1 Ordinary least squares

1.1 Introduction

A system of linear equations is considered *overdetermined* if there are more equations than unknown variables. If all equations of an overdetermined system are linearly independent, the system has no exact solution.

A *linear least-squares problem* is the problem of finding an approximate solution to an overdetermined linear system. It often arises in applications where a theoretical model is fitted to experimental data.

1.2 Linear least-squares problem

Consider a linear system

$$\mathbf{A}\mathbf{c} = \mathbf{b} \,, \tag{1}$$

where $\mathbf{A}$ is an $n \times m$ matrix, $\mathbf{c}$ is an m-component vector of unknown variables and $\mathbf{b}$ is an n-component vector of the right-hand side terms. If the number of equations n is larger than the number of unknowns m, the system is overdetermined and generally has no solution.

However, it is still possible to find an approximate solution — the one where $\mathbf{A}\mathbf{c}$ is only approximately equal $\mathbf{b}$ — in the sence that the Euclidean norm of the difference between $\mathbf{A}\mathbf{c}$ and $\mathbf{b}$ is minimized,

$$\mathbf{c} : \min_{\mathbf{c}} \|\mathbf{A}\mathbf{c} - \mathbf{b}\|^2 \,. \tag{2}$$

The problem (2) is called the ordinary least-squares problem and the vector $\mathbf{c}$ that minimizes $\|\mathbf{A}\mathbf{c} - \mathbf{b}\|^2$ is called the *least-squares solution*.

1.3 Solution via QR-decomposition

The linear least-squares problem can be solved by QR-decomposition. The matrix $\mathbf{A}$ is factorized as $\mathbf{A} = \mathbf{Q}\mathbf{R}$, where $\mathbf{Q}$ is $n \times m$ matrix with orthogonal columns, $\mathbf{Q}^\mathsf{T}\mathbf{Q} = 1$, and $\mathbf{R}$ is an $m \times m$ upper triangular matrix. The Euclidean norm $\|\mathbf{A}\mathbf{c} - \mathbf{b}\|^2$ can then be rewritten as

$$\begin{aligned} \|\mathbf{A}\mathbf{c} - \mathbf{b}\|^2 &= \|\mathbf{Q}\mathbf{R}\mathbf{c} - \mathbf{b}\|^2 \\ &= \|\mathbf{R}\mathbf{c} - \mathbf{Q}^\mathsf{T}\mathbf{b}\|^2 + \|(1 - \mathbf{Q}\mathbf{Q}^\mathsf{T})\mathbf{b}\|^2 \geq \|(1 - \mathbf{Q}\mathbf{Q}^\mathsf{T})\mathbf{b}\|^2 \,. \end{aligned} \tag{3}$$

The term $\|(1 - \mathbf{Q}\mathbf{Q}^\mathsf{T})\mathbf{b}\|^2$ is independent of the variables $\mathbf{c}$ and can not be reduced by their variations. However, the term $\|\mathbf{R}\mathbf{c} - \mathbf{Q}^\mathsf{T}\mathbf{b}\|^2$ can be reduced down to zero by solving the $m \times m$ system of linear equations

$$\mathbf{Rc} = \mathbf{Q}^\mathsf{T}\mathbf{b} \; . \tag{4}$$

The system is right-triangular and can be readily solved by back-substitution.

Thus the solution to the ordinary least-squares problem (2) is given by the solution of the triangular system (4).

1.4 Ordinary least-squares curve fitting

Ordinary least-squares curve fitting is a problem of fitting n (experimental) data points $\{x_i, y_i \pm \Delta y_i\}_{i=1,\dots,n}$, where Δy_i are experimental errors, by a linear combination, $F_\mathbf{c}$, of m functions $\{f_k(x)\}_{k=1,\dots,m}$,

$$F_\mathbf{c}(x) = \sum_{k=1}^{m} c_k f_k(x) \; , \tag{5}$$

where the coefficients c_k are the fitting parameters.

The objective of the least-squares fit is to minimize the square deviation, called χ^2, between the fitting function $F_\mathbf{c}(x)$ and the experimental data,

$$\chi^2 = \sum_{i=1}^{n} \left(\frac{F(x_i) - y_i}{\Delta y_i} \right)^2 \; . \tag{6}$$

where the individual deviations from experimental points are weighted with their inverse errors in order to promote contributions from the more precise measurements.

