.13** (*Momentum for daily returns on the 25 FF portfolios*) Figure 14.13 suggests that there is considerable momentum in the cross-section of the 25 FF portfolios. Investing in past winners earns high returns.

**Empirical Example 14.14** (*Mean reversion of daily S&P 500 returns*) Figure 14.14 shows that extreme S&P 500 returns are followed by mean-reverting movements the following day (negative autocorrelation)—which suggests that a trading strategy should sell after a high return and buy after a low return. Compare with Figure 14.2.

**Empirical Example 14.15** (*Mean reversion of daily returns for different size categories*) Figure 14.15 compares the results for daily returns on different size categories —and

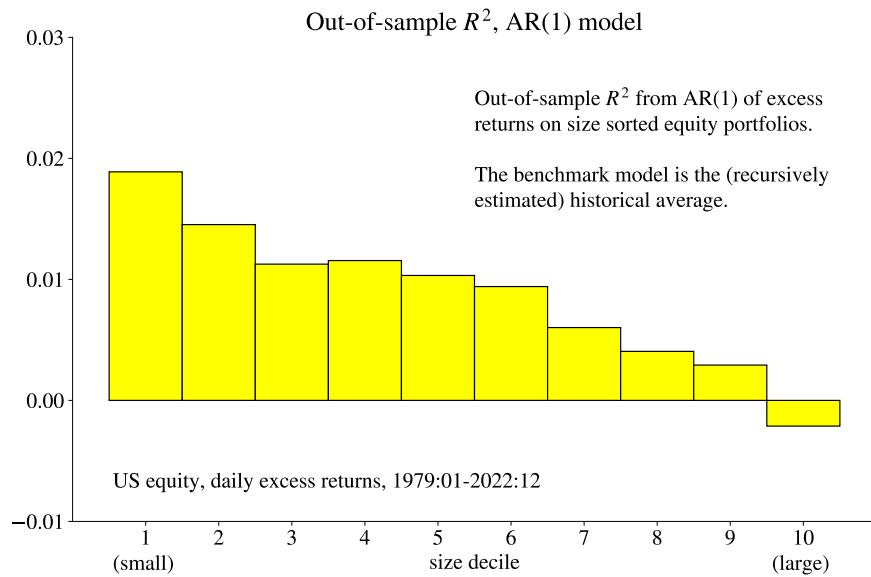


Figure 14.11: Predictability of daily US stock returns, out-of-sample

illustrates that there is more predictability (indicating positive autocorrelation) for small stocks. Once again, compare with Figure 14.2.

**Empirical Example 14.16** (*Long run S&P 500 after different p/e values*) Figure 14.16 shows average one-year return on S&P 500 for different bins of the p/e ratio (at the beginning of the year). The figure illustrates that buying when the market is undervalued (low p/e) might be a winning strategy. Compare with Figure 14.9 (in-sample, but there we used  $e/p$ , not  $p/e$ ) but also Figure 14.12 (out-of-sample evaluation of regression results).

### 14.3.3 Technical Analysis

Main reference: Bodie, Kane, and Marcus (2002) 12.2; Reilly and Brown (2012) 16; Neely (1997) (overview, foreign exchange market)

Further reading: Murphy (1999) (practical, a believer's view); The Economist (1993) (overview, the perspective of the early 1990s); Brock, Lakonishok, and LeBaron (1992) (empirical, stock market); Lo, Mamaysky, and Wang (2000) (academic article on return distributions for "technical portfolios")

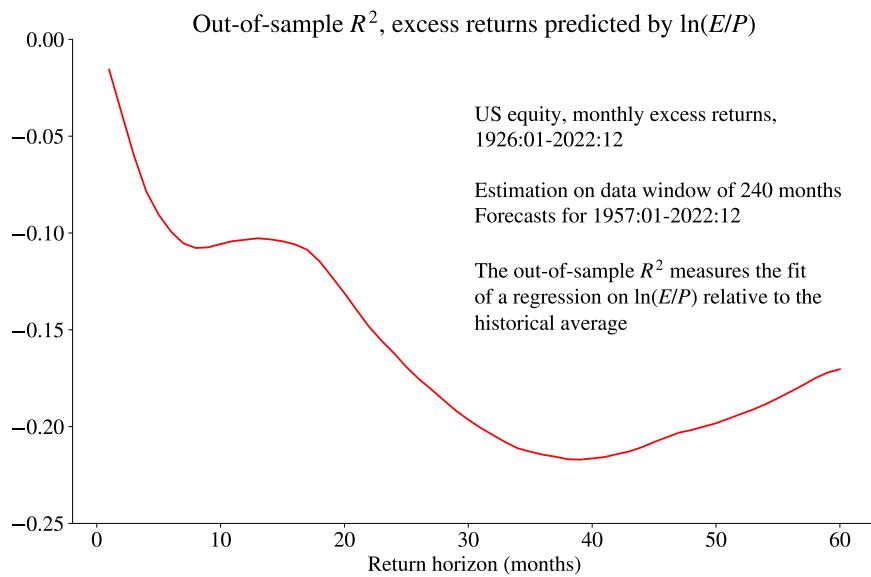


Figure 14.12: Predictability of long run US stock returns, out-of-sample

### General Idea of Technical Analysis

Technical analysis is typically a data mining exercise which looks for local trends or systematic non-linear patterns. The basic idea is that markets are not instantaneously efficient: prices react somewhat slowly and predictably to news. The logic is that an observed price move must be due to some news (exactly which one is not very important) and that old patterns can tell us where the price will move in the near future. This is an attempt to gather more detailed information than that used by the market as a whole. In practice, much of technical analysis amounts to plotting different transformations (for instance, a moving average) of prices—and to spot systematic patterns. It is also common to incorporate information from other markets (for instance, the CBOE put/call ratio is often interpreted as a bearish attitude), trading volume or measures of market wide trends (the “breadth” of the market compares the number of assets with price increase/decrease).

This section summarizes some simple trading rules.

### Technical Analysis and Local Trends

Many trading rules rely on some kind of local trend which can be thought of as positive autocorrelation in price movements, also called momentum.<sup>1</sup>

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<sup>1</sup>In physics, momentum equals the mass times speed.

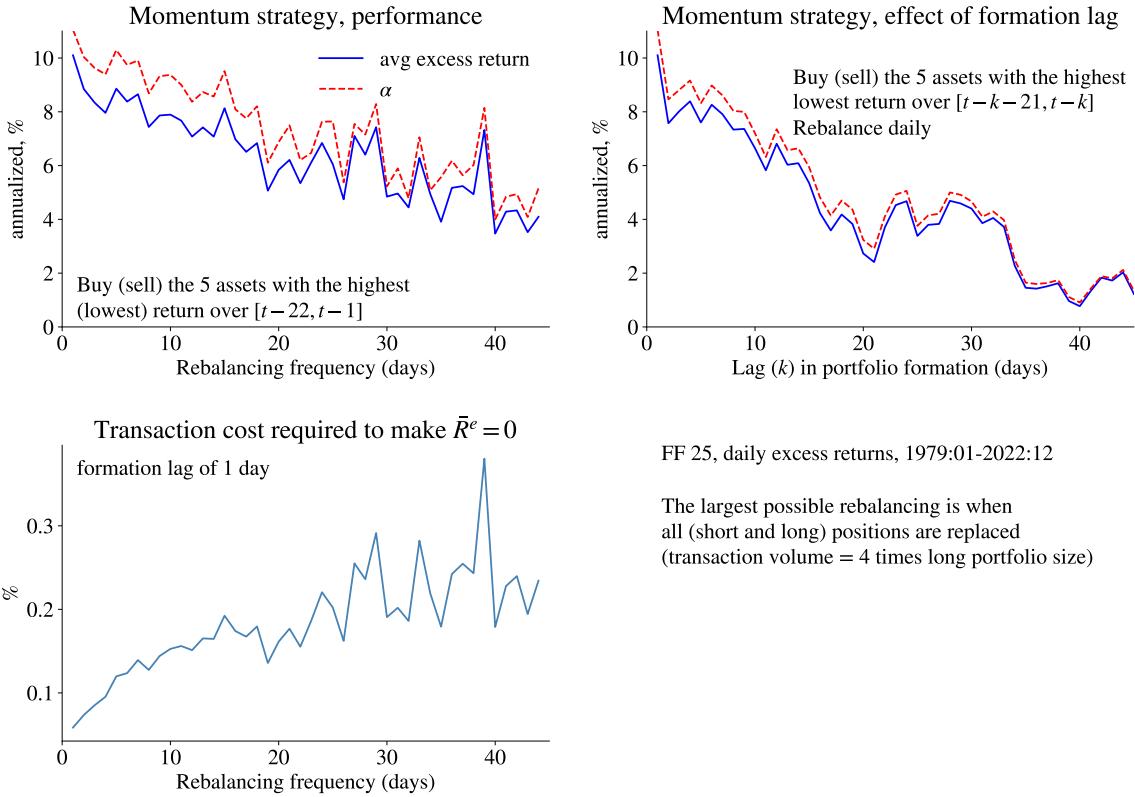


Figure 14.13: Predictability of daily US stock returns, momentum strategy

A *moving average rule* is to buy if a short moving average (equally weighted or exponentially weighted) goes above a long moving average. The idea is that the event signals a new upward trend. Let  $S$  ( $L$ ) be the lag order of a short (long) moving average, with  $S < L$  and let  $b$  be a bandwidth (perhaps 0.01). Then, a MA rule for period  $t$  could be

$$\begin{bmatrix} \text{buy in } t \text{ if } MA_{t-1}(S) > MA_{t-1}(L)(1+b) \\ \text{sell in } t \text{ if } MA_{t-1}(S) < MA_{t-1}(L)(1-b) \\ \text{no change otherwise} \end{bmatrix}, \text{ where} \quad (14.11)$$

$$MA_{t-1}(S) = (p_{t-1} + \dots + p_{t-S})/S.$$

The difference between the two moving averages is called an *oscillator*

$$\text{oscillator}_t = MA_t(S) - MA_t(L), \quad (14.12)$$

(or sometimes, moving average convergence divergence, MACD) and the sign is taken

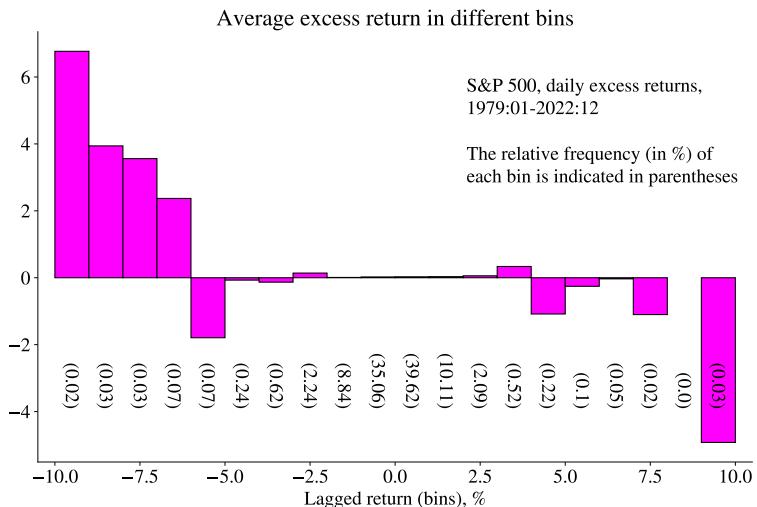


Figure 14.14: Predictability of daily US stock returns, out-of-sample

as a trading signal (this is the same as a moving average crossing, MAC).<sup>2</sup> A version of the moving average oscillator is the *relative strength index*<sup>3</sup>, which is the ratio of average price level (or returns) on “up” days to the average price (or returns) on “down” days—during the last  $z$  (14 perhaps) days. Yet another version is to compare the oscillator <sub>$t$</sub>  to an moving average of the oscillator (also called a signal line).

The *trading range break-out rule* typically amounts to buying when the price rises above a previous peak (local maximum). The idea is that a previous peak is a *resistance level* in the sense that some investors are willing to sell when the price reaches that value (perhaps because they believe that prices cannot pass this level; clear risk of circular reasoning or self-fulfilling prophecies). Round numbers often play the role as resistance levels. Once this artificial resistance level has been broken, the price can possibly rise substantially. On the downside, a *support level* plays the same role: some investors are willing to buy when the price reaches that value. To implement this, it is common to let the resistance/support levels be proxied by minimum and maximum values over a data

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<sup>2</sup>Yes, the rumour is true: the tribe of chartists is on the verge of developing their very own language.

<sup>3</sup>Not to be confused with relative strength, which typically refers to the ratio of two different asset prices (for instance, an equity compared to the market).

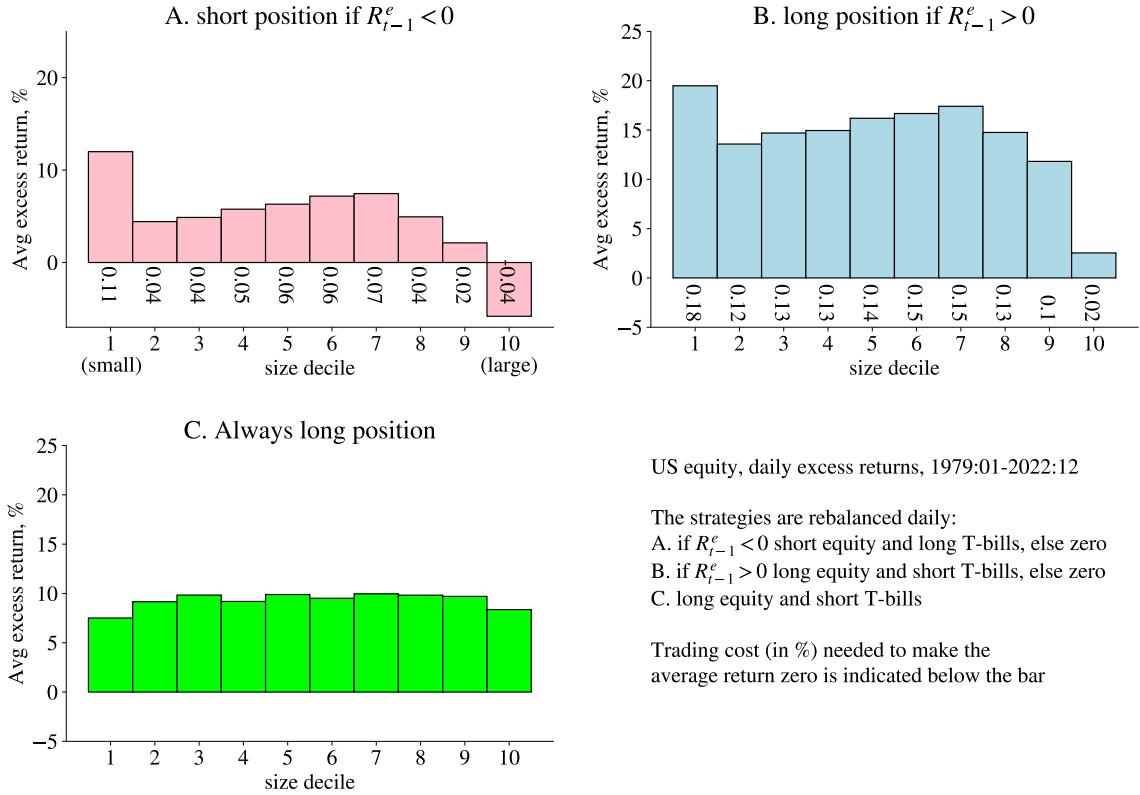


Figure 14.15: Predictability of daily US stock returns, out-of-sample

window of length  $L$ . With a bandwidth  $b$  (perhaps 0.01), the rule for period  $t$  could be

$$\begin{bmatrix} \text{buy in } t \text{ if } P_t > M_{t-1}(1+b) \\ \text{sell in } t \text{ if } P_t < m_{t-1}(1-b) \\ \text{no change otherwise} \end{bmatrix}, \text{ where} \quad (14.13)$$

$$M_{t-1} = \max(p_{t-1}, \dots, p_{t-S})$$

$$m_{t-1} = \min(p_{t-1}, \dots, p_{t-S}).$$

When the price is already trending up, then the trading range break-out rule may be replaced by a *channel rule*, which works as follows. First, draw a *trend line* through previous lows and a *channel line* through previous peaks. Extend these lines. If the price moves above the channel (band) defined by these lines, then buy. A version of this is to define the channel by a *Bollinger band*, which is  $\pm 2$  standard deviations from a moving data window around a moving average.

A *head and shoulder* pattern is a sequence of three peaks (left shoulder, head, right

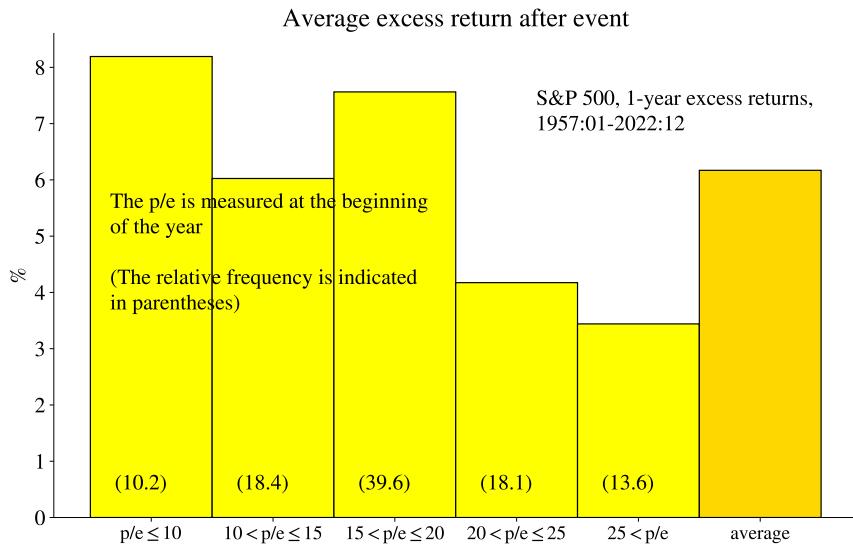


Figure 14.16: Predictability of annual US stock returns, out-of-sample

shoulder), where the middle one (the head) is the highest, with two local lows in between on approximately the same level (neck line). (Easier to draw than to explain in a thousand words.) If the price subsequently goes below the neckline, then it is thought that a negative trend has been initiated. (An inverse head and shoulder has the inverse pattern.)

Clearly, we can replace “buy” in the previous rules with something more aggressive, for instance, replace a short position with a long.

The trading volume is also often taken into account. If the trading volume of assets with declining prices is high relative to the trading volume of assets with increasing prices, then this is interpreted as a market with selling pressure. (The basic problem with this interpretation is that there is a buyer for every seller, so we could equally well interpret the situations as if there is a buying pressure.)

### Technical Analysis and Mean Reversion

If we instead believe in mean reversion of the prices, then we can essentially reverse the previous trading rules: we would typically sell when the price is high.

**Empirical Example 14.17** (*Daily trading strategy for S&P 500 and riskfree*) See Figure 14.17 for an illustration (over a short subsample) of an inverted MA strategy: buy when the recent index values leave the band on the downside et vice versa. The performance (over a longer sample) is reported in Table 14.1, which suggests that buy and sell

*signals actually contain information. However, a daily rebalancing might be too costly (transaction costs).*

Some investors argue that markets show periods of mean reversion and then periods with trends—and that both can be exploited. Clearly, the concept of support and resistance levels (or more generally, a channel) is based on mean reversion between these points. A new trend is then supposed to be initiated when the price breaks out of this band.

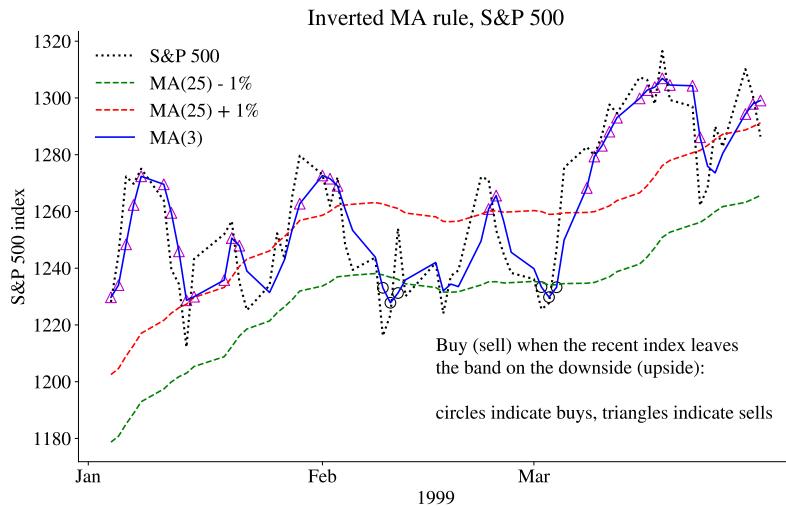


Figure 14.17: Example of a daily trading rule

	Mean	Std
All days	6.6	18.2
After buy signal	16.4	27.8
After neutral signal	5.2	14.7
After sell signal	2.5	13.8
Strategy	9.2	27.9
Transaction cost	0.1	

Table 14.1: Excess returns (annualized, in %) from technical trading rule (Inverted MA rule). Daily S&P 500 data 1990:01-2022:12. The trading strategy involves (a) on every day: hold one unit of the index and short the riskfree; (b) on days after a buy signal: double the position in (a); (c) on days after a sell signal: short sell the position in (a), effectively having a zero investment. The transaction costs shows the cost (in %) of trade that the strategy can pay and still perform as well as the static holding of (a).

## 14.4 Forecast Averaging

Reference: Elliot and Timmermann (2016) 14

Averaging across forecasts have often proved to be a good way of producing a superior forecast.

There are two main cases: (1) when we have access to the forecasts and also the data/model that produced them and (2) when we have access to the forecasts only. We discuss them in reverse order.

Suppose we have access to  $K$  different forecasts ( $\hat{R}_t^i$  for  $i = 1$  to  $K$ ) of the return  $R_t$ . All these forecasts are made in period  $t - h$  (with  $h \geq 1$ ). We form a weighted average as

$$R_t^* = \sum_{i=1}^K w_i \hat{R}_t^i, \text{ with } \sum_{i=1}^K w_i = 1. \quad (14.14)$$

For instance,  $w$  may be chosen as to minimize the forecast error variance or the MSE over the sample up to and including  $t - h$ . In practice, it seems difficult to beat an unweighted average or an unweighted average after having pruned the most extreme forecasts (“trimmed mean”).

Instead, suppose we have access also to the models and data that produce the various forecasts. It can then be argued that the proper way to proceed is to pool all the data and apply the model selection techniques. However, the unweighted average across forecasts often perform reasonably well.

## 14.5 Evaluating Forecasting Performance

Further reading: Diebold (2001) 11; Stekler (1991); Diebold and Mariano (1995); Clark and West (2007)

To do a solid evaluation of the forecast performance (of some forecaster/forecast method/forecast institute), we need a sample (history) of the forecasts and the resulting forecast errors. The reason is that the forecasting performance for a single period is likely to be dominated by luck, so we can only expect to find systematic patterns by looking at results for several periods.

To set up tests of the forecasting performance, let  $\varepsilon_t$  be the forecast error in period  $t$

$$\varepsilon_t = R_t - \hat{R}_t, \quad (14.15)$$

where  $\hat{R}_t$  is the forecast (made in  $t - h$ ) and  $R_t$  the actual outcome. (Warning: some

authors prefer to work with  $\hat{R}_t - R_t$  as the forecast error instead.)

Quite often, we compare a forecast method (or forecasting institute) with a benchmark forecast like a “no change,” a random walk or the historical average. The idea of such a comparison is to study if the resources employed in creating the forecast really bring value added compared to a very simple (and inexpensive) forecast.

Ultimately, the ranking of forecasting methods should be done based on the true benefits/costs of forecast errors—which may differ between organizations. For instance, a forecasting agency has a reputation (and eventually customers) to lose, while an investor has more immediate pecuniary concerns. Unless the relation between the forecast error and the losses are immediately understood, the ranking of two forecast methods is typically done based on a number of standard criteria. Several of those criteria are inspired by basic statistics.

Most statistical forecasting methods are based on the idea of minimizing the sum of squared forecast errors,  $\sum_{t=1}^T \varepsilon_t^2$ . For instance, the least squares (LS) method picks the regression coefficient in

$$R_t = \beta_0 + \beta_1 x_{t-h} + \varepsilon_t \quad (14.16)$$

to minimize the sum of squared residuals. This will, among other things, give a zero mean of the fitted residuals and also a zero correlation between the fitted residual and the regressor. As usual, rational forecasts should have forecast errors that cannot be predicted (by past regressors or forecast errors).

The evaluation of a forecast often involves extending these ideas to the forecast method, irrespective of whether a LS regression has been used or not. In practice, this means studying (i) whether the forecast error,  $e_t$ , has a zero mean; (ii) the mean squared (or absolute value) of the forecast error ; (iii) the fraction of times the squared (or absolute value) of the forecast error is lower than some threshold; (iv) the profit from investing by following a forecasting model; (v) if the forecast errors are autocorrelated or correlated with past information.

To perform formal tests of forecasting performance a Diebold and Mariano (1995) test is typically performed. To implement it, consider two different forecasts. For instance, the first forecast could come from a naive forecasting model (for instance, no change) that you hope to beat (forecast errors  $e_t$ ) and the other is your estimated model (forecast errors  $\varepsilon_t$ ). To test the different aspects discussed before, let  $\delta(x)$  be an indicator function that is one if  $x$  is true and zero otherwise, and let  $R_t^e$  and  $R_t^\varepsilon$  denote the returns from following trading strategies based on the different forecasts. Then, we could consider, for instance,

the following moment conditions

$$g_t = e_t - \varepsilon_t, \text{ or} \quad (14.17)$$

$$g_t = e_t^2 - \varepsilon_t^2 \text{ or } g_t = |e_t| - |\varepsilon_t|, \text{ or} \quad (14.18)$$

$$g_t = \delta[\text{sign}(\tilde{R}_t) \neq \text{sign}(R_t)] - \delta[\text{sign}(\hat{R}_t) \neq \text{sign}(R_t)], \quad (14.19)$$

where  $\delta(x) = 1$  if  $x$  is true and zero otherwise.

The different moment conditions correspond to the different aspects of the forecasts discussed above. For instance, (14.17) is for testing if the two methods have the same average forecast error, while (14.18) tests the MSE, which is an application of the Mariano-Diebold approach. In contrast, (14.19) tests if the  $e$  model forecasts the wrong sign of the return more often than the  $\varepsilon$  model does.

From the usual properties of a sample average and the assumption that  $g_t$  is not auto-correlated, we typically have that

$$\bar{g} \xrightarrow{d} N(0, \text{Var}(g_t)/T), \quad (14.20)$$

where  $\bar{g} = \sum_{t=1}^T g_t / T$  is the average. Alternatively, the variance could be estimated by a Newey-West approach.

The null hypothesis is that  $E g_t = 0$  (the two models perform equally well). In a two-sided test the alternative hypothesis is  $E g_t \neq 0$  (are the forecast errors different?). The null is then rejected whenever the  $t$ -stat calculated from (14.20) is large in absolute value (for instance,  $|t| > 1.645$  for the 10% significance level). A one-sided test (where the alternative is  $E g_t > 0$  or  $E g_t < 0$ ) is also easy to perform.

However, when the models behind  $e$  and  $\varepsilon$  are *nested* (say,  $e$  is generated by a special case of the model that generates  $\varepsilon$ ), then the asymptotic distribution is non-normal so an adjustment must be applied (see Clark and McCracken (2001) and Clark and West (2007)), which typically means that instead of studying  $g_t = e_t^2 - \varepsilon_t^2$ , we use  $g_t = 2e_t(e_t - \varepsilon_t)$ .

**Empirical Example 14.18** (*Empirical results on predicting annual S&P 500 returns*) Table 14.2 summarizes results for predicting 1-year S&P 500 returns. The combined model seems to do slightly better than the two individual models, AR(1) and E/P regression.

	AR(1)		E/P		Combination	
	mean	t-stat	mean	t-stat	mean	t-stat
MSE in-sample	290.04		280.51			
$R^2_{oos}$	-0.04		-0.07		-0.03	
$e - \varepsilon$	0.22	1.93	-1.47	-1.47	-0.62	-1.22
$e^2 - \varepsilon^2$	-12.79	-1.56	-21.71	-0.93	-9.17	-0.81
$ e  -  \varepsilon $	-0.21	-1.49	-0.81	-1.16	-0.32	-0.91
$2e(e - \varepsilon)$	-11.88	-1.50	9.39	0.39	-1.24	-0.11

Table 14.2: Mariano-Diebold (and Clark-West) tests of forecasting 1-year S&P returns with different models. The total sample is 1946–2021, but the forecasts are made for 1971–2021. The  $e$  forecasts are the historical average returns while the  $\varepsilon$  forecasts are out-of-sample and based on the different regressions. Estimation is done on an expanding data window. The std use a NW approach with 1 lag (year).

## 14.6 Security Analysts

Reference: Makridakis, Wheelwright, and Hyndman (1998) 10.1 and Elton, Gruber, Brown, and Goetzmann (2010) 26

### 14.6.1 Evidence on Analysts' Performance

Makridakis, Wheelwright, and Hyndman (1998) 10.1 shows that there is little evidence that the average stock analyst beats (on average) the market (a passive index portfolio). In fact, less than half of the analysts beat the market. However, there are analysts which seem to outperform the market for some time, but the autocorrelation in over-performance is weak. The evidence from mutual funds is similar. For them it is typically also found that their portfolio weights do not anticipate price movements.

It should be remembered that many analysts also are sales persons: either of a stock (for instance, since the bank is underwriting an offering) or of trading services. It could well be that their objective function is quite different from minimizing the squared forecast errors—or whatever we typically use in order to evaluate their performance. (The number of litigations in the US after the technology boom/bust should serve as a strong reminder of this.)

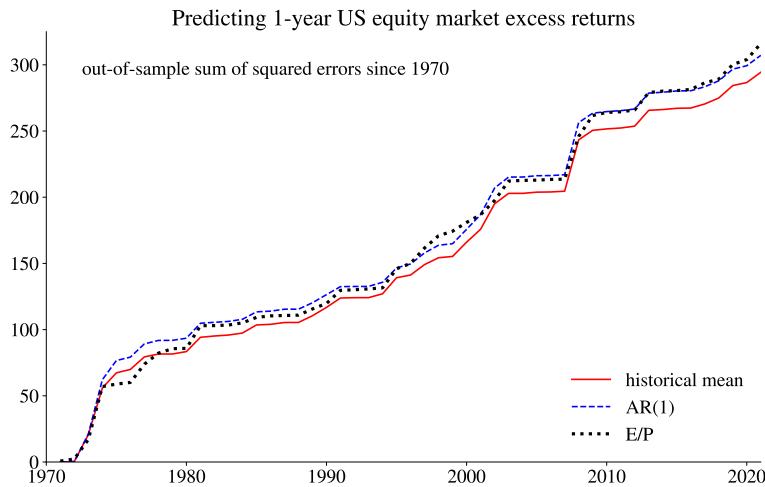


Figure 14.18: Accumulation of the (oos) MSE from three different forecasting models

#### 14.6.2 Do Security Analysts Overreact?

The paper by Bondt and Thaler (1990) compares the (semi-annual) forecasts (one- and two-year time horizons) with actual changes in earnings per share (1976-1984) for several hundred companies. The paper has regressions like

$$\text{Actual change} = \alpha + \beta(\text{forecasted change}) + \text{residual},$$

and then studies the estimates of the  $\alpha$  and  $\beta$  coefficients. With rational expectations (and a long enough sample), we should have  $\alpha = 0$  (no constant bias in forecasts) and  $\beta = 1$  (proportionality).

The main result is that  $0 < \beta < 1$ , so that the forecasted change tends to be too wild in a systematic way: a forecasted change of 1% is (on average) followed by a less than 1% actual change in the same direction. This means that analysts in this sample tended to be too extreme—to exaggerate both positive and negative news.

#### 14.6.3 High-Frequency Trading Based on Recommendations from Stock Analysts

Barber, Lehavy, McNichols, and Trueman (2001) give a somewhat different picture. They focus on the profitability of a trading strategy based on the recommendations of analysts. They use a huge data set (some 360,000 recommendations, US stocks) for the period 1985-1996. They sort stocks into five portfolios depending on the consensus (average) recommendation—and redo the sorting every day (if a new recommendation is published).

They find that such a daily trading strategy gives an annual 4% abnormal return on the portfolio of the most highly recommended stocks, and an annual –5% abnormal return on the least favourably recommended stocks.

This strategy requires a lot of trading (a turnover of 400% annually), so trading costs would typically reduce the abnormal return on the best portfolio to almost zero. A less frequent rebalancing (weekly, monthly) gives a very small abnormal return for the best stocks, but still a negative abnormal return for the worst stocks. [Chance and Hemler \(2001\)](#) obtain similar results when studying the investment advise by 30 professional “market timers.”

#### 14.6.4 Economic Experts

Several papers, for instance, [Bondt \(1991\)](#) and [Söderlind \(2010\)](#), have studied whether economic experts can predict the broad stock markets. The results suggests that they cannot. For instance, [Söderlind \(2010\)](#) shows that the economic experts that participate in the semi-annual Livingston survey (mostly bank economists) forecast the S&P worse than the historical average (recursively estimated), and that their forecasts are strongly correlated with recent market data (which in itself, cannot predict future returns).

#### 14.6.5 Bond Rating Agencies versus Stock Analysts

[Ederington and Goh \(1998\)](#) use data on all corporate bond rating changes by Moody’s between 1984 and 1990 and the corresponding earnings forecasts (by various stock analysts).

The idea of the paper by [Ederington and Goh \(1998\)](#) is to see if bond ratings drive earnings forecasts (or vice versa), and if they affect stock returns (prices).

1. To see if stock returns are affected by rating changes, they first construct a “normal” return by a market model:

$$\text{normal stock return}_t = \alpha + \beta \times \text{return on stock index}_t,$$

where  $\alpha$  and  $\beta$  are estimated on a normal time period (not including the rating change). The abnormal return is then calculated as the actual return minus the normal return. They then study how such abnormal returns behave, on average, around the dates of rating changes. Note that “time” is then measured, individually for each stock, as the distance from the day of rating change. The result is that there

are significant negative abnormal returns following downgrades, but zero abnormal returns following upgrades.

2. They next turn to the question of whether bond ratings drive earnings forecasts or vice versa. To do that, they first note that there are some predictable patterns in revisions of earnings forecasts. They therefore fit a simple autoregressive model of earnings forecasts, and construct a measure of earnings forecast revisions (surprises) from the model. They then relate this surprise variable to the bond ratings. In short, the results are the following:

- (a) both earnings forecasts and ratings react to the same information, but there is also a direct effect of rating changes, which differs between downgrades and upgrades.
- (b) downgrades: the ratings have a strong negative direct effect on the earnings forecasts; the returns react even quicker than analysts
- (c) upgrades: the ratings have a small positive direct effect on the earnings forecasts; there is no effect on the returns

A possible reason for why bond ratings could drive earnings forecasts and prices is that bond rating firms typically have access to more inside information about firms than stock analysts and investors.

A possible reason for the observed asymmetric response of returns to ratings is that firms are quite happy to release positive news, but perhaps more reluctant to release bad news. If so, then the information advantage of bond rating firms may be particularly large after bad news. A downgrading would then reveal more new information than an upgrade.

The different reactions of the earnings forecasts and the returns are hard to reconcile.

#### **14.6.6 International Differences in Analyst Forecast Properties**

Ang and Ciccone (2001) study earnings forecasts for many firms in 42 countries over the period 1988 to 1997. Some differences are found across countries: forecasters disagree more and the forecast errors are larger in countries with low GDP growth, less accounting disclosure, and less transparent family ownership structure.

However, the most robust finding is that forecasts for firms with losses are special: forecasters disagree more, are more uncertain, and are more overoptimistic about such firms.

### **14.6.7 Analysts and Industries**

Boni and Womack (2006) study data on some 170,000 recommendations for a very large number of U.S. companies for the period 1996–2002. Focusing on revisions of recommendations, the papers shows that analysts are better at ranking firms within an industry than ranking industries.

### **14.6.8 Insiders**

Corporate insiders *used to* earn superior returns, mostly driven by selling off stocks before negative returns. (There is little/no systematic evidence of insiders gaining by buying before high returns.) Actually, investors who followed the insider's registered transactions (in the U.S., these are made public six weeks after the reporting period), also used to earn some superior returns. It seems as if these patterns have more or less disappeared.

# Chapter 15

## Event Studies\*

Reference: Bodie, Kane, and Marcus (2005) 12.3 or Copeland, Weston, and Shastri (2005) 11

Reference (advanced): Campbell, Lo, and MacKinlay (1997) 4

More advanced material is denoted by a star (\*). It is not required reading.

### 15.1 Basic Structure of Event Studies

The idea of an event study is to study the effect (on stock prices or returns) of a special event by using a cross-section of such events. For instance, what is the average (across firms) effect of a stock split announcement on the share price? Other events could be debt issues, mergers and acquisitions, earnings announcements, or monetary policy moves.

The event is typically assumed to be a binary variable. For instance, it could be a merger or not or if the monetary policy surprise was positive (lower interest rates than expected) or not. The basic approach is then to study what happens to the returns of those assets that have such an event.

Only news should move the asset price, so it is often necessary to explicitly model the previous expectations to define the event. For earnings, the event is typically taken to be the earnings announcement minus (some average of) analysts' forecast. Similarly, for monetary policy moves, the event could be specified as the interest rate decision minus previous forward rates (as a measure of previous expectations).

Similarly, we typically study the *abnormal return* around such events, defined as (for asset  $i$  in period  $t$ )

$$u_{it} = R_{it} - R_{it}^{normal}, \quad (15.1)$$

where  $R_{it}$  is the actual return and the last term is the normal return (which may differ

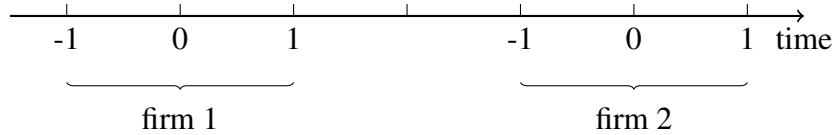


Figure 15.1: Event days and windows

across assets and time). The definition of the normal return is discussed below. The idea of the “abnormal return” is that the event is likely to change the return relative to what it would otherwise have been on the same date (the normal return).

Suppose we have a sample of  $n$  such events (“assets”). To keep the notation (reasonably) simple, we “normalize” the time so period 0 is the time of the event. Clearly the actual calendar time of the events for assets  $i$  and  $j$  are likely to differ, but we shift the time line for each asset individually so the time of the event is normalized to zero for every asset. See Figure 15.1 for an illustration.

To control for information leakage and slow price adjustment, the abnormal return is often calculated for some time before and after the event: the “event window” (often  $\pm 20$  days or so). For day  $s$  (that is,  $s$  days after the event time 0), the cross sectional average abnormal return is

$$\bar{u}_s = \sum_{i=1}^n u_{is}/n. \quad (15.2)$$

For instance,  $\bar{u}_2$  is the average abnormal return two days after the event, and  $\bar{u}_{-1}$  is for one day before the event.

The cumulative abnormal return (CAR) of asset  $i$  is simply the sum of the abnormal return in (15.1) over some period around the event. It is often calculated from the beginning of the event window (or from day 0). For instance, if the event window starts at  $-20$ , then the 3-period (day?) car for firm  $i$  is

$$\text{car}_{i3} = u_{i,-20} + u_{i,-19} + u_{i,-18}. \quad (15.3)$$

More generally, if the event window starts at  $w$  (say,  $-20$ ), then the  $q$ -period car for firm  $i$  is

$$\text{car}_{iq} = \sum_{\tau=w}^{w+q-1} u_{i,\tau}. \quad (15.4)$$

The cross sectional average of the  $q$ -period car is

$$\overline{\text{car}}_q = \sum_{i=1}^n \text{car}_{iq} / n. \quad (15.5)$$

**Empirical Example 15.1** (*Cumulative abnormal returns*) See Figure 15.2 for results on IPOs.

**Example 15.2** (*Abnormal returns for  $\pm 1$  day around event, two firms*) Suppose there are two firms and the event window contains  $\pm 1$  day around the event day, and that the abnormal returns (in percent) are

Time	Firm 1	Firm 2	Cross-sectional Average
-1	0.2	-0.1	0.05
0	1.0	2.0	1.5
1	0.1	0.3	0.2

We have the following cumulative returns

Time	Firm 1	Firm 2	Cross-sectional Average
-1	0.2	-0.1	0.05
0	1.2	1.9	1.55
1	1.3	2.2	1.75

## 15.2 Models of Normal Returns

This section summarizes the most common ways of calculating the normal return in (15.1). The parameters in these models are typically estimated on a recent sample, the “estimation window,” which ends before the event window. See Figure 15.3 for an illustration. (When there is no return data before the event window for instance, when the event is an IPO, then the estimation window can be after the event window.)

In this way, the estimated behaviour of the normal return should be unaffected by the event. It is almost always assumed that the event is exogenous in the sense that it is not due to the movements of the asset price during either the estimation window or the event window. This allows us to get a clean estimate of the normal return.

The *constant mean return model* assumes that the return of asset  $i$  fluctuates randomly

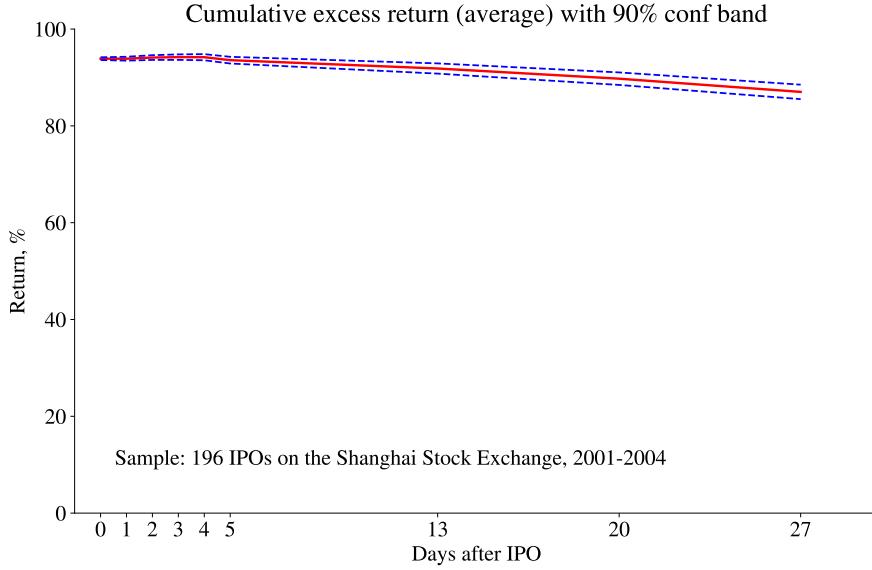


Figure 15.2: Event study of IPOs in Shanghai 2001–2004. (Data from Nou Lai.)

around some mean  $\mu_i$

$$R_{it} = \mu_i + \varepsilon_{it} \text{ with} \quad (15.6)$$

$$\mathbb{E}(\varepsilon_{it}) = 0 \text{ and } \text{Cov}(\varepsilon_{it}, \varepsilon_{i,t-s}) = 0.$$

This mean is estimated by the sample average (during the estimation window). The normal return in (15.1) is then the estimated mean,  $\hat{\mu}_i$ . During the event window, we calculate the abnormal return as

$$u_{it} = R_{it} - \hat{\mu}_i. \quad (15.7)$$

The standard error of this is estimated by the standard error of  $\hat{\varepsilon}_{it}$  (in the estimation window). This means that we disregard the sampling uncertainty of the estimated mean, which makes sense if the estimation window is not very short (recall that the variance of a sample average is  $\text{Var}(R_{it})/T$ , where  $T$  is the number of data points in the estimation window). The same applies to the other models discussed below.

The *market model* is a linear regression of the return of asset  $i$  on the market return

$$R_{it} = \alpha_i + \beta_i R_{mt} + \varepsilon_{it} \text{ with} \quad (15.8)$$

$$\mathbb{E}(\varepsilon_{it}) = 0, \text{Cov}(\varepsilon_{it}, \varepsilon_{i,t-s}) = 0 \text{ and } \text{Cov}(\varepsilon_{it}, R_{mt}) = 0.$$

Notice that we typically do not impose the CAPM restrictions on the intercept in (15.8).

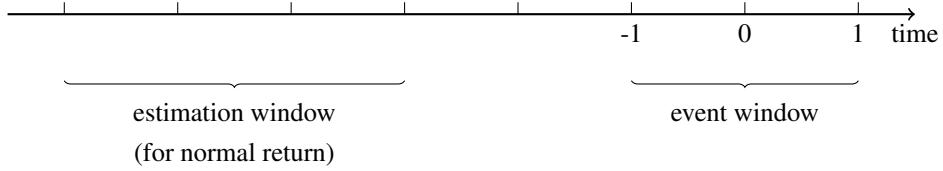


Figure 15.3: Event and estimation windows

The normal return in (15.1) is then calculated by combining the regression coefficients with the actual market return as  $\hat{\alpha}_i + \hat{\beta}_i R_{mt}$ . For the event window we calculate the abnormal return as

$$u_{it} = R_{it} - \hat{\alpha}_i - \hat{\beta}_i R_{mt}. \quad (15.9)$$

The standard error of this is estimated by the standard error of  $\hat{\varepsilon}_{it}$  (in the estimation window).

Recently, the market model has increasingly been replaced by a multi-factor model which uses several regressors instead of only the market return. For instance, Fama and French (1993) argue that (15.8) needs to be augmented by a portfolio that captures the different returns of small and large firms and also by a portfolio that captures the different returns of firms with high and low book-to-market ratios.

When we restrict  $\alpha_i = 0$  and  $\beta_i = 1$  in (15.8), then this approach is called the *market-adjusted-return model*. This is a particularly useful approach when there is no return data before the event, for instance, with an IPO. For the event window we calculate the abnormal return as

$$u_{it} = R_{it} - R_{mt} \quad (15.10)$$

and the standard error of it is estimated by  $\text{Std}(R_{it} - R_{mt})$  in the estimation window.

Finally, another approach is to construct a normal return as the actual return on assets which are very similar to the asset with an event. For instance, if asset  $i$  is a small manufacturing firm (with an event), then the normal return could be calculated as the average (in the cross-section, but same day) return for other small manufacturing firms (without events). In this case, the abnormal return becomes the difference between the actual return and the average return on the matching portfolio. This type of *matching portfolio* is becoming increasingly popular. For the event window we calculate the abnormal return

as

$$u_{it} = R_{it} - R_{pt}, \quad (15.11)$$

where  $R_{pt}$  is the return of the matching portfolio. The standard error of it is estimated by  $\text{Std}(R_{it} - R_{pt})$  in the estimation window.

All the methods discussed here try to take into account the risk premium on the asset. It is captured by the mean in the constant mean mode, the beta in the market model, and by the way the matching portfolio is constructed.

Apart from accounting for the risk premium, does the choice of the model of the normal return matter? Yes, but only if the model produces a higher coefficient of determination ( $R^2$ ) than competing models. In that case, the variance of the abnormal return is smaller which makes the tests more precise.

To illustrate the importance of the model for normal returns, consider the market model (15.8). Under the null hypothesis that the event has no effect on the return, the abnormal return would be just the residual in the regression (15.8). It has the variance (assuming we know the model parameters)

$$\text{Var}(u_{it}) = \text{Var}(\varepsilon_{it}) = (1 - R^2) \text{Var}(R_{it}), \quad (15.12)$$

where  $R^2$  is the coefficient of determination of the regression (15.8).

**Proof.** (of (15.12)) Recall that  $R^2$  is defined as

$$R^2 = 1 - \frac{\text{Var}(\varepsilon_{it})}{\text{Var}(R_{it})}.$$

Rearrange to get (15.12). ■

This variance is crucial for testing the hypothesis of no abnormal returns: the smaller is the variance, the easier it is to reject a false null hypothesis (see Section 15.3). The constant mean model has  $R^2 = 0$ , so the market model could potentially give a much smaller variance. If the market model has  $R^2 = 0.75$ , then the standard deviation of the abnormal return is only half that of the constant mean model (since  $\sqrt{1 - 0.75} = 0.5$ ). More realistically,  $R^2$  might be 0.43 (or less), so the market model gives a 25% decrease in the standard deviation. Experience with multi-factor models also suggest that they give relatively small improvements of the  $R^2$  compared to the market model. For these reasons, and for reasons of convenience, the market model is still the dominating model of normal returns.

High frequency data can be very helpful, provided the time of the event is known.

High frequency data effectively allows us to decrease the volatility of the abnormal return since it filters out irrelevant (for the event study) shocks to the return while still capturing the effect of the event.

### 15.3 Testing the Abnormal Return

In testing if the abnormal return is different from zero, there are two sources of sampling uncertainty. First, the parameters of the normal return model are uncertain. Second, even if we knew the normal return for sure, the returns are random variables—and they will always deviate from their population means in any finite sample. The first source of uncertainty is likely to be much smaller than the second—provided the estimation window is much longer than the event window. This is the typical situation, so the rest of the discussion will focus on the second source of uncertainty.

It is typically assumed that the abnormal returns are uncorrelated across time and across assets. The first assumption is motivated by the very low autocorrelation of returns. The second assumption makes a lot of sense if the events are not overlapping in time, so that the event of assets  $i$  and  $j$  happen at different (calendar) times. In contrast, if the events happen at the same time, the cross-correlation must be handled somehow (see below). This is, for instance, the case if the events are macroeconomic announcements or monetary policy moves. For the rest of this section we assume no autocorrelation or cross correlation.

Let  $\sigma_i^2 = \text{Var}(u_{it})$  be the variance of the abnormal return of asset  $i$ . The *variance of the cross-sectional* (across the  $n$  assets) *average*,  $\bar{u}_s$  in (15.2), is then

$$\text{Var}(\bar{u}_s) = (\sigma_1^2 + \sigma_2^2 + \dots + \sigma_n^2) / n^2 = \sum_{i=1}^n \sigma_i^2 / n^2, \quad (15.13)$$

since all covariances are assumed to be zero. In a large sample (where the asymptotic normality of a sample average starts to kick in), we can therefore use a  $t$ -test

$$\bar{u}_s / \text{Std}(\bar{u}_s) \xrightarrow{d} N(0, 1). \quad (15.14)$$

In most applications the  $\sigma_i^2$  values used in (15.13) are from the estimation window, as discussed in Section 15.2.

**Remark 15.3** (\*An alternative way to test  $\bar{u}_s$ , using the cross-sectional standard deviation of  $u_{is}$ ) An alternative and intuitive approach to calculate  $\text{Var}(\bar{u}_s)$  is to use  $\sigma_{CR}^2 / n$ , where where  $\sigma_{CR}^2$  is the cross-sectional variance of  $u_{is}$ . In fact, it can be shown that the

*cross-sectional variance*  $\sigma_{CR}^2$  is an unbiased estimate of  $\sum_{i=1}^n \sigma_i^2 / n$ . This suggests that using (15.13) and  $\sigma_{CR}^2 / n$  are conceptually the same. (The extension to cumulative returns over  $q$  period is straightforward: just multiply the one-period variance by  $q$ .) However,  $\sigma_{CR}^2$  suffers from the drawback that it is an estimate based on only  $n$  data points, so it is likely to be a noisy estimate when the number of events ( $n$ ) is small. This speaks in favour of using (15.13) and a large estimation window for each of the assets.

The *cumulative abnormal return* over  $q$  period,  $car_{i,q}$ , can also be tested with a  $t$ -test. Since the returns are assumed to have no autocorrelation the variance of the  $car_{i,q}$

$$\text{Var}(car_{i,q}) = q\sigma_i^2. \quad (15.15)$$

This variance is increasing in  $q$  since we are considering cumulative returns (not the time average of returns).

If the abnormal returns are uncorrelated across time, then the *cross-sectional average*  $car_{i,q}$  is

$$\text{Var}(\bar{car}_q) = q \text{Var}(\bar{u}_s), \quad (15.16)$$

where  $\text{Var}(\bar{u}_s)$  is defined in (15.13).

**Empirical Example 15.4** (Testing CAR) See Figure 15.2 for results on IPOs.

**Example 15.5** (Variances of abnormal returns) If the standard deviations of the daily abnormal returns of the two firms in Example 15.2 are  $\sigma_1 = 0.1$  and  $\sigma_2 = 0.2$ , then we have the following variances for the abnormal returns at different days

Time	Firm 1	Firm 2	Cross-sectional Average
-1	$0.1^2$	$0.2^2$	$(0.1^2 + 0.2^2) / 4$
0	$0.1^2$	$0.2^2$	$(0.1^2 + 0.2^2) / 4$
1	$0.1^2$	$0.2^2$	$(0.1^2 + 0.2^2) / 4$

Similarly, the variances for the cumulative abnormal returns are

Time	Firm 1	Firm 2	Cross-sectional Average
-1	$0.1^2$	$0.2^2$	$(0.1^2 + 0.2^2) / 4$
0	$2 \times 0.1^2$	$2 \times 0.2^2$	$2 \times (0.1^2 + 0.2^2) / 4$
1	$3 \times 0.1^2$	$3 \times 0.2^2$	$3 \times (0.1^2 + 0.2^2) / 4$

**Example 15.6** (Tests of abnormal returns) By dividing the numbers in Example 15.2 by the square root of the numbers in Example 15.5 (that is, the standard deviations) we get

the test statistic for the abnormal returns

<u>Time</u>	<u>Firm 1</u>	<u>Firm 2</u>	<u>Cross-sectional Average</u>
-1	2	-0.5	0.4
0	10	10	13.4
1	1	1.5	1.8

Similarly, the variances for the cumulative abnormal returns we have

<u>Time</u>	<u>Firm 1</u>	<u>Firm 2</u>	<u>Cross-sectional Average</u>
-1	2	-0.5	0.4
0	8.5	6.7	9.8
1	7.5	6.4	9.0

**Remark 15.7** (*Normalized cumulative abnormal returns\**). We now consider a normalization of the results whereby we report the cumulative abnormal return from the start of the event window until period  $s$ , denoted  $\text{car}(-w, s)$ , minus the cumulative abnormal return up to and including the event day, denoted  $\text{car}(-w, 0)$ ,

$$\text{car}^n(-w, s) = \text{car}(-w, s) - \text{car}(-w, 0).$$

For instance, with  $(w = -2)$  we clearly have

$$\begin{aligned}\text{car}^n(-2, -2) &= u_{-2} - (u_{-2} + u_{-1} + u_0) = -(u_{-1} + u_0) \\ \text{car}^n(-2, -1) &= u_{-2} + u_{-1} - (u_{-2} + u_{-1} + u_0) = -u_0 \\ \text{car}^n(-2, 0) &= 0 \\ \text{car}^n(-2, 1) &= u_{-2} + u_{-1} + u_0 + u_1 - (u_{-2} + u_{-1} + u_0) = u_1 \\ \text{car}^n(-2, 2) &= u_{-2} + u_{-1} + u_0 + u_1 + u_2 - (u_{-2} + u_{-1} + u_0) = u_1 + u_2.\end{aligned}$$

If the abnormal returns are uncorrelated across time, then it is clear that the variances of the  $\text{car}^n(-w, s)$  is zero on the event day and scales with  $|s|$  for the days (fanning out from  $s = 0$ )

$$\text{Var}[\text{car}^n(-w, s)] = |s|\sigma^2.$$

### 15.3.1 When Events are Clustered

When events (for different assets or firms) occur on the same days (are clustered), then we may have to consider the possibility that the abnormal returns are correlated, especially

when we test the cross-sectional average abnormal return.

The easiest approach to handle clustered events is demonstrate that they are still unlikely to be correlated. For instance, if we use the market model for normal returns, then the abnormal returns for firms in different industries might be uncorrelated. The second easiest approach is to create a portfolio which includes all assets (firms) with an event—and use that as the (only) test asset in an event study. Alternatively, we keep the cross-sectional data on the abnormal returns, but explicitly handle the cross-sectional correlations. To illustrate that, suppose there are only two assets, so the cross-sectional average is

$$\bar{u}_s = (u_{1s} + u_{2s})/2, \quad (15.17)$$

where  $u_{is}$  is the abnormal return on asset  $i$  on day  $s$ . In general, the variance of this average is

$$\text{Var}(\bar{u}_s) = (\sigma_1^2 + \sigma_2^2 + 2\sigma_{12})/4, \quad (15.18)$$

where  $\sigma_{12}$  is the covariance of  $u_{1s}$  and  $u_{2s}$ . Previously we assumed that  $\sigma_{12} = 0$  since the abnormal returns of the two assets refer to different calendar days. Here, we instead have to estimate  $\sigma_{12}$  in the estimation window and include it in the calculations. Notice that we can write this in matrix form as

$$\text{Var}(\bar{u}_s) = \begin{bmatrix} 1 \\ 1 \end{bmatrix}' \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{21} & \sigma_2^2 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \end{bmatrix} / 4, \quad (15.19)$$

where the matrix in the middle is the variance-covariance matrix of the two returns. (It is symmetric so  $\sigma_{12} = \sigma_{21}$ .) With  $n$  assets, the formula becomes

$$\text{Var}(\bar{u}_s) = \mathbf{1}' \Sigma \mathbf{1} / n^2, \quad (15.20)$$

where  $\Sigma$  is the variance-covariance matrix of all  $n$  assets and  $\mathbf{1}$  is a column ( $n$  rows) vectors filled with ones. Clearly, this is the same as summing all the elements of the variance-covariance matrix and then dividing by  $n^2$ . We then replace  $\text{Var}(\bar{u}_s)$  in (15.13) and (15.16) with (15.20). The rest of the analysis is unchanged.

## 15.4 Quantitative Events

Some events are not easily classified as binary variables. For instance, the effect of positive earnings surprise is likely to depend on how large the surprise is—not just if there was a positive surprise. This can be studied by regressing the abnormal return (typically

the cumulative abnormal return) on the value of the event ( $x_i$ )

$$\text{car}_{iq} = a + bx_i + \xi_i. \quad (15.21)$$

The slope coefficient is then a measure of how much the cumulative abnormal return reacts to a change of one unit of  $x_i$ .

# Chapter 16

## Maximum Likelihood Estimation

Reference: Verbeek (2012) 6

More advanced material is denoted by a star (\*). It is not required reading.

### 16.1 Maximum Likelihood

Maximum likelihood estimation (MLE) fits a distribution to (some transformation of) data by choosing the parameters of the distribution (for instance, mean and variance) so as to maximise the overlap of the fitted distribution and data. See Figure 16.1 for an example.

Implementing MLE involves two main steps: (1) specify the likelihood function; (2) maximize it by choosing the parameter values. This estimator (estimation method) has very nice properties, provided the basic distributional assumptions are correct, that is, if we maximize the right likelihood function. In that case, MLE is typically the most efficient/precise estimators (at least in very large samples). ML also provides a coherent framework for testing hypotheses (including the Wald, LM, and LR tests). In addition, MLE is a way to construct a new estimator when there is no existing method that is tailor made for your model.

To understand the principle of maximum likelihood estimation, consider the following examples.

#### 16.1.1 Example: Estimating the Mean with ML

Suppose we know  $x_t \sim N(\mu, \sigma^2)$ , but we don't know the value of  $\mu$  (for now, assume we know the variance). Since  $x_t$  is a random variable, there is a probability of every

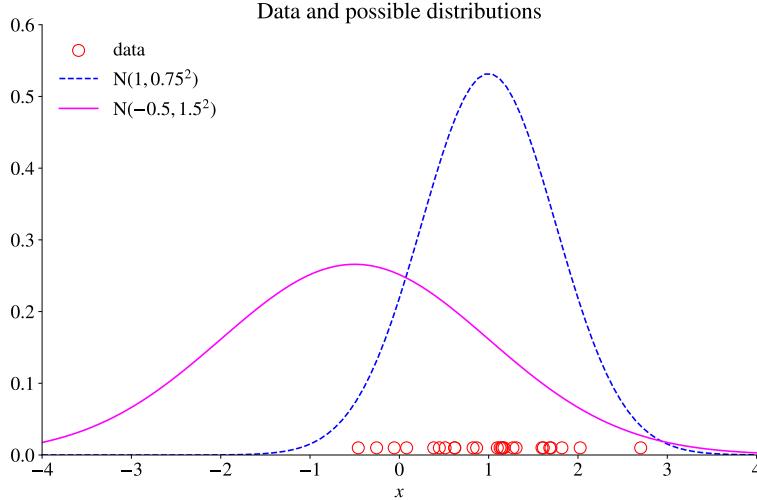


Figure 16.1: Example of data and possible distributions

observation and the density function of  $x_t$  is

$$L_t = \text{pdf}(x_t) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left[-\frac{1}{2}\frac{(x_t - \mu)^2}{\sigma^2}\right], \quad (16.1)$$

where  $L$  stands for “likelihood” and  $L_t$  denotes that this is the contribution of observation  $t$ . The basic idea of maximum likelihood estimation (MLE) is to pick model parameters to make the observed data have the highest possible probability. In case we had only observation  $t$  in our sample, we would get  $\hat{\mu} = x_t$ . This is the maximum likelihood estimator for this trivial sample.

What if there are  $T$  observations,  $x_1, x_2, \dots, x_T$ ? In the simplest case where  $x_i$  and  $x_j$  are *independent*, then the joint pdf is just the product of the individual pdfs (for instance,  $\text{pdf}(x_i, x_j) = \text{pdf}(x_i) \text{pdf}(x_j)$ ) so

$$L = \text{pdf}(x_1) \times \text{pdf}(x_2) \times \dots \times \text{pdf}(x_T) \quad (16.2)$$

$$= (2\pi\sigma^2)^{-T/2} \exp\left[-\frac{1}{2}\left(\frac{(x_1 - \mu)^2}{\sigma^2} + \frac{(x_2 - \mu)^2}{\sigma^2} + \dots + \frac{(x_T - \mu)^2}{\sigma^2}\right)\right] \quad (16.3)$$

We want to maximize  $L$  with respect to  $\mu$ . We clearly get the same result if we instead maximize  $\ln L$  (since the logarithmic function is an increasing monotone function), which

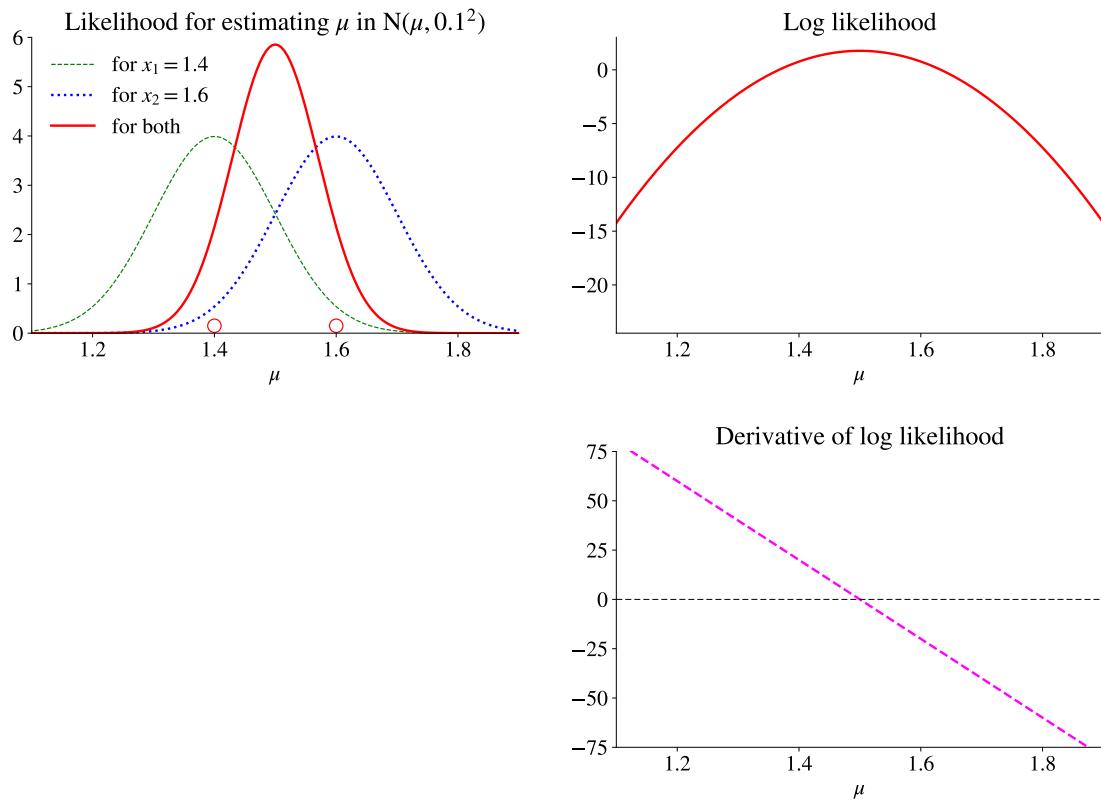


Figure 16.2: Likelihood function for estimating a sample mean

is sometimes easier. Therefore, take logs (to get the *log likelihood function*)

$$\ln L = \sum_{t=1}^T \ln L_t, \text{ where} \quad (16.4)$$

$$\ln L_t = -\frac{1}{2} \ln(2\pi) - \frac{1}{2} \ln(\sigma^2) - \frac{1}{2\sigma^2} (x_t - \mu)^2. \quad (16.5)$$

See Figure 16.2 for an illustration. For instance, the figure shows that a distribution centered on  $\mu = 1.4$  gives a higher pdf for a data point  $x_t = 1.4$  than a distribution with  $\mu = 1.6$ . However, for another  $x_t$  value, another  $\mu$  might be better. For a sample (here with 2 data points), the optimal  $\mu$  is a compromise.

The derivative with respect to  $\mu$  is

$$\frac{\partial \ln L}{\partial \mu} = \frac{1}{\sigma^2} [(x_1 - \mu) + (x_2 - \mu) + \dots + (x_T - \mu)]. \quad (16.6)$$

To maximize the likelihood function, find the value of  $\hat{\mu}$  that makes  $\partial \ln L / \partial \mu = 0$ .

Clearly, that is the usual sample average

$$\hat{\mu} = (x_1 + x_2 + \dots + x_T) / T. \quad (16.7)$$

**Remark 16.1** (*Correlated data\**) Suppose now that  $x_t$  is correlated with  $x_{t-1}$ . We would then replace  $\text{pdf}(x_t)$  in (16.2)–(16.3) by the conditional density function  $\text{pdf}(x_t|x_{t-1})$ . In practice, this means that we need to model/estimate also the mechanism for the correlation. For instance, if  $x_t$  is a MA(1) process,  $x_t = \mu + \varepsilon_t + \theta\varepsilon_{t-1}$  where  $\varepsilon_t$  is iid  $N(0, \sigma^2)$ , then  $\varepsilon_t = x_t - \mu - \theta\varepsilon_{t-1}$ . Assuming  $\varepsilon_0 = 0$  (and values of  $(\mu, \sigma^2, \theta)$ ) allows us to calculate  $\ln L_t = -\ln(2\pi)/2 - \ln(\sigma^2)/2 - \varepsilon_t^2/(2\sigma^2)$ . Maximising  $\ln L = \sum_{t=1}^T \ln L_t$  with respect to  $(\mu, \sigma^2, \theta)$  gives the MLE.

### 16.1.2 Example: Estimating the Variance with ML

To instead estimate the variance (now assuming you know the mean  $\mu$ ), use (16.4) and find the value  $\sigma^2$  that makes  $\partial \ln L / \partial \sigma^2 = 0$

$$\begin{aligned} 0 &= \frac{\partial \ln L}{\partial \sigma^2} \\ &= -\frac{T}{2} \frac{1}{\sigma^2} + \frac{1}{2(\sigma^2)^2} [(x_1 - \mu)^2 + (x_2 - \mu)^2 + \dots + (x_T - \mu)^2], \end{aligned} \quad (16.8)$$

so

$$\hat{\sigma}^2 = \frac{1}{T} [(x_1 - \mu)^2 + (x_2 - \mu)^2 + \dots + (x_T - \mu)^2]. \quad (16.9)$$

This is clearly the usual formula for a sample variance, although we divide by  $T$ , not by  $T - 1$  (so  $\hat{\sigma}^2$  is biased, but the bias disappears as  $T \rightarrow \infty$ ).

### 16.1.3 MLE of a Regression

To apply this idea to a (multiple) regression model

$$y_t = \beta' x_t + u_t, \quad (16.10)$$

we assume that  $u_t$  is iid  $N(0, \sigma^2)$ . The probability density function of  $u_t$  is then

$$\text{pdf}(u_t) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp(-\frac{1}{2}u_t^2/\sigma^2). \quad (16.11)$$

Since the errors are independent, we get the joint pdf of the  $u_1, u_2, \dots, u_T$  by multiplying the marginal pdfs of each of the errors

$$\begin{aligned} L &= \text{pdf}(u_1) \times \text{pdf}(u_2) \times \dots \times \text{pdf}(u_T) \\ &= (2\pi\sigma^2)^{-T/2} \exp\left[-\frac{1}{2}\left(\frac{u_1^2}{\sigma^2} + \frac{u_2^2}{\sigma^2} + \dots + \frac{u_T^2}{\sigma^2}\right)\right]. \end{aligned} \quad (16.12)$$

We divide by the same  $\sigma^2$  in all terms, since we assumed iid residuals—which implies (among other things) that the variance is the same for all observations.

Substitute  $y_t - \beta'x_t$  for  $u_t$  and take logs to get the log likelihood function of the sample

$$\ln L = \sum_{t=1}^T \ln L_t, \text{ where} \quad (16.13)$$

$$\ln L_t = -\frac{1}{2} \ln(2\pi) - \frac{1}{2} \ln(\sigma^2) - \frac{1}{2\sigma^2} (y_t - \beta'x_t)^2. \quad (16.14)$$

Suppose (for simplicity) that we happen to know the value of  $\sigma^2$ . It is then clear that this likelihood function is maximized by minimizing the last term, which is proportional to the sum of squared errors: LS is ML when the errors are iid normally distributed (but only then). (This holds also when we do not know the value of  $\sigma^2$ —just slightly messier to show it.) See Figure 16.3.

**Example 16.2** Consider the regression model  $y_t = \beta_1 x_t + u_t$ , where we (happen to) know that  $u_t \sim N(0, 1)$ . Suppose we have the following data

<u><math>t</math></u>	<u><math>x</math></u>	<u><math>y</math></u>
1	-1	-1.5
2	0	-0.6
3	1	2.1

With  $\beta_1 = 1.6$  we get

<u><math>t</math></u>	<u><math>u_t</math></u>	<u><math>u_1^2</math></u>	<u><math>\ln \text{pdf}(u_1)</math></u>
1	$-1.5 - 1.6 \times (-1) = 0.1$	0.01	-0.924
2	$-0.6 - 1.6 \times 0 = -0.6$	0.36	-1.099
3	$2.1 - 1.6 \times 1 = 0.5$	0.25	-1.044
<i>sum</i>	0	0.62	-3.067

With  $\beta = 1.8$  and  $\beta = 2.0$  we instead get

<u>t</u>	<u>u<sub>t</sub></u>	<u>u<sub>1</sub><sup>2</sup></u>	ln pdf(u <sub>1</sub> )
1	$-1.5 - \mathbf{1.8} \times (-1) = 0.3$	0.09	-0.964
2	$-0.6 - \mathbf{1.8} \times 0 = -0.6$	0.36	-1.099
3	$2.1 - \mathbf{1.8} \times 1 = 0.3$	0.09	-0.964
sum	0	0.54	-3.027

<u>t</u>	<u>u<sub>t</sub></u>	<u>u<sub>1</sub><sup>2</sup></u>	ln pdf(u <sub>1</sub> )
1	$-1.5 - \mathbf{2.0} \times (-1) = 0.5$	0.25	-1.044
2	$-0.6 - \mathbf{2.0} \times 0 = -0.6$	0.36	-1.099
3	$2.1 - \mathbf{2.0} \times 1 = 0.1$	0.01	-0.924
sum	0	0.62	-3.067

Among these alternatives,  $\beta = 1.8$  has the highest log likelihood value (it is actually the optimum). See Figure 16.3.

#### 16.1.4 MLE of a Regression with GARCH(1,1) Errors

Consider a regression model where the residuals are uncorrelated across time, but have time-varying volatility

$$y_t = b'x_t + u_t, \text{ where } u_t \text{ is } N(0, \sigma_t^2). \quad (16.15)$$

The variance follows the GARCH(1,1) process

$$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta \sigma_{t-1}^2. \quad (16.16)$$

(It is assumed that  $\omega > 0$ ;  $\alpha, \beta \geq 0$ ; and  $\alpha + \beta < 1$ .)

To estimate this model (that is, the parameters in  $(b, \omega, \alpha, \beta)$ ), we could use a numerical optimization routine to maximize the log likelihood function

$$\ln L = \sum_{t=1}^T L_t, \text{ where } L_t = -\frac{1}{2} \ln(2\pi) - \frac{1}{2} \ln \sigma_t^2 - \frac{1}{2\sigma_t^2} u_t^2, \quad (16.17)$$

where  $u_t$  is calculated from (16.15) and  $\sigma_t^2$  from (16.16). This is very similar to the linear regression (16.13)–(16.14), except that there is a time-subscript (and model for)  $\sigma_t^2$ .

The optimization routine searches for the values of  $(b, \omega, \alpha, \beta)$  that makes the value of

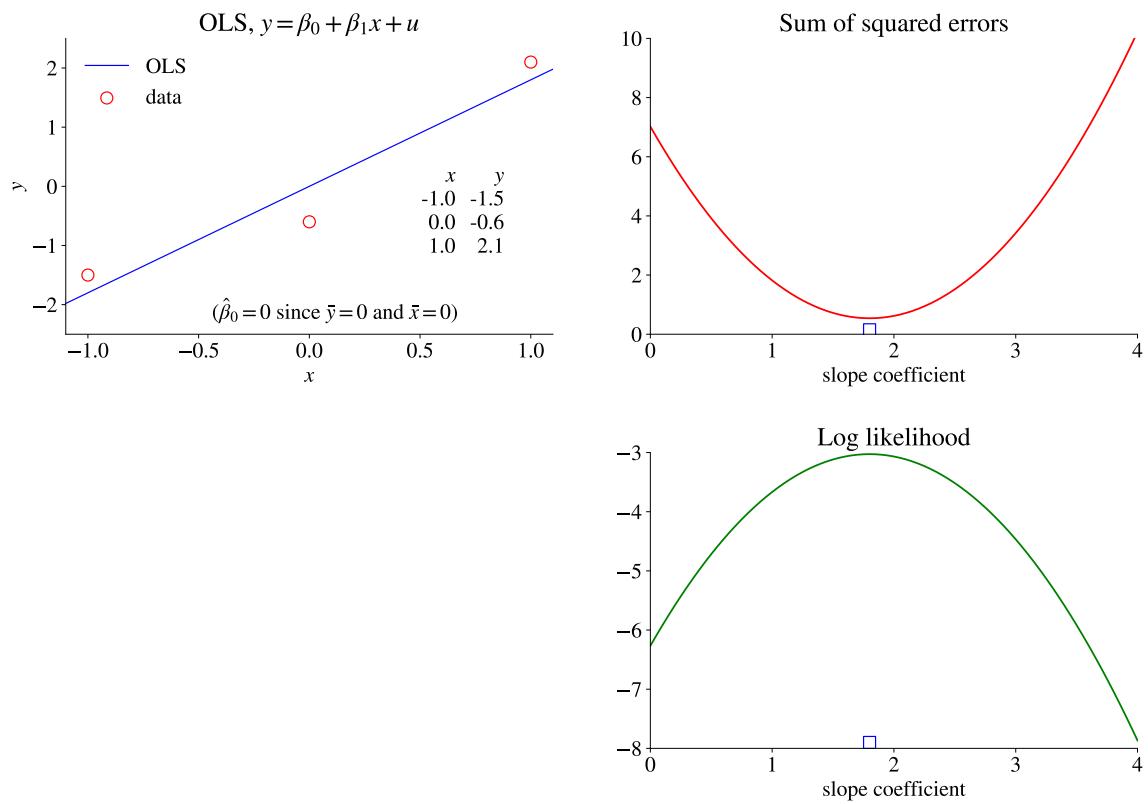


Figure 16.3: Example of OLS and ML estimation

the log likelihood function as large as possible. (However, it may be necessary to impose the parameter restrictions mentioned above.)

**Empirical Example 16.3 (MLE of a GARCH model)** See Figure 16.4 for a MLE of a GARCH(1,1) model.

## 16.2 Key Properties of MLE

There are no general results on small-sample properties of MLE: it can be biased or not.

In contrast, MLE has very nice asymptotic (large-sample) properties, provided we maximize the right likelihood function. If so, then:

1. MLE is consistent ( $\Pr(|\hat{\beta} - \beta| > a^2) \rightarrow 0$ ) gets very small as  $T$  gets large, for any choice of  $a$ )

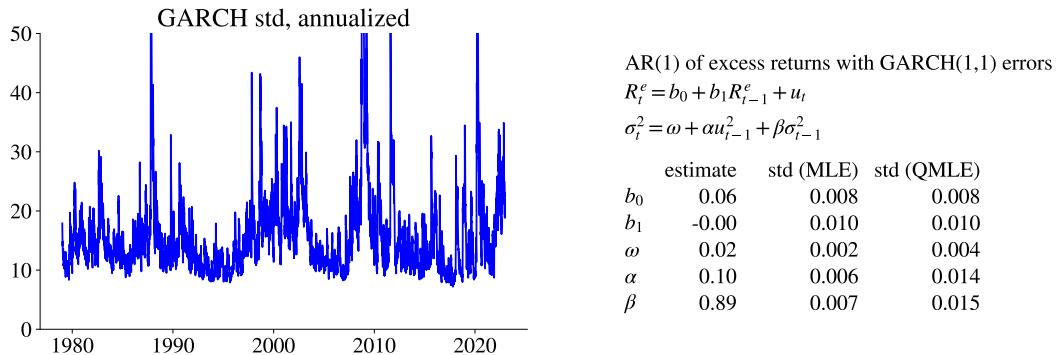


Figure 16.4: GARCH estimates

2. MLE is the most efficient/precise estimator, at least asymptotically (efficient = smallest variance)
3. MLE estimates ( $\hat{\theta}$ ) are normally distributed,

$$\sqrt{T}(\hat{\theta} - \theta) \xrightarrow{d} N(0, V), \quad (16.18)$$

$$V = I(\theta)^{-1} \text{ with } I(\theta) = -E \frac{\partial^2 \ln L}{\partial \theta \partial \theta} / T. \quad (16.19)$$

( $I(\theta)$  is called the “information matrix”).

4. ML also provides a coherent framework for testing hypotheses (including the Wald, LM, and LR tests).

**Remark 16.4** (\*Calculating  $I(\theta)$ ) Notice that  $-E \frac{\partial^2 \ln L}{\partial \theta \partial \theta} / T = -E \frac{\partial^2 \log L_t}{\partial \theta \partial \theta}$ , where  $\ln L_t$  is the log likelihood contribution of observation  $t$ . This is also the same as  $-\frac{\partial^2 E \log L_t}{\partial \theta \partial \theta}$ , that is, we can calculate the derivatives of the average  $\log L_t$  value. This sometimes helps the numerical implementation.

### 16.2.1 Example of the Information Matrix

Differentiate (16.6), assuming we know  $\sigma^2$ , to get

$$\frac{\partial^2 \ln L}{\partial \mu \partial \mu} = -\frac{T}{\sigma^2}. \quad (16.20)$$

The information matrix is

$$I(\theta) = -E \frac{\partial^2 \ln L}{\partial \theta \partial \theta} / T = \frac{1}{\sigma^2}, \quad (16.21)$$

which we combine with (16.18)–(16.19) to get

$$\sqrt{T}(\hat{\mu} - \mu) \xrightarrow{d} N(0, \sigma^2) \text{ or } \hat{\mu} \xrightarrow{d} N(\mu, \sigma^2 / T). \quad (16.22)$$

This is the standard expression for the distribution of a sample average. In practice, we replace  $\sigma^2$  by the sample variance.

### 16.3 Three Test Principles

*Wald test:* estimate  $\theta$  with MLE, check if  $\hat{\theta} - \theta_{H_0}$  is too large. Example: t-test and F-test.

*Likelihood ratio test:* estimate  $\theta$  with MLE as usual, estimate again by imposing the  $H_0$  restrictions, test if  $\ln L(\hat{\theta}) - \ln L(\text{"}\hat{\theta}\text{ with } H_0\text{ restrictions"}) = 0$ . Example: compare the  $R^2$  from a model without and with a restriction on some coefficient (for instance, that it is zero).

*Lagrange multiplier test.* Estimate  $\theta$  under the  $H_0$  restrictions, check if  $\partial \ln L / \partial \theta = 0$  for unconstrained model is true when evaluated at “ $\hat{\theta}$  with  $H_0$  restrictions.”

### 16.4 QMLE

A MLE based on the wrong likelihood function (distribution) may still be useful.

Suppose we use the likelihood function  $\tilde{L}$  and get estimates  $\hat{\theta}$  by

$$\frac{\partial \ln \tilde{L}}{\partial \theta} = \mathbf{0} \quad (16.23)$$

If  $\tilde{L}$  is wrong (therefore, it carries a tilde), then we are maximizing the wrong thing. For instance, we might have constructed  $\tilde{L}$  by assuming that the regression residuals are normally distributed, while they are, in fact, following a  $t$ -distribution. With some luck, we still get reasonable (consistent) estimates.

**Example 16.5 (LS and QMLE)** In a linear regression,  $y_t = x'_t \beta + \varepsilon_t$ , the first order condition for MLE based on the assumption that  $\varepsilon_t \sim N(0, \sigma^2)$  is  $\sum_{t=1}^T (y_t - x'_t \hat{\beta}) x_t = \mathbf{0}$ . This has an expected value of zero (at the true parameters), even if the shocks have a, say,  $t_{22}$  distribution (which would define the correct likelihood function).

The example suggests that if

$$E \frac{\partial \ln \tilde{L}}{\partial \theta} = \mathbf{0}, \quad (16.24)$$

then the estimates are still consistent. We are doing *quasi-MLE* (or pseudo-MLE).

With QMLE,  $\sqrt{T}(\hat{\theta} - \theta) \rightarrow^d N(0, V)$ , but with the “sandwich” variance-covariance matrix

$$V = I(\theta)^{-1} E \left[ \frac{\partial \ln \tilde{L}_t}{\partial \theta} \left( \frac{\partial \ln \tilde{L}_t}{\partial \theta} \right)' \right] I(\theta)^{-1}. \quad (16.25)$$

**Empirical Example 16.6** (*MLE of a GARCH model*) See Figure 16.4 for a MLE of a GARCH(1,1) model. For some of the parameters, the robust standard errors are distinctly higher.

The practical implication: this is perhaps a “safer” way of constructing tests—since it is less restrictive than assuming that we have the exactly correct likelihood function.

# Chapter 17

## ARCH and GARCH

Reference: Bodie, Kane, and Marcus (2005) 13.4

Reference (advanced): Taylor (2005) 8–9; Verbeek (2012) 8; Campbell, Lo, and MacKinlay (1997) 12; Franses and van Dijk (2000)

### 17.1 Heteroskedasticity

#### 17.1.1 Descriptive Statistics of Heteroskedasticity

Time-variation in volatility (heteroskedasticity) is a common feature of macroeconomic and financial data.

The perhaps most straightforward way to gauge heteroskedasticity is to estimate a time-series of variances on “rolling samples.” For a zero-mean variable,  $u_t$ , this could be

$$\sigma_t^2 = (u_{t-1}^2 + u_{t-2}^2 + \dots + u_{t-q}^2)/q. \quad (17.1)$$

Notice that  $\sigma_t^2$  depends on lagged information, and could therefore be thought of as the prediction (made in  $t - 1$ ) of the volatility in  $t$ . This method can be used for detecting time variation in volatility—and the estimates (for instance, over a month) are sometimes called *realised volatility*. Alternatively, this method can also be used to gauge seasonality in volatility by estimating the variance for each “season,” for instance, Mondays.

**Empirical Example 17.1** (*Time-varying FX volatility*) See Figures 17.1 and 17.2 for examples based on high-frequency FX data.

**Empirical Example 17.2** (*Time-varying equity volatility*) See Figure 17.4 for a comparison of realized S&P 500 volatility with an option based measure (VIX).

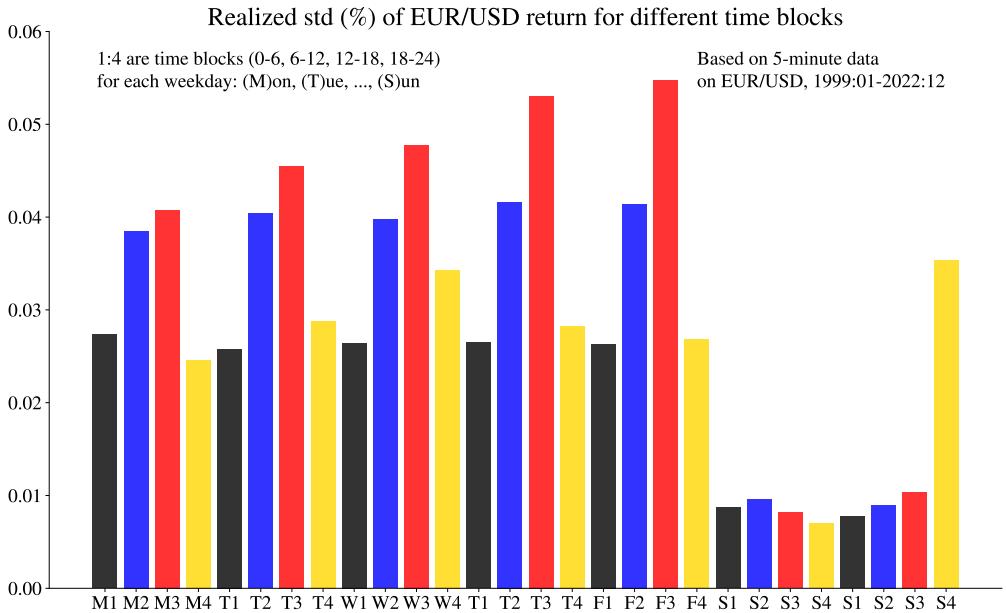


Figure 17.1: Standard deviation

Unfortunately, the approach in (17.1) can produce quite abrupt changes in the estimate. An alternative is to apply an exponentially weighted moving average (EWMA) estimator of volatility, which uses all data points since the beginning of the sample—but where recent observations carry larger weights. The weight for lag  $s$  is  $(1 - \lambda)\lambda^s$  where  $0 < \lambda < 1$ , so

$$\sigma_t^2 = (1 - \lambda)(u_{t-1}^2 + \lambda u_{t-2}^2 + \lambda^2 u_{t-3}^2 + \dots). \quad (17.2)$$

See Figure 17.3 for an illustration of the weights. (The weights clearly sum to one.) This can also be calculated in a recursive way as

$$\sigma_t^2 = (1 - \lambda)u_{t-1}^2 + \lambda\sigma_{t-1}^2. \quad (17.3)$$

The initial value (before the sample) could be assumed to be zero or (perhaps better) the unconditional variance in a historical sample.

This method is commonly used by practitioners. For instance, the RISK Metrics uses this method with  $\lambda = 0.94$  for use on daily data. Alternatively,  $\lambda$  can be chosen to minimize some criterion function.

**Empirical Example 17.3 (Choosing  $\lambda$  by ML)** See Figure 17.5 for an example of estimating  $\lambda$  maximum likelihood (assuming a normal distribution): maximize (17.9) where

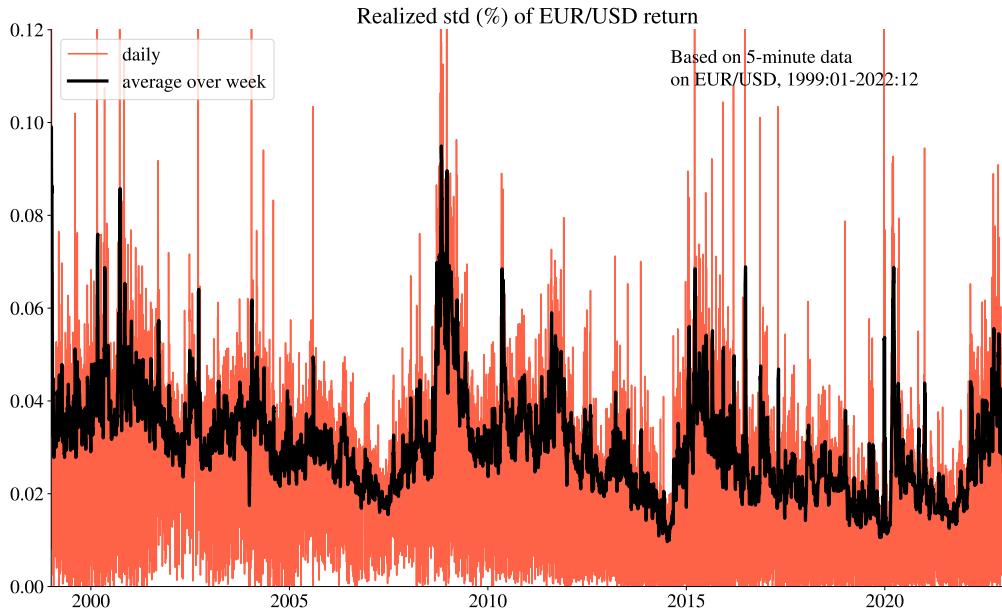


Figure 17.2: Standard deviation for EUR/USD exchange rate changes

$$u_t = R_t - \mu_t.$$

**Remark 17.4** (*EWMA on a limited data window\**) To implement the EWMA method on a moving data window over  $q$  data points ( $t - q$  to  $t - 1$ ) use

$$\sigma_t^2 = \frac{1 - \lambda}{1 - \lambda^q} (u_{t-1}^2 + \lambda u_{t-2}^2 + \dots + \lambda^{q-1} u_{t-q}^2).$$

Notice that the weights sum to one, provided  $\lambda \neq 1$ . This can also be written on recursive form as

$$\sigma_t^2 = \frac{1 - \lambda}{1 - \lambda^q} (u_{t-1}^2 - \lambda^q u_{t-q-1}^2) + \lambda \sigma_{t-1}^2.$$

### 17.1.2 Predicting Realized Volatility

Volatility and correlations are often predictable, at least for horizons up to a couple of months.

**Empirical Example 17.5** (*Predicting equity and FX volatility*) See Tables 17.1 – 17.2 for examples of very simple prediction equations. The latter includes week day dummies to handle seasonality.

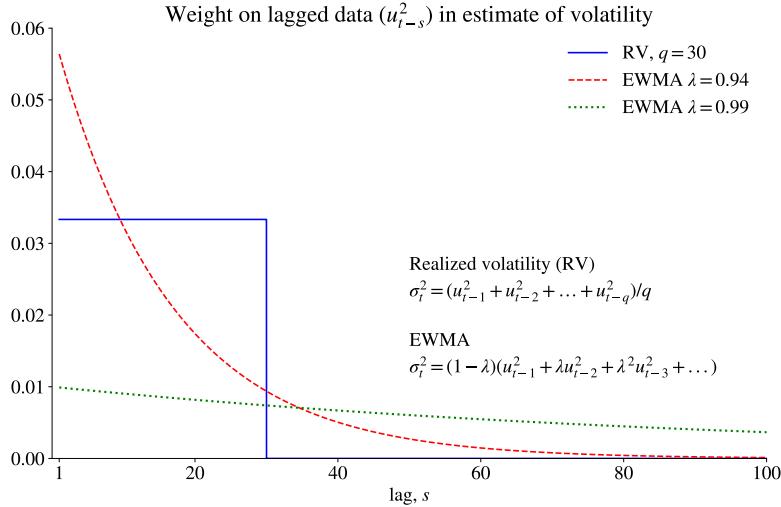


Figure 17.3: Weights on old data in the EMA approach to estimate volatility

### 17.1.3 Heteroskedastic Residuals in a Regression

Suppose we have a regression model

$$y_t = x_t' \beta + u_t, \text{ where} \quad (17.4)$$

$$\mathbb{E} u_t = 0 \text{ and } \text{Cov}(x_{it}, u_t) = 0.$$

In the standard case we assume that  $u_t$  is iid (independently and identically distributed), which rules out heteroskedasticity.

OLS is still a useful estimator when the residuals actually are heteroskedastic. It is consistent (we get the correct values as the sample becomes really large)—and it is reasonably efficient (in terms of the variance of the estimates), although not the most efficient (MLE is). However, the standard expression for the standard errors (of the coefficients) is typically not correct. To be precise, it is not heteroskedasticity in itself that invalidates the standard OLS standard errors—only the type of heteroskedasticity that is related to the (squares of) the regressors. In fact, this is exactly what White's test of heteroskedasticity is aimed at.

There are two ways to handle this problem. First, we could use MLE to incorporate the structure of the heteroskedasticity. For instance, we could combine the regression model (17.4) with an ARCH structure of the residual. As a by-product we get the correct standard errors—provided, of course, the assumed distribution is correct. Second, we

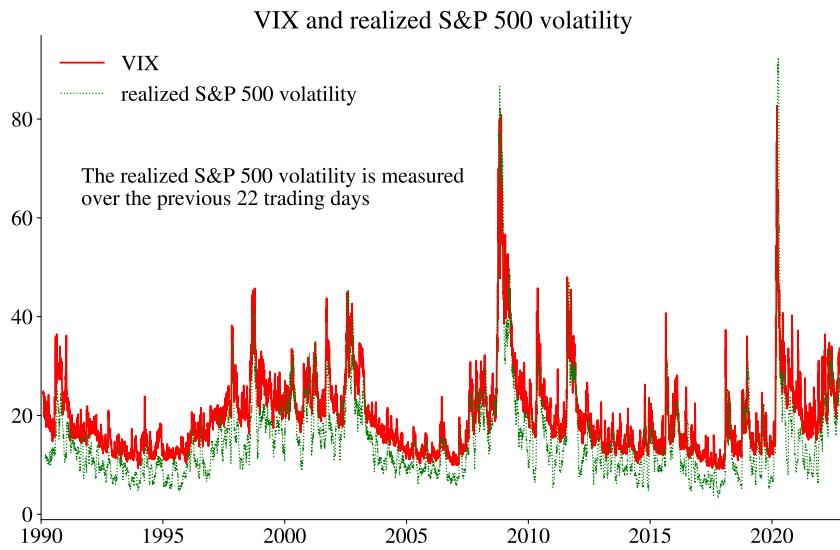


Figure 17.4: VIX and realized volatility (variance)

could stick to OLS, but use another expression for the variance of the coefficients: a “heteroskedasticity consistent covariance matrix,” among which “White’s covariance matrix” is the most common.

#### 17.1.4 Autoregressive Conditional Heteroskedasticity (ARCH)

Autoregressive heteroskedasticity is a special form of heteroskedasticity—and it is often found in financial data which shows volatility clustering.

To test for ARCH features, *Engle's test of ARCH* is perhaps the most straightforward. Let  $u_t$  be a zero-mean variable, for instance, the residuals from OLS. Then, estimate an AR( $q$ ) model for the squares

$$u_t^2 = \omega + a_1 u_{t-1}^2 + \dots + a_q u_{t-q}^2 + v_t. \quad (17.5)$$

Under the null hypothesis of no ARCH effects, all slope coefficients are zero and the  $R^2$  of the regression is zero. (This can be tested by noting that, under the null hypothesis,  $TR^2/(1 - R^2) \sim \chi_q^2$ .) Notice, however, that it is not evident that ARCH effects make the standard expression for the LS covariance matrix invalid (use White's test for that).

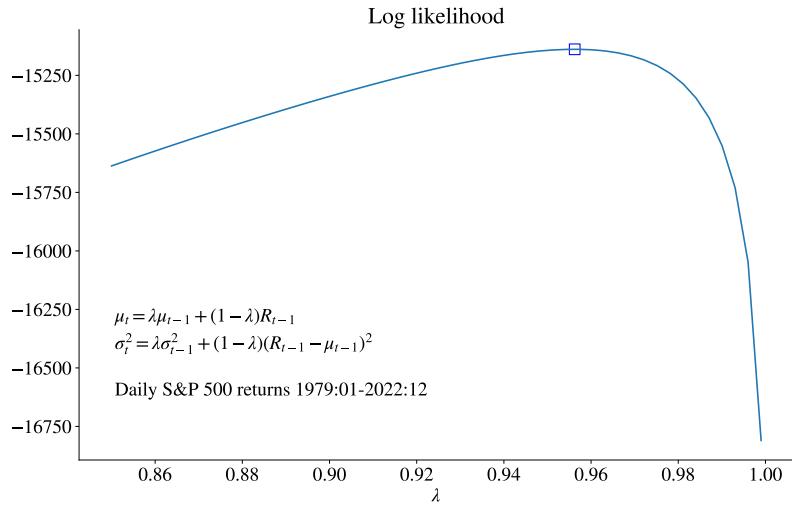


Figure 17.5: Estimation of  $\lambda$  in the EWMA method.

## 17.2 ARCH Models

This section discusses the Autoregressive Conditional Heteroskedasticity (ARCH) model. It is a model of how volatility depends on past volatility.

There are two basic reasons for being interested in an ARCH model. First, if residuals of the regression model (17.4) have ARCH features, then an ARCH model (that is, a specification of exactly how the ARCH features are generated) can help us estimate the regression model by maximum likelihood. Second, we may be interested in understanding the ARCH features more carefully, for instance, as an input in a portfolio choice process or for option pricing.

### 17.2.1 Properties of ARCH(1)

In the ARCH(1) model the residual in the regression equation (17.4), or some other zero-mean variable, can be written

$$u_t \sim N(0, \sigma_t^2), \text{ with} \quad (17.6)$$

$$\sigma_t^2 = \omega + \alpha u_{t-1}^2, \text{ with } \omega > 0 \text{ and } 0 \leq \alpha < 1. \quad (17.7)$$

Notice that  $\sigma_t^2$  is the conditional variance of  $u_t$ , and it is known already in  $t - 1$ . (Warning: some authors use a different convention for the time subscripts.) The non-negativity restrictions on  $\omega$  and  $\alpha$  are needed in order to guarantee  $\sigma_t^2 > 0$  and the upper bound

	(1)	(2)	(3)
log RV ( $t - 22$ )	0.68 (20.18)		0.10 (2.08)
log VIX ( $t - 22$ )		1.06 (26.46)	0.94 (14.64)
constant	0.83 (9.68)	-0.51 (-4.30)	-0.41 (-3.57)
$R^2$	0.46	0.57	0.57
obs	8236	8257	8236

Table 17.1: Regression of 22-day log realized S&P return volatility 1990:02-2022:12. All daily observations are used, so the residuals are likely to be autocorrelated. Numbers in parentheses are t-stats, based on Newey-West with 30 lags.

$\alpha < 1$  is needed in order to make the conditional variance stationary (more later).

If we assume that  $u_t$  is iid  $N(0, \sigma_t^2)$ , then the distribution of  $u_t$ , conditional on the information in  $t - 1$ , is  $N(0, \sigma_t^2)$ , where  $\sigma_t^2$  is known already in  $t - 1$ . Therefore, the one-step ahead distribution is normal—which can be used for estimating the model with ML.

However, the distribution of  $u_{t+1}$  (still conditional on the information in  $t - 1$ ) is more complicated. In particular, its variance is  $\sigma_{t+1}^2 = \omega + \alpha u_t^2$ , where  $u_t$  contains a random element. This makes  $u_{t+1}$  have a non-normal distribution. In fact, it will have fatter tails than a normal distribution with the same variance (excess kurtosis)—which is a common feature of financial data.

It is straightforward to show that the ARCH(1) model implies that we in period  $t$  can forecast the future conditional variance in  $t + s$  as

$$E_t \sigma_{t+s}^2 = \bar{\sigma}^2 + \alpha^{s-1} (\sigma_{t+1}^2 - \bar{\sigma}^2), \text{ with } \bar{\sigma}^2 = \frac{\omega}{1 - \alpha}, \quad (17.8)$$

where  $\bar{\sigma}^2$  is the unconditional variance and we recall that since  $\sigma_{t+1}^2$  is known in  $t$ . The conditional volatility behaves like an AR(1), and  $0 \leq \alpha < 1$  is necessary to keep it positive and stationary.

**Empirical Example 17.6 (ARCH and GARCH models)** See Figure 17.6 for an illustration of the fitted volatilities.

	log RV(EUR)	log RV(GBP)	log RV(CHF)	log RV(JPY)
lagged log RV	0.77 (73.16)	0.74 (45.71)	0.74 (51.20)	0.75 (56.66)
constant	-0.60 (-29.82)	-0.61 (-25.02)	-0.59 (-24.15)	-0.61 (-25.81)
D(Tue)	0.43 (22.02)	0.40 (17.30)	0.35 (17.22)	0.40 (16.96)
D(Wed)	0.38 (19.32)	0.35 (16.95)	0.30 (15.78)	0.36 (15.68)
D(Thu)	0.36 (17.58)	0.35 (16.53)	0.27 (13.88)	0.29 (12.50)
D(Fri)	0.30 (13.07)	0.30 (12.88)	0.21 (10.06)	0.29 (11.40)
$R^2$	0.61	0.55	0.56	0.58
obs	6259	6259	6259	6259

Table 17.2: Regression of daily log realized variance 1999:01-2022:12. All exchange rates are against the USD. The daily variances are calculated from 5 minute data. Numbers in parentheses are t-stats, based on Newey-West with 1 lag.

### 17.2.2 Estimation of the ARCH(1) Model

The most common way to estimate the model is to assume that  $u_t \sim \text{iid } N(0, \sigma_t^2)$ , as we did in (17.6), and to set up the likelihood function. The log likelihood is easily found, since the model is conditionally Gaussian. It is

$$\ln L = \sum_{t=1}^T L_t, \text{ where } L_t = -\frac{1}{2} \ln(2\pi) - \frac{1}{2} \ln \sigma_t^2 - \frac{1}{2} \frac{u_t^2}{\sigma_t^2}. \quad (17.9)$$

The estimates are found by maximizing the likelihood function (by choosing the parameters). This has to be done by a numerical optimization routine (which should preferably impose the constraints in (17.7)).

If  $u_t$  is just a zero-mean variable (so we have no regression equation), then this maximisation amounts to choosing the parameters ( $\omega$  and  $\alpha$ ) in (17.7). Instead, if  $u_t$  is a residual from a regression equation (17.4), then we instead need to choose both the regression coefficients ( $\beta$ ) in (17.4) and the parameters ( $\omega$  and  $\alpha$ ) in (17.7).

In either case, we need a starting value of  $\sigma_1^2 = \omega + \alpha u_0^2$ . This most common approach is to use the first observation as a “starting point,” that is, we actually have a sample from ( $t = 0$  to  $T$ ), but observation 0 is only used to construct a starting value of  $\sigma_1^2$ , and only

$\alpha :$	$\underline{\gamma = 0}$		$\underline{\gamma = 1}$	
	0	1	0	1
Simulated	7.1	18.8	13.5	25.1
OLS formula	7.1	13.3	13.4	19.3
White's	7.0	18.5	13.3	24.3
Bootstrap	7.1	18.5	13.4	24.3
Bootstrap 2	7.0	18.5	13.3	24.3
Jackknife	7.1	18.9	13.5	24.8
FGLS	7.5	17.3	14.0	24.2

Table 17.3: Standard error of OLS slope (%) under heteroskedasticity (simulation evidence). Model:  $y_t = 1 + 0.9x_t + \epsilon_t$ , where  $\epsilon_t \sim N(0, \sigma_t^2)$ , with  $\sigma_t^2 = (1 + \gamma|z_t| + \alpha|x_t|)^2$ , where  $z_t$  is iid  $N(0, 1)$  and independent of  $x_t$ . Sample length: 200. Number of simulations: 25000. The bootstrap draws pairs  $(y_s, x_s)$  with replacement while bootstrap 2 is a wild bootstrap.

observations 1 to  $T$  are used in the calculation of the likelihood function value.

Notice that if we estimate a regression function and an ARCH model simultaneous with MLE, then we automatically get the right standard errors of the regression coefficients from the information matrix. There is no need to use any adjusted (“White”) values.

**Remark 17.7** (*Regression with ARCH(1) residuals*) To estimate the full model (17.4) and (17.7) by MLE, we can do as follows.

First, guess values of the parameters  $\beta$  (a vector if  $x_t$  is), and  $\omega$ , and  $\alpha$ . The guess of  $\beta$  can be taken from an LS estimation of (17.4), and the guess of  $\omega$  and  $\alpha$  from an LS estimation of  $\hat{u}_t^2 = \omega + \alpha \hat{u}_{t-1}^2 + \varepsilon_t$  where  $\hat{u}_t$  are the fitted residuals from the LS estimation of (17.4).

Second, loop over the sample (first  $t = 1$ , then  $t = 2$ , etc.) and calculate  $u_t$  from (17.4) and  $\sigma_t^2$  from (17.7). Plug in these numbers in (17.9) to find the likelihood value.

Third, make better guesses of the parameters and do the second step again. Repeat until the likelihood value converges (at a maximum).

**Remark 17.8** (*Imposing parameter constraints on ARCH(1)*) To impose the restrictions in (17.7), iterate over values of  $(\beta, \tilde{\omega}, \tilde{\alpha})$  and let  $\omega = \tilde{\omega}^2$  and  $\alpha = \exp(\tilde{\alpha})/[1 + \exp(\tilde{\alpha})]$ .

It is sometimes found that the *standardized residuals*,  $u_t/\sigma_t$ , still have too fat tails compared with  $N(0, 1)$ . This would violate the assumption about a normal distribution in

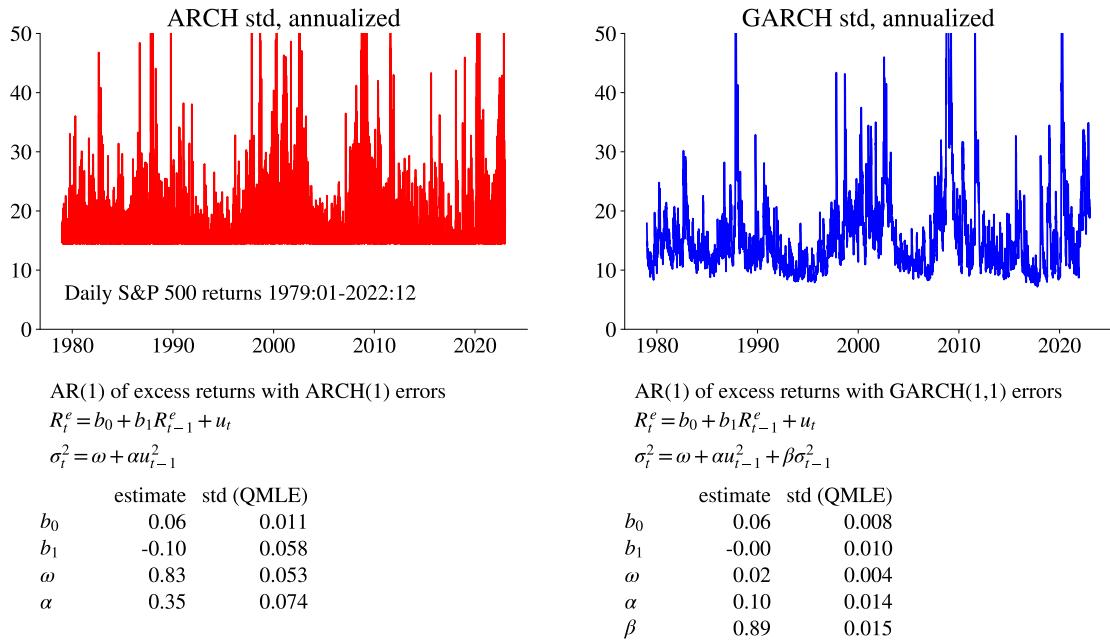


Figure 17.6: ARCH and GARCH estimates

(17.9). Estimation using other likelihood functions, for instance, for a t-distribution can then be used. Or the estimation can be interpreted as a quasi-ML (is typically consistent, but requires different calculation of the covariance matrix of the parameters).

It is straightforward to add more lags to (17.7). For instance, an ARCH( $p$ ) would be

$$\sigma_t^2 = \omega + \alpha_1 u_{t-1}^2 + \dots + \alpha_p u_{t-p}^2. \quad (17.10)$$

The form of the likelihood function is the same except that we now need  $p$  starting values and that the upper boundary constraint should now be  $\sum_{j=1}^p \alpha_j \leq 1$ .

### 17.3 GARCH Models

Instead of specifying an ARCH model with many lags, it is typically more convenient to specify a low-order GARCH (Generalized ARCH) model. The GARCH(1,1) is a simple and surprisingly general model, where the volatility follows

$$\begin{aligned} \sigma_t^2 &= \omega + \alpha u_{t-1}^2 + \beta \sigma_{t-1}^2, \text{with} \\ \omega &> 0; \alpha, \beta \geq 0; \text{ and } \alpha + \beta < 1. \end{aligned} \quad (17.11)$$

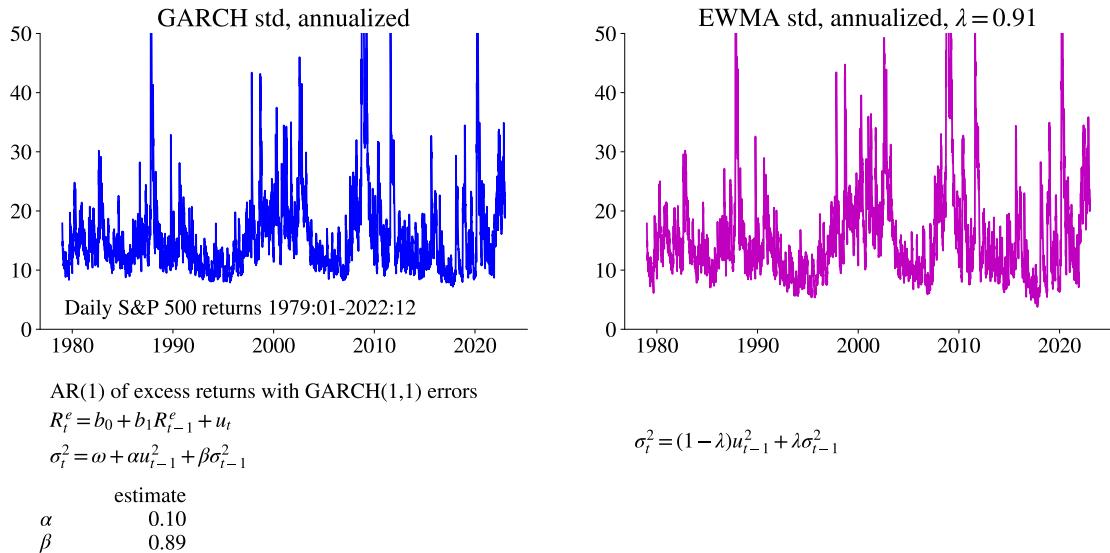


Figure 17.7: Conditional standard deviation, estimated by GARCH(1,1) model

The non-negativity restrictions are needed in order to guarantee that  $\sigma_t^2 > 0$  in all periods. The upper bound  $\alpha + \beta < 1$  is needed in order to make the  $\sigma_t^2$  stationary and therefore the unconditional variance finite.

**Remark 17.9** *The GARCH(1,1) has many similarities with the exponential moving average estimator of volatility (17.3). The main differences are that the exponential moving average does not have a constant and volatility is non-stationary (the coefficients sum to unity).*

**Empirical Example 17.10 (GARCH(1,1) vs EWMA)** See Figure 17.7 for an example.

The GARCH(1,1) corresponds to an ARCH( $\infty$ ) with geometrically declining weights, which is seen by solving (17.11) recursively by substituting for  $\sigma_{t-1}^2$  (and then  $\sigma_{t-2}^2, \sigma_{t-3}^2, \dots$ )

$$\sigma_t^2 = \frac{\omega}{1-\beta} + \alpha \sum_{j=0}^{\infty} \beta^j u_{t-1-j}^2. \quad (17.12)$$

This suggests that a GARCH(1,1) might be a reasonable approximation of a high-order ARCH.

Also, the GARCH(1,1) model implies that we in period  $t$  can forecast the future conditional variance ( $\sigma_{t+s}^2$ ) as

$$E_t \sigma_{t+s}^2 = \bar{\sigma}^2 + (\alpha + \beta)^{s-1} (\sigma_{t+1}^2 - \bar{\sigma}^2), \text{ with } \bar{\sigma}^2 = \frac{\omega}{1-\alpha-\beta}, \quad (17.13)$$

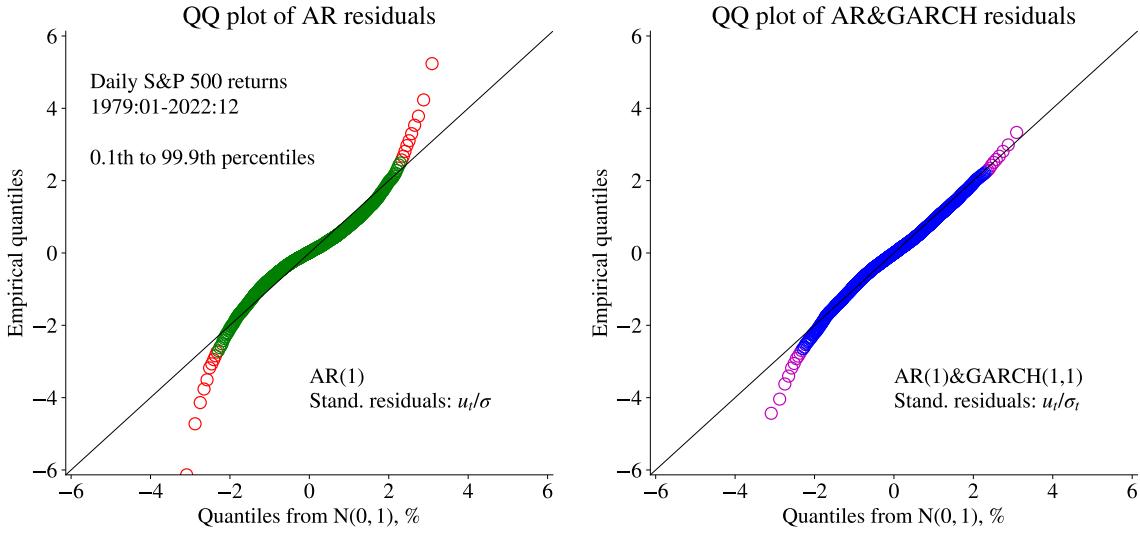


Figure 17.8: QQ-plot of residuals

which is of the same form as for the ARCH model (17.8), but where the sum of  $\alpha$  and  $\beta$  is like an AR(1) parameter.