Minimization of χ^2 with respect to the coefficiendt c_k in (5) is apparently equivalent to the least-squares problem (2) where

$$A_{ik} = \frac{f_k(x_i)}{\Delta y_i} \; , \; b_i = \frac{y_i}{\Delta y_i} \; . \tag{7}$$

If $\mathbf{QR} = \mathbf{A}$ is the QR-decomposition of the matrix $\mathbf{A}$, the formal least-squares solution to the fitting problem is

$$\mathbf{c} = \mathbf{R}^{-1}\mathbf{Q}^\mathsf{T}\mathbf{b} \; . \tag{8}$$

In practice of course one rather back-substitutes the right-triangular system $\mathbf{Rc} = \mathbf{Q}^\mathsf{T}\mathbf{b}$.

1.4.1 Variances and correlations of fitting parameters

Suppose δy_i is a small deviation of the measured value of the physical observable at hand from its exact value. The corresponding deviation δc_k of the fitting coefficient is then given as

$$\delta c_k = \sum_i \frac{\partial c_k}{\partial y_i} \delta y_i \ . \tag{9}$$

In a good experiment the deviations δy_i are statistically independent and distributed normally with the standard deviations Δy_i. The deviations (9) are then also distributed normally with *variances*

$$\langle \delta c_k \delta c_k \rangle = \sum_i \left(\frac{\partial c_k}{\partial y_i} \Delta y_i \right)^2 = \sum_i \left(\frac{\partial c_k}{\partial b_i} \right)^2 \ . \tag{10}$$

The standard errors in the fitting coefficients are then given as the square roots of variances,

$$\Delta c_k = \sqrt{\langle \delta c_k \delta c_k \rangle} = \sqrt{\sum_i \left(\frac{\partial c_k}{\partial b_i} \right)^2} \ . \tag{11}$$

The variances are diagonal elements of the *covariance matrix*, Σ, made of *covariances*,

$$\Sigma_{kq} \equiv \langle \delta c_k \delta c_q \rangle = \sum_i \frac{\partial c_k}{\partial b_i} \frac{\partial c_q}{\partial b_i} \ . \tag{12}$$

Covariances $\langle \delta c_k \delta c_q \rangle$ are measures of to what extent the coefficients c_k and c_q change together if the measured values y_i are varied. The normalized covariances,

$$\frac{\langle \delta c_k \delta c_q \rangle}{\sqrt{\langle \delta c_k \delta c_k \rangle \langle \delta c_q \delta c_q \rangle}} \tag{13}$$

are called *correlations*.

Using (12) and (8) the covariance matrix can be calculated as

$$\Sigma = \left(\frac{\partial \mathbf{c}}{\partial \mathbf{b}} \right) \left(\frac{\partial \mathbf{c}}{\partial \mathbf{b}} \right)^{\mathsf{T}} = R^{-1}(R^{-1})^{\mathsf{T}} = (R^{\mathsf{T}} R)^{-1} = (A^{\mathsf{T}} A)^{-1} \ . \tag{14}$$

The square roots of the diagonal elements of this matrix provide the estimates of the errors $\Delta \mathbf{c}$ of the fitting coefficients,

$$\Delta c_k = \sqrt{\Sigma_{kk}} \Big|_{k=1 \ldots m} \ , \tag{15}$$

and the (normalized) off-diagonal elements provide the estimates of their correlations.

Here is a C-implementation of the ordinary least squares fit via QR decomposition,

```
void lsfit(vector* x, vector* y, vector* dy,
int nf, float f(int k, float x), vector* c, matrix* S){
 int n=x->size, m=nf;
 matrix *A = matrix_alloc(n,m), *R = matrix_alloc(m,m);
 vector *b = vector_copy_alloc(y); vector_div(b,dy);
 for(int i=0;i<n;i++){
  float xi=vector_get(x,i), dyi=vector_get(dy,i);
  for(int k=0;k<m;k++) matrix_set(A,i,k,f(k,xi)/dyi);
  }
 givens_qr(A); givens_qr_unpack_R(A,R);
 givens_qr_solve_inplace(A,b);
 for(int i=0;i<m;i++)vector_set(c,i,vector_get(b,i));
 matrix* Rinv=matrix_alloc(m,m);
 givens_qr_inverse(R,Rinv); matrixT_times_matrix(Rinv,Rinv,S);
 matrix_free(A); matrix_free(R); matrix_free(Rinv); vector_free(b);
}
```

An illustration of a fit is shown on Figure 1 where a polynomial is fitted to a set of data.