To estimate the model consisting of (17.4) and (17.11) we can still use the likelihood function (17.9) and do a MLE (but we now have to choose a value of  $\beta$  as well). We typically create the starting value of  $u_0^2$  as in the ARCH(1) model, but this time we also need a starting value of  $\sigma_0^2$ . It is often recommended to use  $\sigma_0^2 = \text{Var}(u_t)$ .

**Remark 17.11** (*Imposing parameter constraints on GARCH(1,1)*) To impose the restrictions in (17.11), iterate over values of  $(b, \tilde{\omega}, \tilde{\alpha}, \tilde{\beta})$  and let  $\omega = \omega^2$ ,  $\alpha = \exp(\tilde{\alpha})/[1 + \exp(\tilde{\alpha}) + \exp(\tilde{\beta})]$ , and  $\beta = \exp(\tilde{\beta})/[1 + \exp(\tilde{\alpha}) + \exp(\tilde{\beta})]$ .

**Empirical Example 17.12** (*Distribution of normalised residuals*) See Figure 17.8 for evidence of how the residuals become more normally distributed once the heteroskedasticity is handled.

**Empirical Example 17.13** (*Value at Risk*) The 95% value at risk (as fraction of the investment) is the (negative of the ) 0.05 quantile of the return distribution. In particular,  $\text{VaR}_{0.95} = 0.08$  says that there is only an 5% chance that the loss will be greater than 8% of the investment. See Figure 17.9 for an illustration. When the return has an  $N(\mu, \sigma^2)$  distribution, then  $\text{VaR}_{95\%} = -(\mu - 1.64\sigma)$ . See Figure 17.10 for an example of time-varying VaR, based on a GARCH model.

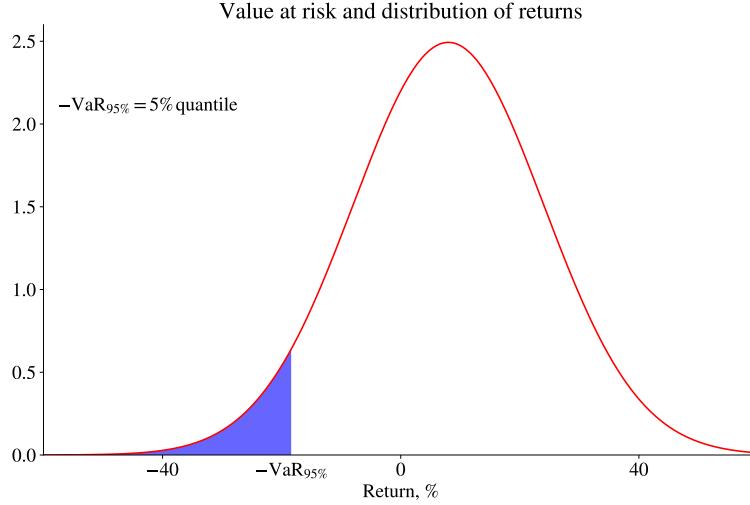


Figure 17.9: Value at risk

## 17.4 Non-Linear Extensions

A very large number of extensions have been suggested. I summarize a few of them, which can be estimated by MLE using the likelihood function (17.9).

An asymmetric GARCH (Glosten, Jagannathan, and Runkle (1993), GJR) can be constructed as

$$\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta \sigma_{t-1}^2 + \gamma \delta(u_{t-1} < 0) u_{t-1}^2, \text{ where} \quad (17.14)$$

$$\delta(q) = \begin{cases} 1 & \text{if } q \text{ is true} \\ 0 & \text{else.} \end{cases}$$

This means that the effect of the shock  $u_{t-1}^2$  is  $\alpha + \gamma$  if the shock was negative and  $\alpha$  if the shock was positive. With  $\gamma > 0$ , volatility increases more in response to a negative  $u_{t-1}$  (“bad news”) than to a positive  $u_{t-1}$ .

The EGARCH (exponential GARCH, Nelson (1991)) sets

$$\ln \sigma_t^2 = \omega + \alpha \frac{|u_{t-1}|}{\sigma_{t-1}} + \beta \ln \sigma_{t-1}^2 + \gamma \frac{u_{t-1}}{\sigma_{t-1}} \quad (17.15)$$

Apart from being written in terms of the log (which is a smart trick to make  $\sigma_t^2 > 0$  hold without any restrictions on the parameters), this is an asymmetric model. The  $|u_{t-1}|$  term is symmetric: both negative and positive values of  $u_{t-1}$  affect the volatility in the same way. The linear term in  $u_{t-1}$  modifies this to make the effect asymmetric. In particular,

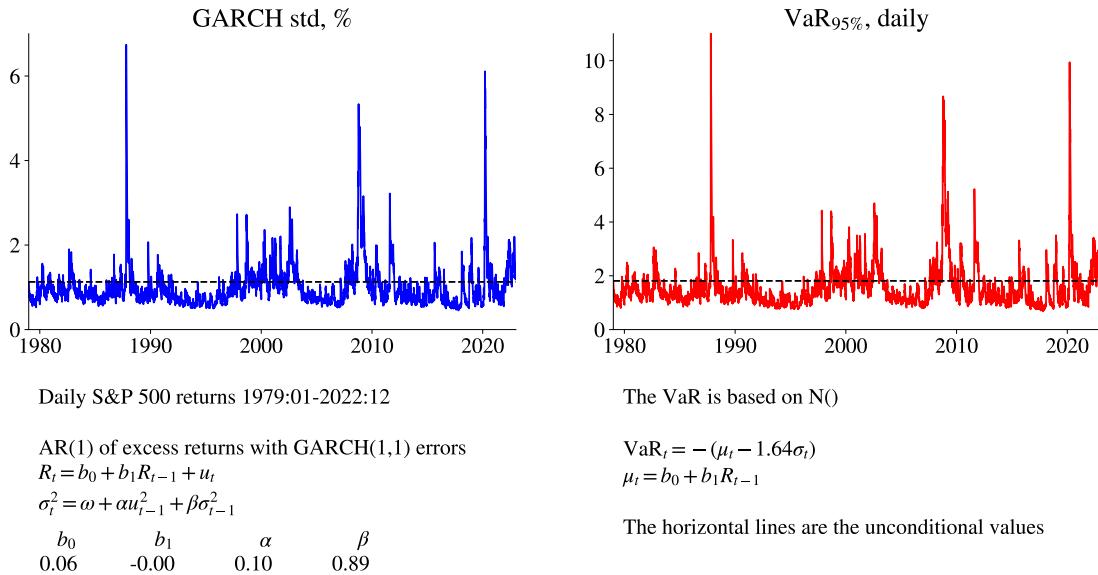


Figure 17.10: Conditional volatility and VaR

if  $\gamma < 0$ , then the volatility increases more in response to a negative  $u_{t-1}$  (“bad news”) than to a positive  $u_{t-1}$ . This model is stationary if  $|\beta| < 1$ .

Hentschel (1995) estimates several models of this type, as well as a very general formulation on daily stock index data for 1926 to 1990 (some 17,000 observations). Most standard models are rejected in favour of a model where  $\sigma_t$  depends on  $\sigma_{t-1}$  and  $|u_{t-1} - b|^{3/2}$ .

## 17.5 (G)ARCH-M\*

It can make sense to let the conditional volatility enter the regression equation—for instance, as a proxy for risk which may influence the expected return.

We modify the regression (“mean”) equation (17.4) to include the conditional variance  $\sigma_t^2$  (taken from any of the models for heteroskedasticity) as a regressor

$$y_t = x'_t b + \varphi \sigma_t^2 + u_t. \quad (17.16)$$

Note that  $\sigma_t^2$  is predetermined, since it is a function of information in  $t - 1$ . This model can be estimated by using the likelihood function (17.9) to do MLE.

**Remark 17.14** (*Coding of (G)ARCH-M*) We can use the same approach as in Remark

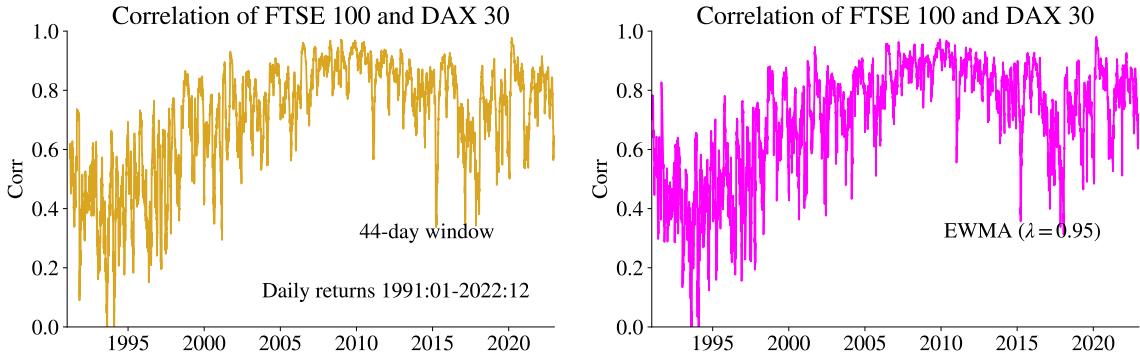


Figure 17.11: Time-varying correlations (different EWMA estimates)

[17.7](#), except that we use (17.16) instead of (17.4) to calculate the residuals (and that we obviously also need a guess of  $\varphi$ ).

**Example 17.15** (*Theoretical motivation of GARCH-M*) An implication from mean-variance portfolio choice and CAPM is that  $E(R_m - R_f) = k\sigma_m^2$ , which says that the expected excess market return is increasing in both the market volatility ( $\sigma_m^2$ ) and risk aversion ( $k$ ).

## 17.6 Multivariate (G)ARCH

A first approach to estimate a time varying covariance of two series ( $u_{it}$  and  $u_{jt}$ ) is the EWMA

$$\sigma_{ij,t} = (1 - \lambda)u_{i,t-1}u_{j,t-1} + \lambda\sigma_{ij,t-1}. \quad (17.17)$$

Combining this with similar estimates of the time varying volatility of each series ( $\sigma_{i,t}^2$  and  $\sigma_{j,t}^2$ ) allows us to calculate a time varying correlation as

$$\rho_{ij,t} = \sigma_{ij,t}/(\sigma_{i,t}\sigma_{j,t}). \quad (17.18)$$

**Empirical Example 17.16** (*Time-varying equity index correlations*) See [Figure 17.11](#).

### 17.6.1 Different Multivariate Models

This section gives a brief summary of some multivariate models of heteroskedasticity. Suppose  $u_t$  is an  $n \times 1$  vector. For instance,  $u_t$  could be the residuals from  $n$  different regressions or just  $n$  different demeaned return series.

We define the conditional (on the information set in  $t - 1$ ) covariance matrix of  $u_t$  as

$$\Sigma_t = \mathbf{E}_{t-1} u_t u_t' \quad (17.19)$$

**Remark 17.17** (*The vech operator*)  $\text{vech}(A)$  of a matrix  $A$  gives a vector with the elements on and below the principal diagonal  $A$  stacked on top of each other (column wise).

$$\text{For instance, } \text{vech} \begin{bmatrix} \mathbf{a}_{11} & a_{12} \\ \mathbf{a}_{21} & \mathbf{a}_{22} \end{bmatrix} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{22} \end{bmatrix}.$$

It may seem as if a multivariate (matrix) version of the GARCH(1,1) model would be simple, but it is not. The reason is that it would contain far too many parameters. Although we only need to care about the unique elements of  $\Sigma_t$ , that is,  $\text{vech}(\Sigma_t)$ , this still gives very many parameters

$$\text{vech}(\Sigma_t) = C + A \text{vech}(u_{t-1} u_{t-1}') + B \text{vech}(\Sigma_{t-1}). \quad (17.20)$$

For instance, with  $n = 2$  we have

$$\begin{bmatrix} \sigma_{11,t} \\ \sigma_{21,t} \\ \sigma_{22,t} \end{bmatrix} = C + A \begin{bmatrix} u_{1,t-1}^2 \\ u_{1,t-1} u_{2,t-1} \\ u_{2,t-1}^2 \end{bmatrix} + B \begin{bmatrix} \sigma_{11,t-1} \\ \sigma_{21,t-1} \\ \sigma_{22,t-1} \end{bmatrix}, \quad (17.21)$$

where  $C$  is  $3 \times 1$ ,  $A$  is  $3 \times 3$ , and  $B$  is  $3 \times 3$ . This gives 21 parameters, which is already hard to manage. We have to limit the number of parameters. We also have to find a way to impose restrictions so  $\Sigma_t$  is positive definite. Indeed a variance-covariance matrix must be positive definite in order to guarantee that every possible linear combination of the variables has a positive variance (compare the restrictions of positive coefficients in (17.11)). If not, something is wrong.

## The Diagonal Model

The *diagonal model* assumes that  $A$  and  $B$  are diagonal. This means that every element of  $\Sigma_t$  follows a univariate process. With  $n = 2$  we have

$$\begin{bmatrix} \sigma_{11,t} \\ \sigma_{21,t} \\ \sigma_{22,t} \end{bmatrix} = \begin{bmatrix} c_1 \\ c_2 \\ c_3 \end{bmatrix} + \begin{bmatrix} a_1 & 0 & 0 \\ 0 & a_2 & 0 \\ 0 & 0 & a_3 \end{bmatrix} \begin{bmatrix} u_{1,t-1}^2 \\ u_{1,t-1} u_{2,t-1} \\ u_{2,t-1}^2 \end{bmatrix} + \begin{bmatrix} b_1 & 0 & 0 \\ 0 & b_2 & 0 \\ 0 & 0 & b_3 \end{bmatrix} \begin{bmatrix} \sigma_{11,t-1} \\ \sigma_{21,t-1} \\ \sigma_{22,t-1} \end{bmatrix}, \quad (17.22)$$

which gives  $3 + 3 + 3 = 9$  parameters. To make sure that  $\Sigma_t$  is positive definite we have to impose further restrictions. The obvious drawback of this model is that there is no spillover of volatility from one variable to another.

### The Constant Correlation Model

The *constant correlation model* (CCC) assumes that every variance follows a univariate GARCH process and that the conditional correlations are constant. With  $n = 2$  the covariance matrix is

$$\begin{bmatrix} \sigma_{11,t} & \sigma_{12,t} \\ \sigma_{12,t} & \sigma_{22,t} \end{bmatrix} = \begin{bmatrix} \sqrt{\sigma_{11,t}} & 0 \\ 0 & \sqrt{\sigma_{22,t}} \end{bmatrix} \begin{bmatrix} 1 & \rho_{12} \\ \rho_{12} & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\sigma_{11,t}} & 0 \\ 0 & \sqrt{\sigma_{22,t}} \end{bmatrix} \quad (17.23)$$

and each of  $\sigma_{11t}$  and  $\sigma_{22t}$  follows a GARCH process. Assuming a GARCH(1,1) as in (17.11) gives 7 parameters ( $2 \times 3$  GARCH parameters and one correlation), which is convenient. The price is, of course, the assumption of no movements in the correlations. To get a positive definite  $\Sigma_t$ , each individual GARCH model must generate a positive variance (same restrictions as before), and that all the estimated (constant) correlations are between  $-1$  and  $1$ .

**Remark 17.18** (*Estimating the constant correlation model*) A quick (and dirty) method is to first estimate the individual GARCH processes and then estimate the correlation of the standardized residuals  $u_{1t}/\sqrt{\sigma_{11,t}}$  and  $u_{2t}/\sqrt{\sigma_{22,t}}$ .

By also specifying how the correlation can change over time, we get a *dynamic correlation model* (DCC). It is slightly harder to estimate.

**Empirical Example 17.19** (*Time-varying equity index correlations*) See Figure 17.12 for an illustration and Figure 17.11 for a comparison with the EWMA approach.

### The Dynamic Correlation Model

The *dynamic correlation model* (DCC) discussed in Engle (2002)) allows the correlation to change over time. The model assumes that each conditional variance follows a univariate GARCH process and the conditional correlation matrix is (essentially) allowed to follow a univariate GARCH equation.

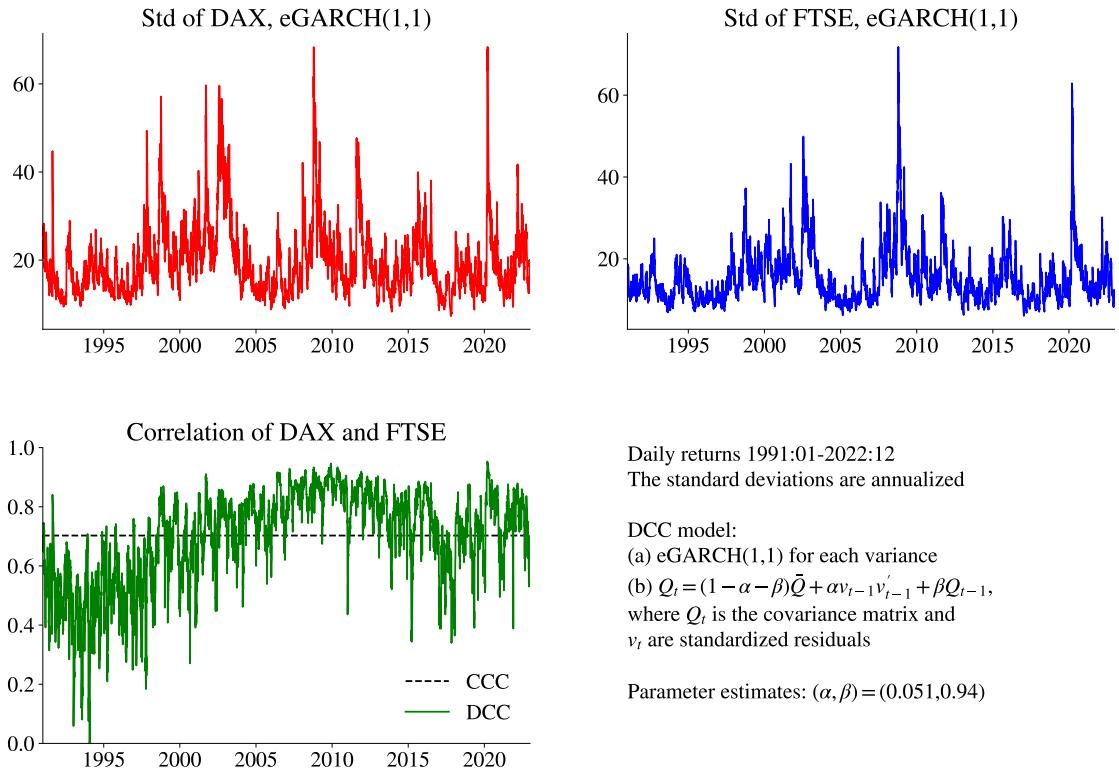


Figure 17.12: Results for multivariate eGARCH models

The conditional covariance matrix is (by definition)

$$\Sigma_t = D_t R_t D_t, \text{ with } D_t = \text{diag}(\sqrt{\sigma_{ii,t}}), \quad (17.24)$$

and  $R_t$  is the conditional correlation matrix, which is modelled below.

**Remark 17.20** (*diag( $a_i$ ) notation*)  $\text{diag}(a_i)$  denotes the  $n \times n$  matrix with elements  $a_1, a_2, \dots, a_n$  along the main diagonal and zeros elsewhere. For instance, if  $n = 2$ , then

$$\text{diag}(a_i) = \begin{bmatrix} a_1 & 0 \\ 0 & a_2 \end{bmatrix}.$$

The conditional correlation matrix  $R_t$  is allowed to change like in a univariate GARCH model, but with a transformation that guarantees that it is actually a valid correlation matrix. First, let  $v_t$  be the vector of standardized residuals and let  $\bar{Q}$  be the unconditional correlation matrix of  $v_t$ . For instance, if we assume a GARCH(1,1) structure for the

correlation matrix, then we have

$$\begin{aligned} Q_t &= (1 - \alpha - \beta) \bar{Q} + \alpha v_{t-1} v'_{t-1} + \beta Q_{t-1}, \text{ with} \\ v_{i,t} &= u_{i,t} / \sqrt{\sigma_{ii,t}}, \end{aligned} \quad (17.25)$$

where  $\alpha$  and  $\beta$  are two scalars and  $\bar{Q}$  is the unconditional covariance matrix of the normalized residuals ( $v_t$ ). We require that  $\alpha \geq 0$  and that  $\alpha + \beta < 1$ .

To guarantee that the conditional correlation matrix is indeed a correlation matrix,  $Q_t$  is treated as if it were a covariance matrix and  $R_t$  is simply the implied correlation matrix. That is,

$$R_t = \text{diag}(1/\sqrt{q_{ii,t}}) Q_t \text{diag}(1/\sqrt{q_{ii,t}}). \quad (17.26)$$

The basic idea of this model is to estimate a conditional correlation matrix as in (17.26) and then scale up with conditional variances (from univariate GARCH models) to get a conditional covariance matrix as in (17.24). The DCC model is used in a study of asset pricing in, for instance, Duffee (2005).

**Empirical Example 17.21** (DCC estimation, daily equity returns) Figure 17.12 suggests that the DCC correlations look similar to what the EWMA method delivers. Figure 17.13 shows a scatter of the standard deviations for a long-short portfolio according to several methods. The results suggest that a DCC model is better at capturing the volatility patterns than a CCC model.

**Example 17.22** (Dynamic correlation model,  $n = 2$ ) With  $n = 2$  the covariance matrix  $\Sigma_t$  is

$$\begin{bmatrix} \sigma_{11,t} & \sigma_{12,t} \\ \sigma_{12,t} & \sigma_{22,t} \end{bmatrix} = \begin{bmatrix} \sqrt{\sigma_{11,t}} & 0 \\ 0 & \sqrt{\sigma_{22,t}} \end{bmatrix} \begin{bmatrix} 1 & \rho_{12,t} \\ \rho_{12,t} & 1 \end{bmatrix} \begin{bmatrix} \sqrt{\sigma_{11,t}} & 0 \\ 0 & \sqrt{\sigma_{22,t}} \end{bmatrix},$$

and each of  $\sigma_{11t}$  and  $\sigma_{22t}$  follows a GARCH process. To estimate the dynamic correlations, we first calculate (where  $\alpha$  and  $\beta$  are two scalars)

$$\begin{bmatrix} q_{11,t} & q_{12,t} \\ q_{12,t} & q_{22,t} \end{bmatrix} = (1 - \alpha - \beta) \begin{bmatrix} 1 & \bar{q}_{12} \\ \bar{q}_{12} & 1 \end{bmatrix} + \alpha \begin{bmatrix} v_{1,t-1} \\ v_{2,t-1} \end{bmatrix} \begin{bmatrix} v_{1,t-1} \\ v_{2,t-1} \end{bmatrix}' + \beta \begin{bmatrix} q_{11,t-1} & q_{12,t-1} \\ q_{12,t-1} & q_{22,t-1} \end{bmatrix},$$

where  $v_{i,t-1} = u_{i,t-1} / \sqrt{\sigma_{ii,t-1}}$  and  $\bar{q}_{ij}$  is the unconditional correlation of  $v_{i,t}$  and  $v_{j,t}$  and we get the conditional correlations by

$$\begin{bmatrix} 1 & \rho_{12,t} \\ \rho_{12,t} & 1 \end{bmatrix} = \begin{bmatrix} 1 & q_{12,t} / \sqrt{q_{11,t} q_{22,t}} \\ q_{12,t} / \sqrt{q_{11,t} q_{22,t}} & 1 \end{bmatrix}.$$

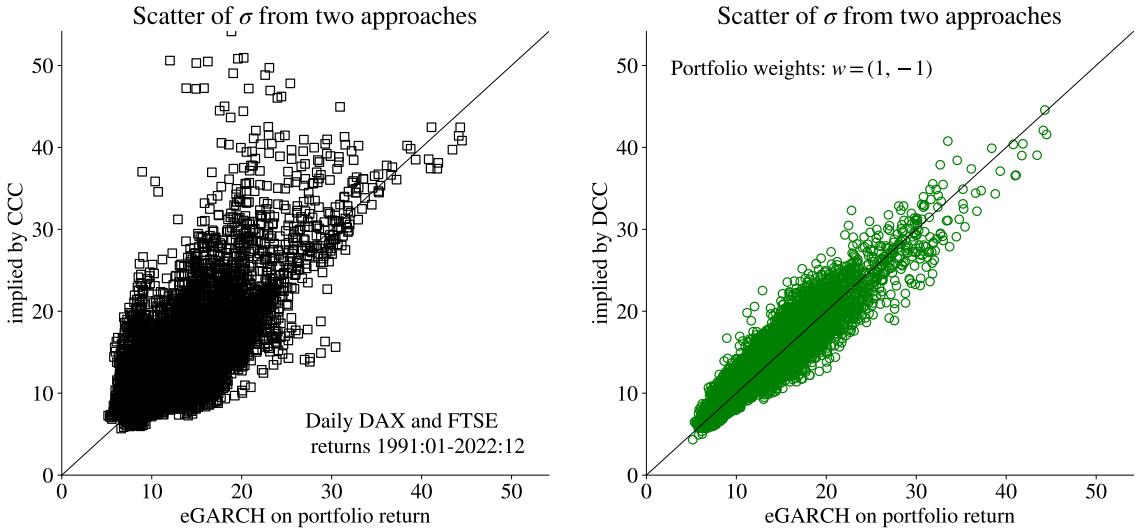


Figure 17.13: Backtesting multivariate eGARCH models

Assuming a GARCH(1,1) as in (17.11) gives 9 parameters ( $2 \times 3$  GARCH parameters,  $(\bar{q}_{12}, \alpha, \beta)$ ).

To see what DCC generates, consider the correlation coefficient from a bivariate model

$$\rho_{12,t} = \frac{q_{12,t}}{\sqrt{q_{11,t}} \sqrt{q_{22,t}}}, \text{ where} \quad (17.27)$$

$$\begin{aligned} q_{12,t} &= (1 - \alpha - \beta)\bar{q}_{12} + \alpha v_{1,t-1}v_{2,t-1} + \beta q_{12,t-1} \\ q_{11,t} &= (1 - \alpha - \beta) + \alpha v_{1,t-1}v_{1,t-1} + \beta q_{11,t-1} \\ q_{22,t} &= (1 - \alpha - \beta) + \alpha v_{2,t-1}v_{2,t-1} + \beta q_{22,t-1}. \end{aligned}$$

This is a complicated expression, but the numerator is the main driver:  $q_{11,t}$  and  $q_{22,t}$  are variances of normalized variables—so they should not be too far from unity. Therefore,  $q_{12,t}$  is close to being the correlation itself. The equation for  $q_{12,t}$  shows that it has a GARCH structure: it depends on  $v_{1,t-1}v_{2,t-1}$  and  $q_{12,t-1}$ . Provided  $\alpha$  and  $\beta$  are large numbers, we can expect the correlation to be strongly autocorrelated.

### 17.6.2 Estimation of a Multivariate Model\*

In principle, it is straightforward to specify the likelihood function of the model and then maximize it with respect to the model parameters. For instance, if  $u_t$  is iid  $N(0, \Sigma_t)$ , then

the log likelihood function is

$$\ln \mathcal{L} = -\frac{Tn}{2} \ln(2\pi) - \frac{1}{2} \sum_{t=1}^T \ln |\Sigma_t| - \frac{1}{2} \sum_{t=1}^T u_t' \Sigma_t^{-1} u_t. \quad (17.28)$$

In practice, the optimization problem can be difficult since there are typically many parameters. At least, good starting values are required.

**Remark 17.23** (*Starting values of a constant correlation GARCH(1,1) model*) Estimate GARCH(1,1) models for each variable separately, then estimate the correlation matrix on the standardized residuals.

**Remark 17.24** (*Estimation of the dynamic correlation model*) The DCC model can be estimated by two-step procedure. First, estimate the univariate GARCH processes. Second, use the standardized residuals to estimate the dynamic correlations by maximizing the likelihood function (17.28 if we assume normally distributed errors) with respect to the parameters  $\alpha$  and  $\beta$ . In this second stage, both the parameters for the univariate GARCH process and the unconditional covariance matrix  $\bar{Q}$  are kept constant. A grid search over  $\alpha$  and  $\beta$  is sometimes useful in order to avoid local maxima. Notice that in the second step, we calculate  $\Sigma_t$  (in each iteration over the parameter values) by using  $R_t$  from (17.26) in (17.24).

# Chapter 18

## Risk Measures

Reference: Hull (2006) 18; McDonald (2006) 25; Fabozzi, Focardi, and Kolm (2006) 4–5; McNeil, Frey, and Embrechts (2005); Alexander (2008b)

### 18.1 Value at Risk

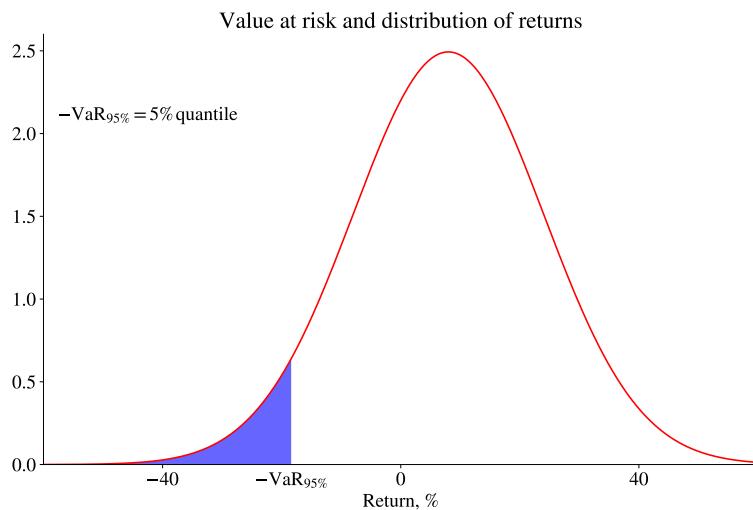


Figure 18.1: Value at risk

The mean-variance framework is often criticized for failing to distinguish between downside of the return distribution (considered to be risk) and upside (considered to be potential). The Value at Risk is one way of focusing on the downside.

**Remark 18.1** (*Quantile of a distribution*) *The 0.05 quantile is the value such that there is only a 5% probability of a lower number,  $\Pr(R \leq \text{quantile}_{0.05}) = 0.05$ .*

The 95% Value at Risk ( $\text{VaR}_{95\%}$ ) is a number such that there is only a 5% chance that the loss ( $-R$ ) is larger than  $\text{VaR}_{95\%}$

$$\Pr(-R \geq \text{VaR}_{95\%}) = 5\%. \quad (18.1)$$

Here, 95% is the confidence level of the VaR. For instance, if  $\text{VaR}_{95\%} = 18\%$ , then we are 95% sure that we will not lose more than 18% of our investment. To convert the value at risk into value terms (CHF, say), just multiply the VaR for returns with the value of the investment (portfolio).

Clearly,  $-R \geq \text{VaR}_{95\%}$  is true when (and only when)  $R \leq -\text{VaR}_{95\%}$ , so (18.1) can also be expressed as

$$\Pr(R \leq -\text{VaR}_{95\%}) = 5\%. \quad (18.2)$$

This says that  $-\text{VaR}_{95\%}$  is a number such that there is only a 5% chance that the return is below it. That is,  $-\text{VaR}_{95\%}$  is the 0.05 quantile (5th percentile) of the return distribution. Using (18.2) allows us to work directly with the return distribution (not the loss distribution), which is often convenient. See Figure 18.1 for an illustration. If the return is normally distributed,  $R \sim N(\mu, \sigma^2)$  then

$$\text{VaR}_{95\%} = -(\mu - 1.64\sigma). \quad (18.3)$$

**Example 18.2** (*VaR with  $R \sim N(\mu, \sigma^2)$* ) If daily returns have  $\mu = 8\%$  and  $\sigma = 16\%$ , then the 1-day  $\text{VaR}_{95\%} = -(0.08 - 1.64 \times 0.16) \approx 0.18$ ; we are 95% sure that we will not lose more than 18% of the investment over one day, that is,  $\text{VaR}_{95\%} = 0.18$ .

More generally, we can consider the confidence level  $\alpha$  instead of just 0.95, so

$$\Pr(R \leq -\text{VaR}_\alpha) = 1 - \alpha, \text{ so} \quad (18.4)$$

$$\text{VaR}_\alpha = -(1 - \alpha)^{\text{th}} \text{ quantile of } R. \quad (18.5)$$

If the return is normally distributed,  $R \sim N(\mu, \sigma^2)$ , then

$$\text{VaR}_\alpha = -(\mu + c\sigma), \quad (18.6)$$

where  $c$  is the  $(1 - \alpha)^{\text{th}}$  for a  $N(0, 1)$  distribution, for instance,  $-1.64$  for  $1 - \alpha = 0.05$ .

This is illustrated in Figure 18.2.

**Remark 18.3** (*Critical values of  $N(\mu, \sigma^2)$* ) If  $R \sim N(\mu, \sigma^2)$ , then there is a 5% probability that  $R \leq \mu - 1.64\sigma$ , a 2.5% probability that  $R \leq \mu - 1.96\sigma$ , and a 1% probability that  $R \leq \mu - 2.33\sigma$ .

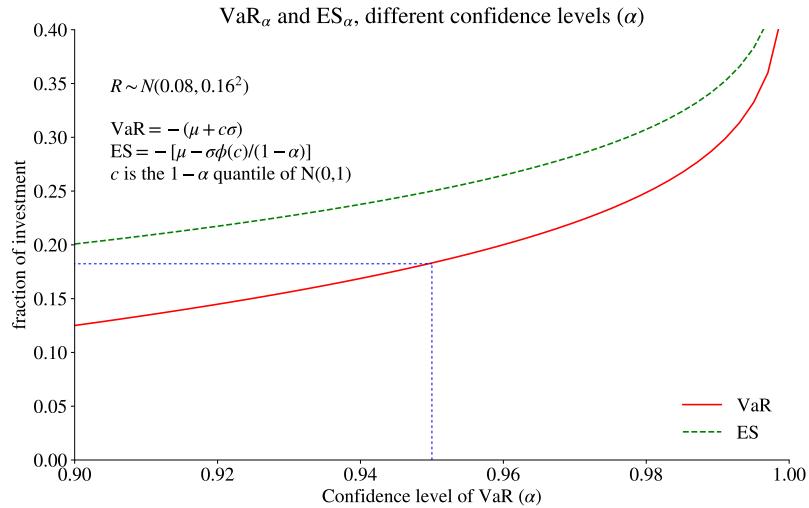


Figure 18.2: Value at risk, different probability levels

**Example 18.4** (VaR with  $R \sim N(\mu, \sigma^2)$ ) If  $R \sim N(\mu, \sigma^2)$  with  $\mu = 8\%$  and  $\sigma = 16\%$ , then  $\text{VaR}_{97.5\%} = -(0.08 - 1.96 \times 0.16) \approx 0.24$ .

**Empirical Example 18.5** (Static (unconditional) VaR for S&P 500 returns) Figure 18.3 shows the distribution and VaRs (for different probability levels) for the daily S&P 500 returns. Two different types of VaRs are shown: (i) based on a normal distribution and (ii) as the empirical VaR (from the empirical quantiles of the distribution).

**Example 18.6** (VaR and regulation of bank capital) Bank regulations have used 3 times the 99% VaR for 10-day returns as the required bank capital.

Notice that the return distribution depends on the investment horizon, so a VaR is typically calculated for a stated investment period (for instance, one day). Multi-period VaRs are calculated by either explicitly constructing the distribution of multi-period returns, or by making simplifying assumptions about the relation between returns in different periods (for instance, that they are iid).

**Remark 18.7** (Multi-period VaR) If the returns are iid, then a  $q$ -period return has the mean  $q\mu$  and variance  $q\sigma^2$ , where  $\mu$  and  $\sigma^2$  are the mean and variance of the one-period returns respectively. If the mean is zero, then the  $q$ -day VaR is  $\sqrt{q}$  times the one-day VaR.

**Empirical Example 18.8** (Dynamic (time-varying) VaR for S&P 500 returns) Figure 18.4 shows VaR calculated from  $N(\mu_t, \sigma_t^2)$ , but where the  $\mu_t, \sigma_t$  values are allowed to change over time according to an AR(1)+GARCH(1,1) estimation.

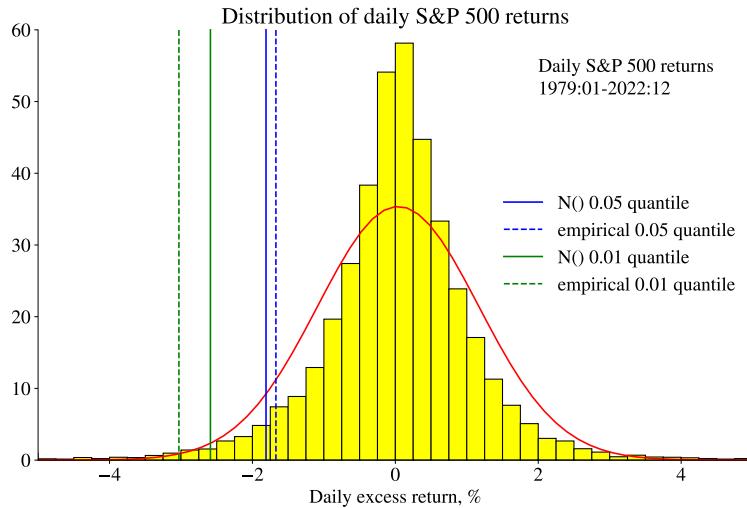


Figure 18.3: Return distribution and VaR for S&P 500

## 18.2 Backtesting a VaR Model

*Backtesting* a VaR model amounts to checking if (historical) data fits with the VaR numbers. For instance, we first find the  $\text{VaR}_{95\%}$  and then calculate what fraction of returns that is actually below (the negative of) this number. If the model is correct it should be 5%. We then repeat this for  $\text{VaR}_{96\%}$ : only 4% of the returns should be below (the negative of ) this number.

**Empirical Example 18.9** (*Backtesting a static and a dynamic VaR for S&P 500 returns*)  
*See Figure 18.5 for results based on a static (constant) VaR model and Figure 18.6 for results from a VaR model where the volatility follows a GARCH process (to capture the time varying volatility). The evidence suggests that this model, combined with the assumption that the return is normally distributed (but with time-varying parameters), works relatively well except for very high confidence levels.*

It is also important to see if there are medium- to long-run deviations from the VaR confidence level.

**Empirical Example 18.10** (*Evaluating the VaR model on moving subsamples*) *See Figure 18.7 for results based on a static (constant) VaR model and Figure 18.8 for results from the GARCH model.*

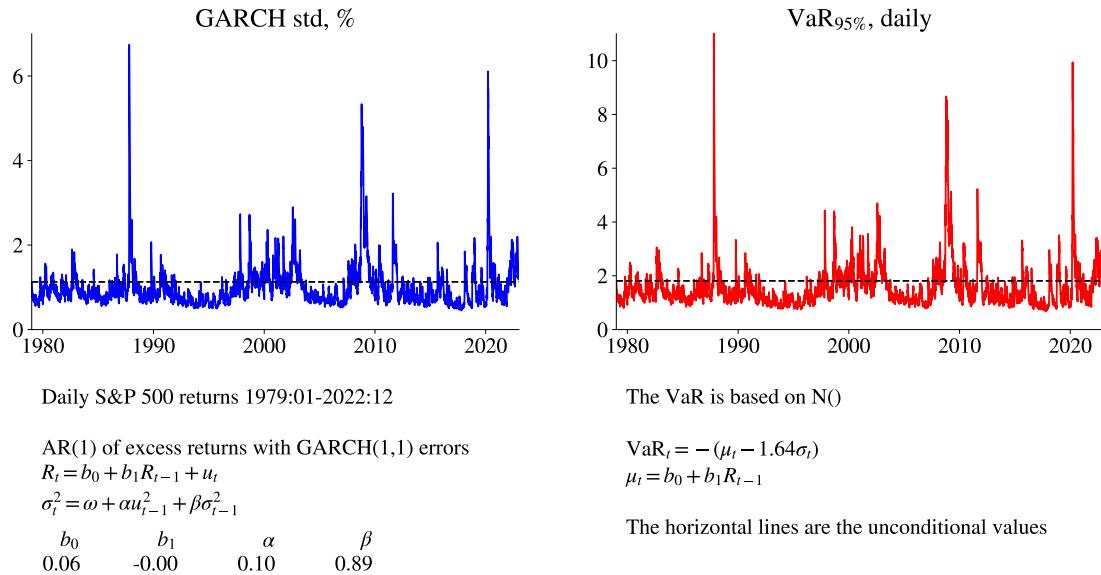


Figure 18.4: Conditional volatility and VaR

**Remark 18.11** (*Bernoulli and binomial distributions*) In a Bernoulli distribution, the random variable  $X$  can only take two values: 1 or 0, with probability  $p$  and  $1 - p$  respectively. This gives  $E(X) = p$  and  $\text{Var}(X) = p(1 - p)$ . After  $n$  independent trials, the number of successes ( $y$ ) has a binomial distribution with  $E(y) = np$  and  $\text{Var}(y) = np(1 - p)$ . For the average outcome,  $y/n$ , we then get  $E(y/n) = p$  and  $\text{Var}(y/n) = p(1 - p)/n$ .

To perform a statistical back test of a VaR model, define a variable that is one if the loss is greater than the VaR

$$d_t = \begin{cases} 1 & \text{if } R_t < -\text{VaR}_\alpha \\ 0 & \text{otherwise} \end{cases} \quad (18.7)$$

By using the properties of a binomial distribution, we notice that a sample average of  $d_t$  has the following distribution

$$\frac{1}{T} \sum_{t=1}^T d_t \xrightarrow{d} N(1 - \alpha, \alpha(1 - \alpha)/T). \quad (18.8)$$

This can be used to create a t-stat or a confidence interval.

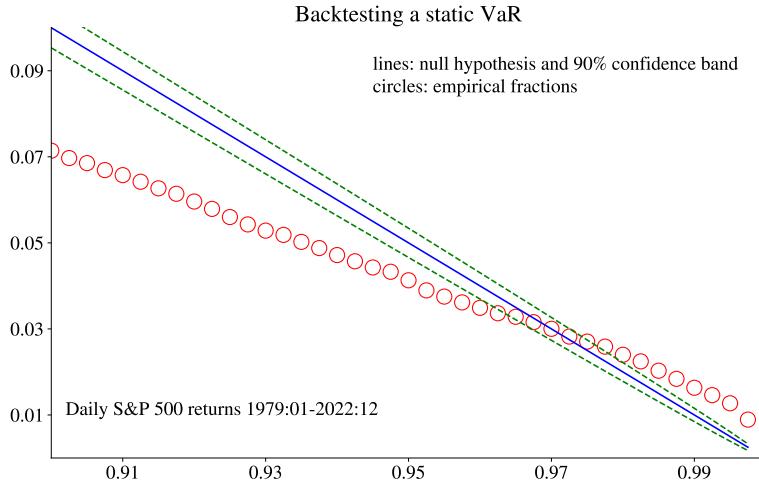


Figure 18.5: Backtesting a static VAR, assuming normally distributed shocks

### 18.3 Expected Shortfall

The VaR concept has been criticized for having poor aggregation properties. In particular, the VaR for a portfolio is not necessarily (weakly) lower than the portfolio of the VaRs, which contradicts the notion of diversification benefits. (To get this unfortunate property, the return distributions must be heavily skewed.) The expected shortfall has better aggregation properties.

The expected shortfall (also called conditional VaR, average value at risk and expected tail loss) is the expected loss when the return actually is below the  $\text{VaR}_\alpha$ , that is,

$$\text{ES}_\alpha = -\mathbb{E}(R|R \leq -\text{VaR}_\alpha). \quad (18.9)$$

This might be more informative than the  $\text{VaR}_\alpha$ , which is the *minimum loss* that will happen with a  $1 - \alpha$  probability. See Figure 18.9 for an illustration.

For a normally distributed return  $R \sim N(\mu, \sigma^2)$  we have

$$\text{ES}_\alpha = -\left[\mu - \frac{\phi(c_{1-\alpha})}{1-\alpha}\sigma\right], \quad (18.10)$$

where  $\phi()$  is the pdf of a  $N(0, 1)$  variable and where  $c_{1-\alpha}$  is the  $1 - \alpha$  quantile of a  $N(0, 1)$  distribution (for instance,  $-1.64$  for  $1 - \alpha = 0.05$ ).

**Proof.** (of (18.10)) If  $x \sim N(\mu, \sigma^2)$ , then  $\mathbb{E}(x|x \leq b) = \mu - \sigma\phi(b_0)/\Phi(b_0)$  where  $b_0 = (b - \mu)/\sigma$  and where  $\phi()$  and  $\Phi()$  are the pdf and cdf of a  $N(0, 1)$  variable

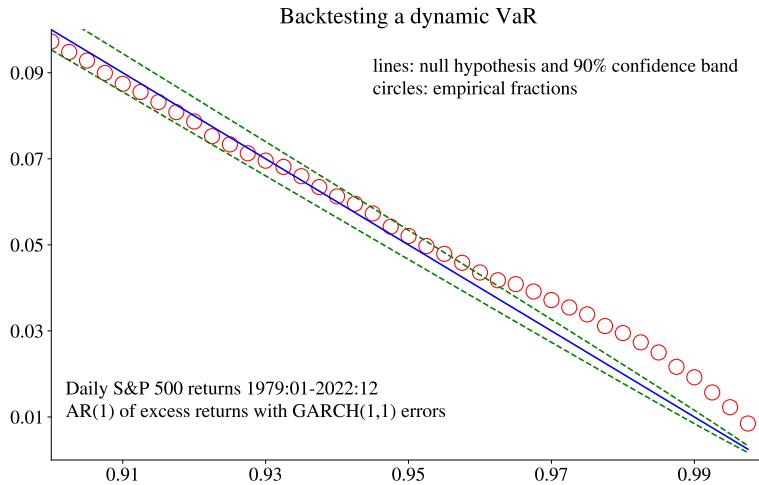


Figure 18.6: Backtesting a dynamic VaR, assuming normally distributed shocks

respectively. To apply this, use  $b = -\text{VaR}_\alpha$  so  $b_0 = c_{1-\alpha}$ . Clearly,  $\Phi(c_{1-\alpha}) = 1 - \alpha$  (by definition of the  $1 - \alpha$  quantile). Multiply by  $-1$ . ■

**Example 18.12 (ES)** If  $\mu = 8\%$  and  $\sigma = 16\%$ , the 95% expected shortfall is  $ES_{95\%} = -(0.08 - 2.08 \times 0.16) \approx 0.25$  (since  $\phi(-1.64)/0.05 \approx 2.08$ ) and the 97.5% expected shortfall is  $ES_{97.5\%} = -(0.08 - 2.34 \times 0.16) \approx 0.29$  (since  $\phi(-1.96)/0.025 \approx 2.34$ )

See Figure 18.10 for an illustration.

**Empirical Example 18.13** (*Comparison of different downside risk measures for two equity portfolios*) See Table 18.1 for an empirical comparison of the VaR, ES and some more downside risk measures (discussed below).

	Small growth	Large value
Std	8.1	5.8
VaR (95%)	12.9	8.9
ES (95%)	18.1	13.2
SemiStd	5.7	3.9
Drawdown	78.4	63.2

Table 18.1: Risk measures of monthly returns of two stock indices (%), US data 1970:01-2022:12.

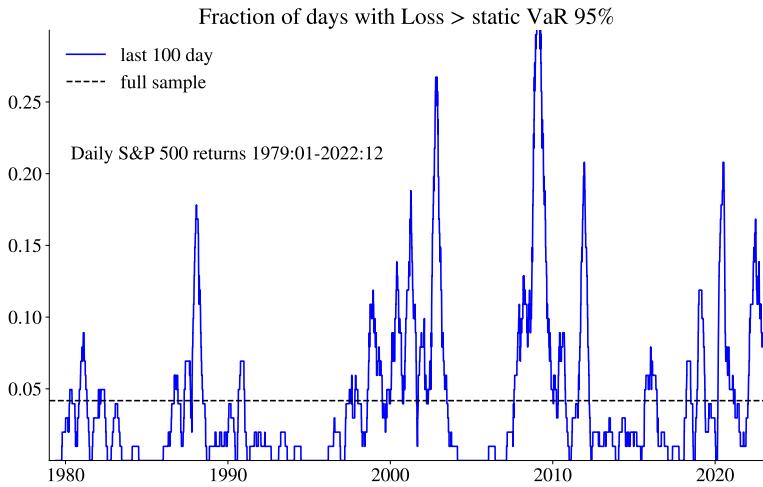


Figure 18.7: Backtesting a static VaR model on a moving data window

## 18.4 Semivariance and Max Drawdown

Reference: Bawa and Lindenberg (1977) and Nantell and Price (1979)

A semivariance is defined as

$$\lambda^2 = E[\min(R - E R, 0)^2]. \quad (18.11)$$

The square root of  $\lambda^2$  is called the semi-standard deviation. In comparison with a variance only negative deviations from the mean are given any weight.

To estimate the semivariance from data use

$$\lambda^2 = \frac{1}{T} \sum_{t=1}^T \delta(R_t \leq \bar{R})(R_t - \bar{R})^2, \quad (18.12)$$

where  $\delta(q) = 1$  if  $q$  is true and zero otherwise.

An alternative measure is the (percentage) *maximum drawdown* over a given horizon, for instance, 5 years, say. This is the largest loss from peak to bottom within the given horizon. This is a useful measure when the investor do not know exactly when he/she has to exit the investment—since it indicates the worst (peak to bottom) outcome over the sample.

**Empirical Example 18.14** (*Max drawdown for different assets*) See Figure 18.13.

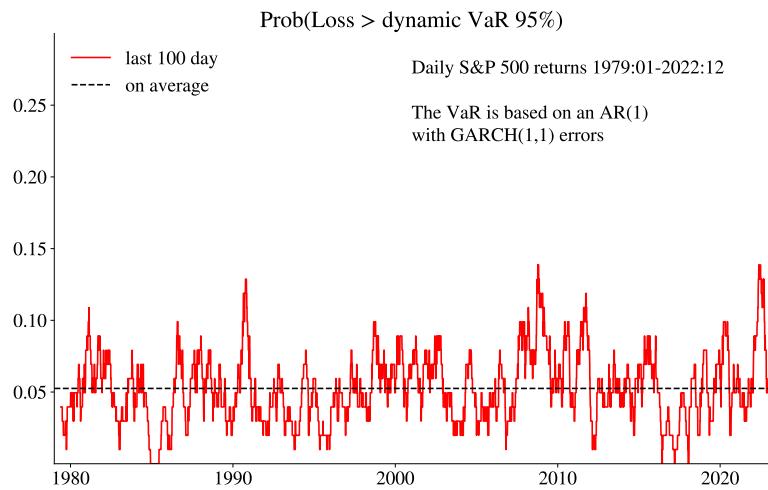


Figure 18.8: Backtesting a dynamic VaR on a moving data window

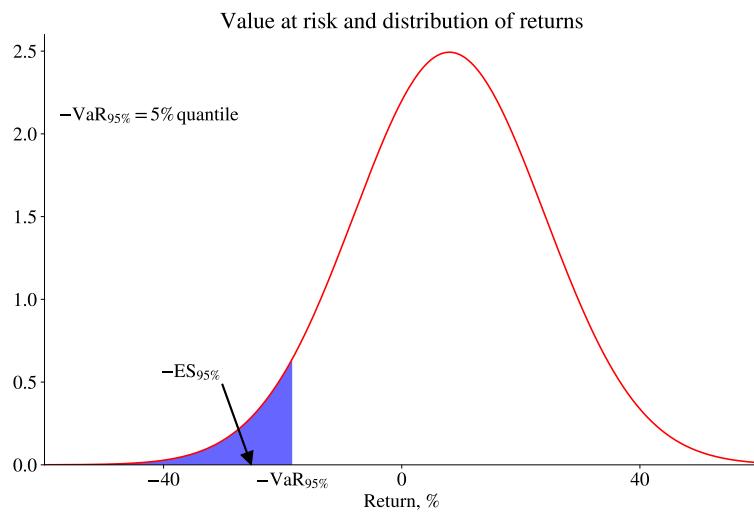


Figure 18.9: Value at risk and expected shortfall

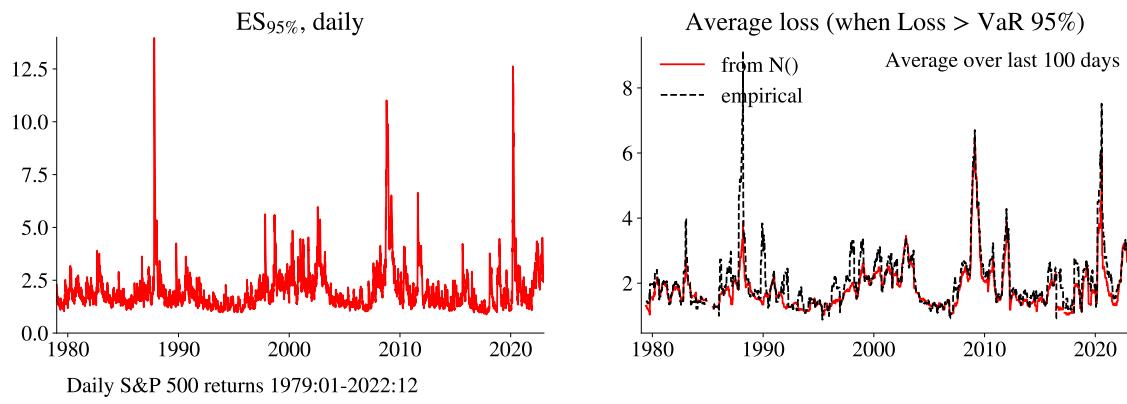


Figure 18.10: Expected shortfall from GARCH model (with backtesting)

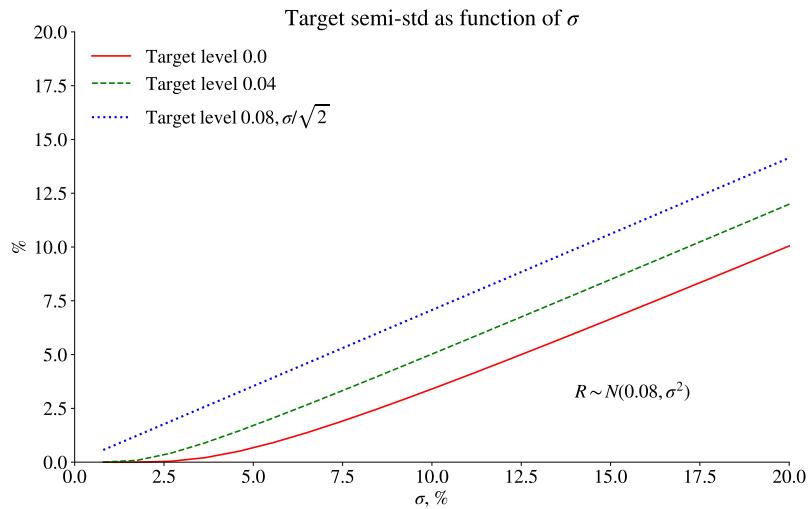


Figure 18.11: Target semivariance for a  $N(\mu, \sigma^2)$  variable

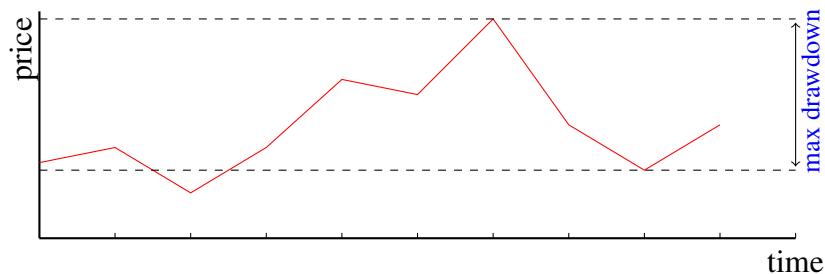


Figure 18.12: Max drawdown

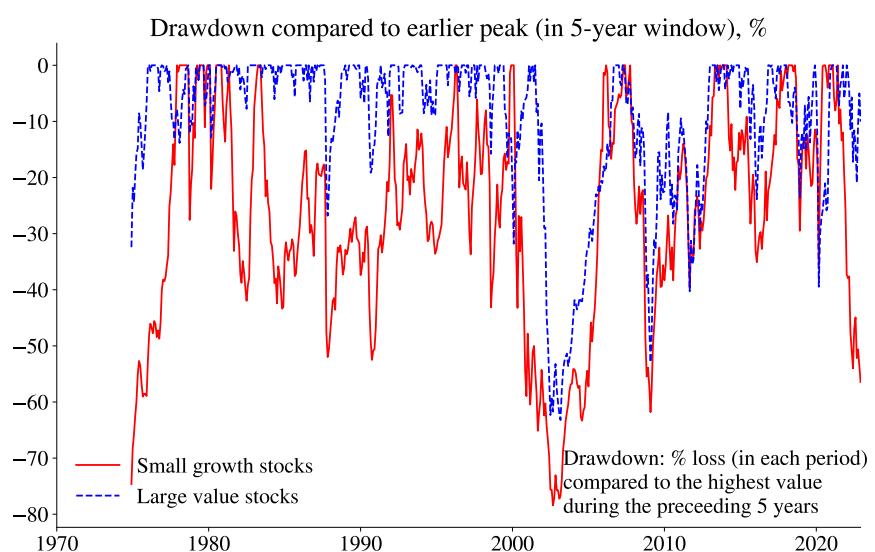


Figure 18.13: Drawdown in moving (rolling) data window

# Chapter 19

## Return Distributions (Univariate)\*

Sections denoted by a star (\*) is not required reading.

### 19.1 Estimating and Testing Distributions

Reference: Harvey (1989) 260, Davidson and MacKinnon (1993) 267, Silverman (1986); Mittelhammer (1996), DeGroot (1986)

#### 19.1.1 A Quick Recap of a Univariate Distribution

The cdf (cumulative distribution function) measures the probability that the random variable  $X_i$  is below or at some numerical value  $x_i$ ,

$$F_i(x_i) = \Pr(X_i \leq x_i). \quad (19.1)$$

For instance, with an  $N(0, 1)$  distribution,  $F(-1.64) = 0.05$ . Clearly, the cdf values are between (and including) 0 and 1. The distribution of  $X_i$  is often called the *marginal distribution* of  $X_i$ —to distinguish it from the joint distribution of  $X_i$  and  $X_j$ . (See below for more information on joint distributions.)

The pdf (probability density function)  $f_i(x_i)$  is the “height” of the distribution in the sense that the cdf  $F(x_i)$  is the integral of the pdf from minus infinity to  $x_i$

$$F_i(x_i) = \int_{s=-\infty}^{x_i} f_i(s)ds. \quad (19.2)$$

(This clearly means that the pdf is the derivative of the cdf,  $f_i(x_i) = \partial F_i(x_i)/\partial x_i$ .) A pdf must be non-negative,  $f_i(s) \geq 0$ . The Gaussian pdf (the normal distribution) is bell shaped.

**Remark 19.1** (*Quantile of a distribution*) The  $\alpha$  quantile of a distribution ( $\xi_\alpha$ ) is the value of  $x$  such that there is a probability of  $\alpha$  of a lower value. We can solve for the quantile by inverting the cdf,  $\alpha = F(\xi_\alpha)$  as  $\xi_\alpha = F^{-1}(\alpha)$ . For instance, the 5% quantile of a  $N(0, 1)$  distribution is  $-1.64 = \Phi^{-1}(0.05)$ , where  $\Phi^{-1}()$  denotes the inverse of an  $N(0, 1)$  cdf. See Figure 19.1 for an illustration.

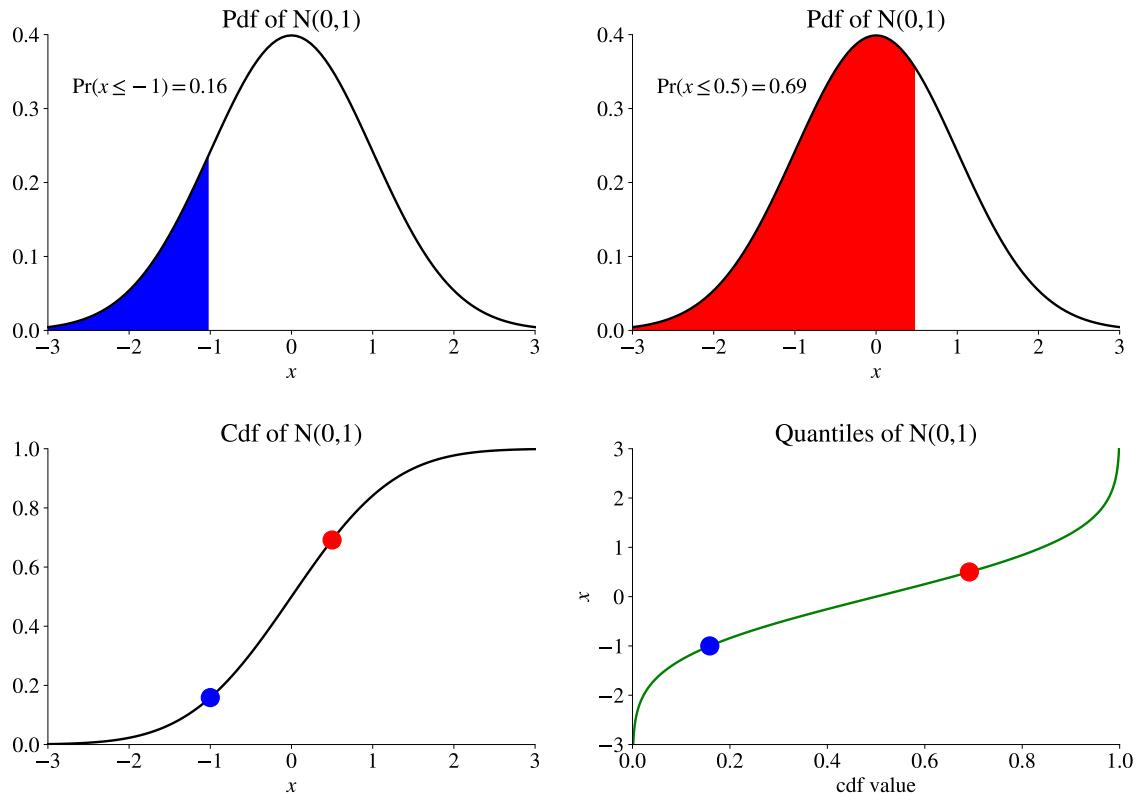


Figure 19.1: Finding quantiles of a  $N(\mu, \sigma^2)$  distribution

### 19.1.2 Histograms and Averaged Shifted Histograms

Histograms like Figure 19.2 are very useful for gauging the shape of the distribution. The histogram either shows the number of occurrences or a scaled version where the area under the histogram integrates to one (like a pdf).

The formal definition of a scaled histogram is: at any value  $x$  in the bin  $c \pm h/2$  (for

instance, for  $x = 0.4$  which is in the bin  $0 \pm 0.5$ ) the value is

$$\hat{f}(x) = \frac{1}{Th} \sum_{t=1}^T \delta(c - h/2 < x_t \leq c + h/2). \quad (19.3)$$

where  $\delta(q)$  is an indicator function:  $\delta(q) = 1$  if  $q$  is true, and  $\delta(q) = 0$  otherwise.

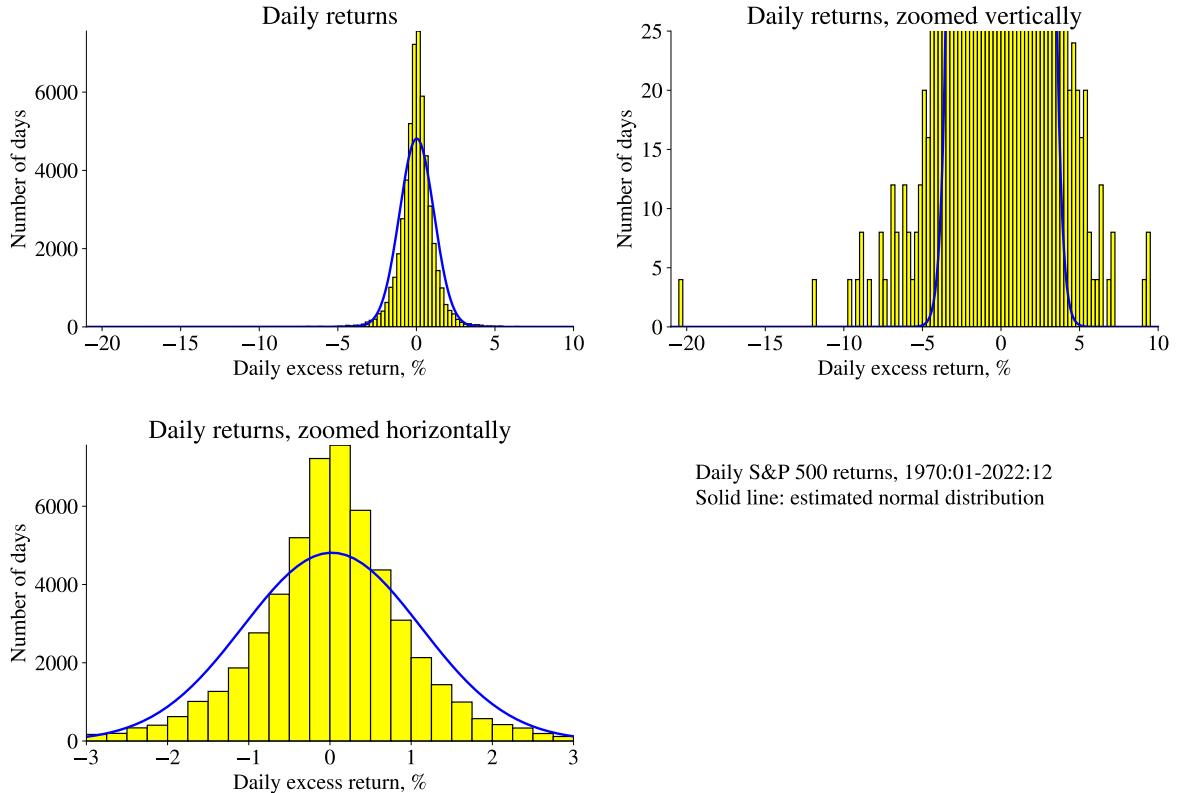


Figure 19.2: Distribution of daily S&P returns

Within each bin (different  $x$  values within the same bin), the histogram value is constant, so the  $\hat{f}(x)$  is a step function. See Figure 19.3.

To calculate the histogram, we need to make two choices: the width of the bins and their location. These choice are often made to facilitate interpretation of the results (for instance, bins for returns might be  $(0\%, 1\%]$ ,  $(1\%, 2\%]$ , etc), but the properties of the data set should also be considered: there are useful recommendations for how to set the bin widths as functions of the volatility of the data and the sample length (see Remark).

**Remark 19.2** (*Histogram bin width\**) *It is often recommended to use histogram bins that are  $h = 3.5\sigma / T^{1/3}$  wide (alternatively,  $h = 2 \text{IQR} / T^{1/3}$  where IQR is the interquartile*

range,  $\text{quantile}(0.75) - \text{quantile}(0.25)$ ). Clearly, if  $c$  is the bin midpoint, then the bin is  $c \pm h/2$ .

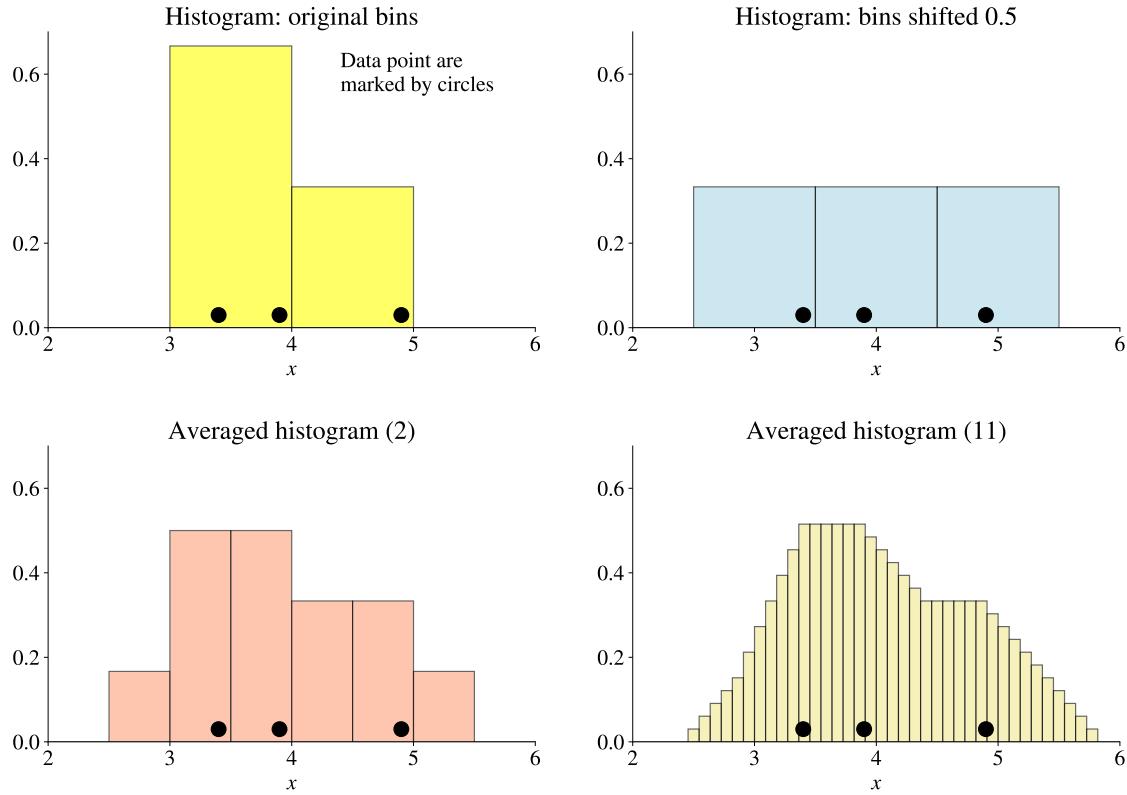


Figure 19.3: Example of histograms on a very small sample

The choice of the location (equivalently, the bin mid points) can be tricky. See Figure 19.3 for an illustration.

The *averaged shifted histogram* (ASH, Scott (1985)) is a way to reduce the importance of the location choice. The idea is to calculate several histograms using different bin locations—and then average across them (at the same  $x$  value). Figure 19.3 shows the average of 2 (and also of many more) histograms.

**Remark 19.3** (*Calculating the ASH* \*) Figure 19.4 shows the original bin  $0 \pm h/2$  and also bins that are shifted  $h/2$ . This implicitly defines a set of smaller bins  $(-h, -h/2]$ ,  $(-h/2, 0]$  etc. The  $n_i$  indicate the number of data points in each of smaller bins. It is clear that the scaled ASH at  $x$  (which is in the original bin) equals  $(n_0 + n_1 + n_{-1} + n_0)/(2hT)$ .

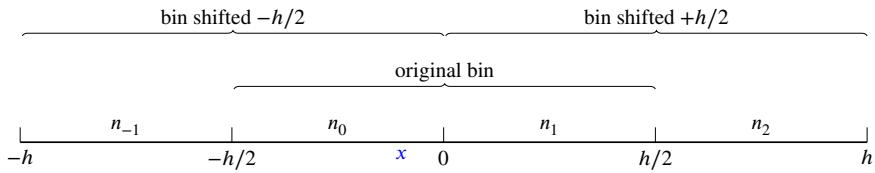


Figure 19.4: Calculation of averaged shifted histogram

The more general expression with  $m$  shifts inside a bin (the figure show  $m = 2$ )

$$\hat{f}(x) = \frac{1}{mTh} \sum_{i=1-m}^{m-1} (m - |i|)n_i.$$

This can also be written

$$\hat{f}(x) = \frac{1}{Th} \sum_{i=1-m}^{m-1} (1 - |i|/m)n_i,$$

which has strong similarities with a kernel density estimator (see below) with a triangular  $(1 - |i|/m)$  kernel.

### 19.1.3 QQ Plots

Are returns normally distributed? Mostly not, but it depends on the asset type and on the return horizon. Options returns typically have very non-normal distributions (in particular, since the return is  $-100\%$  on many expiration days). Stock returns are typically distinctly non-linear at short horizons, but can look somewhat normal at longer horizons.

To assess the normality of returns, the usual econometric techniques (Bera–Jarque and Kolmogorov-Smirnov tests) are useful, but a visual inspection of the histogram and a QQ-plot also give useful clues.

**Empirical Example 19.4** (*QQ plots of equity and FX returns*) See Figures 19.2 – 19.7 for illustrations.

**Remark 19.5** (*Reading a QQ plot*) A QQ plot is a way to assess if the empirical distribution conforms reasonably well to a prespecified theoretical distribution, for instance, a normal distribution where the mean and variance have been estimated from the data. The QQ plot is a scatter plot where each point shows a specific percentile (quantile) according to the empirical as well as according to the theoretical distribution. For instance, if the 2nd percentile (0.02 quantile) is at  $-10$  in the empirical distribution, but at only  $-3$  in the

*theoretical distribution, then this indicates that the two distributions have very different left tails.*

There is one important caveat to this way of studying data: it only provides evidence on the unconditional distribution. Suppose instead that we have estimated a model for time-variation in the mean and variance (denoted  $\mu_t$  and  $\sigma_t^2$ , respectively), then it makes more sense to study the distribution (QQ plot) of the standardised return

$$\tilde{R}_t = \frac{R_t - \mu_t}{\sigma_t}. \quad (19.4)$$

As a simple example, the mean could be estimated by an AR(1) model (so we would have  $\mu_t = a + \rho R_{t-1}$ ) and the variance by a GARCH model (so we would have  $\sigma_t^2 = \omega + \alpha u_{t-1}^2 + \beta \sigma_{t-1}^2$  where  $u_{t-1}$  is the surprise to the return in  $t-1$ ).

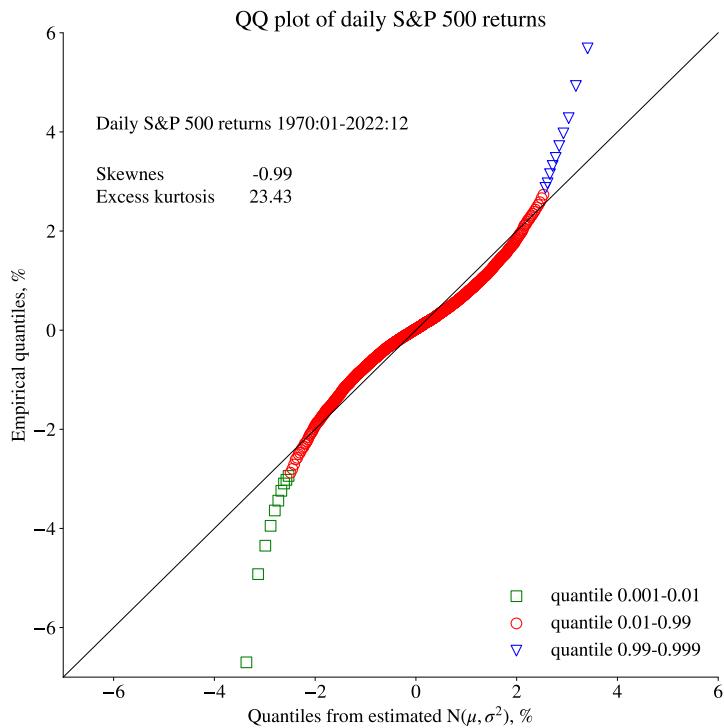


Figure 19.5: Quantiles of daily S&P returns

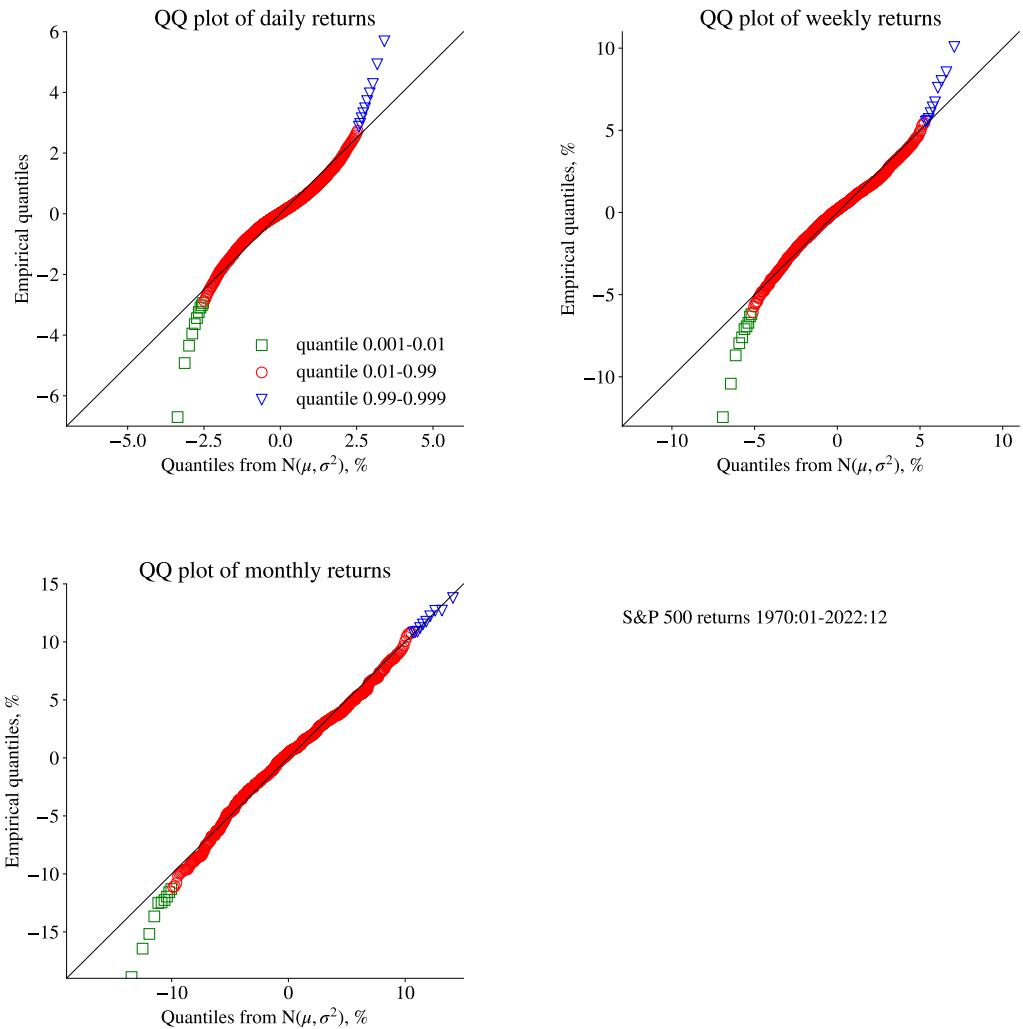


Figure 19.6: Distribution of S&P returns (different horizons)

#### 19.1.4 Parametric Tests of Normal Distribution

The skewness, kurtosis and Bera-Jarque test for normality are useful diagnostic tools. They are

	Test statistic	Distribution	
skewness	$\frac{1}{T} \sum_{t=1}^T \left( \frac{x_t - \mu}{\sigma} \right)^3$	$N(0, 6/T)$	(19.5)
kurtosis	$\frac{1}{T} \sum_{t=1}^T \left( \frac{x_t - \mu}{\sigma} \right)^4$	$N(3, 24/T)$	
Bera-Jarque	$\frac{T}{6} \text{skewness}^2 + \frac{T}{24} (\text{kurtosis} - 3)^2$	$\chi^2_2$	

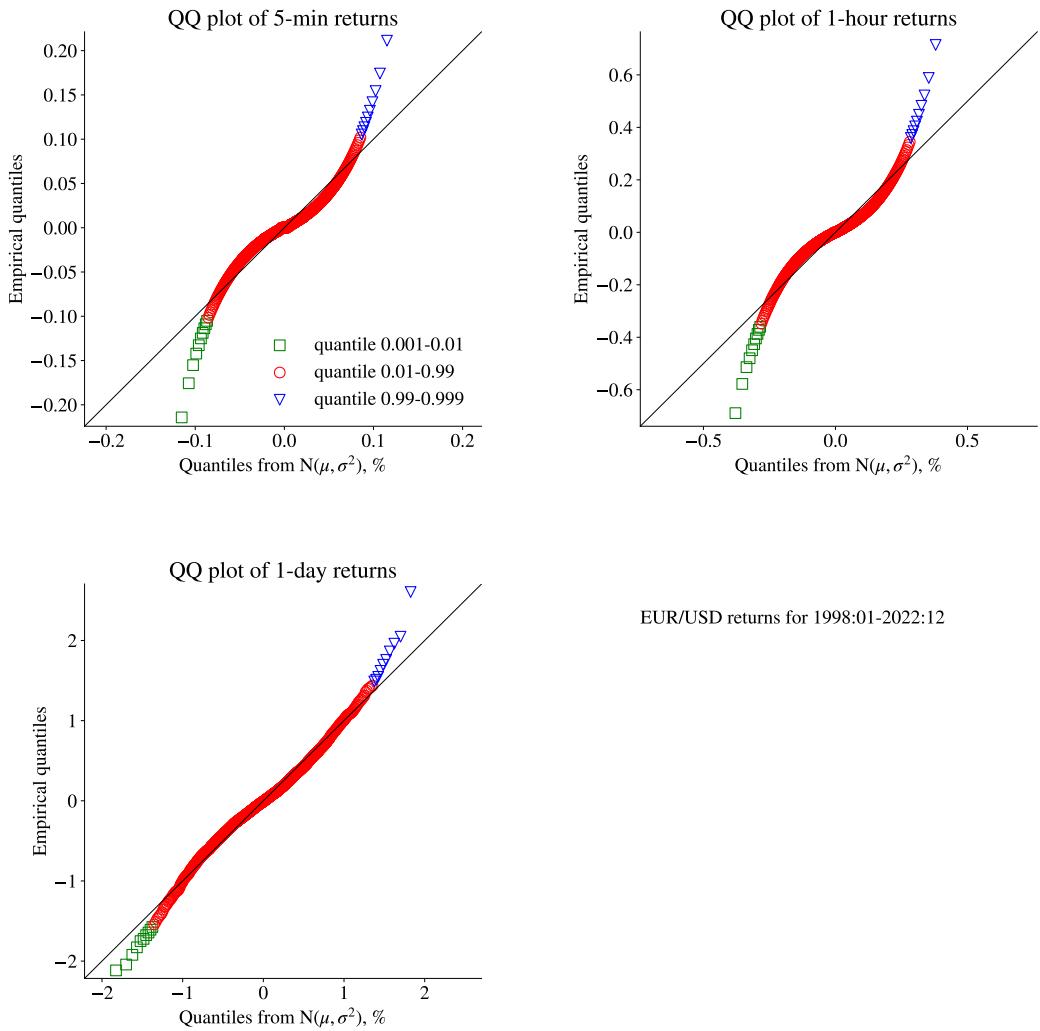


Figure 19.7: Distribution of exchange rate returns (different horizons)

This is implemented by using the estimated mean and standard deviation. The distributions stated on the right hand side of (19.5) are under the null hypothesis that  $x_t$  is iid  $N(\mu, \sigma^2)$ . The “excess kurtosis” is defined as the kurtosis minus 3.

The intuition for the  $\chi^2_2$  distribution of the Bera-Jarque test is that both the skewness and kurtosis are, if properly scaled,  $N(0, 1)$  variables. It can also be shown that they, under the null hypothesis, are uncorrelated. The Bera-Jarque test statistic is therefore a sum of the square of two uncorrelated  $N(0, 1)$  variables, which has a  $\chi^2_2$  distribution.

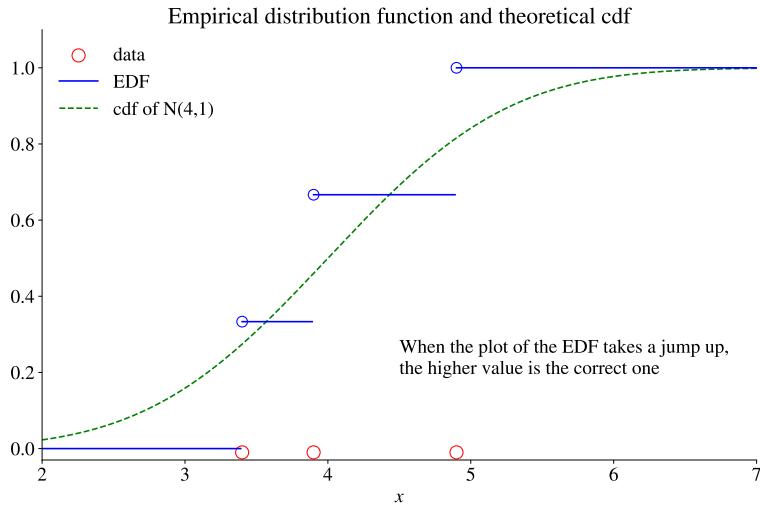


Figure 19.8: Example of empirical distribution function

### 19.1.5 Nonparametric Tests of General Distributions

The *Kolmogorov-Smirnov* test is designed to test if an empirical distribution function,  $\text{EDF}(x)$ , conforms with a theoretical cdf,  $F(x)$ . The empirical distribution function is defined as the fraction of observations which are less or equal to  $x$ , that is,

$$\text{EDF}(x) = \frac{1}{T} \sum_{t=1}^T \delta(x_t \leq x). \quad (19.6)$$

The  $\text{EDF}(x_t)$  and  $F(x_t)$  are often plotted against the sorted (in ascending order) sample  $\{x_t\}_{t=1}^T$ . See Figure 19.8 for an illustration.

Define the absolute value of the maximum distance

$$D = \max_x |\text{EDF}(x) - F(x)|. \quad (19.7)$$

This max is across all possible  $x$  values (not just the observed data), but there is a simple way to identify the maximum (see the Remark below). See Figure 19.9 for an illustration.

**Remark 19.6** (*Calculating the D statistic\**) *The maximum in in (19.7) must be at or just before a data point (where the EDF jumps up). Let  $(z_1, \dots, z_T)$  be the sorted  $x$  sample. At a data point calculate  $|\text{EDF}(z_i) - F(z_i)|$  as  $|i/T - F(z_i)|$ . Just before a data point, the theoretical cdf is (almost)  $F(z_i)$  and the EDF is  $(i-1)/T$ , so calculate  $|((i-1)/T) - F(z_i)|$ . Find the largest value across the two numbers and then across the sample.*

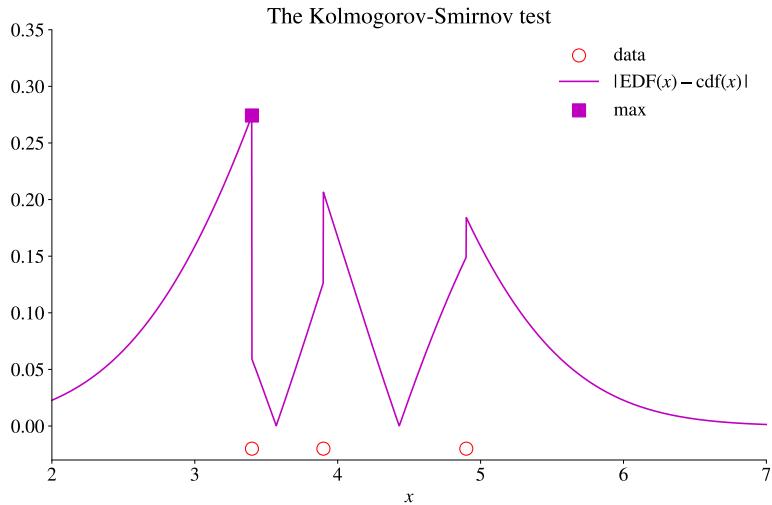


Figure 19.9: K-S test

We reject the null hypothesis that  $\text{EDF}(x) = F(x)$  if  $\sqrt{T}D > c$ , where  $c$  is a critical value ((1.36, 1.48, 1.63) are the critical values on the (5%, 2.5%, 1%) significance levels), see Mittelhammer (1996) 10. Instead, if the  $F(x_t)$  distribution is  $N(\mu, \sigma^2)$  with estimated parameters, then the critical values should be changed to (0.80, 0.89, 1.03).

**Remark 19.7** (*K-S test for comparing two EDFs\**) Let  $\text{EDF}_1(x)$  be the edf for variable 1 (from a sample with  $T_1$  observations) and  $\text{EDF}_2(x)$  for variable 2 (from a sample with  $T_2$  observations). Define  $D = \max_x |\text{EDF}_1(x) - \text{EDF}_2(x)|$  and reject the null hypothesis that they are from the same distribution if  $\sqrt{T_1 T_2 / (T_1 + T_2)} D > c$  where  $c$  is the same critical value as before. To find the maximum, try all  $x = \text{data}_i$  values from the union of the two samples.

Pearson's  $\chi^2$  test does the same thing as the K-S test but for a discrete distribution. Suppose you have  $K$  categories with  $N_i$  values in category  $i$ . The theoretical distribution predicts that the fraction  $p_i$  should be in category  $i$ , with  $\sum_{i=1}^K p_i = 1$ . Then

$$\sum_{i=1}^K \frac{(N_i - T p_i)^2}{T p_i} \sim \chi^2_{K-1}. \quad (19.8)$$

There is a corresponding test for comparing two empirical distributions.

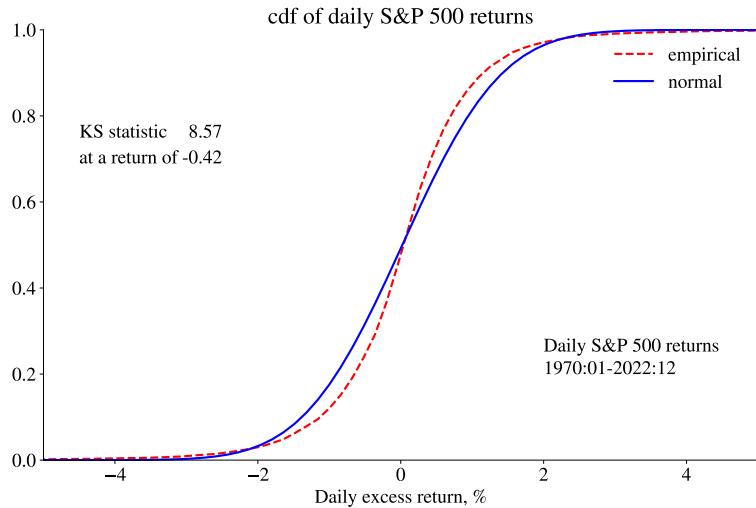


Figure 19.10: K-S test

### 19.1.6 Kernel Density Estimation

Reference: Silverman (1986)

A histogram is just a count of the relative number of observations that fall in (pre-specified) non-overlapping intervals. If we also divide by the width of the interval, then the area under the histogram is unity, so this scaled histogram can be interpreted as a density function. The scaled histogram at the point  $x$  (say,  $x = 2.3$ ) can actually be defined as

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^T \frac{1}{h} \delta\left(\left|\frac{x_t - x}{h}\right| \leq 1/2\right), \text{ where} \quad (19.9)$$

$$\delta(q) = \begin{cases} 1 & \text{if } q \text{ is true} \\ 0 & \text{else.} \end{cases}$$

In this case, the intervals (“bins”) are  $h$  wide around a point  $x$ :  $x - h/2$  to  $x + h/2$ .

In fact, that  $\frac{1}{h} \delta(|x_t - x| \leq h/2)$  is the pdf value of a uniformly distributed variable (over the interval  $x - h/2$  to  $x + h/2$ ). This shows that our estimate of the pdf (here: the histogram) can be thought of as a average of hypothetical pdf values of the data in the neighbourhood of  $x$ .

However, we can gain efficiency and get a smoother (across  $x$  values) estimate by using another density function than the uniform. In particular, using a density function that tapers off continuously instead of suddenly dropping to zero (as the uniform density

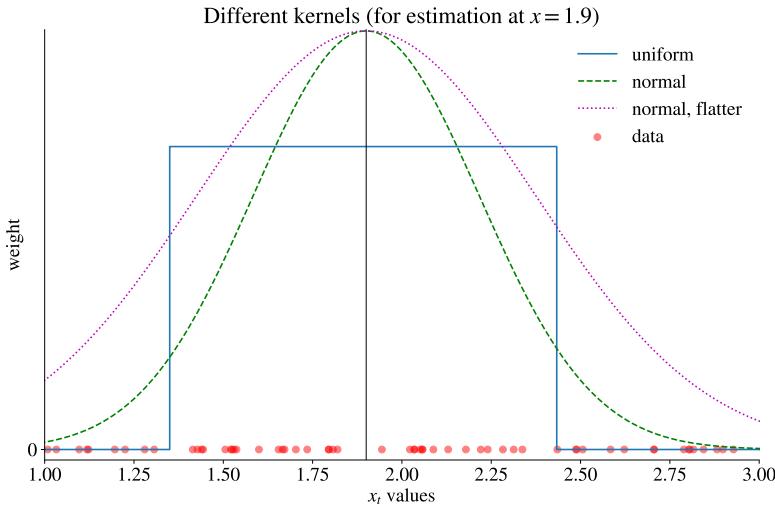


Figure 19.11: Different weighting functions for kernel density estimate

does) improves the properties. In fact, a normal pdf is often used. The kernel density estimator of the pdf at some point  $x$  is then

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^T \frac{1}{h\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{x_t - x}{h}\right)^2\right]. \quad (19.10)$$

Notice that the function in the summation is the density function of a  $N(x, h^2)$  distribution. See Figure 19.11 for an example of the weights in the calculation.

The value  $h = 1.06 \text{Std}(x_t)T^{-1/5}$  is sometimes recommended, since it can be shown to be the optimal choice (in MSE sense) if data is normally distributed and the gaussian kernel is used. A more robust choice is to replace  $\text{Std}(x_t)$  in the formula by  $\min(\text{Std}(x_t), \text{IQR}/1.34)$ , where IQR is the inter-quartile range.

**Empirical Example 19.8** (*Kernel density estimate of equity returns*) See Figure 19.12.

It can be shown that (with iid data and a Gaussian kernel) the asymptotic distribution is

$$\sqrt{Th}[\hat{f}(x) - f(x)] \xrightarrow{d} N\left[0, \frac{1}{2\sqrt{\pi}}f(x)\right]. \quad (19.11)$$

We can also estimate multivariate pdfs. Let  $x_t$  be a  $d \times 1$  matrix and  $\hat{\Omega}$  be the estimated covariance matrix of  $x_t$ . We can then estimate the pdf at a point  $x$  by using a multivariate Gaussian kernel as

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^T \frac{1}{(2\pi)^{d/2}|H^2\hat{\Omega}|^{1/2}} \exp\left[-\frac{1}{2}(x_t - x)'(H^2\hat{\Omega})^{-1}(x_t - x)\right]. \quad (19.12)$$

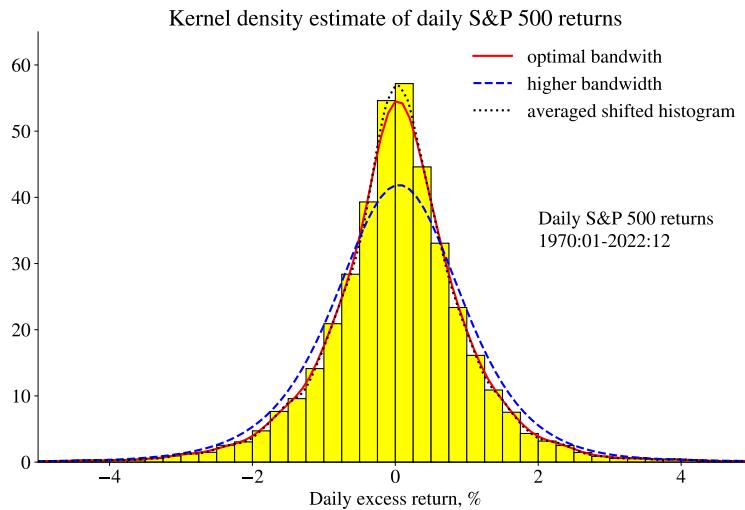


Figure 19.12: Distribution of stock returns

Notice that the function in the summation is the (multivariate) density function of a  $N(x, H^2 \hat{\Omega})$  distribution. The value  $H = 1.06T^{-1/(d+4)}$  is sometimes recommended.

**Remark 19.9** ((19.12) with  $d = 1$ ) With just one variable, (19.12) becomes

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^T \frac{1}{H \text{Std}(x_t) \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{x_t - x}{H \text{Std}(x_t)} \right)^2 \right],$$

which is the same as (19.10) if  $h = H \text{Std}(x_t)$ .

### 19.1.7 “Foundations of Technical Analysis...” by Lo, Mamaysky and Wang (2000)

Reference: Lo, Mamaysky, and Wang (2000)

Topic: is the distribution of the return different after a “signal?” This paper uses kernel regressions to identify and implement some technical trading rules, and then tests if the distribution (of the return) after a signal is the same as the unconditional distribution (using Pearson’s  $\chi^2$  test and the Kolmogorov-Smirnov test). They reject that hypothesis in many cases, using daily data (1962–1996) for around 50 (randomly selected) stocks.

**Empirical Example 19.10** (*Kernel density estimates of equity returns after buy/sell signals*) See Figures 19.13–19.14 for an illustration.

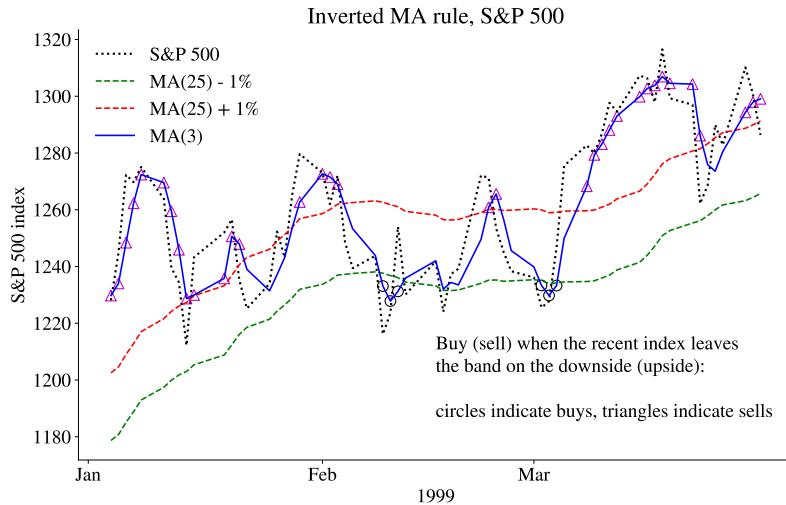


Figure 19.13: Examples of trading rules

## 19.2 Tail Distribution\*

Reference: McNeil, Frey, and Embrechts (2005) 7, Alexander (2008b) 3

In risk control, the focus is on the distribution of losses beyond some threshold level. This has three direct implications. First, the object under study is the loss

$$X = -R, \quad (19.13)$$

that is, the negative of the return. Second, the attention is on how the distribution looks like beyond a threshold and also on the probability of exceeding this threshold. In contrast, the exact shape of the distribution below that point is typically disregarded. Third, modelling the tail of the distribution is best done by using a distribution that allows for a much heavier tail than suggested by a normal distribution. The generalized Pareto (GP) distribution is often used.

### 19.2.1 Loss Distribution and the Generalized Pareto Distribution

The generalized Pareto (GP) distribution is often used to model the tail of the loss distribution. See Figure 19.15 for an illustration.

**Remark 19.11** (*Cdf and pdf of the generalized Pareto distribution*) *The generalized Pareto distribution is described by a scale parameter ( $\beta > 0$ ) and a shape parameter ( $\xi$ ). The*

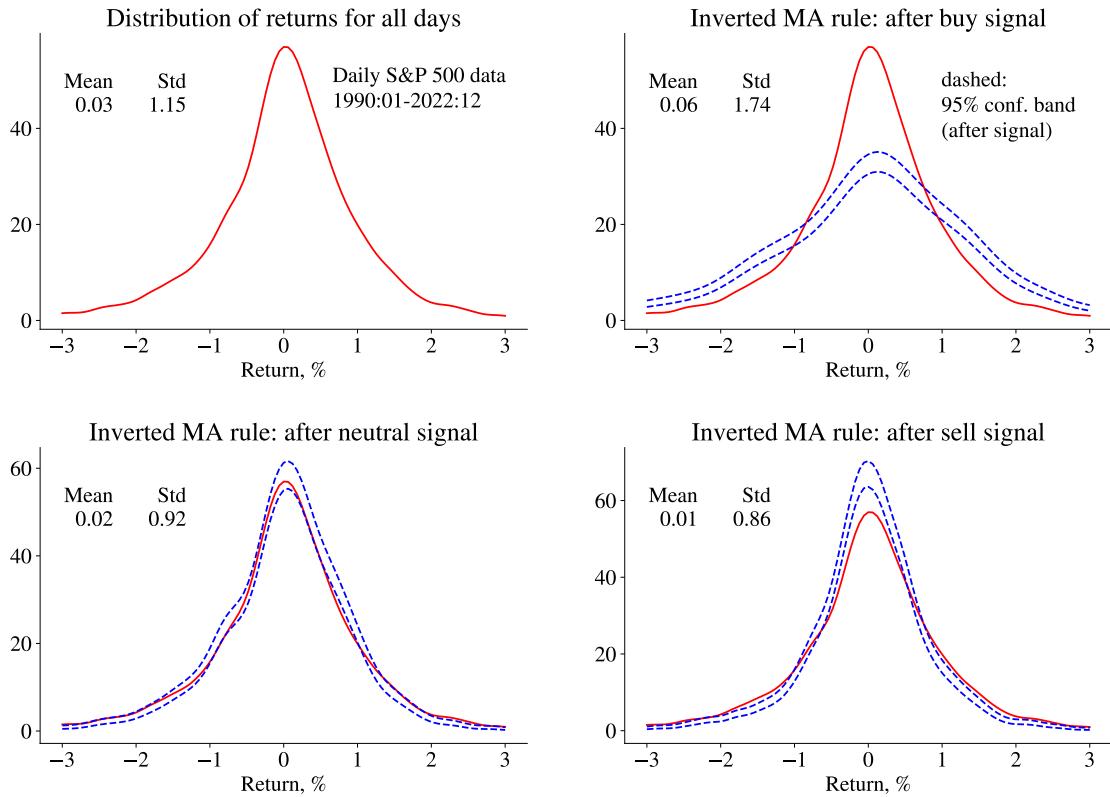


Figure 19.14: Examples of trading rules

*cdf* ( $\Pr(Z \leq z)$ , where  $Z$  is the random variable and  $z$  is a value) is

$$G(z) = \begin{cases} 1 - (1 + \xi z / \beta)^{-1/\xi} & \text{if } \xi \neq 0 \\ 1 - \exp(-z / \beta) & \xi = 0, \end{cases}$$

for  $0 \leq z$  if  $\xi \geq 0$  and  $0 \leq z \leq -\beta / \xi$  in case  $\xi < 0$ . The pdf is

$$g(z) = \begin{cases} \frac{1}{\beta} (1 + \xi z / \beta)^{-1/\xi - 1} & \text{if } \xi \neq 0 \\ \frac{1}{\beta} \exp(-z / \beta) & \xi = 0. \end{cases}$$

The mean is defined (finite) if  $\xi < 1$  and is then  $E(Z) = \beta / (1 - \xi)$ . Similarly, the variance is finite if  $\xi < 1/2$  and is then  $\text{Var}(Z) = \beta^2 / [(1 - \xi)^2 (1 - 2\xi)]$ . See Figure 19.16 for an illustration.

**Remark 19.12** (\*The location of the generalized Pareto distribution) In the application below we will use  $z = x - u$  where  $x$  is a random variable and  $u$  a threshold level. In some texts this  $u$  is part of the definition of the distribution, and is often called the

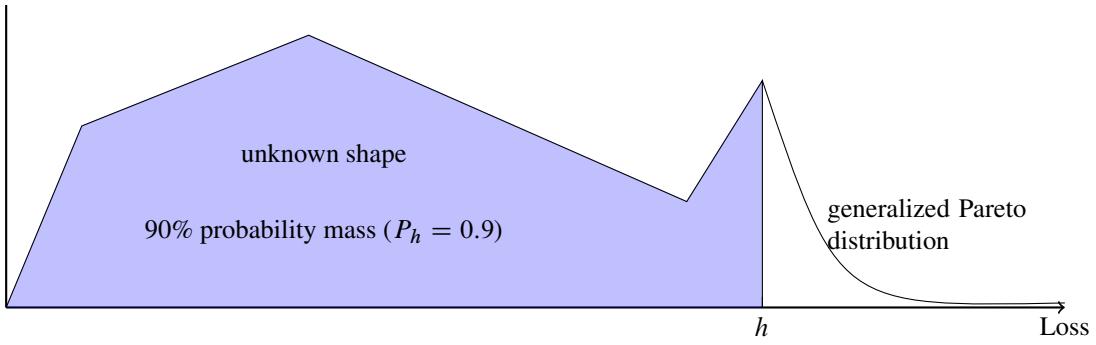


Figure 19.15: Loss distribution

*“location” parameter. This is not done in the text below, and it would not change any of the results.*

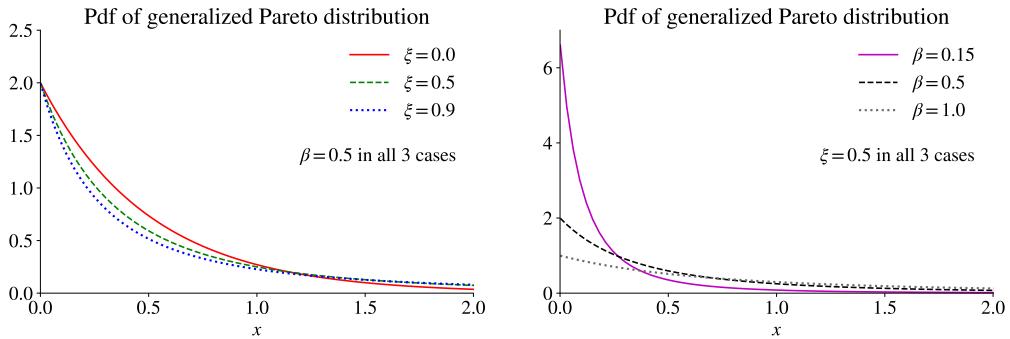


Figure 19.16: Generalized Pareto distributions

Consider the loss  $X$  (the negative of the return) and let  $u$  be a threshold. Assume that the threshold exceedance ( $X - u$ ) has a generalized Pareto distribution. Let  $P_u$  be probability of the loss being smaller than the threshold, that is,  $P_u = \Pr(X \leq u)$ . Then, the cdf of the loss for values greater than the threshold ( $\Pr(X \leq x)$  for  $x > u$ ) can be written

$$\Pr(X \leq x) = F(x) = P_u + G(x - u)(1 - P_u), \text{ for } x > u, \quad (19.14)$$

where  $G(z)$  is the cdf of the generalized Pareto distribution. Noticed that, the cdf value is  $P_u$  at at  $x = u$  (or just slightly above  $u$ ), and that it becomes one as  $x$  goes to infinity.

Clearly, the pdf is

$$f(x) = g(x - u)(1 - P_u), \text{ for } x > u, \quad (19.15)$$

where  $g(z)$  is the pdf of the generalized Pareto distribution. Notice that integrating the pdf from  $x = u$  to infinity shows that the probability mass of  $X$  above  $u$  is  $1 - P_u$ . Since the probability mass below  $u$  is  $P_u$ , it adds up to unity (as it should). See Figures 19.15 and 19.18 for illustrations.

It is often useful to calculate the *tail probability*  $\Pr(X > x)$ , which in the case of the cdf in (19.14) is

$$\Pr(X > x) = 1 - F(x) = (1 - P_u)[1 - G(x - u)], \quad (19.16)$$

where  $G(z)$  is the cdf of the generalized Pareto distribution.

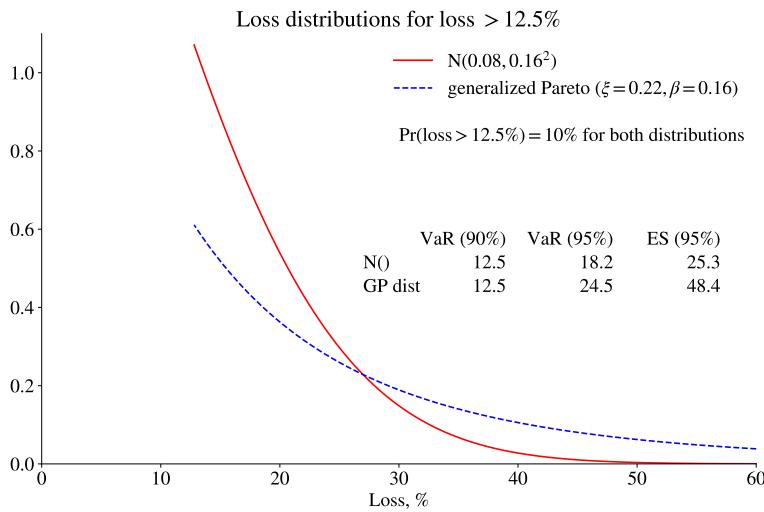


Figure 19.17: Comparison of a normal and a generalized Pareto distribution for the tail of losses

### 19.2.2 VaR and Expected Shortfall of a GP Distribution

The *value at risk*,  $\text{VaR}_\alpha$  (say,  $\alpha = 95\%$ ), is the  $\alpha$ -th quantile of the loss distribution

$$\text{VaR}_\alpha = \text{cdf}_X^{-1}(\alpha), \quad (19.17)$$

where  $\text{cdf}_X^{-1}()$  is the inverse cumulative distribution function of the losses. That is,  $\text{VaR}_\alpha$  is the  $\alpha$  quantile of the loss distribution. For instance,  $\text{VaR}_{95\%}$  is the 0.95 quantile of the loss distribution. This clearly means that the probability of the loss to be less than  $\text{VaR}_\alpha$  equals  $\alpha$

$$\Pr(X \leq \text{VaR}_\alpha) = \alpha. \quad (19.18)$$

(Equivalently, the  $\Pr(X > \text{VaR}_\alpha) = 1 - \alpha$ .)

Assuming  $\text{VaR}_\alpha \geq u$  (that is,  $\alpha \geq P_u$ ), the cdf (19.14) together with the form of the generalized Pareto distribution give the VaR

$$\text{VaR}_\alpha = \begin{cases} u + \frac{\beta}{\xi} \left[ \left( \frac{1-\alpha}{1-P_u} \right)^{-\xi} - 1 \right] & \text{if } \xi \neq 0 \\ u - \beta \ln \left( \frac{1-\alpha}{1-P_u} \right) & \xi = 0 \end{cases}, \text{ for } \alpha \geq P_u. \quad (19.19)$$

**Proof.** (of (19.19)) Set  $F(x) = \alpha$  in (19.14) and use  $z = x - u$  in the cdf from Remark 19.11 and solve for  $x$ . ■

If we assume  $\xi < 1$  (to make sure that the mean is finite), then straightforward integration using (19.15) shows that the *expected shortfall* is

$$\begin{aligned} \text{ES}_\alpha &= \mathbb{E}(X | X \geq \text{VaR}_\alpha) \\ &= \frac{\text{VaR}_\alpha}{1-\xi} + \frac{\beta - \xi u}{1-\xi}, \text{ for } \alpha > P_u \text{ and } \xi < 1. \end{aligned} \quad (19.20)$$

### 19.2.3 Expected Exceedance of a GP Distribution

The *expected exceedance* can help us to specify the cut-off level where the tail “starts,” that is, to choose the value of  $u$ . The average exceedance (in data) over some threshold level  $v$  is the mean of  $X_t - v$  for those observations where  $X_t > v$

$$\begin{aligned} \hat{e}(v) &= \frac{\sum_{t=1}^T (X_t - v) \delta(X_t > v)}{\sum_{t=1}^T \delta(X_t > v)}, \text{ where} \\ \delta(q) &= \begin{cases} 1 & \text{if } q \text{ is true} \\ 0 & \text{else.} \end{cases} \end{aligned} \quad (19.21)$$

(Notice that  $v$  denotes some general threshold level, while  $u$  denotes the threshold we eventually choose for the starting point of the GP distribution.)

The expected exceedance of a GP distribution (with  $\xi < 1$ ) for any threshold  $v > u$  is

$$\begin{aligned} e(v) &= \mathbb{E}(X - v | X > v) \\ &= \frac{\xi v}{1-\xi} + \frac{\beta - \xi u}{1-\xi}, \text{ for } v > u \text{ and } \xi < 1. \end{aligned} \quad (19.22)$$

**Proof.** (of (19.22)) Substitute  $v$  for  $\text{VaR}_\alpha$  in the expected shortfall (19.20)

$$\mathbb{E}(X | X \geq v) = \frac{v}{1-\xi} + \frac{\beta - \xi u}{1-\xi}$$

and subtract  $v$  from both sides to get (19.22). ■

The expected exceedance of a generalized Pareto distribution (with  $0 < \xi < 1$ ) is increasing with the threshold level  $v$ , which indicates that the tail of the distribution is very long. To see that, notice that a normal distribution would typically show a negative relation: see Figure 19.18 for an illustration. This provides a way of assessing which distribution that best fits the tail of the historical histogram. In addition, if we have decided to use the GP distribution for the tail, but do not know where the tail starts (the value of  $u$ ), then it can be chosen as the lowest value (of  $v$ ) after which the average exceedance in data (19.21) appears to be a linear function of the threshold. See Figure 19.19.

**Remark 19.13** (*Expected exceedance from a normal distribution*) If  $X \sim N(\mu, \sigma^2)$ , then

$$\begin{aligned} E(X - v | X > v) &= \mu + \sigma \frac{\phi(v_0)}{1 - \Phi(v_0)} - v, \\ \text{with } v_0 &= (v - \mu)/\sigma \end{aligned}$$

where  $\phi()$  and  $\Phi$  are the pdf and cdf of a  $N(0, 1)$  variable respectively.