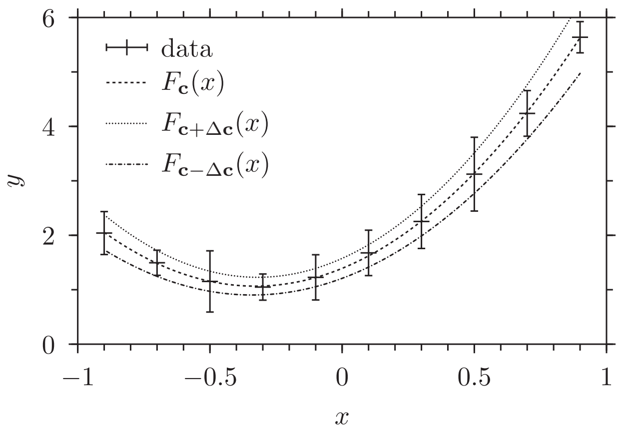

Figure 1: Ordinary least squares fit of $F_{\mathbf{c}}(x) = c_1 + c_2 x + c_3 x^2$ to a set of data. Shown are fits with optimal coefficiens $\mathbf{c}$ as well as with $\mathbf{c} + \Delta\mathbf{c}$ and $\mathbf{c} - \Delta\mathbf{c}$.

1.5 Singular value decomposition

Under the *thin singular value decomposition* we shall understand a representation of a tall $n \times m$ ($n > m$) matrix $\mathbf{A}$ in the form

$$\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^{\mathsf{T}} , \tag{16}$$

where $\mathbf{U}$ is an orthogonal $n \times m$ (tall) matrix ($\mathbf{U}^{\mathsf{T}}\mathbf{U} = \mathbf{1}$), $\mathbf{S}$ is a square $m \times m$ diagonal matrix with non-negative real numbers on the diagonal (called singular values of matrix $\mathbf{A}$), and $\mathbf{V}$ is a square $m \times m$ orthoginal matrix ($\mathbf{V}^{\mathsf{T}}\mathbf{V} = \mathbf{1}$).

Singular value decomposition can be found by diagonalising the $m \times m$ symmetric positive semi-definite matrix $\mathbf{A}^{\mathsf{T}}\mathbf{A}$ (although this method is not the best for practical calculations, it would do as an educational tool),

$$\mathbf{A}^{\mathsf{T}}\mathbf{A} = \mathbf{V}\mathbf{D}\mathbf{V}^{\mathsf{T}} , \tag{17}$$

where $\mathbf{D}$ is a diagonal matrix with eigenvalues of the matrix $\mathbf{A}^{\mathsf{T}}\mathbf{A}$ on the diagonal and $\mathbf{V}$ is the matrix of the corresponding eigenvectors. Indeed it is easy to check that the sought decomposition can the be constructed as $\mathbf{A} = \mathbf{U}\mathbf{S}\mathbf{V}^{\mathsf{T}}$ where $\mathbf{S} = \mathbf{D}^{1/2}$, $\mathbf{U} = \mathbf{A}\mathbf{V}\mathbf{D}^{-1/2}$.

Singular value decomposition can be used to solve our linear least squares problem $\mathbf{A}\mathbf{c} = \mathbf{b}$. Indeed inserting the decomposition into the equation gives

$$\mathbf{U}\mathbf{S}\mathbf{V}^{\mathsf{T}}\mathbf{c} = \mathbf{b} . \tag{18}$$

Multiplying from the left with $\mathbf{U}^{\mathsf{T}}$ and using the orthogonality of $\mathbf{U}$ one gets the projected equation

$$\mathbf{S}\mathbf{V}^{\mathsf{T}}\mathbf{c} = \mathbf{U}^{\mathsf{T}}\mathbf{b} . \tag{19}$$

This is a square system which can be easily solved first by solving the diagonal system

$$\mathbf{S}\mathbf{y} = \mathbf{U}^{\mathsf{T}}\mathbf{b} \tag{20}$$

for $\mathbf{y}$ and then obtaining $\mathbf{c}$ as

$$\mathbf{c} = \mathbf{V}\mathbf{y} . \tag{21}$$

The covariance matrix (14) can be calculated as

$$\mathbf{\Sigma} = (\mathbf{A}^{\mathsf{T}}\mathbf{A})^{-1} = (\mathbf{V}\mathbf{D}\mathbf{V}^{\mathsf{T}})^{-1} = \mathbf{V}\mathbf{D}^{-1}\mathbf{V}^{T} . \tag{22}$$