#### 19.2.4 Estimating a GP Distribution

The estimation of the parameters of the distribution ( $\xi$  and  $\beta$ ) is typically done by maximum likelihood. Alternatively, a comparison of the empirical exceedance (19.21) with the theoretical (19.22) can help. Suppose we calculate the empirical exceedance for different values of the threshold level (denoted  $v_i$ —all large enough so the relation looks linear), then we can estimate (by OLS)

$$\hat{e}(v_i) = a + b v_i + \varepsilon_i. \quad (19.23)$$

Then, the theoretical exceedance (19.22) for a given starting point of the GP distribution ( $u$ ) is related to this regression according to (19.22) which implies

$$\begin{aligned} a &= \frac{\beta - \xi u}{1 - \xi} \text{ and } b = \frac{\xi}{1 - \xi}, \text{ or} \\ \xi &= \frac{b}{1 + b} \text{ and } \beta = a(1 - \xi) + \xi u. \end{aligned} \quad (19.24)$$

See Figure 19.19 for an illustration.

**Remark 19.14** (*Log likelihood function of the loss distribution*) Since we have assumed that the threshold exceedance ( $X - u$ ) has a generalized Pareto distribution, Remark 19.11

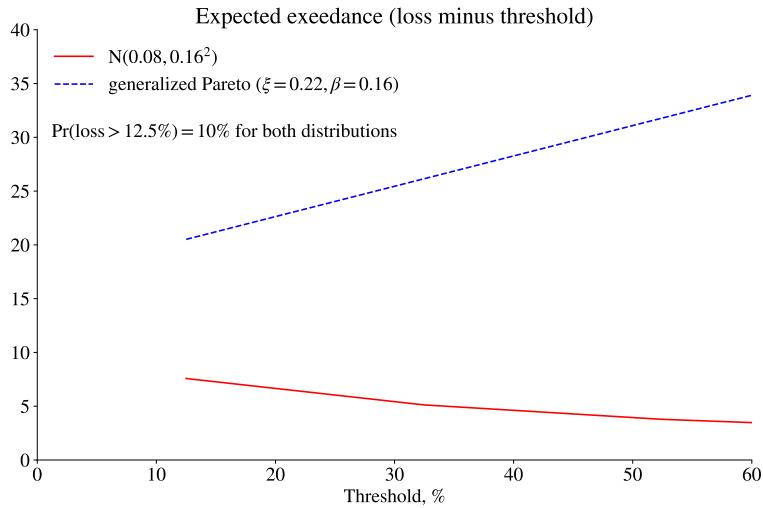


Figure 19.18: Expected exceedance, normal and generalized Pareto distribution

shows that the log likelihood for the observation of the loss above the threshold ( $X_t > u$ ) is

$$L = \sum_{t \text{ st. } X_t > u} L_t$$

$$\ln L_t = \begin{cases} -\ln \beta - (1/\xi + 1) \ln [1 + \xi (X_t - u) / \beta] & \text{if } \xi \neq 0 \\ -\ln \beta - (X_t - u) / \beta & \xi = 0. \end{cases}$$

This allows us to estimate  $\xi$  and  $\beta$  by maximum likelihood. Typically,  $u$  is not estimated, but imposed a priori (based on the expected exceedance).

**Empirical Example 19.15** (Estimation of the generalized Pareto distribution on S&P 500 daily returns). Figure 19.19 (upper left panel) shows that it may be reasonable to fit a GP distribution with a threshold  $u = 1.3$  to S&P 500 daily returns and that OLS estimation of (19.23) can provide useful parameter estimates. The upper right panel illustrates the estimated distribution, while the lower left panel shows that the highest quantiles are well captured by estimated distribution.

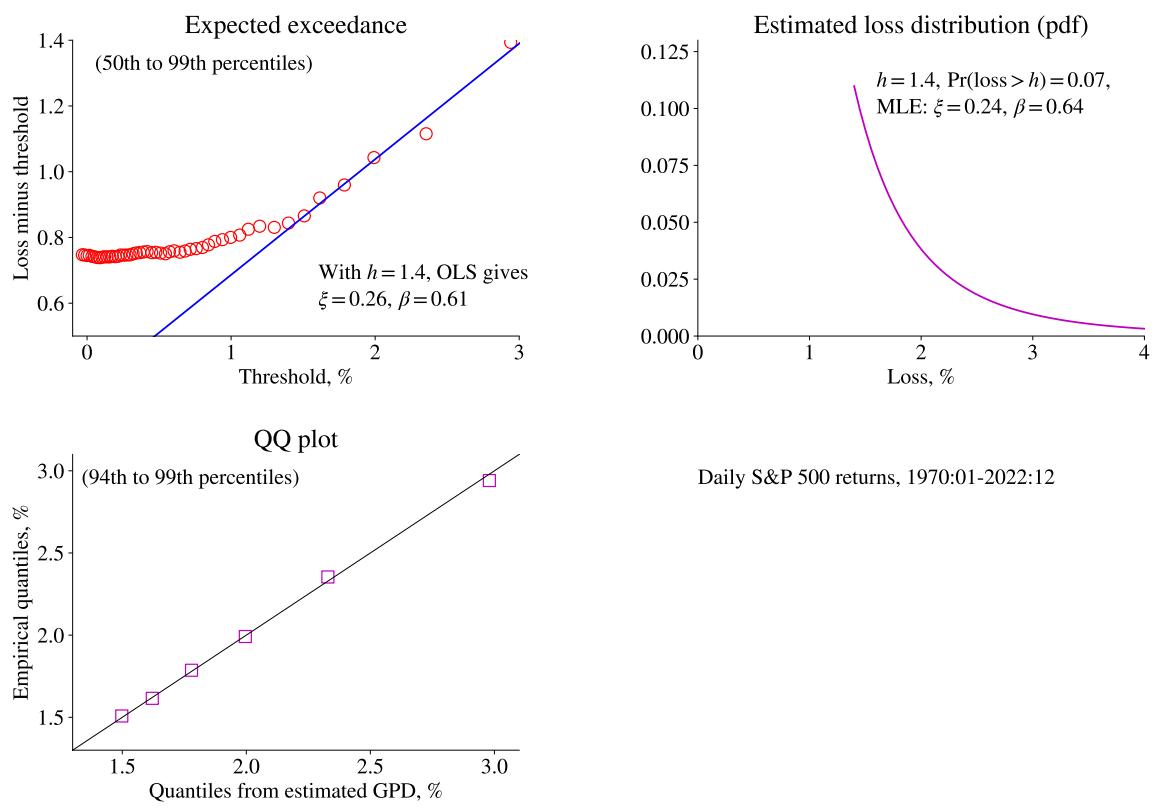


Figure 19.19: Results from S&P 500 data

# Chapter 20

## Return Distributions (Multivariate)\*

More advanced material is denoted by a star (\*). It is not required reading.

### 20.1 Exceedance Correlations\*

Reference: Ang and Chen (2002)

It is often argued that most assets are more strongly correlated in down markets than in up markets. If so, diversification may not be such a powerful tool as what we would otherwise believe.

A straightforward way of examining this is to calculate the correlation of two returns ( $x$  and  $y$ , say) for specific intervals. For instance, we could specify that  $x_t$  should be between  $h_1$  and  $h_2$  and  $y_t$  between  $k_1$  and  $k_2$

$$\text{Corr}(x_t, y_t | h_1 < x_t \leq h_2, k_1 < y_t \leq k_2). \quad (20.1)$$

For instance, by setting the lower boundaries ( $h_1$  and  $k_1$ ) to  $-\infty$  and the upper boundaries ( $h_2$  and  $k_2$ ) to 0, we get the correlation in down markets.

A (bivariate) normal distribution has little probability mass at very low returns, which leads to the correlation being squeezed towards zero as we only consider data far out in the tail. This means that the tail correlation of a normal distribution is always closer to zero than the correlation for all data points. This is illustrated in Figure 20.1.

**Empirical Example 20.1** (*Tail correlations*) Figures 20.2–20.3 suggest (for two US portfolios) that the correlation in the lower tail is high. This suggests that the relation between the two returns in the tails is not well described by a normal distribution. In particular, we need to use a distribution that allows for much stronger dependence in the lower tail. Otherwise, the diversification benefits (in down markets) are likely to be exaggerated.

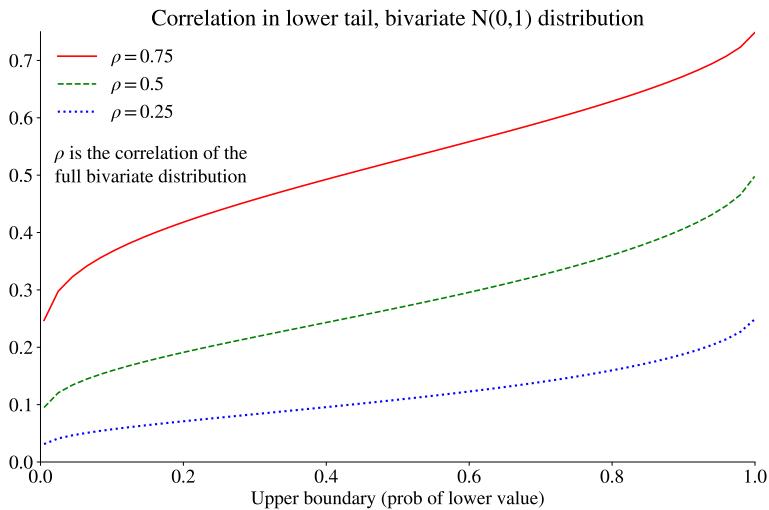


Figure 20.1: Correlation in lower tail when data is drawn from a normal distribution with correlation  $\rho$

## 20.2 Beyond (Linear) Correlations\*

Reference: Alexander (2008a) 6, McNeil, Frey, and Embrechts (2005)

The traditional correlation (also called Pearson's correlation, often denoted  $\rho$ ) measures the linear relation between two variables, that is, to what extent one variable can be explained by a linear function of the other variable (and a constant). That is adequate for most issues in finance, but we sometimes need to capture non-linear relations. It also turns out to be easier to calibrate/estimate copulas (see below) by using other measures of dependency.

*Spearman's rank correlation* (called Spearman's  $\rho$  and often denoted  $\rho_S$ ) measures to what degree two variables have a monotonic relation: it is the correlation of their respective ranks. It measures if one variable tends to be high when the other also is—without imposing the restriction that this relation must be linear. See Figure 20.4 for an illustration.

**Remark 20.2** (*On notation;  $\rho$  vs. Spearman's  $\rho$* ) These notes use  $\rho$  to denote the standard (Person's) correlation coefficient and either “Spearman's  $\rho$ ” or  $\rho_S$  to denote Spearman's rank correlation.

It is computed in two steps. First, the data is *ranked* from the smallest (rank 1) to the largest (ranked  $T$ , where  $T$  is the sample size). Ties (when two or more observations

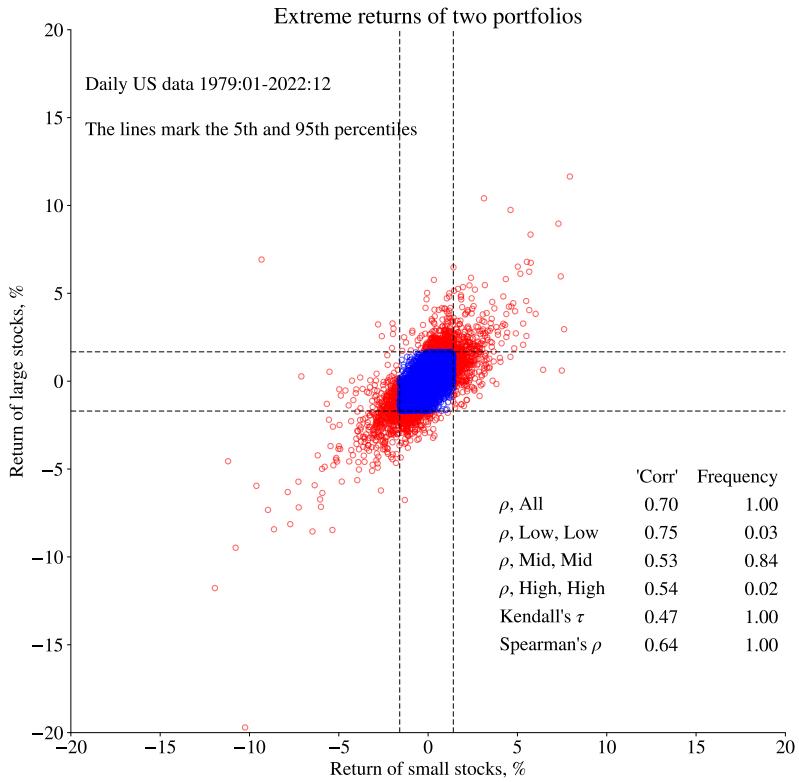


Figure 20.2: Correlation of two portfolios

have the same values) are handled by averaging the ranks. The following illustrates this for two variables

$x_t$	$\text{rank}(x_t)$	$y_t$	$\text{rank}(y_t)$	
2	2.5	7	2	
10	4	8	3	(20.2)
-3	1	2	1	
2	2.5	10	4	

In the second step, simply estimate the correlation of the ranks of two variables

$$\text{Spearman's } \rho = \text{Corr}[\text{rank}(x_t), \text{rank}(y_t)]. \quad (20.3)$$

Clearly, this correlation is between  $-1$  and  $1$ .

**Remark 20.3** (\*Alternative way of calculating the rank correlation) There is an alternative way of calculating the rank correlation based on the difference of the ranks,  $d_t = \text{rank}(x_t) - \text{rank}(y_t)$ , Spearman's  $\rho = 1 - 6\sum_{t=1}^T d_t^2 / (T^3 - T)$ . It gives the same result if there are no tied

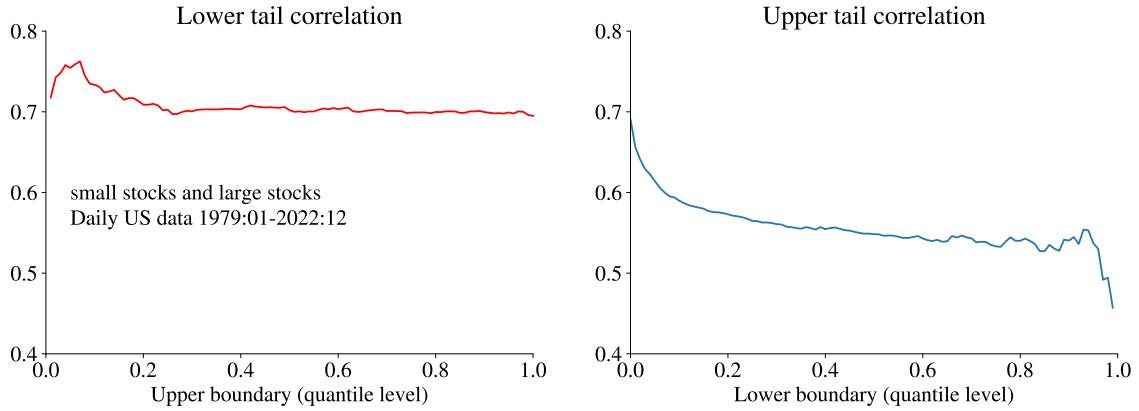


Figure 20.3: Correlation in the tails for two portfolios

ranks.

**Remark 20.4** (\*Formal definition of Spearman's  $\rho$ ) If we have specified the joint distribution of the random variables  $X$  and  $Y$ , then we can also calculate the implied Spearman's  $\rho$  (sometimes only numerically) as  $\text{Corr}[F_X(X), F_Y(Y)]$  where  $F_X(X)$  is the cdf of  $X$  and  $F_Y(Y)$  of  $Y$ .

The rank correlation can be tested by using the fact that (under the null hypothesis)

$$\sqrt{T-1} \times \text{Spearman's } \rho \xrightarrow{d} N(0, 1). \quad (20.4)$$

(For samples of 20 to 40 observations, it is often recommended to use  $\sqrt{(T-2)/(1-\hat{\rho}_S^2)}\hat{\rho}_S$  where  $\hat{\rho}_S$  denotes Spearman's  $\rho$ . This has a  $t_{T-2}$  distribution.)

Kendall's rank correlation (called Kendall's  $\tau$ ) is similar, but is based on comparing changes of  $x_t$  (compared to each of  $x_1, \dots, x_{t-1}$ ) with the corresponding changes of  $y_t$ . For instance, with three data points  $((x_1, y_1), (x_2, y_2), (x_3, y_3))$  we first calculate

$$\begin{array}{ll} \text{Changes of } x & \text{Changes of } y \\ \hline x_2 - x_1 & y_2 - y_1 \\ x_3 - x_1 & y_3 - y_1 \\ x_3 - x_2 & y_3 - y_2, \end{array} \quad (20.5)$$

which gives  $T(T-1)/2$  (here 3) pairs. Then, we investigate if the pairs are concordant

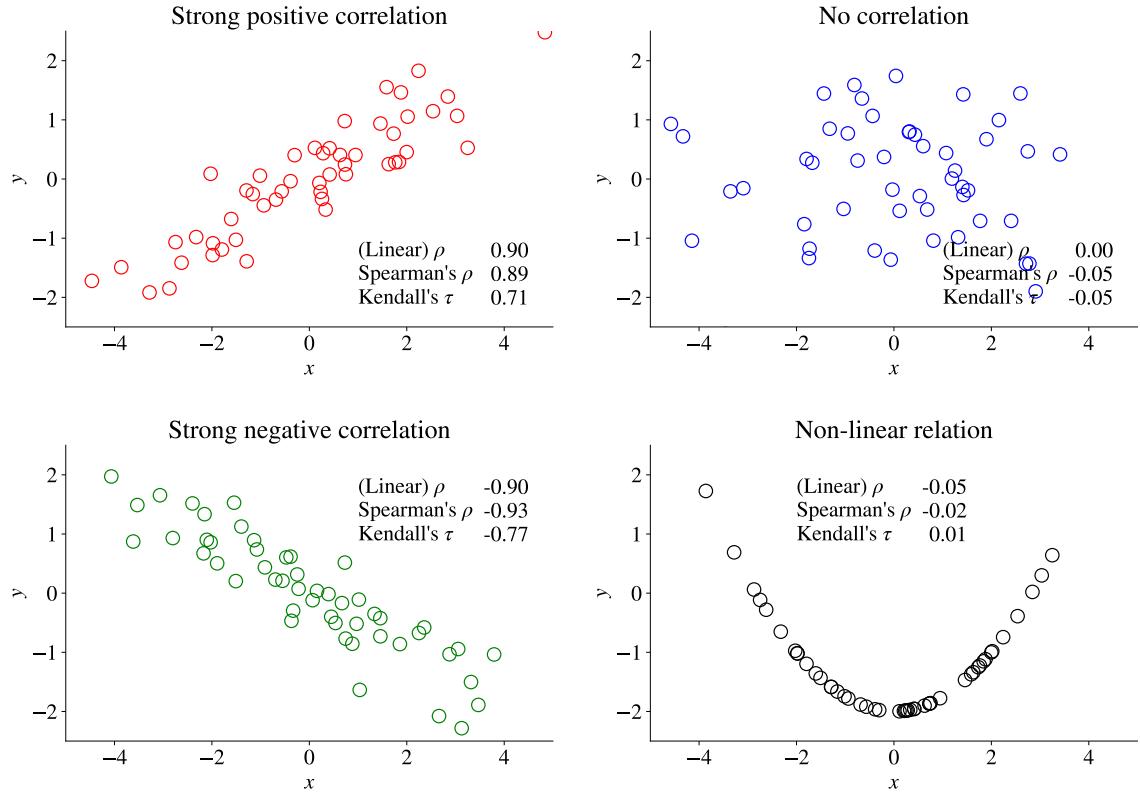


Figure 20.4: Illustration of correlation and rank correlation

(same sign of the change of  $x$  and  $y$ ) or discordant (different signs) pairs

$$ij \text{ is concordant if } (x_j - x_i)(y_j - y_i) > 0 \quad (20.6)$$

$$ij \text{ is discordant if } (x_j - x_i)(y_j - y_i) < 0.$$

Finally, we count the number of concordant ( $T_c$ ) and discordant ( $T_d$ ) pairs and calculate Kendall's  $\tau$  as

$$\text{Kendall's } \tau = \frac{T_c - T_d}{T(T-1)/2}. \quad (20.7)$$

It can be shown that

$$\text{Kendall's } \tau \xrightarrow{d} N\left(0, \frac{4T+10}{9T(T-1)}\right), \quad (20.8)$$

so it is straightforward to test  $\tau$  by a t-test.

**Remark 20.5** (\*Formal definition of Kendall's  $\tau$ ) Let  $x$  and  $\tilde{x}$  be independent draws ("independent copies") from the same distribution, and similarly for  $y$  and  $\tilde{y}$ . Then,  $\tau = E \text{sign}[(x - \tilde{x})(y - \tilde{y})]$ , where  $\text{sign}(0) = 1$  if the argument is positive, 0 if it is zero

and  $-1$  if it is negative.

**Example 20.6** (Kendall's  $\tau$ ) Suppose the data is

$x$	$y$
2	7
10	9
-3	10.

We then get the following changes

<u>Changes of <math>x</math></u>	<u>Changes of <math>y</math></u>	
$x_2 - x_1 = 10 - 2 = 8$	$y_2 - y_1 = 9 - 7 = 2$	<i>concordant</i>
$x_3 - x_1 = -3 - 2 = -5$	$y_3 - y_1 = 10 - 7 = 3$	<i>discordant</i>
$x_3 - x_2 = -3 - 10 = -13$	$y_3 - y_2 = 10 - 9 = 1,$	<i>discordant.</i>

Kendall's  $\tau$  is therefore

$$\tau = \frac{1 - 2}{3(3 - 1)/2} = -\frac{1}{3}.$$

If  $x$  and  $y$  actually has bivariate normal distribution with correlation  $\rho$ , then it can be shown that on average we have

$$\text{Spearman's } \rho = \frac{6}{\pi} \arcsin(\rho/2) \approx \rho \quad (20.9)$$

$$\text{Kendall's } \tau = \frac{2}{\pi} \arcsin(\rho). \quad (20.10)$$

In this case, all three measures give similar messages (although the Kendall's  $\tau$  tends to be closer to zero than the linear correlation and Spearman's  $\rho$ ). This is illustrated in Figure 20.5. Clearly, when data is not normally distributed, then these measures can give distinctly different answers.

A joint  $\alpha$ -quantile exceedance probability measures how often two random variables ( $x$  and  $y$ , say) are both above their respective  $\alpha$  quantiles. Similarly, we can also define the probability that they are *both* below their respective  $\alpha$  quantiles

$$G_\alpha = \Pr(x \leq \xi_{x,\alpha}, y \leq \xi_{y,\alpha}), \quad (20.11)$$

$\xi_{x,\alpha}$  and  $\xi_{y,\alpha}$  are  $\alpha$ -quantile of the  $x$ - and  $y$ -distribution respectively.

In practice, this can be estimated from data by first finding the empirical  $\alpha$ -quantiles ( $\hat{\xi}_{x,\alpha}$  and  $\hat{\xi}_{y,\alpha}$ ) by simply sorting the data and then picking out the value of observation

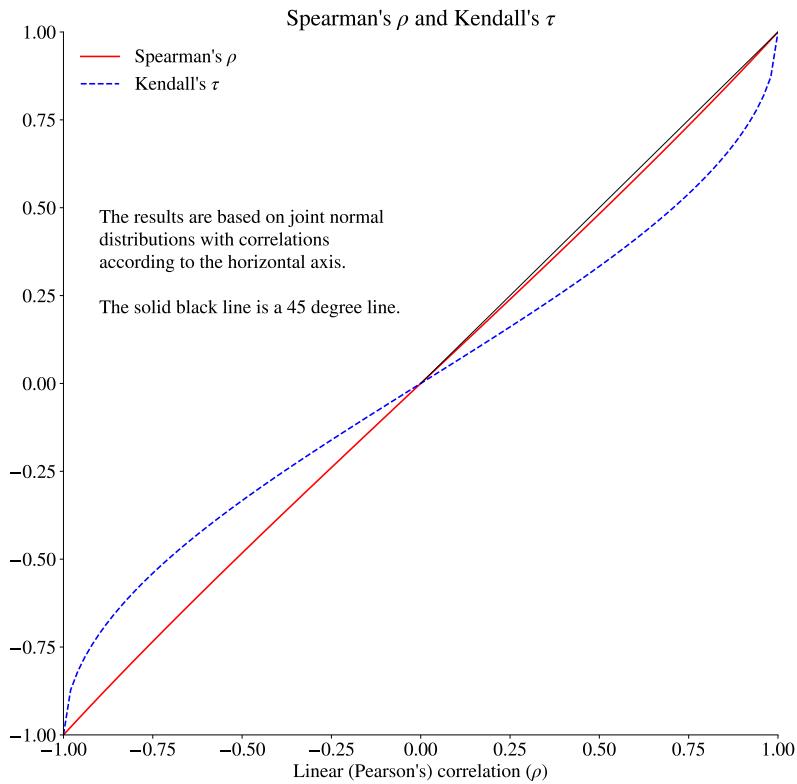


Figure 20.5: Spearman's rho and Kendall's tau if data has a bivariate normal distribution

$\alpha T$  of this sorted list (do this individually for  $x$  and  $y$ ). Then, calculate the estimate

$$\hat{G}_\alpha = \frac{1}{T} \sum_{t=1}^T \delta_t, \text{ where} \quad (20.12)$$

$$\delta_t = \begin{cases} 1 & \text{if } x_t \leq \hat{\xi}_{x,\alpha} \text{ and } y_t \leq \hat{\xi}_{y,\alpha} \\ 0 & \text{otherwise.} \end{cases}$$

See Figure 20.9 for an illustration based on a joint normal distribution.

**Empirical Example 20.7** (*Joint exceedance, equity returns*) Figure 20.6 for an empirical example.

### 20.3 Copulas\*

Reference: McNeil, Frey, and Embrechts (2005), Alexander (2008a) 6, Jondeau, Poon, and Rockinger (2007) 6

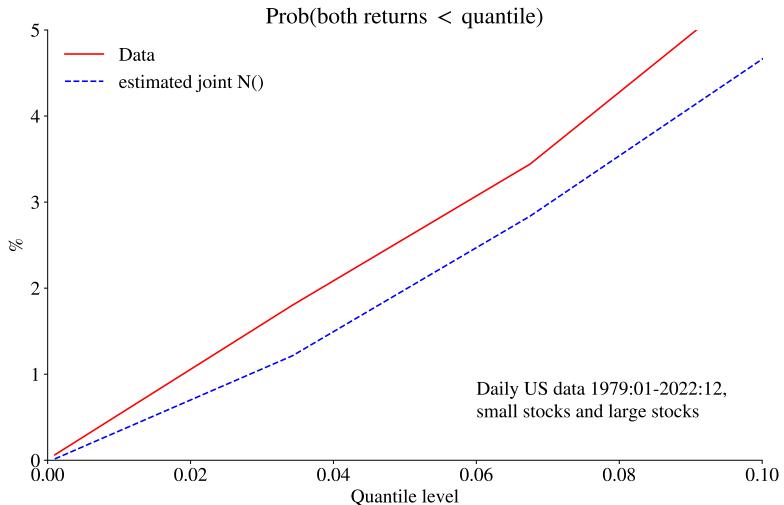


Figure 20.6: Probability of joint low returns

Portfolio choice and risk analysis depend crucially on the joint distribution of asset returns. Empirical evidence suggest that many returns have non-normal distribution, especially when we focus on the tails. There are several ways of estimating complicated joint (non-normal) distributions: using copulas is one. This approach has the advantage that it proceeds in two steps: first we estimate the marginal distribution of each return separately, then we model the comovements by a copula.

### 20.3.1 Multivariate Distributions and Copulas

Any joint (bivariate) pdf can be written as

$$f_{1,2}(x_1, x_2) = c(u_1, u_2) f_1(x_1) f_2(x_2), \text{ with} \quad (20.13)$$

$$u_i = F_i(x_i),$$

where  $c()$  is a *copula density* function,  $u_i = F_i(x_i)$  is short-hand notation for the cdf value and  $f_i(x_i)$  for the pdf values. The extension to three or more random variables is straightforward. Notice that  $u_i = F_i(x_i)$  and  $f_i(x_i)$  both depend refer to the same  $x_i$  value.

Equation (20.13) means that if we know the joint pdf  $f_{1,2}(x_1, x_2)$ —and thus also the cdfs  $F_1(x_1)$  and  $F_2(x_2)$ —then we can figure out what the copula density function is. Alternatively, if we know the marginal (univariate) distributions ( $f_i(x_i)$ ) and thus  $F_i(x_i)$ —and the copula function, then we can construct the joint distribution. (This is called Sklar's

theorem.) This latter approach will turn out to be useful as an alternative way of modelling the joint distribution.

The correlation of  $x_1$  and  $x_2$  depends on both the copula and the marginal distributions. In contrast, both Spearman's  $\rho$  and Kendall's  $\tau$  are determined by the copula only. They therefore provide a way of calibrating/estimating the copula without having to involve the marginal distributions directly.

**Example 20.8** (*Independent random variables*) If  $X_1$  and  $X_2$  are independent, then we know that  $f_{1,2}(x_1, x_2) = f_1(x_1)f_2(x_2)$ , so the copula density function is just a constant equal to one.

**Remark 20.9** (*Joint cdf*) A joint cdf of two random variables ( $X_1$  and  $X_2$ ) is defined as

$$F_{1,2}(x_1, x_2) = \Pr(X_1 \leq x_1 \text{ and } X_2 \leq x_2).$$

This cdf is obtained by integrating the joint pdf  $f_{1,2}(x_1, x_2)$  over both variables

$$F_{1,2}(x_1, x_2) = \int_{s=-\infty}^{x_1} \int_{t=-\infty}^{x_2} f_{1,2}(s, t) ds dt.$$

(Conversely, the pdf is the mixed derivative of the cdf,  $f_{1,2}(x_1, x_2) = \partial^2 F_{1,2}(x_1, x_2) / \partial x_1 \partial x_2$ .) See Figure 20.7 for an illustration.

**Remark 20.10** (*From joint to univariate pdf*) The pdf of  $x_1$  (also called the marginal pdf of  $x_1$ ) can be calculate from the joint pdf as  $f_1(x_1) = \int_{x_2=-\infty}^{\infty} f_{1,2}(x_1, x_2) dx_2$ .

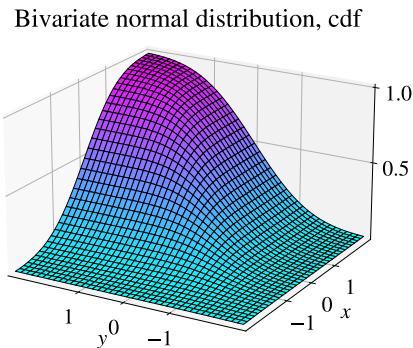
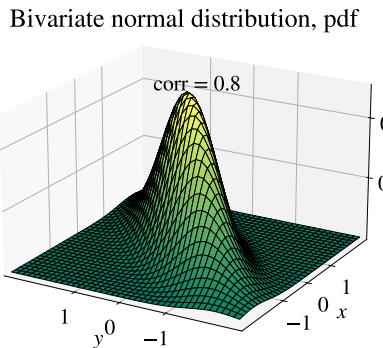


Figure 20.7: Bivariate normal distributions

**Remark 20.11** (*Joint pdf and copula density, n variables*) For  $n$  variables (20.13) generalizes to

$$f_{1,2,\dots,n}(x_1, x_2, \dots, x_n) = c(u_1, u_2, \dots, u_n) f_1(x_1) f_2(x_2) \dots f_n(x_n), \text{ with}$$

$$u_i = F_i(x_i),$$

**Remark 20.12** (*Cdfs and copulas\**) The joint cdf can be written as

$$F_{1,2}(x_1, x_2) = C(u_1, u_2), \text{ with } u_i = F_i(x_i),$$

where  $C()$  is the unique copula function. Taking derivatives gives (20.13) where

$$c(u_1, u_2) = \frac{\partial^2 C(u_1, u_2)}{\partial u_1 \partial u_2}.$$

Notice the derivatives are with respect to  $u_i = F_i(x_i)$ , not  $x_i$ . Conversely, integrating the density over both  $u_1$  and  $u_2$  gives the copula function  $C()$ .

### 20.3.2 The Gaussian Copula

The bivariate *Gaussian copula density function* is

$$c(u) = \frac{1}{|R|^{1/2}} \exp\left[-\frac{1}{2} v' (R^{-1} - I_2)v\right], \text{ with } v = \begin{bmatrix} \Phi^{-1}(u_1) \\ \Phi^{-1}(u_2) \end{bmatrix}, \quad (20.14)$$

where  $\Phi^{-1}(u_1)$  is the inverse of the  $N(0, 1)$  cdf and  $R$  is the correlation matrix of  $u$ . With  $n$  variables, change  $I_2$  to  $I_n$ . See Figure 20.8 for an illustration of how the copula density depends on the correlation.

**Remark 20.13** (*The Gaussian copula function*) It can be shown that integrating (20.14) twice (over  $u_1$  and  $u_2$ ), gives the Gaussian copula function

$$C(u_1, u_2) = \Phi_R(v),$$

where  $\Phi_R$  is the cdf of an joint  $N(\mathbf{0}, R)$  distribution and  $v$  is defined in (20.14). (This result might look surprising given the form of the density in (20.14). The explanation is that we integrate with respect to  $u$ , not  $v$ .)

Notice that when using this function in (20.13) to construct the joint pdf, we take the following steps: (1) calculate the cdf values  $u_i = F_i(x_i)$  from the univariate distribution of  $x_i$  (which may be non-normal); (2) calculate the quantiles of the same  $x_i$  values

according to a standard normal distribution  $\xi_i = \Phi^{-1}(u_i)$ ; (3) use in (20.14); (4) combine the results as in (20.13)). See Figures 20.10–20.11 for illustrations of the resulting joint distribution. These figures show results for two different choices of the marginal distributions—to highlight that the marginal distributions clearly matter for the joint pdf.

It can be shown that assuming that the marginal pdfs ( $f_1(x_1)$  and  $f_2(x_2)$ ) are  $N(\mu_i, \sigma_i^2)$  and then combining with the Gaussian copula density (20.14) recovers a bivariate normal distribution. However, the way we typically use copulas is to assume (and estimate) some other type of univariate marginal distributions, for instance, with fat tails—and then combine with a (perhaps Gaussian) copula density to create the joint distribution.

A zero correlation ( $R = I_2$ ) makes the copula density (20.14) equal to unity—so the joint density is just the product of the marginal densities. A positive correlation makes the copula density high when both  $x_1$  and  $x_2$  deviate from their means in the same direction. The easiest way to *calibrate a Gaussian copula* is therefore to set the linear correlation to

$$\rho = \text{Spearman's } \rho(x_1, x_2) \quad (20.15)$$

as suggested by (20.9). Notice that the rank correlation (Spearman's  $\rho$ ) is the same for  $(x_1, x_2)$  as for  $(u_1, u_2)$ .

Alternatively, the  $\rho$  parameter can be calibrated to fit the properties of the joint tail distribution of data. For instance, to match the joint  $\alpha$ -quantile exceedance probability in data (20.12) and as implied by the copula.

To calculate joint  $\alpha$ -quantile exceedance probability implied by a specific copula (and its parameters), we need to find the copula function (essentially the cdf) corresponding to a copula density. For some copulas (see below), there are analytical results, but in other cases we need to use numerical integration and/or simulations. Some results are given in remarks below. See Figure 20.9: for the Gaussian copula, the figure shows that a higher correlation implies a larger probability that both variables are very low—but that the probabilities quickly become very small as we move towards lower quantiles (lower returns).

### 20.3.3 The Clayton Copula

The Gaussian copula is useful, but it has the drawback that it is symmetric—so the downside and the upside look the same. This is at odds with evidence from many financial markets that show higher correlations across assets in down markets. The *Clayton copula*

*density* is therefore an interesting alternative

$$c(u_1, u_2) = (-1 + u_1^{-\alpha} + u_2^{-\alpha})^{-2-1/\alpha} (u_1 u_2)^{-\alpha-1} (1 + \alpha), \quad (20.16)$$

where  $\alpha \neq 0$ . When  $\alpha > 0$ , then correlation on the downside is much higher than on the upside (where it goes to zero as we move further out in the tail). See Figure 20.8 for an illustration of how the copula density differs from the Gaussian copula. Also, see Figures 20.10–20.11 for illustrations of the resulting joint distribution (contour plots).

**Remark 20.14** (*Multivariate Clayton copula density\**) *The Clayton copula density for  $n$  variables is*

$$c(u) = (1 - n + \sum_{i=1}^n u_i^{-\alpha})^{-n-1/\alpha} (\prod_{i=1}^n u_i)^{-\alpha-1} (\prod_{i=1}^n [1 + (i-1)\alpha]).$$

With Clayton copula, the  $\alpha$  parameter is related to Kendall's  $\tau$  (denoted  $\tau$ ) according to

$$\text{Kendall's } \tau = \frac{\alpha}{\alpha + 2}, \text{ so} \quad (20.17)$$

$$\alpha = \frac{2\tau}{1 - \tau}. \quad (20.18)$$

The easiest way to *calibrate a Clayton copula* is therefore to set the parameter  $\alpha$  according to (20.18), where Kendall's  $\tau$  is estimated from the “data” on  $(u_1, u_2)$ . The latter are obtained by (1) estimate the marginal univariate distributions of  $x_1$  and  $x_2$ ; and (2) calculate the  $u_{i,t} = \hat{F}_i(x_{i,t})$  values (and then estimate  $\tau$  of those).

Figure 20.9 (right subfigure) illustrates how the probability of both variables to be below their respective quantiles depend on the  $\alpha$  parameter. These parameters generate correlations similar to those for the Gaussian copula (see (20.9)–(20.10)) in the left subfigure. The subfigures are therefore comparable—and the main point is that Clayton's copula gives probabilities of joint low values (both variables being low) that do not decay as quickly as according to the Gaussian copulas. Intuitively, this means that the Clayton copula exhibits much higher “correlations” in the lower tail than the Gaussian copula does—although they imply the same overall correlation. That is, according to the Clayton copula more of the overall correlation of data is driven by synchronized movements in the lower tail. This could be interpreted as if the correlation is higher in market crashes than during normal times. See Figures 20.10–20.11 for illustrations.

**Remark 20.15** (*Clayton copula function\**) *The copula function (the cdf) corresponding*

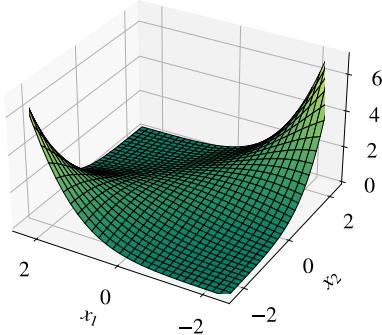
to (20.16) is

$$C(u_1, u_2) = (-1 + u_1^{-\alpha} + u_2^{-\alpha})^{-1/\alpha}$$

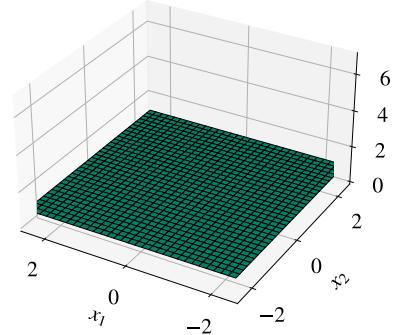
and with  $n$  components

$$C(u) = (1 - n + \sum_{i=1}^n u_i^{-\alpha})^{-1/\alpha}.$$

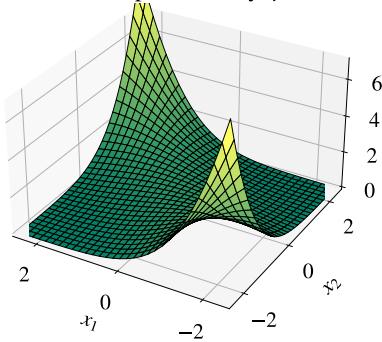
Gaussian copula density,  $\rho = -0.5$



Gaussian copula density,  $\rho = 0$



Gaussian copula density,  $\rho = 0.5$



Clayton copula density,  $\alpha = 1.5$

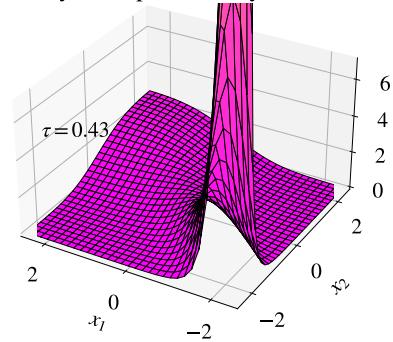


Figure 20.8: Copula densities (as functions of  $x_i$ )

**Remark 20.16 (Tail Dependence\*)** The measure of lower tail dependence starts by finding the probability that  $X_1$  is lower than its  $q$ th quantile ( $X_1 \leq F_1^{-1}(q)$ ) given that  $X_2$  is lower than its  $q$ th quantile ( $X_2 \leq F_2^{-1}(q)$ )

$$\Lambda_l = \Pr[X_1 \leq F_1^{-1}(q) | X_2 \leq F_2^{-1}(q)],$$

and then takes the limit as the quantile goes to zero

$$\lambda_l = \lim_{q \rightarrow 0} \Pr[X_1 \leq F_1^{-1}(q) | X_2 \leq F_2^{-1}(q)].$$

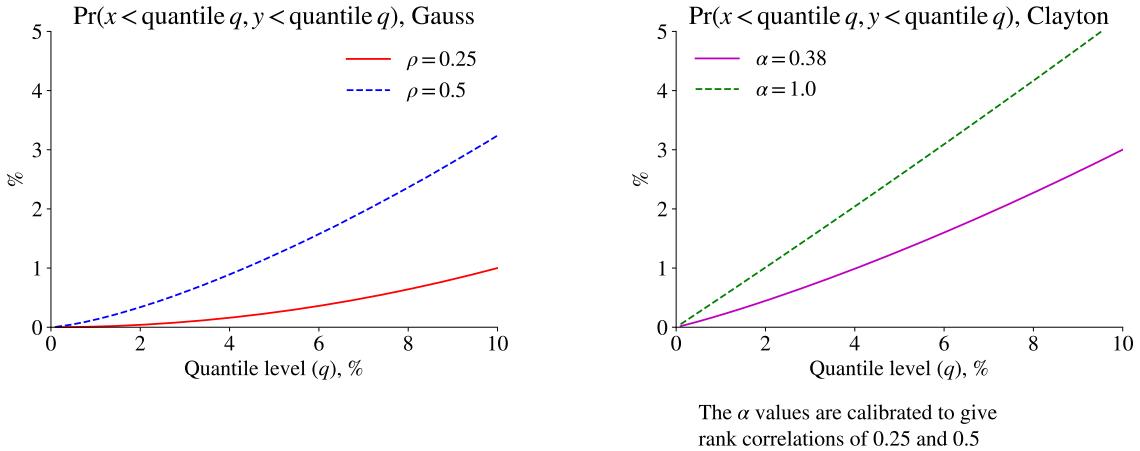


Figure 20.9: Probability of joint low returns, Gaussian and Clayton copulas

*It can be shown that a Gaussian copula gives zero or very weak tail dependence, unless the correlation is 1. It can also be shown that the lower tail dependence of the Clayton copula is*

$$\lambda_l = 2^{-1/\alpha} \text{ if } \alpha > 0$$

*and zero otherwise.*

## 20.4 Simulating Joint Distributions\*

To find the implication for a portfolio of several assets (modelled using copula and perhaps tail distribution approaches), we often resort to simulations. That is, we draw random numbers (returns for each of the assets) from the joint tail distribution and then study the properties of the portfolio (with say, equal weights or whatever). The reason we simulate is that it is difficult to analytically calculate the distribution of the portfolio.

The approach proceeds in two steps. First, draw  $n$  values for the copula ( $u_i, i = 1, \dots, n$ ). Second, calculate the random number (“return”) by inverting the marginal cdfs  $u_i = F_i(x_i)$  in (20.13) as

$$x_i = F_i^{-1}(u_i), \quad (20.19)$$

where  $F_i^{-1}()$  is the inverse of the marginal cdf of  $x_i$ . The following remarks discuss the details.

**Remark 20.17** *(To draw  $n$  random numbers from a Gaussian copula) First, draw  $n$  numbers ( $v_i$  for  $i = 1, \dots, n$ ) from an multivariate  $N(\mathbf{0}, R)$  distribution, where  $R$  is the*

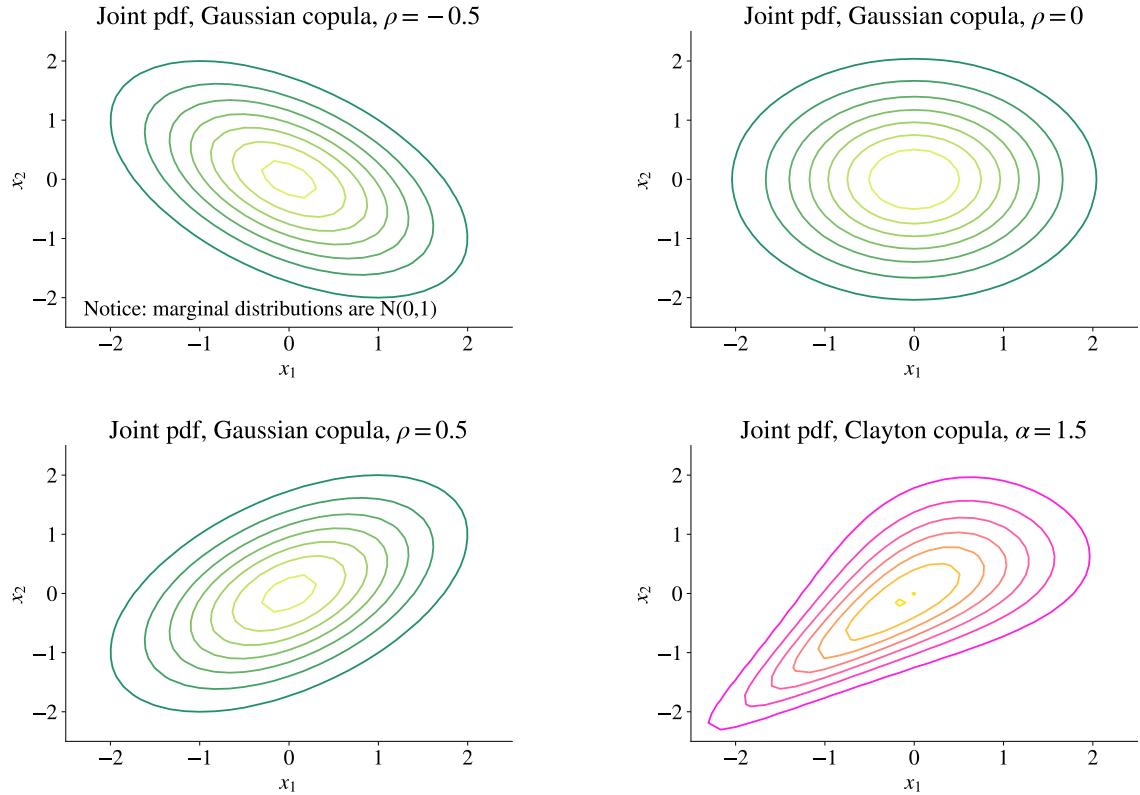


Figure 20.10: Contours of bivariate pdfs

correlation matrix. Second, calculate  $u_i = \Phi(v_i)$ , where  $\Phi$  is the cdf of a standard normal distribution. Third, calculate  $x_i = F_i^{-1}(u_i)$  for each of the  $n$  variables. Notice that the parameters of the  $F_i()$  distribution differ across  $i$ .

**Remark 20.18** (To draw  $n$  random numbers from a Clayton copula) First, draw  $z_i$  for  $i = 1, \dots, n$  from a uniform distribution (between 0 and 1). Second, draw  $X$  from a  $\text{gamma}(1/\alpha, 1)$  distribution. Third, calculate  $u_i = [1 - \ln(z_i)/X]^{-1/\alpha}$  for  $i = 1, \dots, n$ . Fourth, calculate  $x_i = F_i^{-1}(u_i)$  for each of the  $n$  variables.

**Remark 20.19** (Simulating returns from the GP distribution) Consider the case where the cdf for losses  $x \leq h$  is  $F(x) = J(x)P_h/J(h)$ , but for  $x > h$  it is  $F(x) = P_h + G(x-h)(1-P_h)$ . With  $u$  from the copula, let  $\tilde{u} = 1 - u$  (since  $u$  from the copula is for returns and we need to apply GP which is for losses). For  $\tilde{u} \leq P_h$  use

$$\tilde{u} = J(x)P_h/J(h) \text{ and solve as } x = J^{-1}[\tilde{u}J(h)/P_h],$$

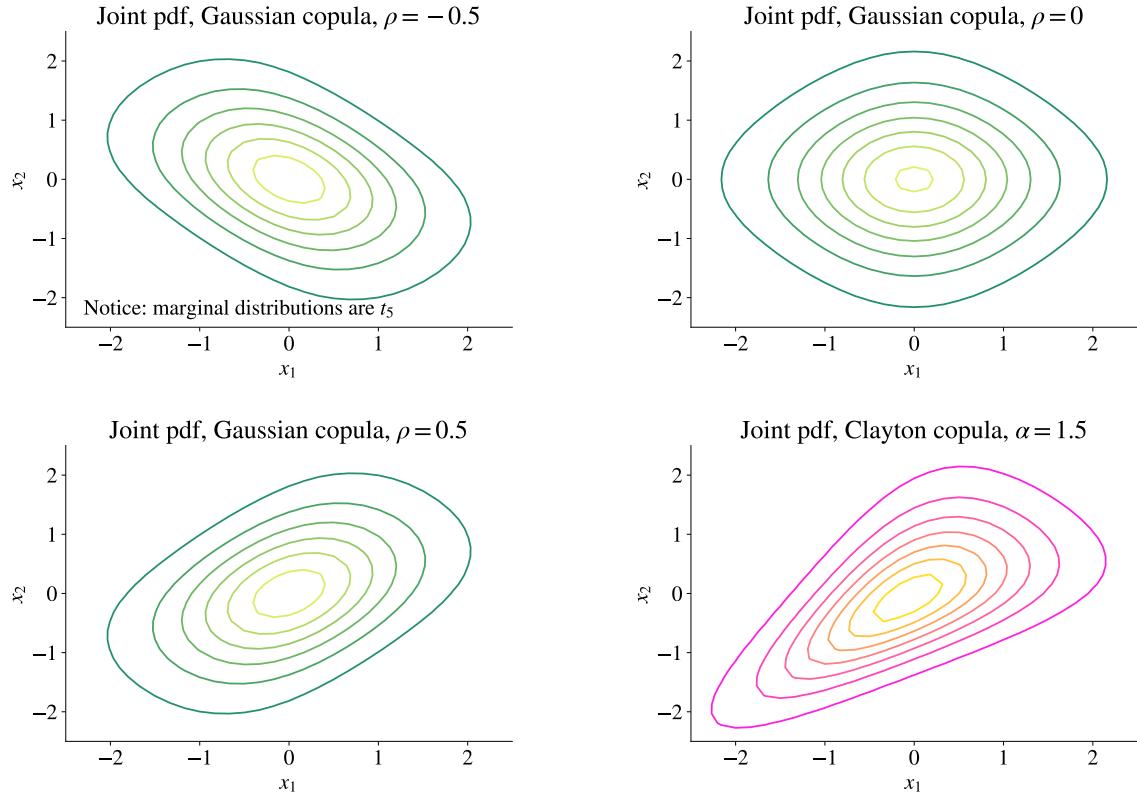


Figure 20.11: Contours of bivariate pdfs

where  $J^{-1}[]$  is the inverse of the  $J()$  cdf. Instead, for  $\tilde{u} > P_h$  set

$$\tilde{u} = P_h + G(x - h)(1 - P_h) \text{ and solve as } x = h + G^{-1}[(\tilde{u} - P_h)/(1 - P_h)],$$

where  $G^{-1}[z]$  is the inverse of the GP cdf (which is easily calculated). Once the loss  $X$  is simulated, the simulated return is just  $R = -X$ .

Such simulations can be used to quickly calculate the VaR and other risk measures for different portfolios. Figures 20.12 –20.13 give an illustration of how the movements in the lower tails get more synchronized as the  $\alpha$  parameter in the Clayton copula increases.

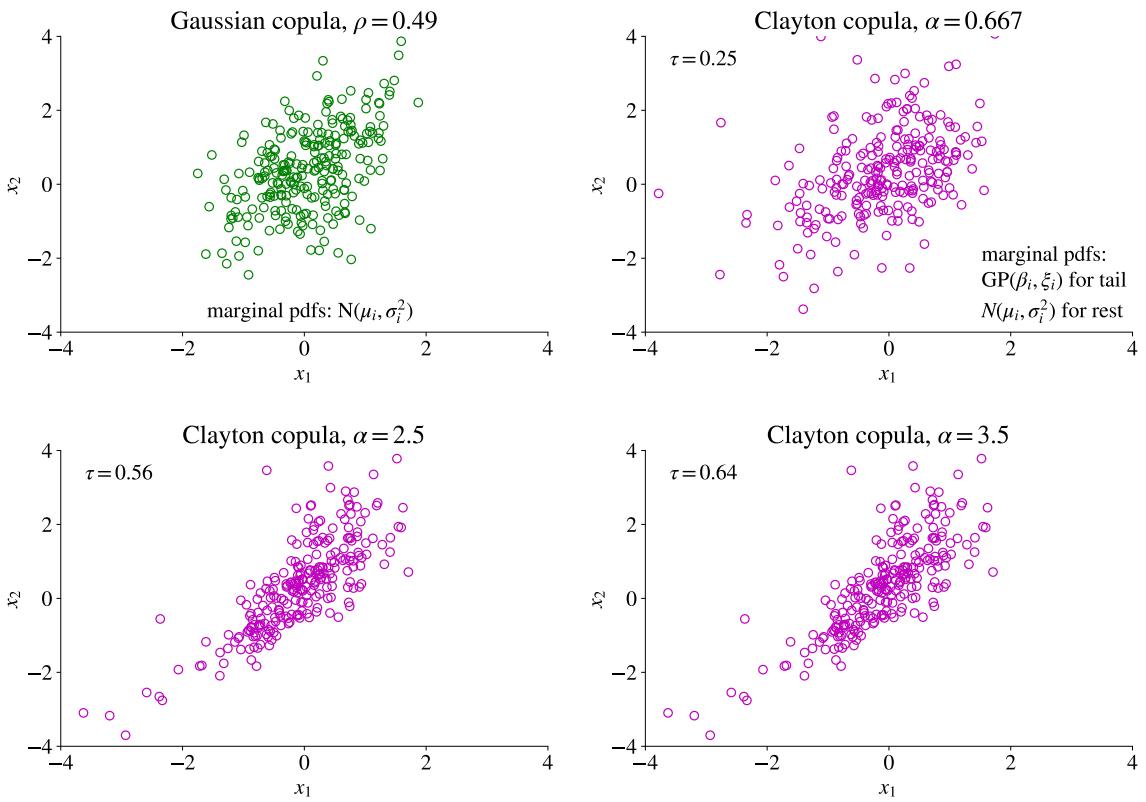


Figure 20.12: Example of scatter plots of two asset returns drawn from different copulas

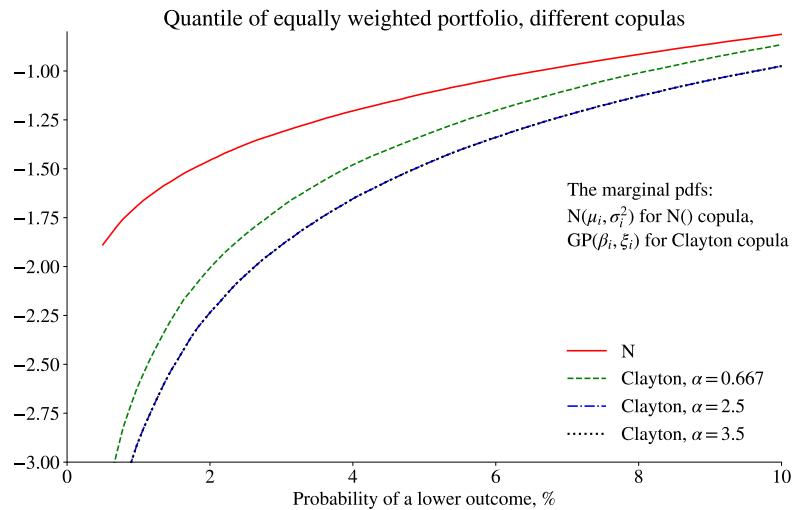


Figure 20.13: Quantiles of an equally weighted portfolio of two asset returns drawn from different copulas

# Chapter 21

## Option Pricing and Estimation of Continuous Time Processes\*

Reference: Hull (2006) 19, Elton, Gruber, Brown, and Goetzmann (2003) 22 or Bodie, Kane, and Marcus (2005) 21

Reference (advanced): Taylor (2005) 13–14; Campbell, Lo, and MacKinlay (1997) 9; Gourieroux and Jasiak (2001) 12–13

More advanced material is denoted by a star (\*). It is not required reading.

### 21.1 The Black-Scholes Model

#### 21.1.1 The Black-Scholes Option Price Model

A European call option contract traded (contracted and paid) in  $t$  may stipulate that the buyer of the contract has the right (not the obligation) to buy one unit of the underlying asset (from the issuer of the option) in  $t + m$  at the strike price  $K$ . The option payoff (in  $t + m$ ) is clearly  $\max(0, S_{t+m} - K)$ , where  $S_{t+m}$  is the asset price at expiration. See Figure 21.1 for the timing convention.

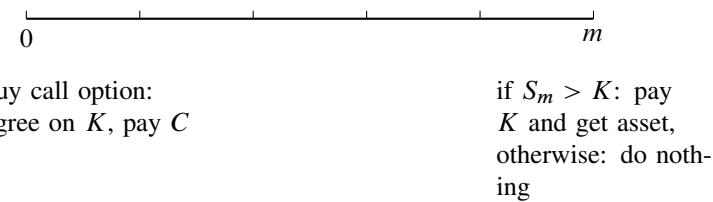


Figure 21.1: Timing convention of option contract

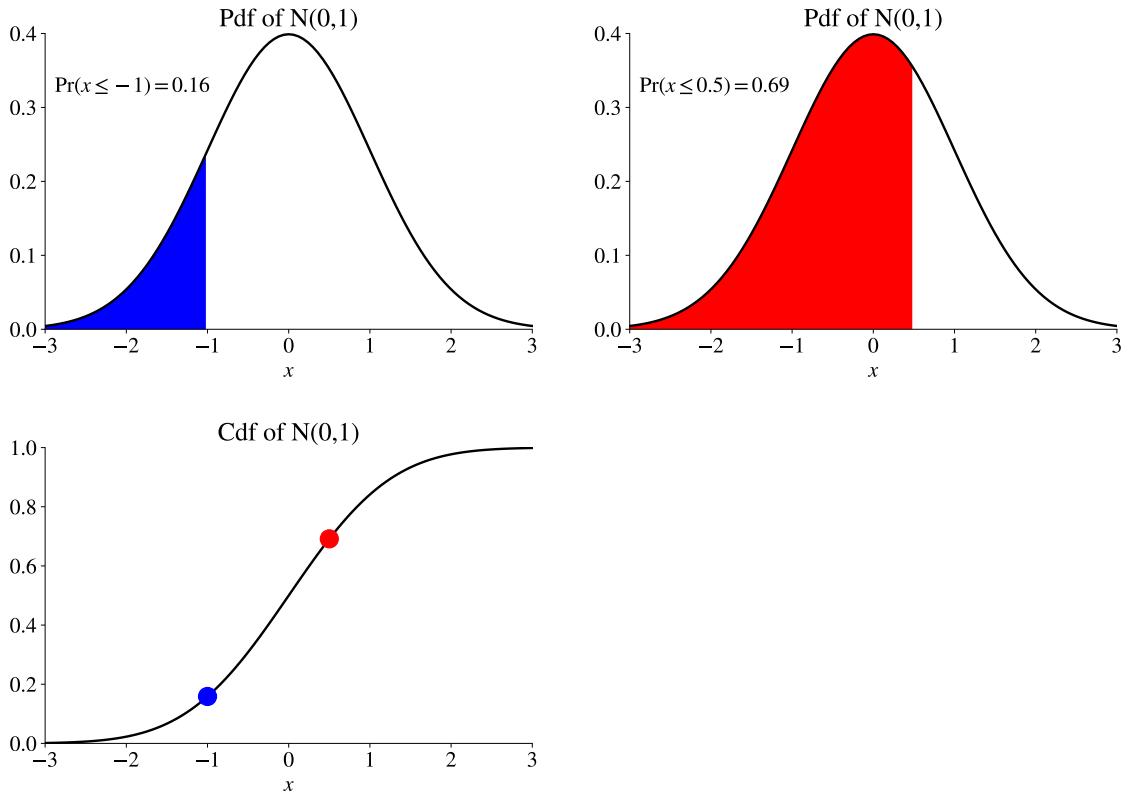


Figure 21.2: Pdf and cdf of  $N(0,1)$

The Black-Scholes formula for a European call option price is

$$C_t = S_t \Phi(d_1) - K e^{-rm} \Phi(d_1 - \sigma \sqrt{m}), \text{ where} \quad (21.1)$$

$$d_1 = \frac{\ln(S_t/K) + (r + \sigma^2/2)m}{\sigma \sqrt{m}}.$$

where  $S_t$  is the price of the underlying asset in period  $t$ , and  $r$  is the continuously compounded interest rate. Also,  $\Phi()$  is the cumulative distribution function of a standard normal,  $N(0, 1)$ , variable. For instance,  $\Phi(2)$  is the probability that the variable is less or equal to two, see Figure 21.2.

Some basic properties of the model are illustrated in Figure 21.3. In particular, the call option price is increasing in the volatility and decreasing in the strike price.

The B-S formula can be derived from several stochastic processes of the underlying asset price (discussed below), but they all imply that the distribution of log asset price in  $t + m$  (conditional on the information in  $t$ ) is normal with some mean  $\alpha$  (not important

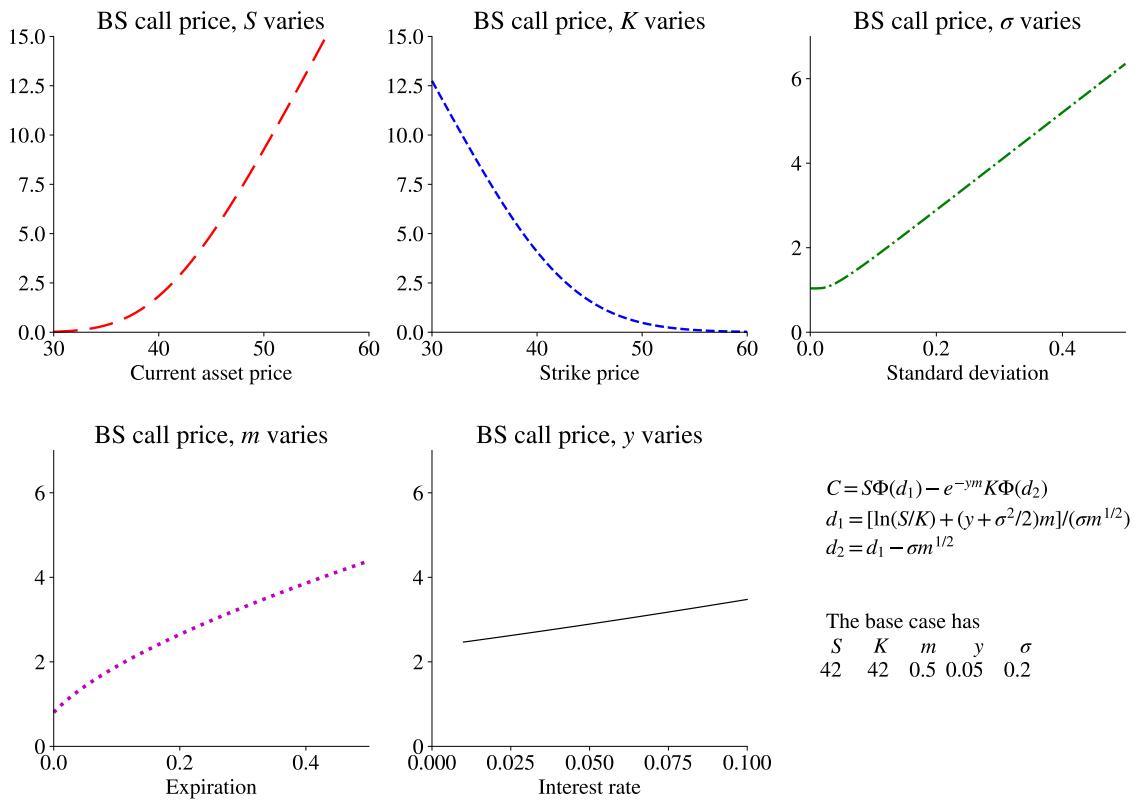


Figure 21.3: Call option price, Black-Scholes model

for the option price) and the variance  $m\sigma^2$

$$\ln S_{t+m} \sim N(\alpha, m\sigma^2). \quad (21.2)$$

Option pricing is basically about forecasting the volatility (until expiration of the option) of the underlying asset. This is clear from the Black-Scholes model where the only unknown parameter is the volatility. It is also true more generally—which can be seen in at least two ways. First, a higher volatility is good for an owner of a call option since it increases the upside potential (higher probability of a really good outcome), at the same time as the down side is protected. Second, many option portfolios highlight how volatility matters for the potential profits. For instance, a straddle (a long position in both a call and a put at the same strike price) pays off if the price of the underlying asset moves a lot (in either direction) from the strike price, that is, when volatility is high. See Figures 21.4–21.5 for illustrations.

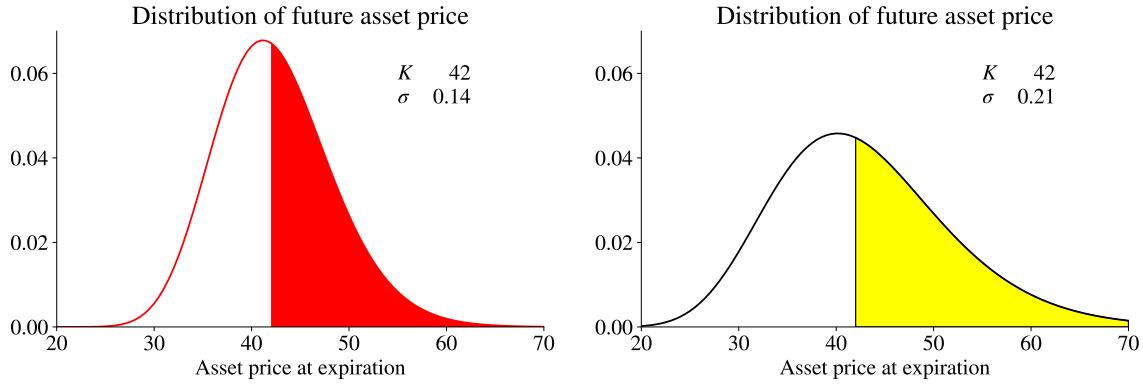


Figure 21.4: Distribution of future stock price

### 21.1.2 Implied Volatility

The pricing formula (21.1) contains only one unknown parameter: the standard deviation  $\sigma$  in the distribution of  $\ln S_{t+m}$ , see (21.2). With data on the option price, spot price, the interest rate, and the strike price, we can solve for standard deviation: the *implied volatility*. This should not be thought of as an estimation of an unknown parameter—rather as just a transformation of the option price. Notice that we can solve (by trial-and-error or some numerical routine) for one implied volatility for each available strike price.

If the Black-Scholes formula is correct, that is, if the assumption in (21.2) is correct, then these volatilities should be the same across strike prices—and it should also be constant over time.

In contrast, it is often found that the implied volatility is a “smirk” (equity markets) or “smile” (FX markets) shaped function of the strike price.

**Empirical Example 21.1** (*Implied volatility for SMI options*) See Figure 21.6 for volatility smiles for a few trading days, and Figure 21.7 for a summary of how the dynamics over time.

One possible explanation for a smirk shape is that market participants assign a higher probability to a dramatic drop in share prices than a normal distribution suggests. A possible explanation for a smile shape is that the (perceived) distribution of the future asset price has more probability mass in the tails (“fat tails”) than a normal distribution has. In addition, the implied volatilities seems to move considerably over time.

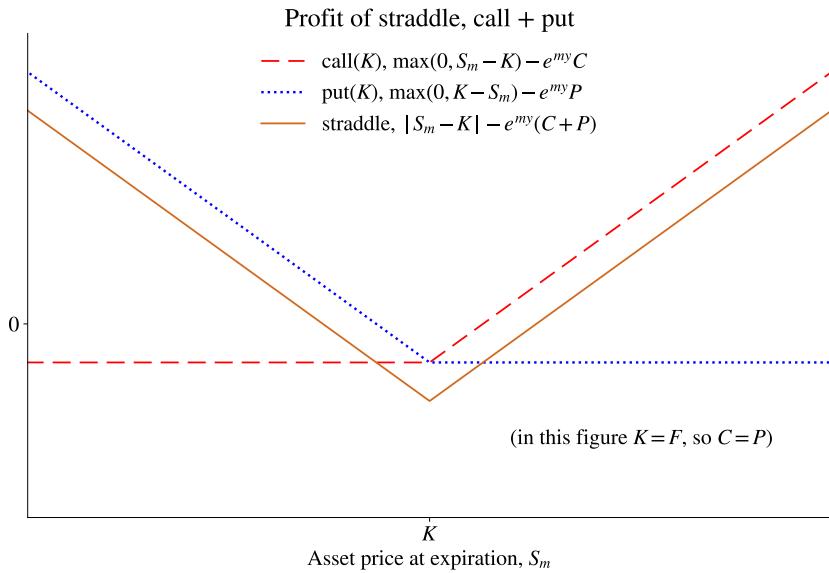


Figure 21.5: Profit of straddle portfolio

**Empirical Example 21.2 (VIX)** See Figure 21.8 for an illustration of how VIX (an index of 1-month S&P 500 implied volatility) has changed over time.

### 21.1.3 Brownian Motion without Mean Reversion: The Random Walk

The basic assumption behind the B-S formula (21.1) is that the log price of the underlying asset,  $\ln S_t$ , follows a geometric Brownian motion—with or without mean reversion.

This section discusses the standard geometric Brownian motion without mean reversion

$$d \ln S_t = \mu dt + \sigma dW_t, \quad (21.3)$$

where  $d \ln S_t$  is the change in the log price (the return) over a very short time interval. On the right hand side,  $\mu$  is the drift (typically expressed on annual basis),  $dt$  just indicates the change in time,  $\sigma$  is the standard deviation (per year), and  $dW_t$  is a random component (Wiener process) that has an  $N(0, 1)$  distribution if we cumulate  $dW_t$  over a year ( $\int_0^1 dW_t \sim N(0, 1)$ ). By comparing (21.1) and (21.3) we notice that only the volatility ( $\sigma$ ), not the drift ( $\mu$ ), show up in the option pricing formula. In essence, the drift is already accounted for by the current spot price in the option pricing formula (as the spot price certainly depends on the expected drift of the asset price).

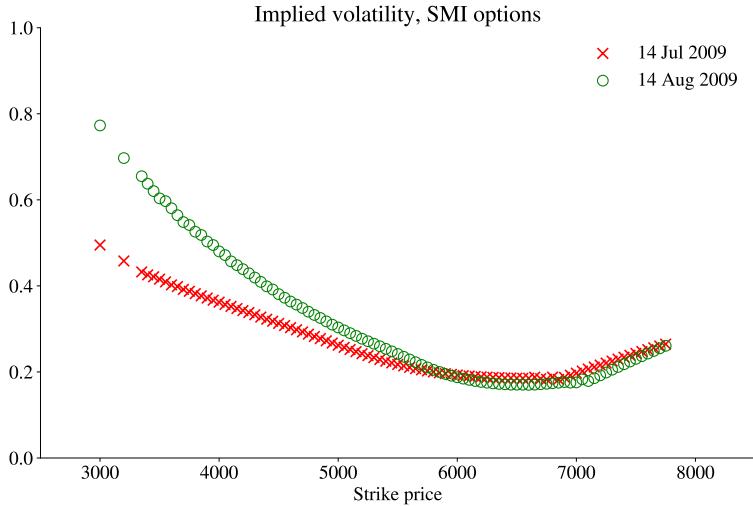


Figure 21.6: Implied volatilities of SMI options, selected dates

**Remark 21.3** (*Alternative stock price process\**) If we instead of (21.3) assume the process  $dS_t = \tilde{\mu}S_t dt + \sigma S_t dW_t$ , then we get the same option price. The reason is that Itô's lemma tells us that (21.3) implies this second process with  $\tilde{\mu} = \mu + \sigma^2/2$ . The difference is only in terms of the drift, which does not show up (directly, at least) in the B-S formula.

**Remark 21.4** ((21.3) as a limit of a discrete time process\*) (21.3) can be thought of as the limit of the discrete time process  $\ln S_{t+h} - \ln S_t = \mu h + \sigma \sqrt{h} \varepsilon_{t+h}$  (where  $\varepsilon_t$  is iid  $N(0, 1)$ ) as the time interval  $h$  becomes very small.

We can only observe the value of the asset price at a limited number of times, so we need to understand what (21.3) implies for discrete time intervals  $(\tau - 1, \tau, \dots)$  which are  $h$  years apart (for instance,  $h = 1/52$  with weekly data and  $h = 252$  with daily data if we only count trading days). Let  $\Delta$  denote the first difference, so  $\Delta x_\tau = x_\tau - x_{\tau-1}$ . Then (21.3) implies that

$$\Delta \ln S_\tau = \alpha + \varepsilon_\tau, \text{ where} \quad (21.4)$$

$$\varepsilon_\tau \text{ is iid } N(0, \sigma^2 h), \text{ and} \quad (21.5)$$

$$\alpha = \mu h. \quad (21.6)$$

That  $\varepsilon_\tau$  is iid implies that  $\text{Cov}(\varepsilon_\tau, \varepsilon_{\tau-1}) = 0$ , which is the same as saying that  $\text{Cov}(\Delta \ln S_\tau, \Delta \ln S_{\tau-1}) = 0$ . Notice that both the drift and the variance scale linearly with the horizon  $h$ . The reason is that the growth rates are iid.

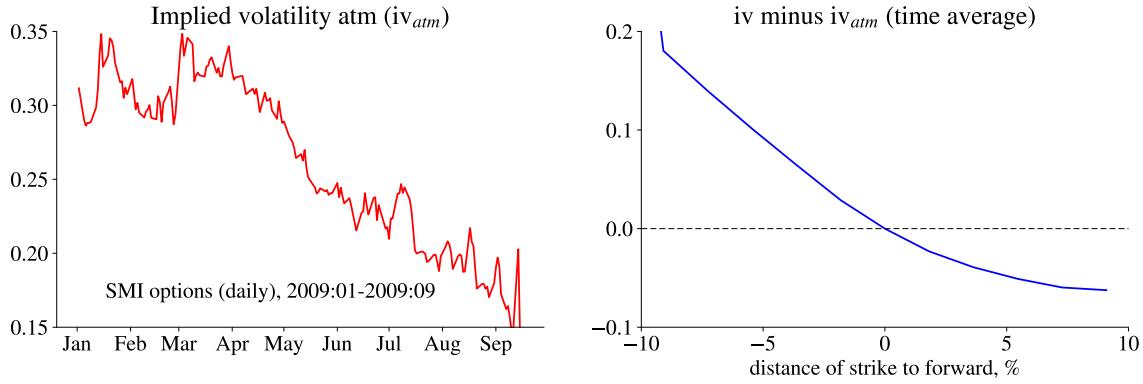


Figure 21.7: Implied volatilities

**Example 21.5** Suppose  $\mu$  and  $\sigma^2$  are 0.1, and 0.25 respectively—and the periods are years. Equations (21.4)–(21.6) then gives the following for weekly ( $h = 1/52$ ) data

$$\ln S_\tau - \ln S_{\tau-1} = 0.1/52 + \varepsilon_\tau \text{ with } \text{Var}(\varepsilon_\tau) = 0.25/52 \approx 0.0048.$$

**Remark 21.6** (iid random variable in discrete time) Suppose  $x_t$  has the constant mean  $\mu$  and a variance  $\sigma^2$ . Then  $E(x_t + x_{t-1}) = 2\mu$  and  $\text{Var}(x_t + x_{t-1}) = 2\sigma^2 + 2\text{Cov}(x_t, x_{t-1})$ . If  $x_t$  is iid, then the covariance is zero, so  $\text{Var}(x_t + x_{t-1}) = 2\sigma^2$ . In this case, both mean and variance scale linearly with the horizon.

#### 21.1.4 Brownian Motion with Mean Reversion\*

The mean reverting Ornstein-Uhlenbeck process is

$$d \ln S_t = \lambda(\mu - \ln S_t)dt + \sigma dW_t, \text{ with } \lambda > 0. \quad (21.7)$$

This process makes  $\ln S_t$  revert back to the mean  $\mu$ , and the mean reversion is faster if  $\lambda$  is large. It is used in, for instance, the Vasicek model of interest rates.

To estimate the parameters in (21.7) on real life data, we (once again) have to understand what the model implies for discretely sampled data (where  $\tau - 1$  and  $\tau$  are  $h$  years apart). It can be shown that it implies a discrete time AR(1)

$$\ln S_\tau = \alpha + \rho \ln S_{\tau-1} + \varepsilon_\tau, \text{ with} \quad (21.8)$$

$$\rho = e^{-\lambda h}, \alpha = \mu(1 - \rho), \text{ and } \varepsilon_t \sim N[0, \sigma^2(1 - \rho^2)/(2\lambda)]. \quad (21.9)$$

We know that the maximum likelihood estimator (MLE) of the discrete AR(1) is least

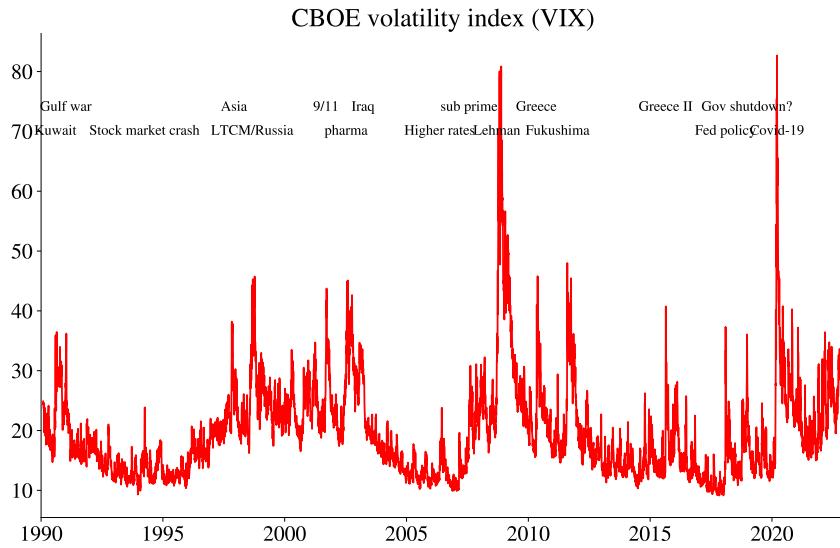


Figure 21.8: CBOE VIX, summary measure of implied volatilities (30 days) on US stock markets

squares combined with the traditional estimator of the residual variance. MLE has the further advantage of being invariant to parameter transformations, which here means that the MLE of  $\lambda$ ,  $\mu$  and  $\sigma^2$  can be backed out from the LS estimates of  $\rho$ ,  $\alpha$  and  $\text{Var}(\varepsilon_t)$  by using (21.9).

**Example 21.7** Suppose  $\lambda$ ,  $\mu$  and  $\sigma^2$  are 2, 0, and 0.25 respectively—and the periods are years. Equations (21.8)–(21.9) then gives the following AR(1) for weekly ( $h = 1/52$ ) data

$$\ln S_\tau = 0.96 \ln S_{\tau-1} + \varepsilon_\tau \text{ with } \text{Var}(\varepsilon_\tau) \approx 0.0046.$$

## 21.2 Estimation of the Volatility of a Random Walk Process

This section discusses different ways of estimating the volatility, since it is the key to option pricing. We will assume that we have data for observations in  $\tau = 1, 2, \dots, n$ . This could be 5-minute intervals, days, weeks or whatever. Let the time between  $\tau$  and  $\tau + 1$  be  $h$  (years). The sample therefore stretches over  $T = nh$  periods (years). For instance, for daily data  $h = 1/365$  (or possibly something like 1/252 if only trading days are counted). Instead, with weekly data  $h = 1/52$ . See Figure 21.9 for an illustration.

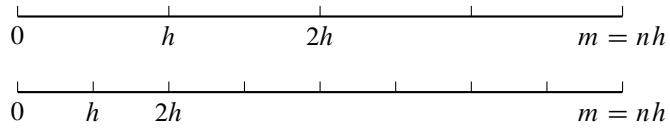


Figure 21.9: Two different samplings with same time span  $T$

### 21.2.1 Standard Approach

We first estimate the variance for the sampling frequency we have, and then convert to the annual frequency.

According to (21.4) the growth rates,  $\ln(S_t/S_{t-h})$ , are iid over any sampling frequency. To simplify the notation, let  $y_\tau = \ln(S_\tau/S_{\tau-1})$  be the observed growth rates. The classical estimator of the variance of an iid data series is

$$\hat{s}^2 = \sum_{\tau=1}^n (y_\tau - \bar{y})^2 / n, \text{ where} \quad (21.10)$$

$$\bar{y} = \sum_{\tau=1}^n y_\tau / n. \quad (21.11)$$

(This is also the maximum likelihood estimator.) To annualise these numbers, use

$$\hat{\sigma}^2 = \hat{s}^2 / h, \text{ and } \hat{\mu} = \bar{y} / h. \quad (21.12)$$

**Example 21.8** If  $(\bar{y}, \hat{s}^2) = (0.001, 0.03)$  on daily data, then the annualized values are  $(\mu, \sigma^2) = (0.001 \times 250, 0.03 \times 250) = (0.25, 7.5)$  if we assume 250 trading days per year.

Notice that it can be quite important to subtract the mean drift,  $\bar{y}$ . Recall that for any random variable, we have

$$\sigma^2 = E(x^2) - \mu^2, \quad (21.13)$$

so a non-zero mean drives a wedge between the variance (which we want) and the second moment (which we estimate if we assume  $\bar{y} = 0$ ).

**Example 21.9 (US stock market volatility)** For the US stock market index excess return since WWII we have approximately a variance of  $0.16^2$  and a mean of 0.08. In this case, (21.13) becomes

$$0.16^2 = E(x^2) - 0.08^2, \text{ so } E(x^2) \approx 0.18^2.$$

Assuming that the drift is zero gives an estimate of the variance equal to  $0.18^2$  which is 25% too high.

**Remark 21.10** (\*Variance vs second moment, the effect of the maturity) Suppose we are interested in the variance over an  $m$ -period horizon, for instance, because we want to price an option that matures in  $t + m$ . How important is it then to use the variance ( $m\sigma^2$ ) rather than the second moment? The relative error is

$$\frac{\text{Second moment} - \text{variance}}{\text{variance}} = \frac{m^2\mu^2}{m\sigma^2} = \frac{m\mu^2}{\sigma^2},$$

where we have used the fact that the second moment equals the variance plus the squared mean (cf (21.13)). Clearly, this relative exaggeration is zero if the mean is zero. The relative exaggeration is small if the maturity is small.

If we have high frequency data on the asset price or the return, then we can choose which sampling frequency to use in (21.10)–(21.11). Recall that a sample with  $n$  observations (where the length of time between the observations is  $h$ ) covers  $T = nh$  periods (years). It can be shown that the asymptotic variances (that is, the variances in a very large sample) of the estimators of  $\mu$  and  $\sigma^2$  in (21.10)–(21.12) are

$$\text{Var}(\hat{\mu}) = \sigma^2/T \text{ and } \text{Var}(\hat{\sigma}^2) = 2\sigma^4/n. \quad (21.14)$$

Therefore, to get a precise estimator of the mean drift,  $\mu$ , we need a sample that stretches over a long period: it does not help to just sample more frequently. However, the sampling frequency is crucial for getting a precise estimator of  $\sigma^2$ , while a sample that stretches over a long period is less important. For estimating the volatility (to use in the B-S model) we should therefore use high-frequency data.

### 21.2.2 Exponentially Weighted Moving Average

The traditional estimator is based on the assumption that volatility is constant—which is consistent with the assumptions of the B-S model. In reality, volatility is time varying.

A practical ad hoc approach to estimate time varying volatility is to modify (21.10)–(21.11) so that recent observations carry larger weight. The exponentially weighted moving average (EWMA) model lets the weight for lag  $s$  be  $(1 - \lambda)\lambda^s$  where  $0 < \lambda < 1$ . If we assume that  $\bar{y}$  is the same in all periods, then we have

$$\hat{s}_\tau^2 = \lambda \hat{s}_{\tau-1}^2 + (1 - \lambda)(y_{\tau-1} - \bar{y})^2, \quad (21.15)$$

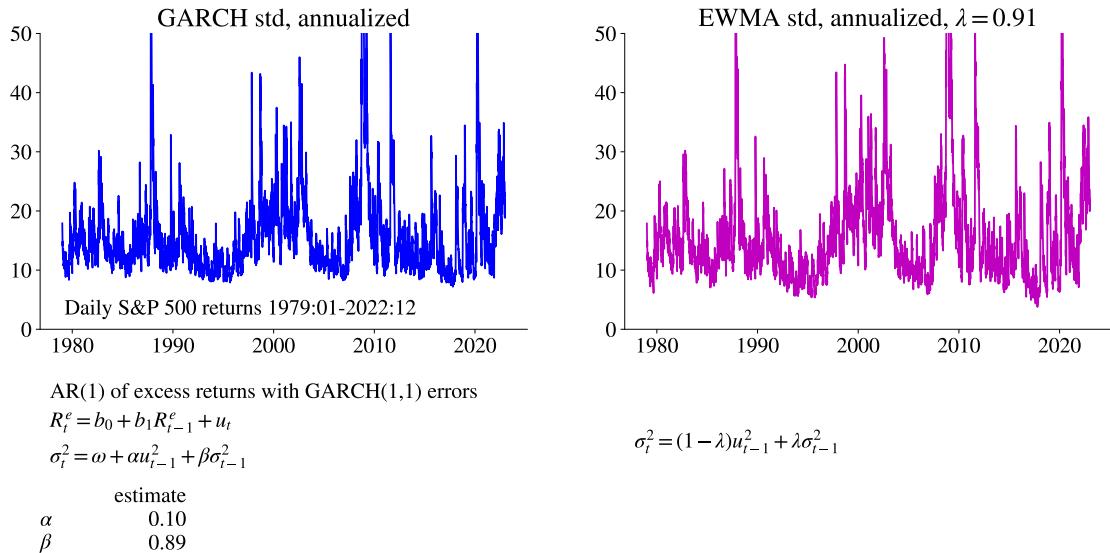


Figure 21.10: Different estimates of US equity market volatility

where  $\tau$  is the current period and  $\tau - 1$  the previous period (say, today and yesterday). Clearly, a higher  $\lambda$  means that old data plays a larger role—and at the limit as  $\lambda$  goes towards one, we have the traditional estimator. For instance, the RISK Metrics is based on  $\lambda = 0.94$  on daily data. This method is commonly used by practitioners. Alternatively,  $\lambda$  can be chosen to minimize some criterion function.

**Empirical Example 21.11** (*Comparison of GARCH and EWMA*) See Figure 21.10 for a comparison of GARCH and EWMA using daily US equity returns. Also, see Figure 21.11 for a comparison with VIX.

**Remark 21.12** (*EWMA with time-variation in the mean\**) If we want also the mean to be time-varying, then we can use the estimator

$$\hat{\sigma}_\tau^2 = (1 - \lambda) [(y_{\tau-1} - \bar{y}_\tau)^2 + \lambda (y_{\tau-2} - \bar{y}_\tau)^2 + \lambda^2 (y_{\tau-3} - \bar{y}_\tau)^2 + \dots]$$

$$\bar{y}_\tau = [y_{\tau-1} + y_{\tau-2} + y_{\tau-3} + \dots] / (\tau - 1).$$

Notice that the mean is estimated as a traditional sample mean, using observations 1 to  $\tau - 1$ . This guarantees that the variance will always be a non-negative number.

It should be noted, however, that the B-S formula is, strictly speaking, not compatible with time-varying volatility. Still, it can be used as an approximation.

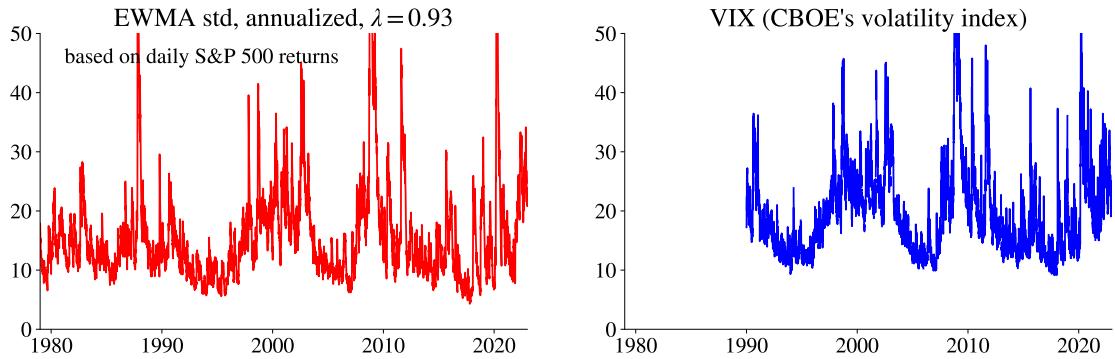


Figure 21.11: Different estimates of US equity market volatility

### 21.2.3 Autoregressive Conditional Heteroskedasticity

The model with Autoregressive Conditional Heteroskedasticity (ARCH) is a useful tool for estimating the properties of volatility clustering. The first-order ARCH expresses volatility as a function of the latest squared shock

$$s_\tau^2 = \alpha_0 + \alpha_1 u_{\tau-1}^2, \quad (21.16)$$

where  $u_\tau$  is a zero-mean variable. The model requires  $\alpha_0 > 0$  and  $0 \leq \alpha_1 < 1$  to guarantee that the volatility stays positive and finite. The variance reverts back to an average variance ( $\alpha_0/(1 - \alpha_1)$ ). The rate of mean reversion is  $\alpha_1$ , that is, the variance behaves much like an AR(1) model with an autocorrelation parameter of  $\alpha_1$ . The model parameters are typically estimated by maximum likelihood. Higher-order ARCH models include further lags of the squared shocks (for instance,  $u_{\tau-2}^2$ ).

Instead of using a high-order ARCH model, it is often convenient to use a first-order generalized ARCH model, the GARCH(1,1) model. It adds a term that directly captures autoregression of the volatility

$$s_\tau^2 = \alpha_0 + \alpha_1 u_{\tau-1}^2 + \beta_1 s_{\tau-1}^2. \quad (21.17)$$

We require that  $\alpha_0 > 0$ ,  $\alpha_1 \geq 0$ ,  $\beta_1 \geq 0$ , and  $\alpha_1 + \beta_1 < 1$  to guarantee that the volatility stays positive and finite. This is very similar to the EWMA in (21.15), except that the variance reverts back to the mean ( $\alpha_0/(1 - \alpha_1 - \beta_1)$ ). The rate of mean reversion is  $\alpha_1 + \beta_1$ , that is, the variance behaves much like an AR(1) model with an autocorrelation parameter of  $\alpha_1 + \beta_1$ .

#### 21.2.4 Time-Variation in Volatility and the B-S Formula

The ARCH and GARCH models imply that volatility is random, so they are (strictly speaking) not consistent with the B-S model. However, they are often combined with the B-S model to provide an approximate option price. See Figure 21.12 for a comparison of the actual distribution of the log asset price (actually, cumulated returns, so assuming that the initial log asset price is zero) at different horizons (1 and 10 days) when the daily returns are generated by a GARCH model—and a normal distribution with the same mean and variance. To be specific, the figure shows the distribution of the future log asset price calculated as

$$\ln S_{t+m} = \ln S_t + r_{t+h}, \text{ or} \quad (21.18)$$

$$= \ln S_t + \sum_{i=1}^{10} r_{t+ih}, \quad (21.19)$$

where each of the returns ( $r_{t+ih}$ ) is drawn from an  $N(0, s_{t+ih}^2)$  distribution where the variance follows the GARCH(1,1) process like in (21.17).

It is clear the normal distribution is a good approximation unless the ARCH component ( $\alpha_1 \times$  lagged squared shock) dominates the GARCH component ( $\beta_1 \times$  lagged variance).

Intuitively, we get (almost) a normal distribution when the random part of the volatility (the ARCH component) is relatively small compared to the non-random part (the GARCH component). For instance, if there is no random part at all, then we get exactly a normal distribution (the sum of independent normally distributed variables is normally distributed—if all the variances are deterministic).

However, to get an option price that is perfectly consistent with a GARCH process, we need to go beyond the B-S model (see, for instance, Heston and Nandi (2000)).

**Remark 21.13** (*Time-varying, but deterministic volatility\**) A time-varying, but non-random volatility could be consistent with (21.2): if  $\ln S_{t+m}$  is the sum (integral) of normally distributed changes with known (but time-varying variances), then this sum has a normal distribution (recall: if the random variables  $x$  and  $y$  are normally distributed, so is  $x+y$ ). A random variance does not fit this case, since a variable with a random variance is not normally distributed.

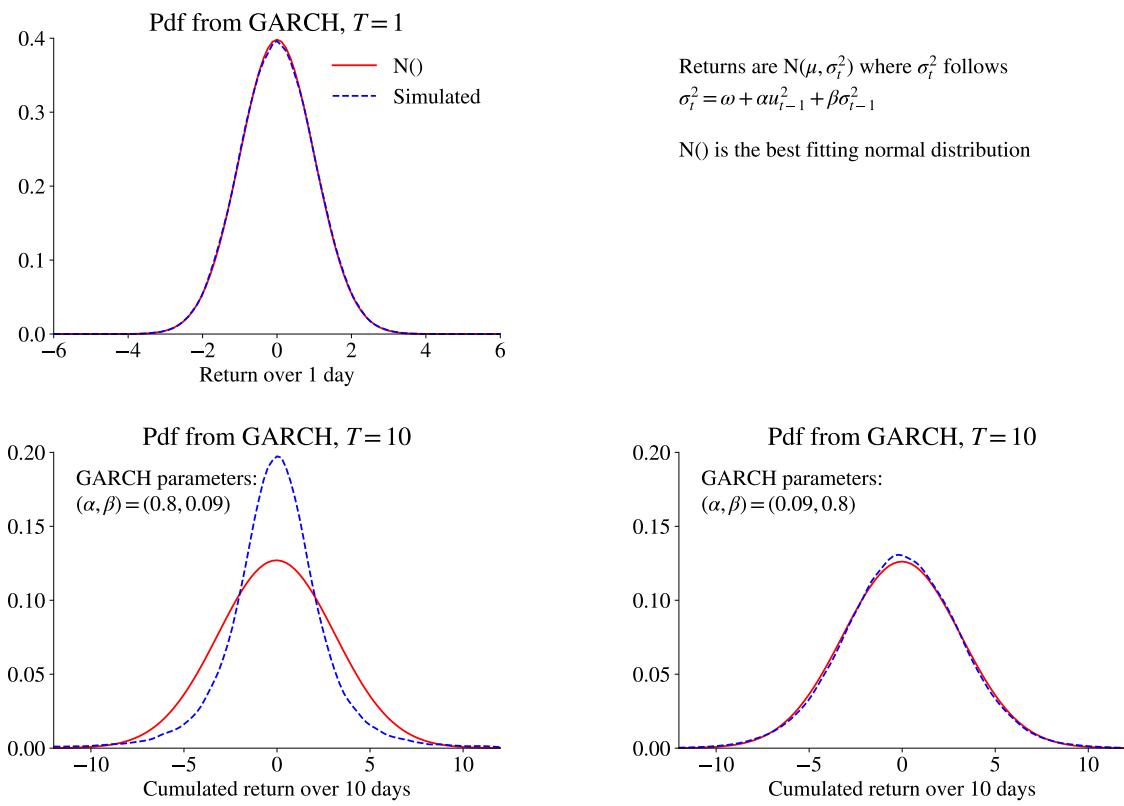


Figure 21.12: Comparison of normal and simulated distribution of  $m$ -period returns

## Chapter 22

# Kernel Density Estimation and Regression\*

## 22.1 Non-Parametric Regression

Reference: Campbell, Lo, and MacKinlay (1997) 12.3; Härdle (1990); Pagan and Ullah (1999); Mittelhammer, Judge, and Miller (2000) 21

### 22.1.1 Simple Kernel Regression

Non-parametric regressions are used when we are unwilling to impose a parametric form on the regression equation—and we have a lot of data.

Let the scalars  $y_t$  and  $x_t$  be related as

$$y_t = b(x_t) + \varepsilon_t, \quad (22.1)$$

where  $\varepsilon_t$  is iid and  $E \varepsilon_t = 0$ ,  $Cov [b(x_t), \varepsilon_t] = 0$  and here  $b()$  is an unknown, possibly non-linear, function. In comparison, in a linear regression we have  $b(x_t) = \beta x_t$ .

One possibility of estimating such a function is to approximate  $b(x_t)$  by a polynomial (or some other basis). This will give quick estimates, but the results are “global” in the sense that the value of  $b(x)$  at a particular  $x$  value ( $x = 1.9$ , say) will depend on all the data points—and potentially very strongly so. The approach in this section is more “local” by down weighting information from data points where  $x_t$  is far from  $x$ .

Suppose the sample had 3 observations (say,  $t = 3, 27$ , and  $99$ ) with exactly the same value of  $x_t$ , say 1.9. A natural way of estimating  $b(x)$  at  $x = 1.9$  would then be to average over these 3 observations as we can expect average of the error terms to be close to zero (iid and zero mean).

Unfortunately, we seldom have repeated observations of this type. Instead, we may try to approximate the value of  $b(x)$  ( $x$  is a single value, 1.9, say) by averaging over

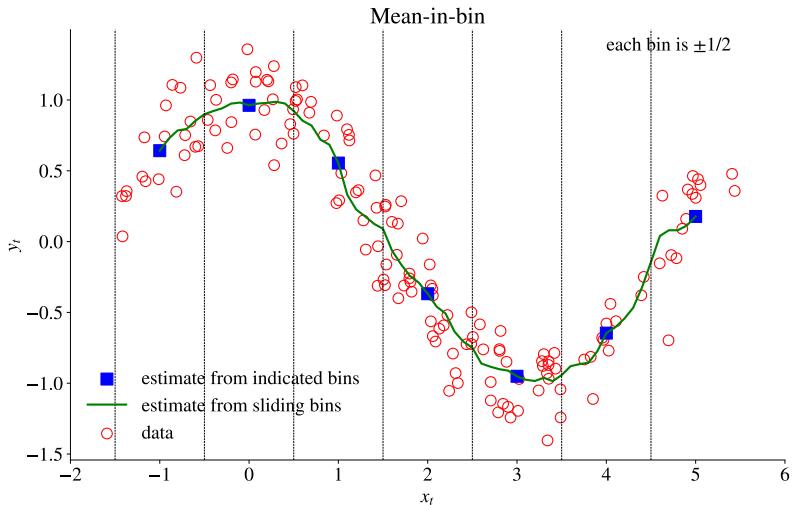


Figure 22.1: Example of a mean-in-bin estimation

observations where  $x_t$  is close to  $x$ . The general form of this type of estimator is

$$\hat{b}(x) = \frac{\sum_{t=1}^T w(x_t - x)y_t}{\sum_{t=1}^T w(x_t - x)}, \quad (22.2)$$

where  $w(x_t - x)/\sum_{t=1}^T w(x_t - x)$  is the weight given to observation  $t$ . The function  $w(x_t - x)$  is positive and (weakly) decreasing in the distance between  $x_t$  and  $x$ . Note that the denominator makes the weights sum to unity. The basic assumption behind (22.2) is that the  $b(x)$  function is smooth so local averaging (around  $x$ ) makes sense.

As an example of a  $w(\cdot)$  function, it could be to give equal weight all values of  $x_t$  that are in a certain bin (“mean-bin”) and zero weight to all other observations. See Figure 22.1 for an example. Alternatively, we can give equal weights to the  $k$  values of  $x_t$  which are closest to  $x$  and zero to all other observations (this is the “ $k$ -nearest neighbor” estimator, see Härdle (1990) 3.2). As another example, the weight function could be defined so that it trades off the expected squared errors,  $E[y_t - \hat{b}(x)]^2$ , and the expected squared acceleration,  $E[d^2\hat{b}(x)/dx^2]^2$ . This defines a cubic spline (often used in macroeconomics when  $x_t = t$ , and is then called the Hodrick-Prescott filter).

A *Kernel regression* uses a probability density function (pdf) as the weight function

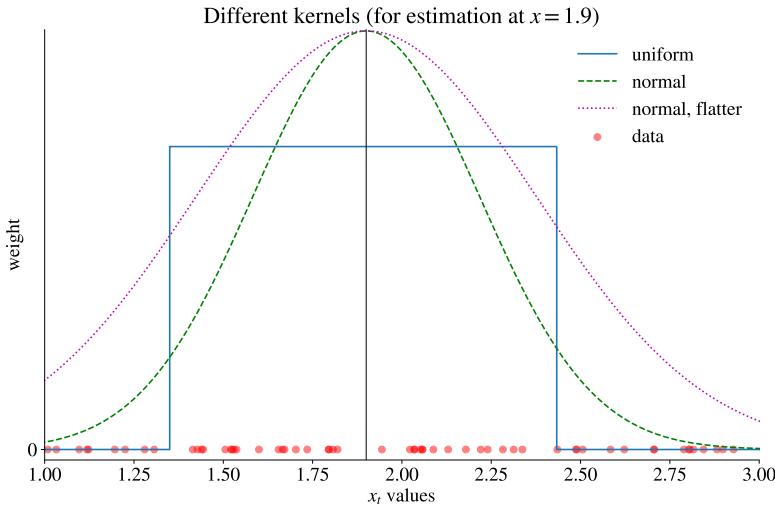


Figure 22.2: Different weighting functions for non-parametric regression

$w(\cdot)$ . The perhaps simplest choice is a uniform density function

$$w(u_t) = \begin{cases} \frac{1}{2\sqrt{3}} & \text{for } |u| \leq \sqrt{3} \\ 0 & \text{otherwise,} \end{cases} \quad (22.3)$$

$$\text{with } u_t = (x_t - x)/h. \quad (22.4)$$

The reason for the  $\sqrt{3}$  terms is that it makes area under the function equal to 1 ( $\int w(u)du = 1$ ) and the variance also equal to one ( $\int w(u)u^2du = 1$ ). This standardisation makes it easy to compare with a  $N(0, 1)$  distribution. In any case, we can adjust  $h$  to get the intervals we want. For instance, with  $h = 1/(2\sqrt{3})$  we get a flat function over  $x - 1/2$  to  $x + 1/2$ . (Notice: some authors use the convention of a uniform distribution over  $(x - h, x + h)$  or  $(x - h/2, x + h/2)$  instead.) The mean-in-bin approach in Figure 22.1 is implemented by using (22.3).

**Remark 22.1** (*Interpretation of the pdf in (22.3)*) If  $w(u_t)$  is a pdf of the  $u_t$  variable, then  $w(u_t)/h$  is the pdf of  $x_t$ . Notice that both give the same result in (22.2).

See Figure 22.2 for an illustration of the weights.

However, we can gain efficiency and get a smoother (across  $x$  values) estimate by using another density function than the uniform. In particular, using a density function that tapers off continuously instead of suddenly dropping to zero improves the properties. The pdf of  $N(x, h^2)$  is commonly used as a kernel, where the choice of  $h$  allows us to

easily vary the relative weights of different observations. With this particular kernel, we get the following weights (for estimation of  $b(x)$  at point  $x$ , for instance,  $x = 1.9$ )

$$w(u_t) = \frac{1}{\sqrt{2\pi}} \exp(-u_t^2/2), \text{ with } u_t = (x_t - x)/h. \quad (22.5)$$

This weighting function is positive so all observations get a positive weight, but the weights are highest for observations close to  $x$  and then tapers off in a bell-shaped way. See Figure 22.2 for an illustration.

In practice we have to estimate  $\hat{b}(x)$  at a finite number of points  $x$ . This could, for instance, be 100 evenly spread points in the interval between the minimum and maximum values observed in the sample. See Figure 22.3 for an illustration

**Empirical Example 22.2** (*Kernel regression of an AR(1) for equity returns*) See Figure 22.5. The results indicate mean reversion but only after extremely low or high returns.

**Example 22.3** Suppose the sample has three data points  $[x_1, x_2, x_3] = [1.5, 2, 2.5]$  and  $[y_1, y_2, y_3] = [5, 4, 3.5]$ . Consider the estimation of  $b(x)$  at  $x = 1.9$ . With  $h = 1$ , the numerator in (22.5) is

$$\begin{aligned} \sum_{t=1}^T w(x_t - x)y_t &= \left( e^{-(1.5-1.9)^2/2} \times 5 + e^{-(2-1.9)^2/2} \times 4 + e^{-(2.5-1.9)^2/2} \times 3.5 \right) / \sqrt{2\pi} \\ &\approx (0.92 \times 5 + 1.0 \times 4 + 0.84 \times 3.5) / \sqrt{2\pi} \\ &= 11.52 / \sqrt{2\pi}. \end{aligned}$$

The denominator is

$$\begin{aligned} \sum_{t=1}^T w(x_t - x) &= \left( e^{-(1.5-1.9)^2/2} + e^{-(2-1.9)^2/2} + e^{-(2.5-1.9)^2/2} \right) / \sqrt{2\pi} \\ &\approx 2.75 / \sqrt{2\pi}. \end{aligned}$$

The estimate at  $x = 1.9$  is therefore

$$\hat{b}(1.9) \approx 11.52 / 2.75 \approx 4.19.$$

### 22.1.2 Choice of Bandwidth ( $h$ )

A low value of  $h$  means that the weights taper off fast—the weight function is then a normal pdf with a low variance. When  $h \rightarrow 0$ , then  $\hat{b}(x)$  evaluated at  $x = x_t$  becomes just  $y_t$ , so no averaging is done. In contrast, as  $h \rightarrow \infty$ ,  $\hat{b}(x)$  becomes the sample average

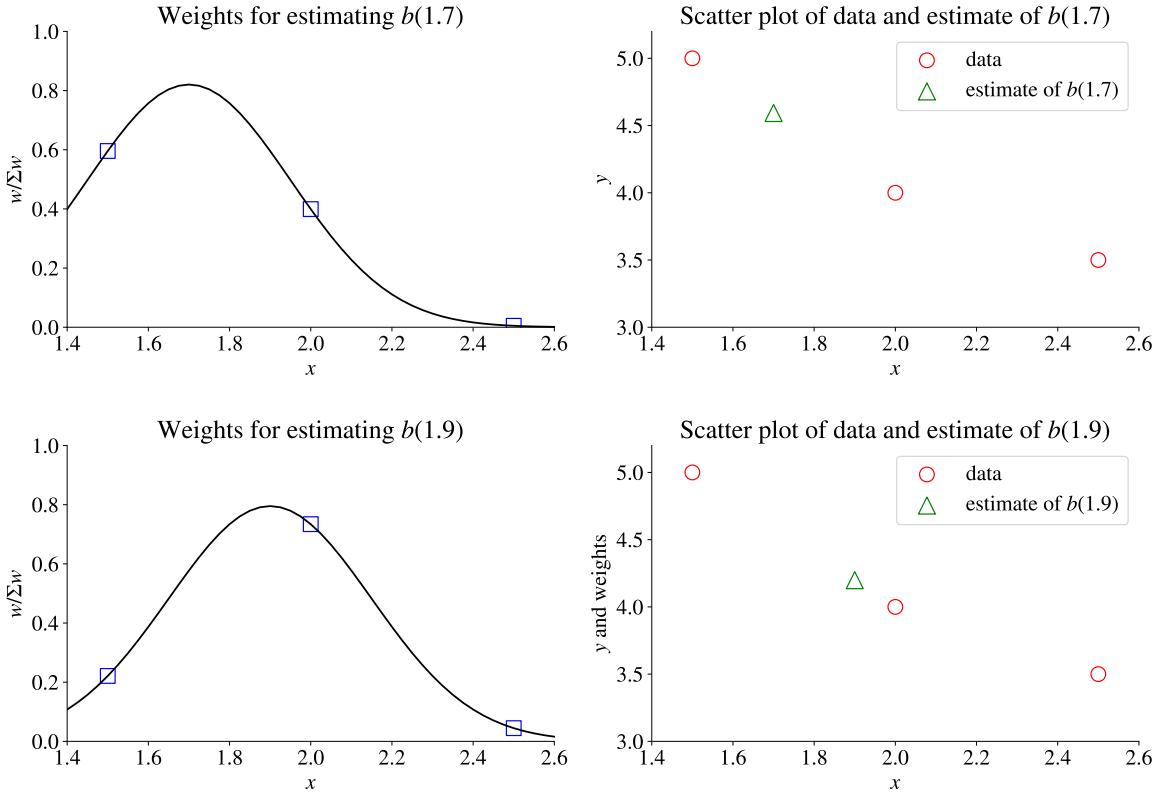


Figure 22.3: Example of kernel regression with three data points

of  $y_t$ , so we have global averaging. Clearly, some value of  $h$  in between is needed. See Figures 22.4 and 22.5 for illustrations.

**Empirical Example 22.4** (*Kernel regression of an AR(1) for equity returns*) Figure 22.5 clearly illustrates the importance of the bandwidth.

A rule of thumb value of  $h$  is

$$h = 0.6 \left( \frac{\sigma_\varepsilon^2 (x_{\max} - x_{\min})}{T \gamma^2} \right)^{1/5}, \quad (22.6)$$

where  $\gamma$  is a from the regression  $y = \alpha + \beta x + \gamma x^2 + \varepsilon$  and  $\sigma_\varepsilon^2$  is the variance of those fitted residuals. In practice, we replace  $x_{\max} - x_{\min}$  by the difference between the 90th and 10th percentiles of  $x$ .

A good (but computationally intensive) approach to choose  $h$  is by the leave-one-out cross-validation technique. This approach would, for instance, choose  $h$  to minimize the

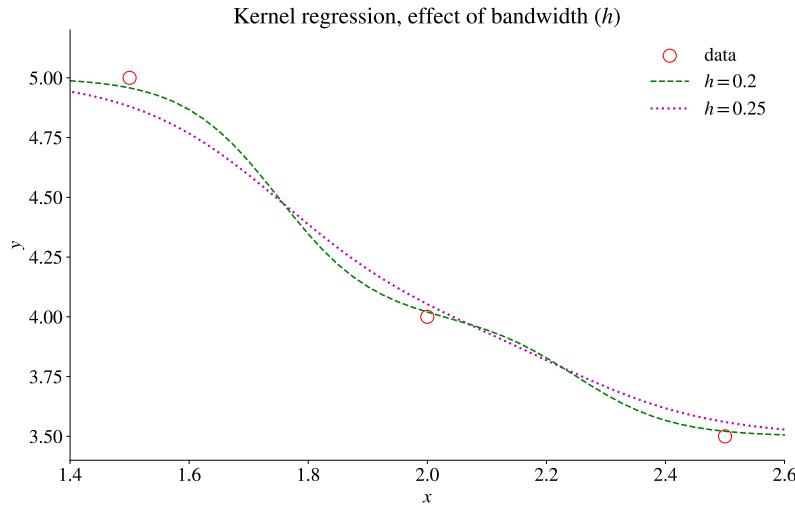


Figure 22.4: Example of kernel regression with three data points

expected (or average) prediction error

$$\text{EPE}(h) = \sum_{t=1}^T [y_t - \hat{b}_{-t}(x_t, h)]^2 / T, \quad (22.7)$$

where  $\hat{b}_{-t}(x_t, h)$  is the fitted value at  $x_t$  when we use a regression function estimated on a sample that excludes observation  $t$ , and a bandwidth  $h$ . This means that each prediction is out-of-sample. To calculate (22.7) we clearly need to make  $T$  estimations (for each  $x_t$ )—and then repeat this for different values of  $h$  to find the minimum.

**Empirical Example 22.5** (*Kernel regression of an AR(1) for equity returns*) Figure 22.6 shows the EPE for different values of the bandwidth for the kernel regressions previously illustrated in Figure 22.5.

**Remark 22.6** (*EPE calculations*) Step 1: pick a value for  $h$

Step 2: estimate the  $b(x)$  function on all data, but exclude  $t = 1$ , then calculate  $\hat{b}_{-1}(x_1)$  and the error  $y_1 - \hat{b}_{-1}(x_1)$

Step 3: redo step 2, but now exclude  $t = 2$  and. calculate the error  $y_2 - \hat{b}_{-2}(x_2)$ . Repeat this for  $t = 3, 4, \dots, T$ . Calculate the EPE as in (22.7).

Step 4: redo steps 1–3, but for another value of  $h$ . Keep doing this until you find the best  $h$  (the one that gives the lowest EPE)

### 22.1.3 Implementing the Kernel Regression as Weighted Least Squares

The kernel regression is about finding a weighted mean of  $y_t$ . This makes it similar to a weighted least squares (WLS) estimation where the only regressor is a constant. Recall that a WLS estimation minimizes the weighted sum of squared residuals

$$\sum_{t=1}^T w_t (y_t - z'_t b)^2, \quad (22.8)$$

where here allow for  $z_t$  to be a  $K$ -vector and  $b$  a corresponding vector of regression coefficients. This general approach will be useful later

It is straightforward to show that this can be implemented by running a regression on transformed variables

$$\tilde{y}_t = \tilde{z}'_t b + \varepsilon_t, \text{ where } \tilde{z}'_t = \sqrt{w_t} z_t \text{ and } \tilde{y}_t = \sqrt{w_t} y_t, \quad (22.9)$$

and the robust (heteroskedasticity consistent) variance-covariance matrix from this regression is a valid approach to estimate  $\text{Var}(\hat{\beta})$ .

In the case of a kernel regression  $z_t = 1$  and  $w_t = w(x_t - x)$ . We can implement the kernel regression by doing one such regression for each choice of  $x$ . The advantage of this approach is that it also gives standard errors—which may often be preferred to the asymptotic results discussed later on.

### 22.1.4 Asymptotic Distribution of the Estimates\*

If the observations are independent, then it can be shown (see Härdle (1990) 4.2 and Pagan and Ullah (1999) 3.3–6) that, with a Gaussian kernel, the estimator at point  $x$  is asymptotically normally distributed

$$\sqrt{Th} [\hat{b}(x) - b(x)] \xrightarrow{d} N \left[ 0, \frac{1}{2\sqrt{\pi}} \frac{\sigma^2(x)}{f(x)} \right], \quad (22.10)$$

where  $\sigma^2(x)$  is the variance of the residuals in (22.1) and  $f(x)$  the marginal density of  $x$ . For this to hold,  $h$  must be decreased (as  $T$  increases) slightly faster than  $T^{-1/5}$  (for instance, suppose  $h = T^{-1.1/5} h_0$ , where  $h_0$  is a constant). Clearly, this means that we have (with sloppy notation)

$$\hat{b}(x) \xrightarrow{d} N \left[ b(x), \frac{1}{2\sqrt{\pi}} \frac{\sigma^2(x)}{f(x)} \frac{1}{Th} \right]. \quad (22.11)$$

As a comparison, a linear regression has  $b(x) = z'\gamma$  where  $z = [1, x]$ , so the variance

of the fitted value is

$$\text{Var}(z'\hat{\gamma}) = z'V(\hat{\gamma})z, \quad (22.12)$$

where  $V(\hat{\gamma})$  is the variance-covariance matrix of  $\hat{\gamma}$ . Notice that this is different from the variance of a forecast error, since the latter also includes the variance of the residual.

To estimate the density function needed in (22.10), we can use a kernel density estimator of the pdf at some point  $x$

$$\hat{f}(x) = \frac{1}{T} \sum_{t=1}^T \frac{1}{h_x \sqrt{2\pi}} \exp \left[ -\frac{1}{2} \left( \frac{x_t - x}{h_x} \right)^2 \right]. \quad (22.13)$$

Notice that  $h_x$  need not be the same as the bandwidth ( $h$ ) used in the kernel regression. The value  $h_x = \text{Std}(x_t)1.06T^{-1/5}$  is sometimes recommended for estimating the density function, since it can be shown to be the optimal choice (in MSE sense) if data is normally distributed and the  $N(0, 1)$  kernel is used.

**Empirical Example 22.7** (*Kernel regression of an AR(1) for equity returns*) See Figure 22.7 for an example where the width of the confidence band varies across  $x$  values—mostly because the sample contains very few observations of extreme  $x$  values. Compare with the linear regression in Figure 22.8, which suggests much less uncertainty for extreme  $x$  values.

To estimate the function  $\sigma^2(x)$  in (22.10), we use a non-parametric regression of the squared fitted residuals on  $x_t$

$$\hat{\varepsilon}_t^2 = \sigma^2(x_t), \text{ where } \hat{\varepsilon}_t = y_t - \hat{b}(x_t), \quad (22.14)$$

where  $\hat{b}(x_t)$  are the fitted values from the non-parametric regression (22.1). Notice that this approach allows the variance to depend on the  $x$  value.

Kernel regressions are typically consistent, provided longer samples are accompanied by smaller values of  $h$ , so the weighting function becomes more and more local as the sample size increases.

## 22.2 Local Linear Regressions\*

Notice that (22.2) solves the problem  $\min_{\alpha_x} \sum_{t=1}^T w(x_t - x)(y_t - \alpha_x)^2$  for each value of  $x$ . For a given value of  $x$ ,  $\alpha_x$  is a constant—but it can vary across  $x$  values. The first order condition (at a given  $x$  value) is  $\sum_{t=1}^T w(x_t - x)(y_t - \alpha_x) = 0$ , so the solution is

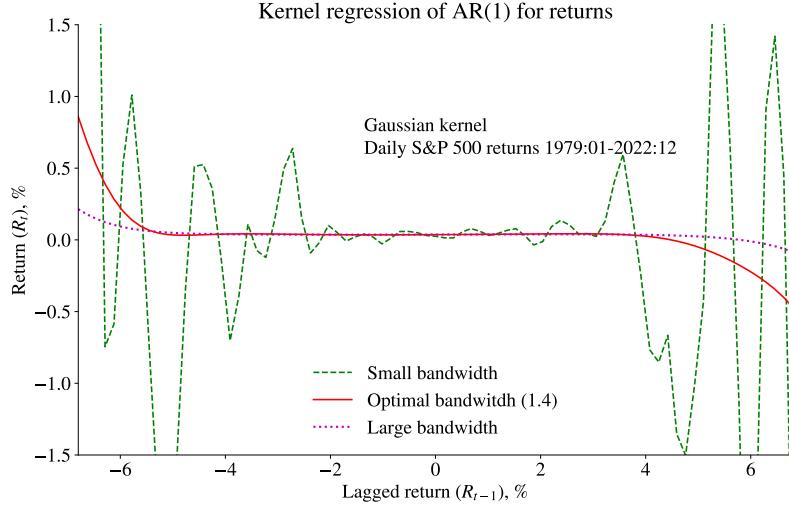


Figure 22.5: Non-parametric regression, importance of bandwidth

as in (22.2), that is,  $\hat{\alpha}_x = \hat{b}(x)$ . This can be interpreted as a “local constant” regression model: for each  $x$  it is just a constant.

This can be extended to solving a problem like

$$\min_{\alpha_x, \gamma_x} \sum_{t=1}^T w(x_t - x)[y_t - \alpha_x - \beta_x(x_t - x)]^2, \quad (22.15)$$

which defines the *local linear estimator*. (Yes, the convention is to use  $x_t - x$  as the regressor, but this could easily be changed.) The first order conditions are similar to the usual normal equations for LS (except that data point  $t$  has the weight  $w(x_t - x)$  and that we use  $x_t - x$  as the regressor). In fact, if we let  $z_t = [1, x_t - x]'$  and collect the coefficients in  $\theta_x = [\alpha_x, \beta_x]'$ , then the first order conditions can be written

$$\sum_{t=1}^T w(x_t - x) z_t y_t = \sum_{t=1}^T w(x_t - x) z_t z_t' \hat{\theta}_x. \quad (22.16)$$

It is straightforward to solve these.

However, it is perhaps even easier if we create  $\tilde{z}_t = \sqrt{w(x_t - x)} z_t$  and  $\tilde{y}_t = \sqrt{w(x_t - x)} y_t$ , because (22.16) is then the same as the first order conditions for a regression of  $\tilde{y}_t$  on  $\tilde{z}_t$ . That is, it can be implemented by a traditional OLS routine as a regression of  $\tilde{y}_t$  on  $\tilde{z}_t$ , and this will also give a valid variance-covariance matrix of  $\hat{\theta}_x$ . (A White’s type of covariance matrix might be a good alternative to the asymptotic result discussed below.)

Clearly, solving (22.16)) gives one  $\hat{\theta}_x$  vector for each  $x$  value that we consider. Once

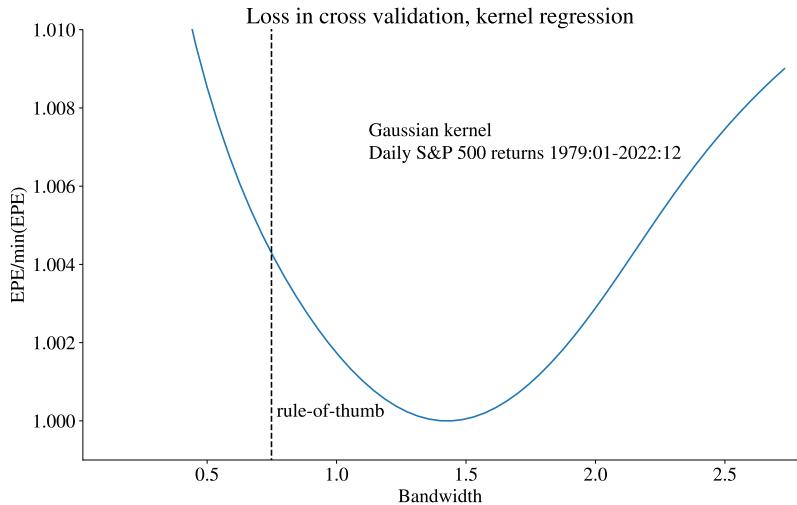


Figure 22.6: Cross-validation

we have the estimates, the fitted value at the value  $x$  is just  $\hat{\alpha}_x$  (since the regression function is  $y_t = \alpha_x + \beta_x(x_t - x) + \varepsilon_t$  and we evaluate it at  $x_t = x$ .)

The bandwidth parameter (which only shows up in the calculations of the weights,  $w(x_t - x)$ ) can be chosen by a rule of thumb or leave-one-out cross validation approach.

It can be shown that the local-linear estimator has the same asymptotic variance as the kernel regression.

**Empirical Example 22.8** (*Local linear regression of an AR(1) for equity returns*) See Figures 22.9 – 22.10.

### 22.2.1 Multivariate Kernel Regression

Suppose that  $y_t$  depends on two variables ( $x_t$  and  $z_t$ )

$$y_t = b(x_t, z_t) + \varepsilon_t, \quad \varepsilon_t \text{ is iid and } E\varepsilon_t = 0. \quad (22.17)$$

This makes the estimation problem more data demanding. To see why, suppose we use a uniform density function as weighting function (see in (22.3)). However, with two regressors, the interval becomes a rectangle. With as little as a 20 intervals of each of  $x$  and  $z$ , we get 400 bins, so we need a large sample to have a reasonable number of observations in every bin.

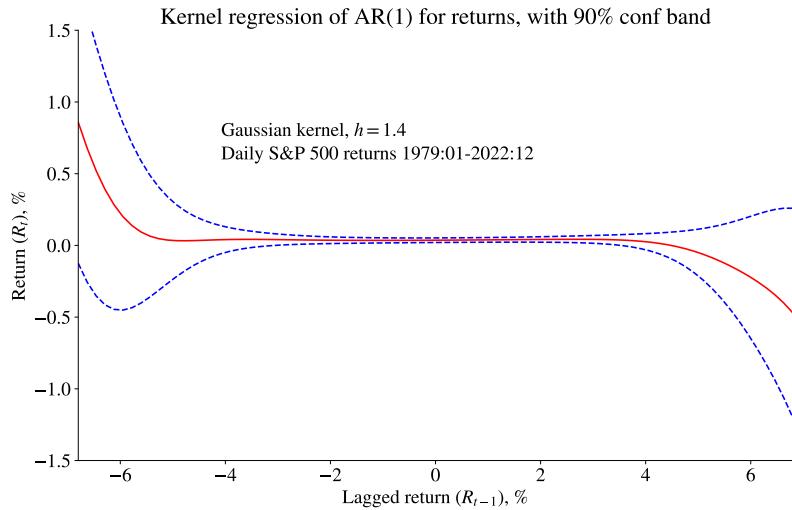


Figure 22.7: Non-parametric regression with confidence bands

In any case, the most common way to implement the kernel regressor is to let

$$\hat{b}(x, z) = \frac{\sum_{t=1}^T w(x_t - x)v(z_t - z)y_t}{\sum_{t=1}^T w(x_t - x)v(z_t - z)}, \quad (22.18)$$

where  $w(x_t - x)$  and  $v(z_t - z)$  are two kernels like in (22.5) and where we may allow the bandwidth ( $h$ ) to be different for  $x_t$  and  $z_t$  (and depend on the variance of  $x_t$  and  $y_t$ ). In this case, the weight of the observation  $(x_t, z_t)$  is proportional to  $w(x_t - x)v(z_t - z)$ , which is high if both  $x_t$  and  $z_t$  are close to  $x$  and  $z$  respectively.

**Empirical Example 22.9** (*Kernel regression of an AR(2) for equity returns*) See Figure 22.11.

## 22.3 Examples of Non-Parametric Estimation

### 22.3.1 A Model for the Short Interest Rate

Interest rate models are typically designed to describe the movements of the entire yield curve in terms of a small number of factors. For instance, the Vasicek model assumes that

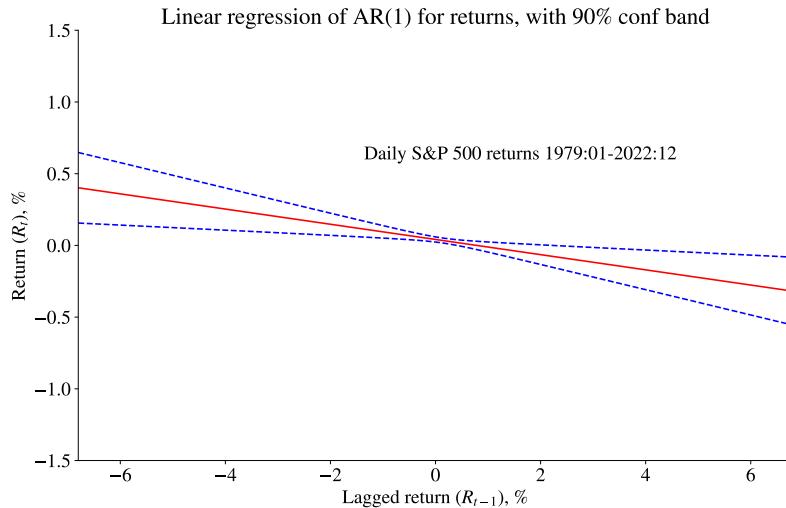


Figure 22.8: Linear regression with confidence bands

the (demeaned) short interest rate,  $r_t$ , is a mean-reverting AR(1) process

$$r_t = \rho r_{t-1} + \varepsilon_t, \text{ where } \varepsilon_t \sim N(0, \sigma^2), \text{ so} \quad (22.19)$$

$$r_t - r_{t-1} = (\rho - 1)r_{t-1} + \varepsilon_t, \quad (22.20)$$

and that all term premia are constant. This means that the drift in (22.20) is decreasing in the interest rate, but that the volatility is constant. For instance, if  $\rho = 0.95$  (a very persistent interest rate), then (22.20) is

$$r_t - r_{t-1} = -0.05r_{t-1} + \varepsilon_t, \quad (22.21)$$

so the reversion to the mean (here zero) is very slow.

(The usual assumption is that the short interest rate follows an Ornstein-Uhlenbeck diffusion process, which implies the discrete time model in (22.19).) It can then be shown that all interest rates (for different maturities) are linear functions of short interest rates.

To capture more movements in the yield curve, models with richer dynamics are used. For instance, Cox, Ingersoll, and Ross (1985) construct a model which implies that the short interest rate follows an AR(1) as in (22.19) except that the variance is proportional to the interest rate level, so  $\varepsilon_t \sim N(0, r_{t-1}\sigma^2)$ .

Non-parametric methods have been used to estimate how the drift and volatility are related to the interest rate level (see, for instance, Ait-Sahalia (1996)).

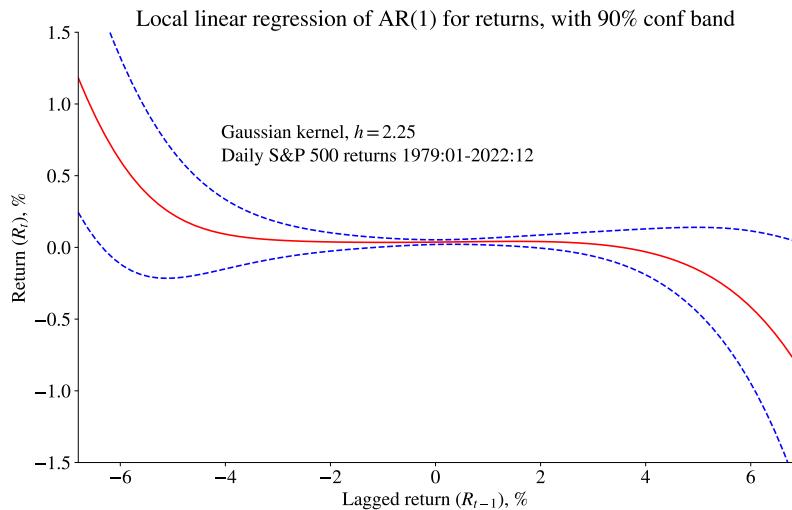


Figure 22.9: Non-parametric local linear regression with confidence bands

**Empirical Example 22.10** (*Kernel regression of a short interest rate process*) Figure 22.12 gives an example. Note that the volatility is defined as the square of the drift minus expected drift (from the same estimation method).

### 22.3.2 Non-Parametric Option Pricing

There seems to be systematic deviations from the Black-Scholes model. For instance, implied volatilities are often higher for options far from the current spot (or forward) price—the volatility smile. This is sometimes interpreted as if the beliefs about the future log asset price put larger probabilities on very large movements (“fat tails”) than what is compatible with the normal distribution.

This has spurred many efforts to both describe the distribution of the underlying asset price and to amend the Black-Scholes formula by adding various adjustment terms. One strand of this literature uses non-parametric regressions to fit observed option prices to the variables that also show up in the Black-Scholes formula (spot price of underlying asset, strike price, time to expiry, interest rate, and dividends). For instance, Ait-Sahalia and Lo (1998) apply this to daily data for Jan 1993 to Dec 1993 on S&P 500 index options (14,000 observations). They find interesting patterns of the implied moments (mean, volatility, skewness, and kurtosis) as the time to expiry changes. In particular, the non-parametric estimates suggest that distributions for longer horizons have increasingly larger skewness and kurtosis.

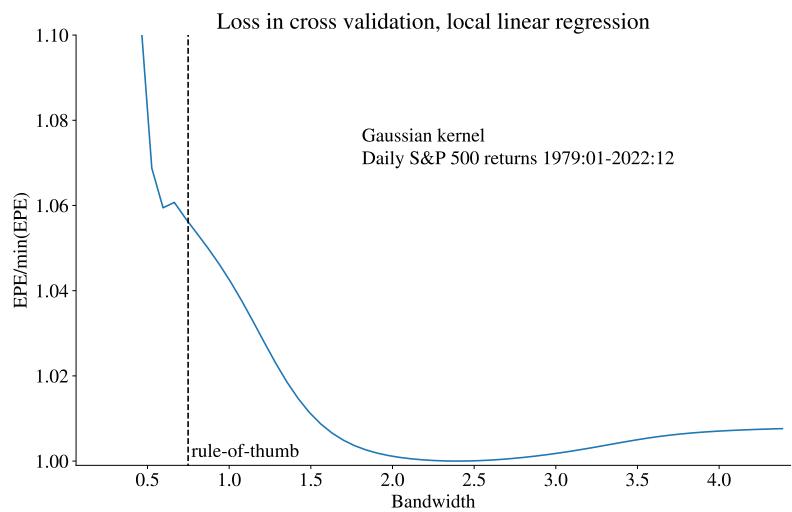


Figure 22.10: Cross-validation

Kernel regression of AR(2) for returns

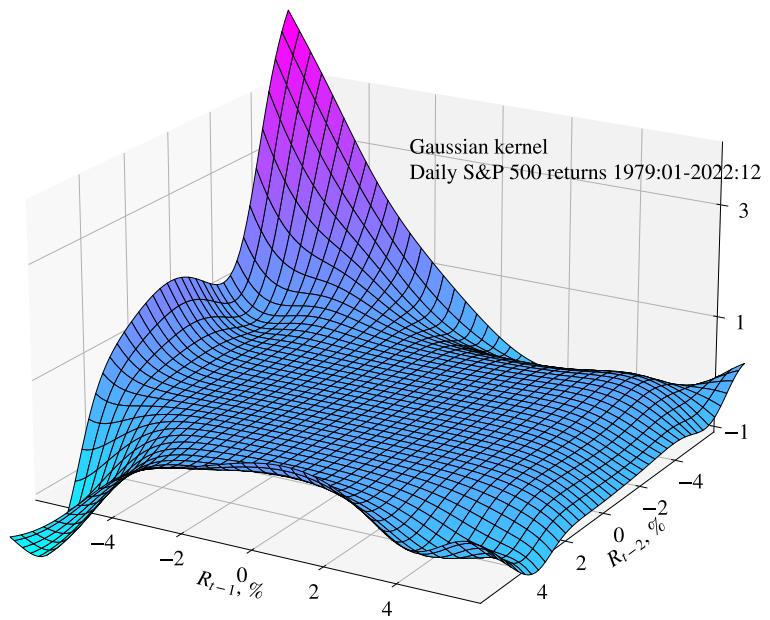


Figure 22.11: Non-parametric regression with two regressors

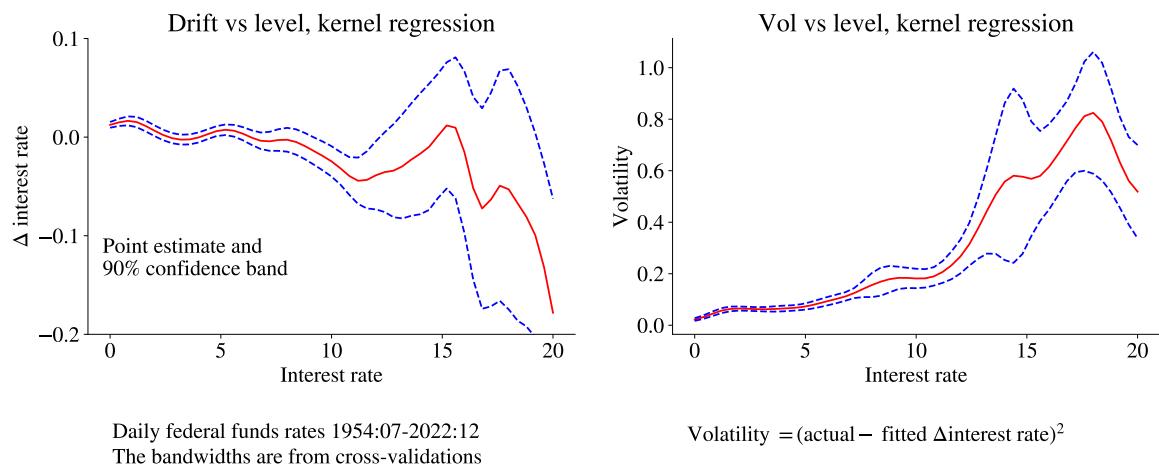


Figure 22.12: Kernel regression, confidence band

# Chapter 23

## Binary Choice and Truncated Models\*

Reference: Verbeek (2012) 7; Greene (2018) 17.

### 23.1 Binary Choice Model

#### 23.1.1 Basic Model Setup

Consider the binary variable

$$y_i = \begin{cases} 0 & \text{firm } i \text{ doesn't pay dividends} \\ 1 & \text{firm } i \text{ pays dividends} \end{cases} \quad (23.1)$$

and suppose we know a few things about firm  $i$ :  $x_i$  (industry, size, profitability...).

We are interested in the probability that firm  $i$  pays dividends—and think it is some function of  $x_i$

$$\Pr(y_i = 1|x_i) = F(x'_i \beta). \quad (23.2)$$

We want to study how  $x_i$  affects the probability that a firm pays dividends ( $y_i = 1$ ), that is, we want to estimate  $\beta$ .

What function  $F()$  should we use in (23.2)? Mostly a matter of convenience. A *probit model* assumes that  $F()$  is a standard normal cumulative distribution function, see Figure 23.1. Other choices of  $F()$  give the *logit model* ( $F()$  is a logistic function) or the *linear probability model* ( $F(x'_i \beta) = x'_i \beta$ ). See Figure 23.2 for an illustration.

**Remark 23.1** (*Logistic function*) The logistic function is  $F(v) = \frac{1}{1+\exp(-v)}$ . The derivative of  $F(v)$  is  $(1 - F(v))F(v)$ .

The results are often interpreted by looking at the marginal effects. For instance, the

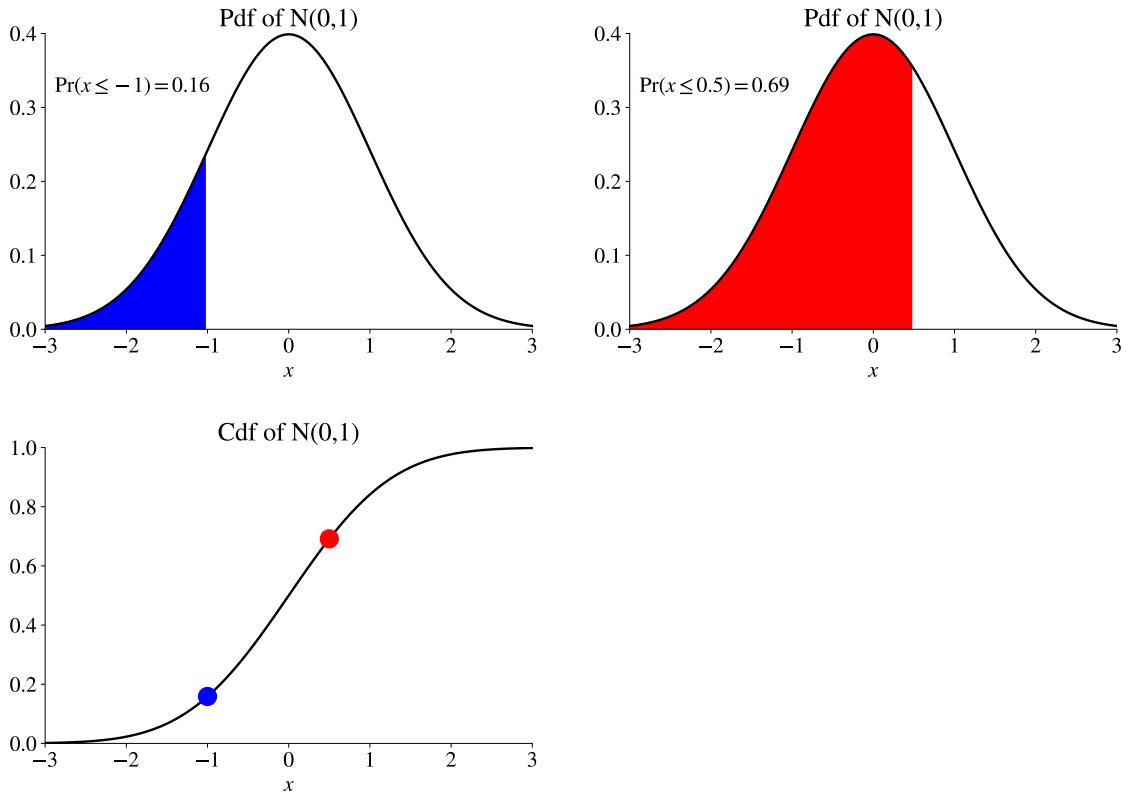


Figure 23.1: Pdf and cdf of  $N(0,1)$

marginal effect of changing regressor  $k$  is

$$\frac{\partial F(x_i' \beta)}{\partial x_{k,i}} = f(x_i' \beta) \beta_k, \quad (23.3)$$

where  $f()$  is the derivative of  $F()$ . (The notation  $x_{k,i}$  is meant to indicate regressor  $k$  for firm  $i$  and  $\beta_k$  is the coefficient on regressor  $k$ ) This is calculated at some typical value  $x_t$  (for instance, at the sample average of the regressors). This could, for instance, answer the question: how does the probability of having dividends change when profits change? Notice that if the  $F()$  function is increasing (all three alternatives mentioned above are), then the derivative (23.3) has the same sign as  $\beta_k$  (since  $f() > 0$ ).

**Example 23.2** Constant plus two more regressors ( $w$  and  $z$ ):  $x_i' \beta = \beta_0 + \beta_1 w_i + \beta_2 z_i$ , then

$$\frac{\partial F(x_i' \beta)}{\partial w} = f(\beta_0 + \beta_1 w_i + \beta_2 z_i) \beta_1,$$

where  $f()$  is the derivative of  $F()$ . This is calculated at some typical values of  $(w_i, z_i)$ .

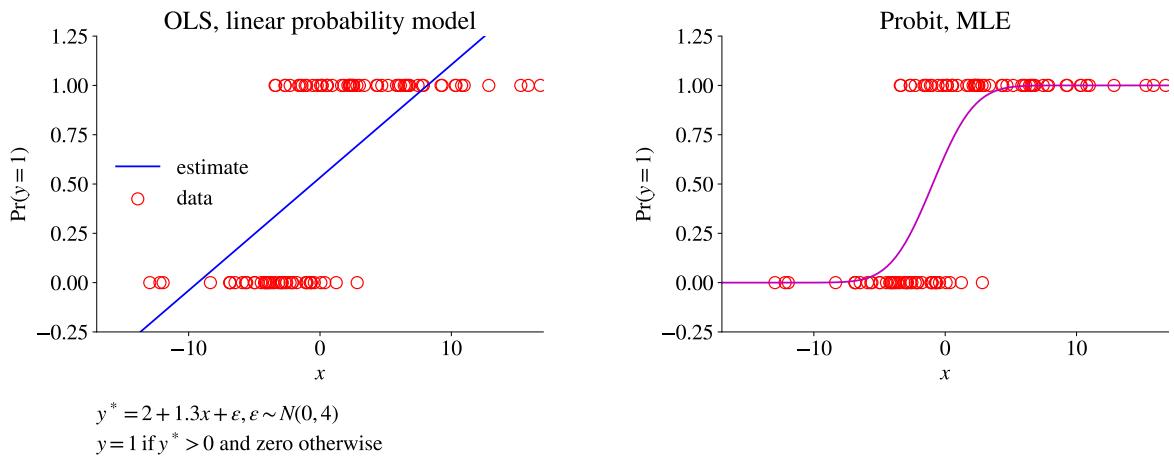


Figure 23.2: Example of probit model

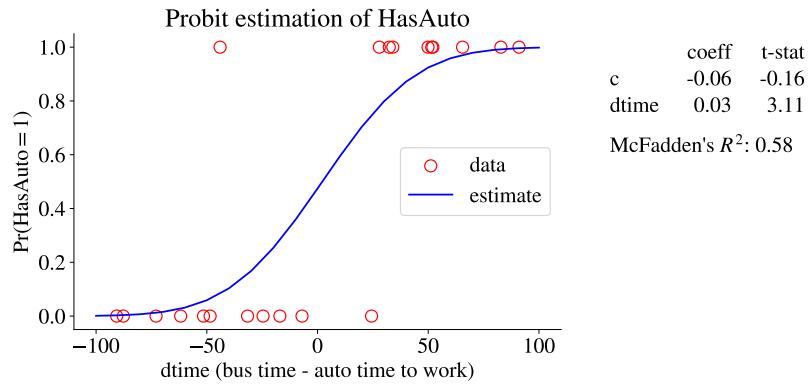


Figure 23.3: Example of probit model, Hill et al (2008), Table 16.1

**Example 23.3** If a regressor is a dummy variable, then use a simple difference instead of attempting a derivative. For instance, if  $z_i$  is either 0 or 1, then we can use

$$F(\beta_0 + \beta_1 w_i + \beta_2) - F(\beta_0 + \beta_1 w_i).$$

This is calculated at some typical value of  $w_i$ .

Notice from (23.3) that the ratio of two coefficients equals the ratio of their marginal effect on the probability

$$\beta_k / \beta_m = \frac{\partial F(x'_i \beta)}{\partial x_{k,i}} / \frac{\partial F(x'_i \beta)}{\partial x_{m,i}}.$$

### 23.1.2 Estimation

The model is typically estimated with MLE. To do that we need to construct the likelihood function

$$\ln L = \sum_{i=1}^N y_i \ln F(x'_i \beta) + (1 - y_i) \ln [1 - F(x'_i \beta)]. \quad (23.4)$$

We find the ML estimate by maximizing this log likelihood function with respect to the parameters  $\beta$ . See Figure 23.3 for an empirical example.

**Proof.** (of (23.4)\*) Recall that a Bernoulli distribution is specified as  $\Pr(y_i = 1) = p_i$ ,  $\Pr(y_i = 0) = 1 - p_i$ . Assume independent observations (here, firm 1 and 2).

Then, the probabilities (likelihoods) for the different outcomes are

$$\begin{aligned} \Pr(y_1 = 1 \text{ and } y_2 = 1) &= p_1 p_2 \\ \Pr(y_1 = 1 \text{ and } y_2 = 0) &= p_1 (1 - p_2) \\ \Pr(y_1 = 0 \text{ and } y_2 = 1) &= (1 - p_1) p_2 \\ \Pr(y_1 = 0 \text{ and } y_2 = 0) &= (1 - p_1) (1 - p_2). \end{aligned} \quad (23.5)$$

At this point  $p_i$  are just symbols for the probabilities. Soon, we use replace them with the specification in (23.2). This will be long (and messy to program) when there are many observations (firms). We therefore use an alternative way of writing the same thing. Notice that

$$p_i^{y_i} (1 - p_i)^{1-y_i} = \begin{cases} p_i & \text{if } y_i = 1 \\ 1 - p_i & \text{if } y_i = 0. \end{cases}$$

For the sample with two data points (firm 1 and 2), the probability (likelihood) can be written

$$L = p_1^{y_1} (1 - p_1)^{1-y_1} \times p_2^{y_2} (1 - p_2)^{1-y_2}.$$

Let  $p_i = F(x'_i \beta)$  from (23.2) and use in the likelihood function

$$L = F(x'_1 \beta)^{y_1} [1 - F(x'_1 \beta)]^{1-y_1} \times F(x'_2 \beta)^{y_2} [1 - F(x'_2 \beta)]^{1-y_2}.$$

or as log (after slight rearranging)

$$\begin{aligned} \ln L &= y_1 \ln F(x'_1 \beta) + y_2 \ln F(x'_2 \beta) \\ &\quad + (1 - y_1) \ln [1 - F(x'_1 \beta)] + (1 - y_2) \ln [1 - F(x'_2 \beta)]. \end{aligned}$$

The extension to  $N$  data points is straightforward. ■

### 23.1.3 Goodness of Fit

To measure the fit, we use several different approaches—since a traditional  $R^2$  is not appropriate for a non-linear model.

First, McFadden's  $R^2$  is a commonly applied measure that has many features in common with a traditional  $R^2$ . It is

$$\text{McFadden's } R^2 = 1 - \frac{\log \text{likelihood value (at max)}}{\log \text{likelihood value (all coeffs=0, except constant)}}. \quad (23.6)$$

Notice:  $\ln L < 0$  since it is a log of a probability (the likelihood function value), but gets closer to zero as the model improves. McFadden's  $R^2$  (23.6) is therefore between 0 (as bad as a model with only a constant) and 1 (a perfect model).

**Example 23.4** If  $\ln L = \ln 0.9$  (at max) and the model with only a constant has  $\ln L = \ln 0.5$

$$\text{McFadden's } R^2 = 1 - \frac{\ln 0.9}{\ln 0.5} \approx 0.84$$

If instead, the model has  $\ln L = \ln 0.8$  (at max), then

$$\text{McFadden's } R^2 = 1 - \frac{\ln 0.8}{\ln 0.5} \approx 0.68$$

An alternative measure of the goodness of fit is an “ $R^2$ ” for the predicted probabilities. To compare predictions to data, let the “predictions” be

$$\hat{y}_i = \begin{cases} 1 & \text{if } F(x'_i \hat{\beta}) > 0.5 \\ 0 & \text{otherwise.} \end{cases} \quad (23.7)$$

This says that if the fitted probability  $F(x'_i \hat{\beta})$  is higher than 50%, then we define the fitted binary variable to be one, otherwise zero. We now cross-tabulate the actual ( $y_i$ ) and predicted ( $\hat{y}_i$ ) values:

	$\hat{y}_i = 0$	$\hat{y}_i = 1$	Total
$y_i = 0$ :	$n_{00}$	$n_{01}$	$N_0$
$y_i = 1$ :	$n_{10}$	$n_{11}$	$N_1$
Total:	$\hat{N}_0$	$\hat{N}_1$	$N$

There are  $n_{01} + n_{10}$  incorrect predictions:  $n_{01}$  are the number of cases when  $y_i = 0$  but  $\hat{y}_i = 1$ , and  $n_{10}$  for the opposite case ( $y_i = 1$  but  $\hat{y}_i = 0$ ). Define an “ $R^2_{pred}$ ” for the prediction as

$$\text{“}R^2_{pred}\text{”} = 1 - \frac{\text{number of incorrect predictions}}{\text{number of incorrect predictions, constant probabilities}}. \quad (23.9)$$

This is somewhat reminiscent of a traditional  $R^2$  since it measures the errors as the number of incorrect predictions—and compare the model with a very static benchmark (constant probability).

The constant probability is just the fraction of data where the binary variable equals one

$$\begin{aligned}\hat{p} &= \text{Fraction of } (y_i = 1) \\ &= N_1/N,\end{aligned}\tag{23.10}$$

where  $N_1 = n_{10} + n_{11}$  are the number of cases when  $y_i = 1$  and  $N$  is the total number of data points.

When  $\hat{p} \leq 0.5$ , the (naive) constant probability model always predicts  $y_i = 0$ , so the number of incorrect predictions (denominator of (23.9)) is  $N_1$ . Otherwise it is  $N_0$ . For the estimated model, the number of incorrect predictions (when  $\hat{y}_i \neq y_i$ ) is  $n_{10} + n_{01}$ . This gives the “ $R^2_{pred}$ ” in (23.9) as

$$“R^2_{pred}” = \begin{cases} 1 - \frac{n_{01} + n_{10}}{N_1} & \text{if } \hat{p} \leq 0.5 \\ 1 - \frac{n_{01} + n_{10}}{N_0} & \text{if } \hat{p} > 0.5. \end{cases}$$

**Example 23.5** Let  $x_i$  be a scalar. Suppose we have the following data

$$\begin{aligned}\begin{bmatrix} y_1 & y_2 & y_3 & y_4 \end{bmatrix} &= \begin{bmatrix} 1 & 0 & 1 & 1 \end{bmatrix} \text{ and} \\ \begin{bmatrix} x_1 & x_2 & x_3 & x_4 \end{bmatrix} &= \begin{bmatrix} 1.5 & -1.2 & 0.5 & -0.7 \end{bmatrix}\end{aligned}$$

See Figure 23.4

Suppose  $\beta = 0$ , then we get the following values

$$F(x'_i \beta) = [0.5 \ 0.5 \ 0.5 \ 0.5]$$

$$\begin{aligned}y_i \log F(x'_i \beta) + (1 - y_i) \log [1 - F(x'_i \beta)] \\ \approx [-0.69 \ -0.69 \ -0.69 \ -0.69] \\ \log L \approx -2.77\end{aligned}$$

Now, suppose instead that  $\beta = 1$

$$F(x'_i \beta) \approx [0.93 \ 0.12 \ 0.69 \ 0.24]$$

$$\begin{aligned}
& y_i \log F(x'_i \beta) + (1 - y_i) \log [1 - F(x'_i \beta)] \\
& \approx \begin{bmatrix} -0.07 & -0.12 & -0.37 & -1.42 \end{bmatrix} \\
& \log L \approx -1.98,
\end{aligned}$$

which is higher than at  $\beta = 0$ . If  $\beta = 1$  happened to maximize the likelihood function (it almost does...), then

$$\text{McFadden's } R^2 = 1 - \frac{-1.98}{-2.77} \approx 0.29$$

and the predicted would be

$$\hat{y}_i \approx \begin{bmatrix} 1 & 0 & 1 & 0 \end{bmatrix}.$$

Cross-tabulation of actual ( $y_i$ ) and predicted ( $\hat{y}_i$ ) values

	$\hat{y}_i = 0$	$\hat{y}_i = 1$	Total
$y_i = 0:$	1	0	1
$y_i = 1:$	1	2	3
Total:	2	2	4

Since the constant probability is

$$\hat{p} = 3/4,$$

the constant probability model always predicts  $y_i = 1$ . We therefore get

$$\text{"}R^2_{pred}\text{"} = 1 - \frac{1}{1+0} = 0.$$

### 23.1.4 Related Models

Multi-response models answers questions like “a little, more, most?” (ordered logit or probit) or “Red, blue or yellow car?” (unordered models: multinomial logit or probit).

Models for count data are useful for answer questions like: “how many visits to the supermarket this week?” They are like a standard model, but  $y_i$  can only take on integer values (0, 1, 2, 3, ..).

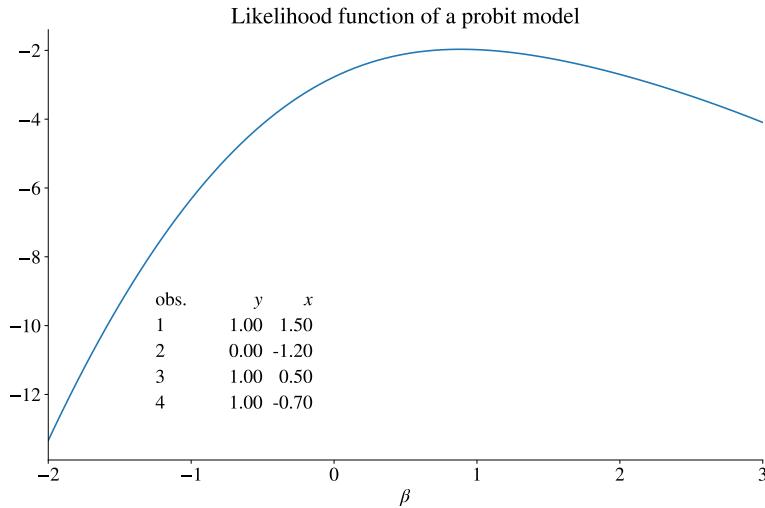


Figure 23.4: Example of ML estimation of probit model

## 23.2 Truncated Regression Model

### 23.2.1 Basic Model Setup

Suppose the correct model is linear

$$y_i^* = x_i' \beta + \varepsilon_i, \quad \varepsilon_i \sim \text{iid}N(0, \sigma^2), \quad (23.11)$$

but that data (also regressors) is completely missing if  $y_i^* \leq 0$

$$\begin{aligned} y_i &= y_i^* && \text{if } y_i^* > 0 \\ (y_i, x_i) &\text{ not observed} && \text{otherwise.} \end{aligned} \quad (23.12)$$

The cutoff at zero is just a normalisation that could easily be changed.

The problem with this is that the sample is no longer random. For instance, suppose  $y_i^*$  is dividends and  $x_i$  is profits—and it so happens that firms with low dividends are not in the sample. This is likely to bias the results. See Figure 23.7 for an illustration. In fact, running OLS to estimate

$$y_i = x_i' \beta + \varepsilon_i \quad (23.13)$$

on the available data will give biased (and inconsistent) estimates.

The reason for the bias is that we only use those data points where  $y_i$  is unusually high (for a given value of  $x_i$ ). That is, for observation  $i$  to be observed, it must be the case

that

$$\varepsilon_i > -x_i' \beta, \quad (23.14)$$

since otherwise (23.13) becomes negative (and those are the observations that do not enter the sample). This which  $\varepsilon_i$  realizations that enter the sample is not random any more—and it depends on the  $x_i$  value (when  $x_i' \beta < 0$ , then only positive  $u_i$  realizations enter the sample and vice versa). This correlation of  $u_i$  and  $x_i$  is a classical reason for why OLS estimates of the regression coefficients are inconsistent.

**Remark 23.6** (*Details on the bias\**) To see the bias, notice that the expected value of  $y_i$ , conditional on  $x_i$  and that we observe the data ( $y_i > 0$ ), is

$$E(y_i | y_i > 0, x_i) = x_i' \beta + E(\varepsilon_i | y_i^* > 0) \quad (23.15)$$

$$= x_i' \beta + E(\varepsilon_i | \varepsilon_i > -x_i' \beta). \quad (23.16)$$

The second line follows from the fact that  $y_i^* > 0$  happens when  $x_i' \beta + \varepsilon_i > 0$  (see (23.12)) which happens when  $\varepsilon_i > -x_i' \beta$ . The key result is that the last term is positive and is correlated with  $x_i$ . (It is positive since  $E(\varepsilon_i | \varepsilon_i > -\infty) = 0$ , and here we are conditioning on  $\varepsilon_i > -x_i' \beta$  which depends on  $x_i$ .)

### 23.2.2 Examples of the Effect of Truncation

This section presents a useful result on truncated normal distributions —and then uses that in a few simple examples of how the truncation affects the OLS estimates.

**Remark 23.7** (*Truncated normal distribution*) Let  $\varepsilon \sim N(\mu, \sigma^2)$ , then

$$E(\varepsilon | \varepsilon > a) = \mu + \sigma \frac{\phi(a_0)}{1 - \Phi(a_0)} \text{ and } a_0 = (a - \mu)/\sigma$$

See Figure 23.5.

**Example 23.8** As a trivial example, suppose the model is  $y_i^* = 0 + \varepsilon_i$  with  $\varepsilon_i \sim iidN(0, 1)$ . Then

$$\begin{aligned} E(y_i | y_i > 0, x_i) &= 0 + E(\varepsilon_i | \varepsilon_i > 0) \\ &= 0 + \frac{\phi(0)}{1 - \Phi(0)} = \sqrt{2/\pi} \approx 0.80, \end{aligned}$$

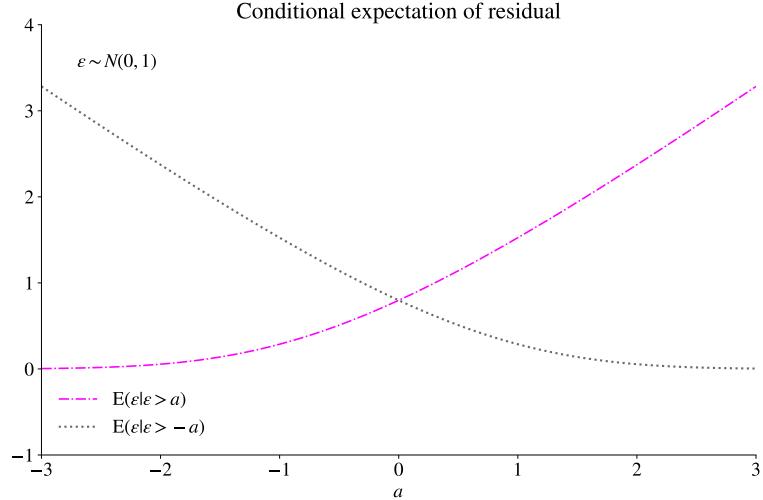


Figure 23.5: Expectations of a truncated variable

which is far from the true mean (0). OLS will therefore estimate an intercept of around 0.8 instead of 0.

**Example 23.9** Suppose the model is  $y_i^* = 2x_i + \varepsilon_i$  with  $\varepsilon_i \sim iidN(0, 1)$  and where  $x_i$  a scalar random variable. Then

$$\begin{aligned} E(y_i | y_i > 0, x_i) &= 2x_i + E(\varepsilon_i | \varepsilon_i > -2x_i) \\ &= 2x_i + \frac{\phi(-2x_i)}{1 - \Phi(-2x_i)} \end{aligned}$$

For some selected values of  $x_i$  we have

$$\begin{aligned} E(y_i | y_i > 0, x_i) &= \\ &= 2x_i + E(\varepsilon_i | \varepsilon_i > -2x_i) \\ &= \begin{cases} 2 \times (-1) + E(\varepsilon_i | \varepsilon_i > 2) & x = -1 \\ 2 \times 0 + E(\varepsilon_i | \varepsilon_i > 0) & x_i = 0 \\ 2 \times 1 + E(\varepsilon_i | \varepsilon_i > -2) & x_i = 1 \end{cases} \\ &= \begin{cases} 2 \times (-1) + 2.37 = 0.37 & x = -1 \\ 2 \times 0 + 0.8 = 0.80 & x_i = 0 \\ 2 \times 1 + 0.06 = 2.06 & x_i = 1 \end{cases} \end{aligned}$$

so the slope is lower than 2: OLS will therefore fit a slope coefficient that is lower than 2. See Figure 23.6. The basic point is that  $E(\varepsilon_i | \varepsilon_i > -2x_i)$  is much higher for low than

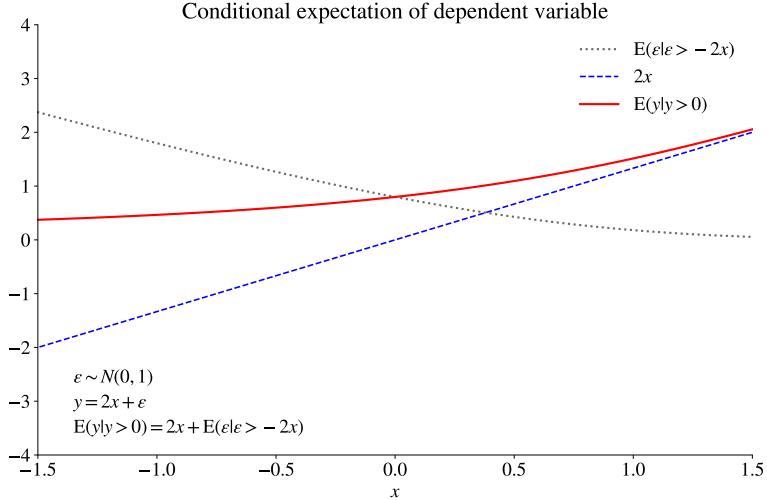


Figure 23.6: Expectations of a truncated variable

for high values of  $x_i$  (compare  $x_i = -1$  and  $x_i = 1$ ), making the regression line look flatter. (Notice that  $\frac{\phi(-2x_i)}{1-\Phi(-2x_i)}$  can also be written  $\frac{\phi(2x_i)}{\Phi(2x_i)}$  since the  $N(0,1)$  distribution is symmetric around zero.)

### 23.2.3 Estimation

**Remark 23.10** (*Pdf of truncated variable*) Let  $\text{pdf}(\varepsilon)$  be the density function of  $\varepsilon$  (without any truncation). The density function, conditional on  $a < \varepsilon \leq b$  is  $\text{pdf}(\varepsilon|a < \varepsilon \leq b) = \text{pdf}(\varepsilon)/\Pr(a < \varepsilon \leq b)$ .

The log likelihood function is

$$\begin{aligned}\ln L &= \sum_{i=1}^N \ln L_i, \text{ where} \\ L_i &= \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2} \frac{(y_i - x'_i \beta)^2}{\sigma^2}\right) / \Phi(x'_i \beta / \sigma).\end{aligned}\tag{23.17}$$

We maximize this likelihood function with respect to  $\beta$  and  $\sigma^2$  (numerical optimization). Notice that  $\Phi(x'_i \beta / \sigma)$  is the new part compared with OLS. See Figure 23.7 for an illustration.

**Proof.** (of (23.17)<sup>\*</sup>) Here, we need the density function of  $y_i$  conditional on  $y_i > 0$

(or equivalently of  $\varepsilon_i$ ), conditional on  $y_i^* = x_i' \beta + \varepsilon_i > 0$  (so  $\varepsilon_i > -x_i' \beta$ ). This is

$$\text{pdf}(\varepsilon_i | \varepsilon_i > -x_i' \beta) = \frac{\text{pdf}(\varepsilon_i)}{\Pr(\varepsilon_i > -x_i' \beta)}.$$

To specify this, we notice the following. *First*, if  $\varepsilon_i \sim N(0, \sigma^2)$ , the denominator is

$$\begin{aligned}\Pr(\varepsilon_i > -x_i' \beta) &= \Pr\left(\varepsilon_i/\sigma > -x_i' \beta/\sigma\right) \\ &= 1 - \Phi\left(-x_i' \beta/\sigma\right) \\ &= \Phi\left(x_i' \beta/\sigma\right).\end{aligned}$$

The last line follows from  $N(0, 1)$  being symmetric around 0, so  $\Phi(z) = 1 - \Phi(-z)$ . *Second*, the numerator (in the first equation of this proof) is the pdf of an  $N(0, \sigma^2)$  variable. *Third*, combining and replacing  $\varepsilon_i$  by  $y_i - x_i' \beta$ , taking logs gives (23.17). ■

### 23.3 Censored Regression Model (Tobit Model)

The censored regression model is similar to truncated model, but we are here fortunate to always observe the regressors.  $x_i$ . We have a bit *more information* than in truncated case, and we should try to use it. In short, the model and data are

$$y_i^* = x_i' \beta + \varepsilon_i, \varepsilon_i \sim \text{iid}N(0, \sigma^2) \quad (23.18)$$

$$\text{Data: } (y_i, x_i) = \begin{cases} (y_i^*, x_i) & \text{if } y_i^* > 0 \\ (0, x_i) & \text{otherwise.} \end{cases}$$

Values  $y_i^* \leq 0$  are said to be *censored* (and assigned the value 0—which is just a normalization). This is the classical *Tobit model*. As an example:  $y_i^*$  is investment into stocks by a household,  $x_i$  is household income—and households with low income are assigned a common value (normalized to  $y_i = 0$ ) in the survey.

If we estimate

$$y_i = x_i' \beta + u_i \quad (23.19)$$

with LS, using all data with  $y_i > 0$ , then we are in same situation as in truncated model: LS is not consistent. See Figure 23.7.

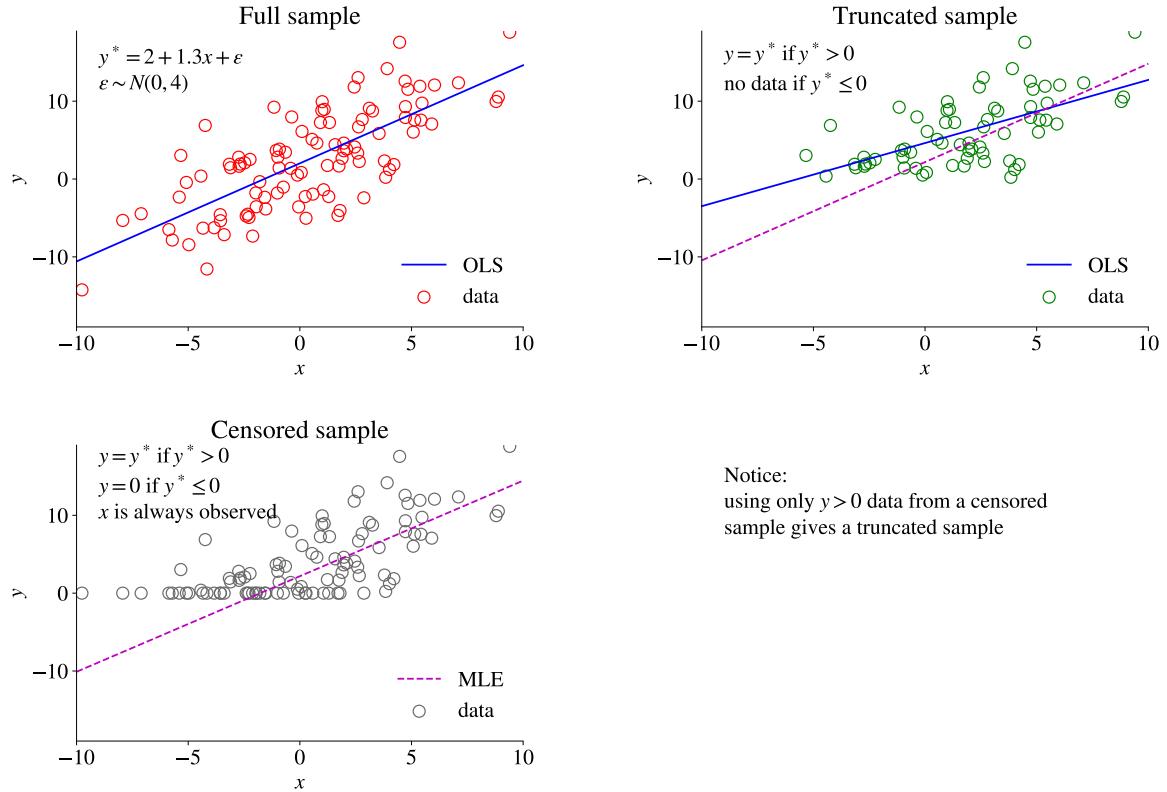


Figure 23.7: Estimation on full, truncated and censored sample

### 23.3.1 Estimation of Censored Regression Model

**Remark 23.11** (*Likelihood function with different “states”*) *The likelihood contribution of observation  $i$  is  $\text{pdf}(y_i)$  which can also be written  $\text{pdf}(y_i|\text{state } K) \times \Pr(\text{state } K)$ . The total likelihood function is the sum over all  $i$  (observations).*

Here there are two states:  $y_i^* \leq 0$  (no data on  $y_i^*$  but on  $x_i$ ) and  $y_i^* > 0$  (data on both  $y_i$  and  $x_i$ ) This gives the likelihood function

$$L = \sum_{i: \text{no data on } y_i} \Phi(-x_i' \beta / \sigma) + \sum_{i: \text{with data}} \frac{1}{\sqrt{2\pi\sigma^2}} \exp\left(-\frac{1}{2} \frac{(y_i - x_i' \beta)^2}{\sigma^2}\right). \quad (23.20)$$

Maximize with respect to  $\beta$  and  $\sigma^2$  (numerical optimization). Compared to OLS, the new part is that we have a way of calculating the probability of censored data (first term)—since we know all  $x_i$  values.

**Proof.** (of (23.20)\*) State  $y_i^* \leq 0$  happens when  $y_i^* = x_i' \beta + \varepsilon_i \leq 0$ , that is, when

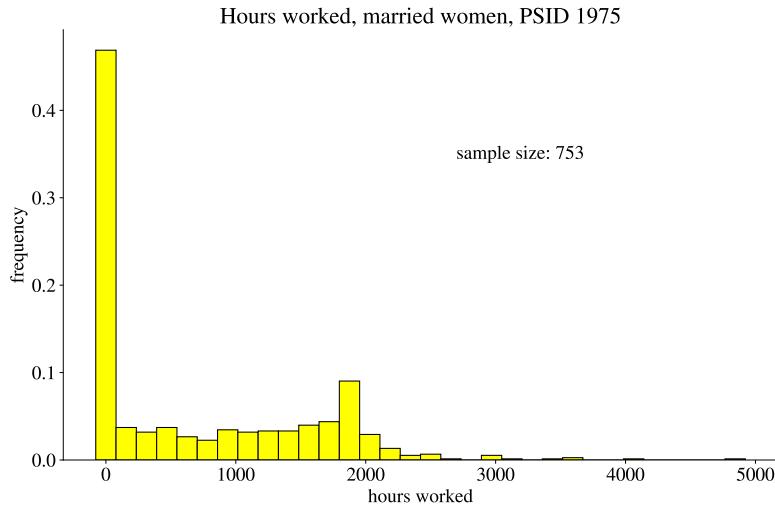


Figure 23.8: Example of probit model, Hill et al (2008), Table 16.1

$\varepsilon_i \leq -x'_i\beta$ . The probability of this is

$$\begin{aligned}\Pr(\varepsilon_i \leq -x'_i\beta) &= \Pr(\varepsilon_i/\sigma \leq -x'_i\beta/\sigma) \\ &= \Phi(-x'_i\beta/\sigma).\end{aligned}$$

The conditional density function in this state has the constant value of one, so the likelihood contribution (see Remark 23.11) is

$$L_i(\text{if } y_i^* \leq 0) = \text{pdf}(y_i | y_i^* \leq 0) \times \Pr(y_i^* \leq 0) = 1 \times \Phi(-x'_i\beta/\sigma).$$

State  $y_i^* > 0$  happens in the same way as in the truncated model (23.19), but the difference here is that the contribution to the likelihood function (again, see Remark 23.11) is

$$\begin{aligned}L_i(\text{if } y_i^* > 0) &= \text{pdf}(\varepsilon_i | \varepsilon_i > -x'_i\beta) \times \Pr(\varepsilon_i > -x'_i\beta) \\ &= \text{pdf}(\varepsilon_i),\end{aligned}$$

where  $\text{pdf}(\varepsilon_i)$  is the pdf of  $N(0, \sigma^2)$ . ■

	OLS	MLE
c	1335.3 (5.7)	1349.9 (3.4)
educ	27.1 (2.2)	73.3 (3.6)
exper	48.0 (13.2)	80.5 (13.1)
age	-31.3 (-7.9)	-60.8 (-9.1)
kids16	-447.9 (-7.7)	-918.9 (-8.0)
N	753.0	753.0

Table 23.1: Tobit estimation of hours worked. Example of a tobit model, Hill et al (2008), Table 16.8. Numbers in parentheses are t-stats ('sandwich' approach for MLE).

### 23.3.2 Interpretation of the Tobit Model

We could be interested in several things. *First*, how is the probability of  $y_i = 0$  affected by a change in regressor  $k$ ? The derivative provides an answer

$$\frac{\partial \Pr(y_i = 0)}{\partial x_{k,i}} = -\phi(x_i'\beta/\sigma)\beta_k/\sigma. \quad (23.21)$$

This derivative is high (in absolute value) when  $x_i'\beta \approx 0$ , since a small change in  $x_k$  can then tip the balance towards  $y_i = 0$ . (Formally, this follows from the fact that the pdf  $\phi()$  peaks when its argument is zero.) In contrast, when  $x_i'\beta$  is very small or very large, then a small change in  $x_k$  does not matter much for the probability (as we are already safely in  $y_i = 0$  or  $y_i = 1$  territory). *Second*, how is the expected value of  $y_i$  affected by a change in regressor  $k$ ? Once again, we can calculate a derivative

$$\frac{\partial \mathbb{E} y_i}{\partial x_{k,i}} = \Phi(x_i'\beta/\sigma)\beta_k. \quad (23.22)$$

This derivative depends on  $x_i'\beta$ . For low values of  $x_i'\beta$ , the derivative is close to zero (since  $\Phi(x_i'\beta/\sigma) \approx 0$ ). In contrast, for high values of  $x_i'\beta$ , the derivative is close to  $\beta_k$ . (To derive these two results, recall that  $\mathbb{E} y_i = (1 - Q)0 + Q \mathbb{E}(y_i | y_i^* > 0)$ , where  $Q$  is the probability of  $y_i^* > 0$ . Then use the remark on expected values from truncated normal distributions.)

## 23.4 Heckit: A Sample Selection Model

Recall that in a Tobit model,  $x_i' \beta + \varepsilon_i$  determines both the probability of observing  $y_i^*$  and its value. The *Heckit model* (sample selection model) relaxes that. It is a two equation model

$$w_i^* = x_{1i}' \beta_1 + \varepsilon_{1i} \quad (23.23)$$

$$h_i^* = x_{2i}' \beta_2 + \varepsilon_{2i}. \quad (23.24)$$

For instance,  $w_i^*$  could be individual productivity (measured by the wage) and  $h_i^*$  could be labour supply, and  $x_{1i}$  and  $x_{2i}$  could contain information about education, age, etc. The data on  $w_i^*$  (hourly wage) is only observed for people who work, and  $h_i^*$  is only observed as 0/1 (doesn't work/works). In short,

$$\text{Data: } (w_i, h_i) = \begin{cases} w_i = w_i^*, h_i = 1 & \text{if } h_i^* > 0 \\ w_i \text{ not observed, } h_i = 0 & \text{otherwise.} \end{cases} \quad (23.25)$$

The regressors  $x_{1i}$  and  $x_{2i}$  are observed for all  $i$ . In the special case where  $\text{Corr}(h_i^*, w_i^*) = 1$ , then we are back in standard Tobit model (where we used the notation  $y_i^*$  for what is here denoted  $w_i^*$ ). This requires that (23.24) is the same (or at least proportional) to (23.23)

It is typical to assume that the residuals in the two equations could be correlated

$$\begin{bmatrix} \varepsilon_{1i} \\ \varepsilon_{2i} \end{bmatrix} \sim N \left( \begin{bmatrix} 0 \\ 0 \end{bmatrix}, \begin{bmatrix} \sigma_1^2 & \sigma_{12} \\ \sigma_{12} & 1 \end{bmatrix} \right). \quad (23.26)$$

Notice that  $\text{Var}(\varepsilon_{2i}) = 1$  is a normalization. A correlation,  $\sigma_{12} \neq 0$ , means that some unobserved characteristics (part of the residuals) are affecting both equations. For instance, “ability” may be hard to measure (so it is not in the  $x_{1i}$  or  $x_{2i}$  vectors, but in the residuals) but is likely to affect both productivity and the labour supply choice.

To understand the properties of this model, notice that the expected value of  $w_i$ , conditional on  $h_i = 1$ , is

$$E(w_i | h_i = 1) = x_{1i}' \beta_1 + \sigma_{12} \lambda_i, \text{ where } \lambda_i = \frac{\phi(x_{2i}' \beta_2)}{\Phi(x_{2i}' \beta_2)}, \quad (23.27)$$

where  $\phi()$  and  $\Phi()$  are the standard normal pdf and cdf ( $\lambda_i$  is called the inverse Mill’s ratio or Heckman’s lambda). The point of (23.27) is that the covariance of the residuals in the two equations (23.23)–(23.24) is crucial. In fact, when  $\sigma_{12} = 0$ , then we can estimate

(23.23) with OLS. Otherwise, it is biased (and inconsistent).

**Proof.** (of (23.27))

$$\begin{aligned} E(w_i | h_i = 1) &= x'_{1i} \beta_1 + \underbrace{E(\varepsilon_{1i} | h_i = 1)}_{E(\varepsilon_{1i} | \varepsilon_{2i} > -x'_{2i} \beta_2)} \\ &= x'_{1i} \beta_1 + E(\varepsilon_{1i} | \varepsilon_{2i} > -x'_{2i} \beta_2), \end{aligned}$$

since  $h_i = 1$  when  $h_i^* = x'_{2i} \beta_2 + \varepsilon_{2i} > 0$ . If  $(\varepsilon_{1i}, \varepsilon_{2i})$  have a joint normal distribution as in (23.26), then it is a standard result that

$$E(\varepsilon_{1i} | \varepsilon_{2i} > -q) = \sigma_{12} \lambda, \text{ where } \lambda = \frac{\phi(q)}{\Phi(q)}.$$

(Showing this is straightforward, but a bit tedious.) ■

Another way to see the problem highlighted by (23.27) is the following. Consider the observable data (when  $h_i = 1$ )

$$w_i = x'_{1i} \beta_1 + \varepsilon_{1i} \quad (23.28)$$

and ask if  $E(x_{1i} \varepsilon_{1i}) = 0$  for this data? To keep it simple, suppose  $x_{2i}$  includes just a constant:  $w_i$  observed only when  $\varepsilon_{2i} > 0$ . If  $\text{Corr}(\varepsilon_{1i}, \varepsilon_{2i}) > 0$ , our sample of  $w_i$  actually contains mostly observations when  $\varepsilon_{1i} > 0$  (so  $\varepsilon_{1i}$  isn't zero on average in the sample). This gives a *sample selection bias*.

Is  $\sigma_{12} \neq 0$ ? To assess that, we must think about the economics of the problem. In wage and labour supply equations:  $\varepsilon_{1t}$  and  $\varepsilon_{2t}$  may capture some unobservable factor that makes a person more productive at the same time as more prone to supply more labour.

What if  $\text{Cov}(x_{1i}, \lambda_i) = 0$  (although  $\sigma_{12} \neq 0$ )? Well, then OLS of (23.28) is consistent (recall the case of uncorrelated regressors: we can then estimate one slope coefficient at a time). The conclusion is that the bias of OLS comes from  $\sigma_{12} \neq 0$  and  $\text{Cov}(x_{1i}, x_{2i}) \neq 0$  since then  $\text{Cov}(x_{1i}, \lambda_i) \neq 0$  (although  $\lambda$  is a non-linear function of  $x_{2i}$ ). As an extreme case, consider  $x_{1i} = x_{2i}$ .

### 23.4.1 Estimation

Use MLE or Heckman's 2-step approach, which is as follows:

1. Estimate (23.24) with the probit method (recall  $h_i = 0$  or 1) using the likelihood function in (23.20). Extract  $x'_{2i} \hat{\beta}_2$  and create  $\hat{\lambda}_i$  as in (23.27). See Table 23.2 for an

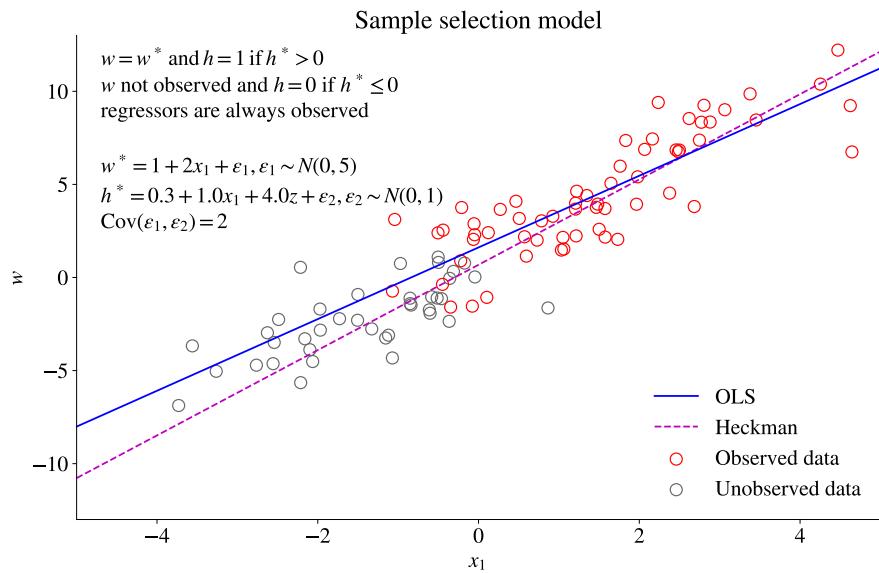


Figure 23.9: Sample selection model

example.

2. Estimate  $(\beta_1$  and  $\sigma_{12})$  with LS

$$w_i = x'_{1i}\beta_1 + \sigma_{12}\hat{\lambda}_i + \eta_i \quad (23.29)$$

on the data where  $w_i$  is observed (and not artificial set to zero or some other value).

This approach gives consistent estimates, but we may need to adjust standard errors (unless you test under the null hypothesis that  $\sigma_{12} = 0$ ).

c	-4.16
	(-2.96)
age	0.19
	(2.78)
age2	-0.00
	(-3.10)
faminc	0.00
	(1.00)
kids	-0.45
	(-3.53)
educ	0.10
	(4.35)

Table 23.2: Probit estimation of labour market participation. 1st step of Heckman estimation. Example of a Heckman model, Greene (2003), Table 22.7 (corrected). Numbers in parentheses are t-stats.

	LS	Heckman
c	-2.56 (-2.77)	-0.97 (-0.48)
exper	0.03 (0.53)	0.02 (0.34)
exper2	-0.00 (-0.14)	0.00 (0.07)
educ	0.48 (7.24)	0.42 (4.24)
cit	0.45 (1.42)	0.44 (1.41)
lambda		-1.10 (-0.88)
	0	

Table 23.3: OLS and Heckman estimation of log wages, married women, PSID 1975. Example of a Heckman model, Greene (2003), Table 22.7 (corrected). Numbers in parentheses are t-stats.

# Chapter 24

## LAD and Quantile Regressions\*

### 24.1 LAD

Reference: Amemiya (1985) 4.6, Greene (2018) 7, Wooldridge (2010) 12.10

The least absolute deviations (LAD) estimator minimizes the sum of absolute residuals (rather than the squared residuals)

$$\hat{b}_{LAD} = \arg \min_b \sum_{t=1}^T |y_t - x'_t b| \quad (24.1)$$

The optimization is a non-linear problem, but a simple iteration works nicely (see below). The estimator is typically less sensitive to outliers than OLS. (There are also other ways to estimate robust regression coefficients.) This is illustrated in Figure 24.1.

**Empirical Example 24.1** (*LAD betas for industry portfolios*) See Figure 24.2.

If we assume that the median of the true residual,  $u_t$ , is zero, then (under strict assumptions, discussed below) we have

$$\begin{aligned} \sqrt{T}(\hat{b}_{LAD} - b_0) &\xrightarrow{d} N\left[0, f(0)^{-2} \Sigma_{xx}^{-1}/4\right], \text{ where} \\ \Sigma_{xx} &= \text{plim} \sum_{t=1}^T x_t x'_t / T, \end{aligned} \quad (24.2)$$

where  $f(0)$  is the value of the pdf of the residual at zero. Unless we know this density function (or else we would probably have used MLE instead of LAD), we need to estimate it—for instance with a kernel density method. However, to arrive at the result in (24.2) we must assume that the residual is independent of the regressors. (This is discussed in some detail below, see quantile regressions).

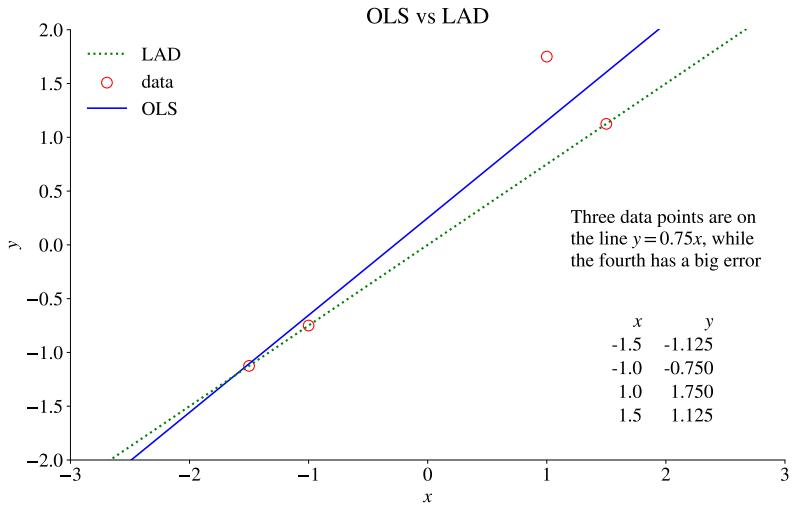


Figure 24.1: Data and regression line from OLS and LAD

**Example 24.2** ( $N(0, \sigma^2)$ ) When  $u_t \sim N(0, \sigma^2)$ , then  $f(0) = 1/\sqrt{2\pi\sigma^2}$  (since  $e^0 = 1$ ), so the covariance matrix in (24.2) becomes  $\pi\sigma^2 \Sigma_{xx}^{-1}/2$ . This is  $\pi/2$  times larger than when using LS.

**Remark 24.3** (Estimation of  $f(0)$ ) The  $f(0)$  value can be estimated as

$$\hat{f}(0) = \frac{1}{T} \sum_{t=1}^T \frac{1}{h\sqrt{2\pi}} \exp\left[-(u_t/h)^2/2\right].$$

**Remark 24.4** (Algorithm for LAD\*) The LAD estimator can be written

$$\begin{aligned} \hat{b}_{LAD} &= \arg \min_b \sum_{t=1}^T w_t \hat{u}_t(b)^2, \text{ where} \\ w_t &= 1/|\hat{u}_t(b)|, \text{ with} \\ \hat{u}_t(\hat{b}) &= y_t - x'_t \hat{b} \end{aligned}$$

so it is a weighted least squares where both  $y_t$  and  $x_t$  are multiplied by  $1/|\hat{u}_t(\hat{b})|^{0.5}$ . It can be shown that iterating on LS with the weights given by  $1/|\hat{u}_t(\hat{b})|^{0.5}$ , where the residuals are from the previous iteration, converges very quickly to the LAD estimator.

### 24.1.1 Reinterpreting the LAD

Consider a linear regression

$$y_t = x'_t b + u_t. \quad (24.3)$$

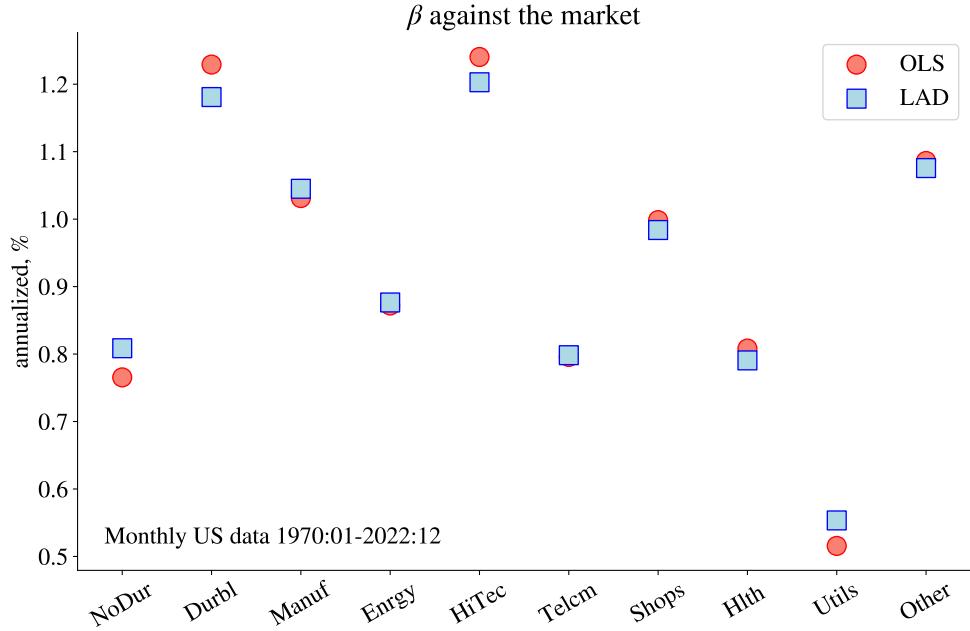


Figure 24.2: Betas of US industry portfolios

In the OLS context we typically assume  $E u_t = 0$  and  $\text{Cov}(x_t, u_t) = 0$ . The latter is the same as  $E(u_t | x_t) = 0$  which means that

$$E(y_t | x_t) = x_t' b. \quad (24.4)$$

We can interpret the LAD estimator as an alternative way of getting good estimates of  $b$ , especially when the error distribution has fat tails. In fact, when the errors have a Laplace distribution,  $f(u) = \exp(-|u|/\sigma)/2\sigma$ , then LAD is the MLE.

**Remark 24.5** ( $E(u|x) = 0$  or  $(E u_t = 0, \text{Cov}(x_t, u_t) = 0)^*$ ) For any random variables  $u$  and  $x$ ,

$$\text{Cov}(x, u) = \text{Cov}[x, E(u|x)].$$

The condition  $E(u|x) = 0$  therefore implies  $\text{Cov}(x, u) = 0$ . It also implies  $E u = 0$  since  $E u = E_x[E(u|x)] = E_x[0] = 0$ .

**Remark 24.6** (Mean and median as solutions to minimization problems) If  $u$  is a random variable, then the mean,  $\mu$ , is the solution to  $\min_{\mu} E(u - \mu)^2$ , while the median,  $m$ , is the solution to  $\min_m E |u - m|$ . (There are some restrictions on  $u$  for this to be true, but we disregard that here.)

The previous remark shows that the LAD estimator (24.1) amounts to finding the  $b$  coefficients (in a linear model) so that

$$\text{Median}(u_t|x_t) = 0, \text{ which implies} \quad (24.5)$$

$$\text{Median}(y_t|x_t) = x_t' b. \quad (24.6)$$

This is the alternative interpretation of the LAD: it tries to set the median of the residuals, at a given  $x_t$  vector, equal to zero. In contrast, OLS tries to set the mean of the residuals, at a given  $x_t$  vector, to zero.

## 24.2 Quantile Regressions

A quantile regression is a generalization of the LAD. Instead of focusing on the 0.5th quantile (the median), as is done in (24.5), it rather states that the  $q$ th quantile (conditional on  $x_t$ ) of the residual is zero

$$Q(u_t|x_t; q) = 0, \text{ which implies} \quad (24.7)$$

$$Q(y_t|x_t; q) = x_t' b^{(q)}. \quad (24.8)$$

Here  $Q(u_t|x_t; q)$  denotes the  $q$ th quantile of  $u_t$  at a particular value of  $x_t$  and we also index the coefficients  $b^{(q)}$  to remember that this refers to the  $q$ th quantile. Clearly, the LAD is the special case when  $q = 0.5$ .

We could estimate (see below for how) such coefficients for various quantiles. When  $x_t$  just contains a constant and one more regressor, then it is easy to illustrate. See Figure 24.3 for an example where the slopes differ across the quantiles and Figure 24.4 where they do not. In particular, in Figure 24.3 the data follows a *location and scale model*

$$y_t = x_t' \beta + u_t \text{ where } u_t = x_t' \gamma \varepsilon_t, \text{ and } \varepsilon_t \text{ is iid.} \quad (24.9)$$

This is basically a linear model ( $y_t = x_t' \beta$ ), but where the residuals ( $u_t$ ) are heteroskedastic. In particular, the volatility of  $u_t$  is increasing in  $|x_t' \gamma|$ . This highlights the key feature of quantile regressions: they are well suited for showing how both the typical (median) and tails (for instance, the 0.1th and 0.9th quantiles) are related to the regressors. Notice, however, that we are always referring to *conditional quantiles*, that is, to quantiles of  $y_t$  at a particular value of  $x_t$ . We are *not* referring to unconditional quantiles of  $y_t$ . This means that the slopes for a high quantile (0.9, say) do not necessarily describe the rela-

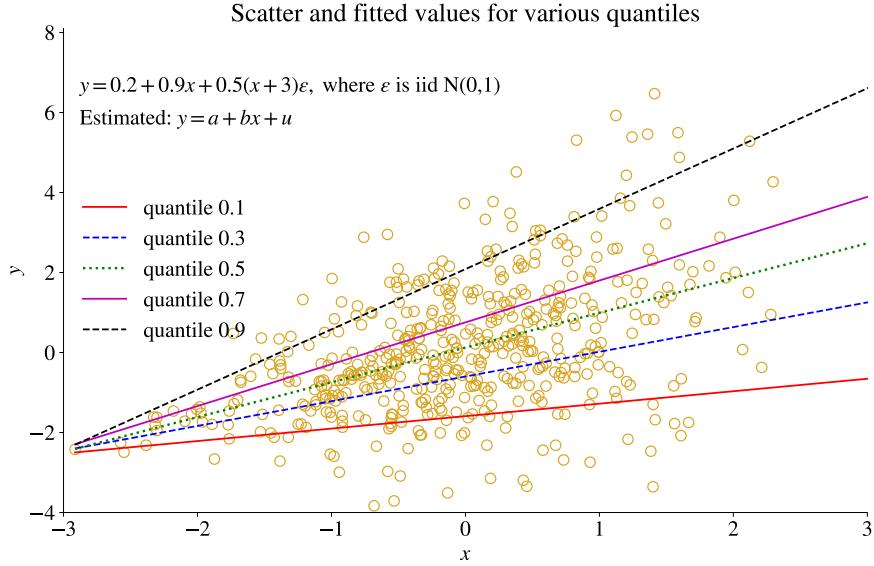


Figure 24.3: Example of quantile regression

tion between  $y_t$  and  $x_t$  at generally (unconditionally) high  $y_t$  (or  $x_t$ ) values—see Figure 24.3. Rather, the slopes describes the relation between  $y_t$  and  $x_t$  at high  $\varepsilon_t$  values. This is perhaps best seen by using the location and scale model in (24.9) which implies

$$Q(y_t|x_t; q) = x_t'\beta + Q(u_t|x_t; q) \quad (24.10)$$

$$= x_t'\beta + x_t'\gamma Q(\varepsilon_t; q) \quad (24.11)$$

$$= x_t'[\beta + \gamma Q(\varepsilon_t; q)]. \quad (24.12)$$

(In the second line,  $Q(\varepsilon_t; q)$  need not be conditioned on  $x_t$  since  $\varepsilon_t$  is independent of  $x_t$ .) Comparing with (24.8) shows that

$$b^{(q)} = \beta + \gamma Q(\varepsilon_t; q). \quad (24.13)$$

For instance, if  $\gamma > 0$ , then  $b^{(q)}$  is increasing with  $q$  (since  $Q(\varepsilon_t; q)$  is). This is the case illustrated in Figure 24.3—where the higher slopes at high quantiles basically capture heteroskedasticity. In contrast, Figure 24.4 shows the case where the  $\gamma$  coefficient on the non-constant regressors are all zero: the  $b^{(q)}$  coefficients (except for the constants) are the same across quantiles.

**Empirical Example 24.7** (*Quantile regressions of an AR(1) for S&P 500 returns*) Figure 24.5 illustrates these points by showing the predicted quantiles of a return as a func-

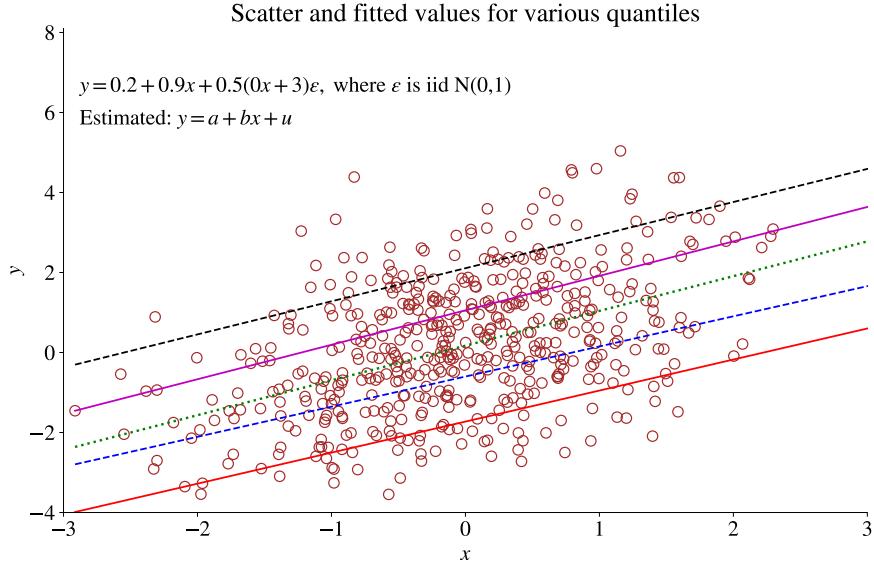


Figure 24.4: Example of quantile regression

*tion of the lagged return. The empirical evidence suggests that the typical (median) effect of a lagged return on today's return is almost zero (there is a weak pattern of negative return to be followed by positive returns and vice versa). More pronounced is the smaller dispersion of returns after positive returns—and this is where the real payoff of the quantile regressions is.*

The estimated coefficients for the  $q$ th quantile,  $b^{(q)}$ , solves the following problem

$$\min_{b^{(q)}} \sum_{t:u_t \geq 0} q|u_t| + \sum_{t:u_t < 0} (1-q)|u_t|, \text{ where } u_t = y_t - x'_t b^{(q)}. \quad (24.14)$$

This is a highly non-linear problem (and the objective function does not have continuous derivatives), which can be solved by either linear programming method, a derivative-free minimization algorithm or an iterative LS approach. As a special case,  $q = 0.5$  gives the LAD where (24.14) becomes

$$\min_{b^{(0.5)}} 0.5 \sum_{t=1}^T |u_t|, \text{ where } u_t = y_t - x'_t b^{(q)}, \quad (24.15)$$

which is clearly the same as (24.1).

**Remark 24.8** (*Algorithm for quantile regressions\**) Applying the same idea as for LAD,

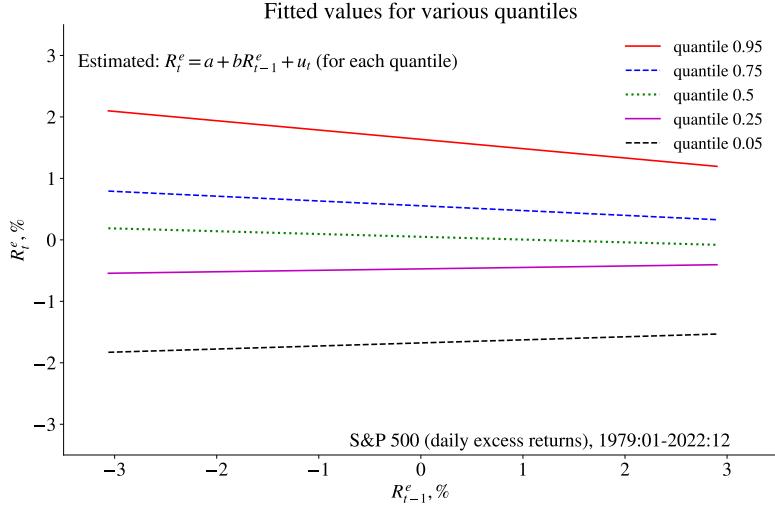


Figure 24.5: Quantile regression of AR(1) of daily returns

we can write (24.14) as

$$\hat{b}_{LAD} = \arg \min_b \sum_{t=1}^T w_t u_t^2, \text{ where}$$

$$w_t = \begin{cases} q / |\hat{u}_t(b)| & \text{if } \hat{u}_t(b) \geq 0 \\ (1-q) / |\hat{u}_t(b)| & \text{otherwise.} \end{cases}$$

We iterate by using the weights from the previous iteration. (By dividing the loss function by  $q(1-q)$ , we could also write the weights as  $1/[(1-q)|\hat{u}_t(b)|]$  and  $1/[q|\hat{u}_t(b)|]$ , which is how some commonly used code sets it up.)

**Remark 24.9** (Alternative way of writing (24.14)) Suppose  $u_1 \geq 0$  and  $u_2 < 0$ , then the sum in (24.14) can be written  $qu_1 + (q-1)u_2$ . This suggests that if we define a dummy  $d_t$  to be 1 if  $u_t < 0$  and zero otherwise, then we can write the sum as  $(q-d_t)u_1 + (q-d_t)u_2$ . In general, the minimisation problem can then be written

$$\min_{b^{(q)}} \sum_{t=1}^T (q - d_t) u_t.$$

The term  $(q - d_t)u_t$  is sometimes written as a function  $\rho_q(u_t)$ , so the sum becomes  $\sum_{t=1}^T \rho_q(u_t)$ . As a function of  $u_t$ , the  $\rho_q(u_t)$  function has a (skewed) v-shape around  $u_t = 0$ . For  $u_t < 0$  the function is  $(q-1)u_t$  so it is linear with a (negative) slope of  $q-1$ , and for  $u_t$  it is also linear but with a slope of  $q$ .

The asymptotic distribution of the estimates is typically

$$\begin{aligned}\sqrt{T}(\hat{b}^{(q)} - b_0^{(q)}) &\xrightarrow{d} N[0, q(1-q)C^{-1}\Sigma_{xx}C^{-1}], \text{ where} \\ \Sigma_{xx} &= \text{plim} \sum_{t=1}^T x_t x_t' / T \text{ and} \\ C &= \text{plim} \sum_{t=1}^T f(0|x_t) x_t x_t' / T,\end{aligned}\quad (24.16)$$

where  $f(0|x_t)$  is the value of the pdf of the residual, conditional on the regressor value, at a zero residual. If  $x_t$  is independent of the regressor, then  $f(0|x_t) = f(0)$  where the latter is the unconditional density of the residual. In this case, the covariance matrix can be written  $q(1-q)f(0)^{-2}\Sigma_{xx}^{-1}$ , which gives the result in (24.2) once we set  $q = 0.5$ .

One way of obtaining a consistent estimate of  $C$  is via a kernel density estimate

$$\begin{aligned}C &= \sum_{t=1}^T w_t x_t x_t' / T, \text{ with} \\ w_t &= \frac{1}{h\sqrt{2\pi}} \exp\left[-(\hat{u}_t/h)^2/2\right],\end{aligned}\quad (24.17)$$

and where  $\hat{u}_t$  is the fitted residual and  $h$  could be chosen as  $h = 1.06 \text{Std}(\hat{u}_t)T^{-1/5}$  (see Silverman (1986)). Alternatively,  $w_t$  could be calculated using the uniform kernel instead,  $w_t = \delta(-h/2 \leq \hat{u}_t \leq h/2)/h$ , where  $\delta(z) = 1$  when  $z$  is true. Notice that the product of  $w_t$  and  $x_t x_t'$  in (24.17) is aimed at capturing the fact that  $f(0|x_t)$  and  $x_t x_t'$  are related—something that was ruled out in (24.2).

# Chapter 25

## GMM\*

Sections denoted by a star (\*) is not required reading.

Reference: Cochrane (2005) 11 and 14; Campbell (2018) 4; Singleton (2006) 2–4; Greene (2018) 13

### 25.1 The Basic GMM

In general, the  $q \times 1$  vector of sample moment conditions in GMM are written

$$\bar{g}(\beta) = \frac{1}{T} \sum_{t=1}^T g_t(\beta) = \mathbf{0}_{q \times 1}, \quad (25.1)$$

where  $\bar{g}(\beta)$  is short hand notation for the sample average. The notation  $g_t(\beta)$  is meant to show that moments conditions depend on the parameter vector ( $\beta$ ) and on data for period  $t$ . We let  $\beta_0$  denote the true value of the  $k \times 1$  parameter vector.

The GMM estimator is

$$\hat{\beta}_{k \times 1} = \arg \min \bar{g}(\beta)' W \bar{g}(\beta), \quad (25.2)$$

where  $W$  is some symmetric positive definite  $q \times q$  weighting matrix. When the model is exactly identified ( $q = k$ ), then we do not have to perform an explicit minimization, since all sample moment conditions can be set equal to zero (there are as many parameters as there are moment conditions). However, we may still have to apply a numerical algorithm to find the  $\hat{\beta}$  values that make  $\bar{g}(\hat{\beta}) = \mathbf{0}_{q \times 1}$  hold, in particular, if  $g_t()$  are non-linear functions.

It can be shown that choosing  $W = S_0^{-1}$ , where  $S_0$  is the covariance matrix of  $\sqrt{T}\bar{g}(\beta_0)$  evaluated at the true parameter values, gives the most efficient estimates (for a given set of moment conditions). To approximate this, an iterative procedure is often

used: start with  $W = I_q$  (or some other reasonable weighting matrix), estimate the parameters and use them to create a  $T \times q$  matrix of moment conditions, estimate  $S_0$ , then (in a second step) use  $W = \hat{S}_0^{-1}$  and reestimate. In most cases this iteration is stopped at this stage, but you could also continue iterating until the point estimates converge.

**Example 25.1** (*Moment conditions for the mean and variance*) To estimate the mean and variance ( $\beta = (\mu, \sigma^2)$ ) of  $x_t$ , use

$$g_t = \begin{bmatrix} x_t - \mu \\ (x_t - \mu)^2 - \sigma^2 \end{bmatrix}.$$

There are two parameters and two moment conditions: exactly identified.

**Example 25.2** (*Moments conditions for OLS*) Consider the linear model  $y_t = x_t' \beta_0 + u_t$ , where  $x_t$  and  $\beta$  are  $k \times 1$  vectors. The  $k$  moments are

$$g_t = x_t(y_t - x_t' \beta).$$

There are as many parameters as moment conditions: exactly identified.

**Example 25.3** (*Moment conditions for estimating a normal distribution*) Suppose you specify four moments for estimating the mean and variance ( $\beta = (\mu, \sigma^2)$ ) of a normal distribution

$$g_t = \begin{bmatrix} x_t - \mu \\ (x_t - \mu)^2 - \sigma^2 \\ (x_t - \mu)^3 \\ (x_t - \mu)^4 - 3\sigma^4 \end{bmatrix}$$

This case is overidentified ( $q = 4$  and  $k = 2$ ), so a weighting matrix is needed.

**Example 25.4** (*Moment conditions for variances and a covariance*) For expositional simplicity, assume that both variables have zero means. The variances and the covariance ( $\beta = (\sigma_{xx}, \sigma_{yy}, \sigma_{xy})$ ) can then be estimated with the moment conditions

$$g_t = \begin{bmatrix} x_t^2 - \sigma_{xx} \\ y_t^2 - \sigma_{yy} \\ x_t y_t - \sigma_{xy} \end{bmatrix}.$$

### 25.1.1 Distribution of the Basic GMM

GMM estimators are typically asymptotically normally distributed, with a covariance matrix that depends on the covariance matrix of the moment conditions ( $S_0$ ) and the mapping from the parameters to the moment conditions ( $D_0$ ). The details of these matrices are discussed below. For now, notice that the distribution of the GMM estimates is

$$\begin{aligned}\sqrt{T}(\hat{\beta} - \beta_0) &\xrightarrow{d} N(0, V) \text{ if } W = S_0^{-1}, \text{ where} \\ V &= (D_0' S_0^{-1} D_0)^{-1},\end{aligned}\quad (25.3)$$

provided we have used  $S_0^{-1}$  as the weighting matrix ( $W = S_0^{-1}$ ) in (25.2). The choice of the weighting matrix is irrelevant if the model is exactly identified, so (25.3) can be applied to this case (even if we did not specify any weighting matrix at all). It can also be noticed that when the model is exactly identified, then we can typically rewrite the covariance matrix as  $V = D_0^{-1} S_0 (D_0^{-1})'$ , which might be easier to calculate. (The case of using another  $W$  matrix is discussed below.)

Let  $S_0$  be the  $(q \times q)$  covariance matrix of  $\sqrt{T}\bar{g}(\beta_0)$ , evaluated at the true parameter values

$$S_0 = \text{Var}[\sqrt{T}\bar{g}(\beta_0)], \quad (25.4)$$

where  $\text{Var}()$  is a variance-covariance matrix. When there is no autocorrelation of the moments, then (25.4) becomes

$$S_0 = \text{Var}[g_t(\beta_0)], \text{ if } g_t \text{ is not autocorrelated.} \quad (25.5)$$

(Recall that  $\text{Var}(\bar{g}) = \text{Var}(g_t)/T$  if  $g_t$  is iid and that (25.4) multiplies by  $T$ .) When there is autocorrelation, then we may use the Newey-West approach to estimate  $S_0$ .

In practice,  $S_0$  is estimated by using the estimated coefficients in the moments to get the data series  $g_t(\hat{\beta})$ , a  $T \times q$  matrix, from which we estimate the covariances needed for (25.4) or (25.5).

**Example 25.5** (*Estimating the mean and variance,*) The moments in Example 25.1 give

$$S_0 = \text{Var}\left(\frac{\sqrt{T}}{T} \sum_{t=1}^T \begin{bmatrix} x_t - \mu \\ (x_t - \mu)^2 - \sigma^2 \end{bmatrix}\right).$$

In practice, we use the point estimates for  $(\mu, \sigma^2)$ . If we suspect autocorrelation, then we may use the NW estimator.  $S_0$  could be simplified if we knew that  $x_t$  was iid normally

distributed. In this case we get  $S_0 = \text{diag}(\sigma^2, 2\sigma^4)$ .

**Example 25.6 (OLS, covariance)** For the moments in Example 25.2, using  $u_t = y_t - x'_t \beta$ , we have

$$S_0 = \text{Var} \left[ \frac{\sqrt{T}}{T} \sum_{t=1}^T x_t u_t \right]$$

In practice, replace  $u_t$  by the fitted residuals and calculate a sample covariance. It can be shown that under the Gauss-Markov assumptions  $S_0 = \sigma^2 \Sigma_{xx}$ . If we suspect that the variance of  $u_t$  is related to  $x_t$ , then we should calculate the covariance matrix of  $g_t$ , which gives White's covariance estimator. In addition we suspect that  $g_t$  is autocorrelated, then we may use the NW estimator of  $\text{Var}(\sqrt{T}\bar{g})$ .

Let  $D_0$  be the  $(q \times k)$  probability limit of the gradient (Jacobian) of the sample moment conditions with respect to the parameters (also evaluated at the true parameters)

$$D_0 = \text{plim} \frac{\partial \bar{g}(\beta_0)}{\partial \beta'}. \quad (25.6)$$

In practice, the gradient  $D_0$  is approximated by using the point estimates and the available sample of data.

**Remark 25.7 (Jacobian)** The Jacobian is of the following format

$$\frac{\partial \bar{g}(\beta_0)}{\partial \beta'} = \begin{bmatrix} \frac{\partial \bar{g}_1(\beta)}{\partial \beta_1} & \dots & \frac{\partial \bar{g}_1(\beta)}{\partial \beta_k} \\ \vdots & & \vdots \\ \vdots & & \vdots \\ \frac{\partial \bar{g}_q(\beta)}{\partial \beta_1} & \dots & \frac{\partial \bar{g}_q(\beta)}{\partial \beta_k} \end{bmatrix} \quad (\text{evaluated at } \beta_0).$$

**Example 25.8 (Estimating a mean, Jacobian)** For the moment in Example 25.1

$$D_0 = \text{plim} \frac{1}{T} \sum_{t=1}^T \begin{bmatrix} -1 & 0 \\ -2(x_t - \mu) & -1 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}$$

which does not involve any parameters or any data.

**Example 25.9 (OLS, Jacobian)** For the moments in Example 25.2

$$D_0 = \text{plim} \left( -\frac{1}{T} \sum_{t=1}^T x_t x'_t \right) = -\Sigma_{xx}.$$

This does not contain any parameters either, but includes data. In practice, we replace  $\Sigma_{xx}$  by a sample estimate.

**Example 25.10** (Estimating/testing a normal distribution, covariance) For the moments in Example 25.3 we have

$$D_0 = \text{plim} \frac{1}{T} \sum_{t=1}^T \begin{bmatrix} -1 & 0 \\ -2(x_t - \mu) & -1 \\ -3(x_t - \mu)^2 & 0 \\ -4(x_t - \mu)^3 & -6\sigma^2 \end{bmatrix} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -3\sigma^2 & 0 \\ -4\mu_3 & -6\sigma^2 \end{bmatrix},$$

where  $\mu_3$  is the third centered moment (which is zero for a symmetric distribution).

**Example 25.11** (Estimating a mean, distribution) For the moment condition in Example 25.1 we have (assuming iid data)

$$\sqrt{T}(\hat{\mu} - \mu_0) \xrightarrow{d} N(0, \sigma^2), \text{ so } \hat{\mu} \stackrel{a}{\sim} N(\mu_0, \sigma^2/T).$$

**Example 25.12** (OLS, distribution) For the moment conditions in Example 25.2

$$V = (\Sigma_{xx} S_0^{-1} \Sigma_{xx})^{-1}.$$

Under the Gauss-Markov assumptions  $S_0 = \sigma^2 \Sigma_{xx}$ , so

$$V = \left[ \Sigma_{xx} (\sigma^2 \Sigma_{xx})^{-1} \Sigma_{xx} \right]^{-1} = \sigma^2 \Sigma_{xx}^{-1}.$$

**Example 25.13** (Estimating/testing a normal distribution, distribution) For the moment conditions in Example 25.3 (assuming iid normally distributed data) we have that the asymptotic covariance matrix of the estimated mean and variance is then  $((D_0' S_0^{-1} D_0)^{-1})$

$$\left( \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -3\sigma^2 & 0 \\ 0 & -6\sigma^2 \end{bmatrix}' \begin{bmatrix} \sigma^2 & 0 & 3\sigma^4 & 0 \\ 0 & 2\sigma^4 & 0 & 12\sigma^6 \\ 3\sigma^4 & 0 & 15\sigma^6 & 0 \\ 0 & 12\sigma^6 & 0 & 96\sigma^8 \end{bmatrix}^{-1} \begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -3\sigma^2 & 0 \\ 0 & -6\sigma^2 \end{bmatrix} \right)^{-1} = \begin{bmatrix} \frac{1}{\sigma^2} & 0 \\ 0 & \frac{1}{2\sigma^4} \end{bmatrix}^{-1} = \begin{bmatrix} \sigma^2 & 0 \\ 0 & 2\sigma^4 \end{bmatrix}.$$

In an overidentified model ( $k < q$ ), we can test if the  $k$  parameters make all  $q$  moment conditions hold. Notice that under the null hypothesis (that the model is correctly

specified)

$$\sqrt{T} \bar{g}(\beta_0) \xrightarrow{d} N(\mathbf{0}_{q \times 1}, S_0), \quad (25.7)$$

where  $q$  is the number of moment conditions. Since  $\hat{\beta}$  is chosen in such a way that  $k$  linear combinations of the moment conditions are zero, there are effectively only  $q - k$  non-degenerate random variables. We can therefore test the hypothesis that  $\bar{g}(\beta_0) = 0$  by the “J test”

$$T \bar{g}(\hat{\beta})' S_0^{-1} \bar{g}(\hat{\beta}) \xrightarrow{d} \chi_{q-k}^2, \text{ if } W = S_0^{-1}. \quad (25.8)$$

The left hand side equals  $T$  times of value of the loss function in (25.2) evaluated at the point estimates. With no overidentifying restrictions ( $q = k$ ) there are no restrictions to test. Indeed, the loss function value is then always zero at the point estimates.

**Example 25.14** (*Estimating/testing a normal distribution, testing*) After having estimated the mean and the variance, we can test if all four moment conditions in Example 25.3 hold. If data is drawn from a normal distribution, they should hold (give and take some randomness).

**Empirical Example 25.15** (*Estimating a mean a variance with GMM*) Table 25.1 reports estimates of the mean and variance of the FF equity market return. The first approach (column) uses only the first two moment conditions of 25.3 (an exactly identified case). Other approaches apply different (suboptimal)  $W$  matrices in solving (25.2). Finally, the last approaches apply (25.12) by using different  $A$  matrices. Table 25.2 reports results from iterating on the  $W$  matrix when solving (25.2). The  $W$  matrix used in the final iteration is shown in Table 25.3.

	ex. ident.	$\bar{g}' W_1 \bar{g}$	$\bar{g}' W_2 \bar{g}$	$A_1 \bar{g}$	$A_2 \bar{g}$
$\mu$	0.57	0.57	0.34	0.57	0.52
$\sigma^2$	21.35	21.35	21.40	21.35	21.35

Table 25.1: Estimates of mean and variance of the FF equity market factor, 1970:01-2022:12. The  $W_1$  and  $A_1$  matrices put equal weights on moment conditions 1–2 and zero weight moment conditions 3–4, while  $W_2$  and  $A_2$  put also a very small weight on moment condition 3.

	iteration				
	0	1	2	3	4
$\mu$	0.57	0.71	0.71	0.71	0.71
$\sigma^2$	21.35	19.18	19.12	19.12	19.12

Table 25.2: Estimates of mean and variance of the FF equity market factor, 1970:01-2022:12. The estimates minimize  $\bar{g}'W_i\bar{g}$ , where  $W_i = S_{i-1}^{-1}$

$$\begin{array}{cccc} 1200.30 & 57.77 & -9.57 & -0.40 \\ 57.77 & 18.74 & -0.62 & -0.07 \\ -9.57 & -0.62 & 0.14 & 0.01 \\ -0.40 & -0.07 & 0.01 & 0.00 \end{array}$$

Table 25.3:  $W_i \times 10000$  used in the last iteration when, minimizing  $\bar{g}'W_i\bar{g}$  to estimate the mean and variance of the FF equity market factor, 1970:01-2022:12.

## 25.2 GMM with a Suboptimal Weighting Matrix

The distribution of the GMM estimates when we use a sub-optimal weighting matrix is similar to (25.3), but the variance-covariance matrix is different (basically, reflecting the fact that the approach does not produce the lowest possible variances anymore).

**Example 25.16** (*Estimating/testing a normal distribution*) Example 25.3 is overidentified since there are four moment conditions but only two parameters. Instead of using the optimal weighting matrix, we could use any other (positive definite)  $4 \times 4$  matrix. For instance,  $W = I_4$  or a matrix that puts almost all weight on the first two moment conditions.

It can be shown that if we use another weighting matrix than  $W = S_0^{-1}$ , then the variance-covariance matrix in (25.3) should be changed to

$$V_2 = V_{A2}D_0'WS_0W'D_0V_{A2}', \text{ where} \quad (25.9)$$

$$V_{A2} = (D_0'WD_0)^{-1}.$$

Similarly, the test of overidentifying restrictions becomes

$$T\bar{g}(\hat{\beta})'\Psi_2^+\bar{g}(\hat{\beta}) \xrightarrow{d} \chi_{q-k}^2, \quad (25.10)$$

where  $\Psi_2^+$  is a generalized inverse of

$$\begin{aligned}\Psi_2 &= \Psi_{A2} S_0 \Psi'_{A2}, \text{ where} \\ \Psi_{A2} &= I_q - D_0 (D'_0 W D_0)^{-1} D'_0 W.\end{aligned}\tag{25.11}$$

The covariance matrix  $\Psi_2$  has a reduced rank, so we must use a generalized inverse in the test.

**Remark 25.17** (*Quadratic form with degenerate covariance matrix*) If the  $n \times 1$  vector  $X \sim N(0, \Sigma)$ , where  $\Sigma$  has rank  $r \leq n$  then  $Y = X' \Sigma^+ X \sim \chi_r^2$  where  $\Sigma^+$  is the pseudo inverse of  $\Sigma$ .

**Example 25.18** (*Pseudo inverse of a square matrix*) For the matrix

$$A = \begin{bmatrix} 1 & 2 \\ 3 & 6 \end{bmatrix}, \text{ we have } A^+ = \begin{bmatrix} 0.02 & 0.06 \\ 0.04 & 0.12 \end{bmatrix}.$$

### 25.3 GMM without a Loss Function

Suppose we sidestep the whole optimization issue and instead specify  $k$  linear combinations of the  $q$  moment conditions directly

$$\mathbf{0}_{k \times 1} = \underbrace{A}_{k \times q} \underbrace{\bar{g}(\hat{\beta})}_{q \times 1},\tag{25.12}$$

where the matrix  $A$  is chosen by the researcher. We can solve (possibly with a numerical algorithm) for the  $\hat{\beta}$  values that make these equations hold.

**Example 25.19** (*Overidentified example: estimating/testing a normal distribution*) Example 25.3 is overidentified since there are four moment conditions but only two parameters. One possible  $A$  matrix would put all weight on the first two moment conditions

$$A = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}.$$

It is straightforward to show that the variance-covariance matrix in (25.3) should be changed to

$$\begin{aligned}V_3 &= V_{A3} A_0 S_0 A'_0 V'_{A3}, \text{ where} \\ V_{A3} &= (A_0 D_0)^{-1},\end{aligned}\tag{25.13}$$

where  $A_0$  is the probability limit of  $A$  (if it is random).

Similarly, in the test of overidentifying restrictions (25.10), we should replace  $\Psi_2$  by

$$\begin{aligned}\Psi_3 &= \Psi_{A3} S_0 \Psi'_{A3}, \text{ where} \\ \Psi_{A3} &= I_q - D_0 (A_0 D_0)^{-1} A_0.\end{aligned}\tag{25.14}$$

The covariance matrix  $\Psi_3$  has a reduced rank, so we must again use a generalized inverse in the test.

**Example 25.20** (*Estimating/testing a normal distribution*) Continuing Example 25.19, we have that  $A_0 D_0$  in (25.13) is

$$V_{A3} = \left( \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}_{A_0} \underbrace{\begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -3\sigma^2 & 0 \\ 0 & -6\sigma^2 \end{bmatrix}}_{D_0} \right)^{-1} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}.$$

**Example 25.21** (*Estimating/testing a normal distribution*) Continuing the previous example,  $\Psi_{A3}$  in (25.14) is

$$\begin{aligned}\Psi_{A3} &= \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}}_{I_4} - \underbrace{\begin{bmatrix} -1 & 0 \\ 0 & -1 \\ -3\sigma^2 & 0 \\ 0 & -6\sigma^2 \end{bmatrix}}_{D_0} \left( \underbrace{\begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}}_{A_0 D_0} \right)^{-1} \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix}}_{A_0} \\ &= \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -3\sigma^2 & 0 & 1 & 0 \\ 0 & -6\sigma^2 & 0 & 1 \end{bmatrix}.\end{aligned}$$

$\Psi_3$  in (25.14) is therefore

$$\begin{aligned}\Psi_3 &= \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -3\sigma^2 & 0 & 1 & 0 \\ 0 & -6\sigma^2 & 0 & 1 \end{bmatrix} \begin{bmatrix} \sigma^2 & 0 & 3\sigma^4 & 0 \\ 0 & 2\sigma^4 & 0 & 12\sigma^6 \\ 3\sigma^4 & 0 & 15\sigma^6 & 0 \\ 0 & 12\sigma^6 & 0 & 96\sigma^8 \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ -3\sigma^2 & 0 & 1 & 0 \\ 0 & -6\sigma^2 & 0 & 1 \end{bmatrix}' \\ &= \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 6\sigma^6 & 0 \\ 0 & 0 & 0 & 24\sigma^8 \end{bmatrix}\end{aligned}$$

**Example 25.22** (Estimating/testing a normal distribution) Continuing the previous example, we have that the test of the overidentifying restrictions (25.10) (assuming iid normally distributed data to calculate  $S_0$ ) is (notice the generalized inverse of  $\Psi_3$ )

$$\begin{aligned}&= T \begin{bmatrix} 0 \\ 0 \\ \Sigma_{t=1}^T (x_t - \mu)^3 / T \\ \Sigma_{t=1}^T [(x_t - \mu)^4 - 3\sigma^4] / T \end{bmatrix}' \begin{bmatrix} 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 1/(6\sigma^6) & 0 \\ 0 & 0 & 0 & 1/(24\sigma^8) \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ \Sigma_{t=1}^T (x_t - \mu)^3 / T \\ \Sigma_{t=1}^T [(x_t - \mu)^4 - 3\sigma^4] / T \end{bmatrix} \\ &= \frac{T}{6} \frac{[\Sigma_{t=1}^T (x_t - \mu)^3 / T]^2}{\sigma^6} + \frac{T}{24} \frac{\{\Sigma_{t=1}^T [(x_t - \mu)^4 - 3\sigma^4] / T\}^2}{\sigma^8}.\end{aligned}$$

When we replace  $\mu$  and  $\sigma$  by their estimates, then this is the same as the Jarque-Bera test of normality.

## 25.4 GMM Example: The Means and Second Moments of Returns

Let  $R_t$  be a vector of net returns of  $N$  assets. We want to estimate the mean vector and the covariance matrix. The moment conditions for the mean vector are

$$\mathbb{E} R_t - \mu = \mathbf{0}_{N \times 1}, \quad (25.15)$$

and the moment conditions for the unique elements of the second moment matrix are

$$\mathbb{E} \text{vech}(R_t R_t') - \text{vech}(\Gamma) = \mathbf{0}_{N(N+1)/2 \times 1}. \quad (25.16)$$

**Remark 25.23** (The vech operator)  $\text{vech}(A)$  where  $A$  is  $m \times m$  gives an  $m(m+1)/2 \times 1$  vector with the elements on and below the principal diagonal  $A$  stacked on top of each other.

other (column wise). For instance,  $\text{vech} \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} a_{11} \\ a_{21} \\ a_{22} \end{bmatrix}$ .

Stack (25.15) and (25.16) and substitute the sample mean for the population expectation to get the GMM estimator

$$\frac{1}{T} \sum_{t=1}^T \begin{bmatrix} R_t \\ \text{vech}(R_t R'_t) \end{bmatrix} - \begin{bmatrix} \hat{\mu} \\ \text{vech}(\hat{\Gamma}) \end{bmatrix} = \begin{bmatrix} \mathbf{0}_{N \times 1} \\ \mathbf{0}_{N(N+1)/2 \times 1} \end{bmatrix}. \quad (25.17)$$

In this case,  $D_0 = -I$ , so the covariance matrix of the parameter vector  $(\hat{\mu}, \text{vech}(\hat{\Gamma}))$  is just  $S_0$  (defined in (25.4)), which is straightforward to estimate.

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