

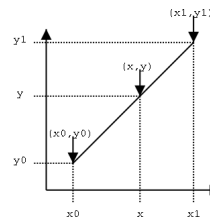
## Interpolation and data fitting

Commonly, in typical experiments, we know  $f(x_i)$  at various  $x_i$ , not necessarily equally spaced. Additionally, we may not quite know the analytical expression of  $f(x)$  that describes the data and allow to calculate its value at arbitrary  $x \neq x_i$ .

If the desired  $x$  is/are between largest and smallest  $x_i$ 's, the problem is of *interpolation*. If outside, then it is *extrapolation*.

*Extrapolation* is a terribly risky endeavor unless backed up by solid theoretical idea(s). Here we study only *interpolation*.

*Interpolating*  $(x, y)$  between  $(x_0, y_0)$  and  $(x_1, y_1)$  with a straight line,



$$\frac{y - y_0}{x - x_0} = \frac{y_1 - y_0}{x_1 - x_0} \Rightarrow y = y_0 + \frac{x - x_0}{x_1 - x_0} (y_1 - y_0)$$

Generalize this idea by considering a polynomial of degree  $N$  to approximate a function from a set of  $N + 1$  points

$$P_N(x_i) \equiv f(x_i) = y_i \quad \text{where } i = 0, 1, \dots, N$$

The general form of  $P_N(x)$  is

$$\begin{aligned} P_N(x) &= a_0 + a_1(x - x_0) + a_2(x - x_0)(x - x_1) + \dots + \\ &\quad a_N(x - x_0)(x - x_1)(x - x_2) \dots (x - x_{N-1}) \\ P_0(x_0) &= a_0 = y_0 = f(x_0) \\ P_1(x_1) &= a_0 + a_1(x_1 - x_0) = y_1 = f(x_1) \\ P_2(x_2) &= a_0 + a_1(x_2 - x_0) + a_2(x_2 - x_0)(x_2 - x_1) = y_2 = f(x_2) \quad \text{etc.} \end{aligned}$$

For linear interpolation  $N = 1$ ,

$$a_0 = y_0, \quad a_1 = \frac{y_1 - y_0}{x_1 - x_0} \Rightarrow P_1(x) = y(x) = y_0 + \frac{x - x_0}{x_1 - x_0} (y_1 - y_0)$$

A particularly useful form, although looks complicated, is

$$P_1(x) = y_0 - \frac{x - x_0}{x_1 - x_0} y_0 + \frac{x - x_0}{x_1 - x_0} y_1 = \frac{x - x_1}{x_0 - x_1} y_0 + \frac{x - x_0}{x_1 - x_0} y_1$$

$P_1(x)$  is the polynomial of degree 1 for 1 + 1 data points.

Generalized interpolation formula by Lagrange

$$P_N(x) = \sum_{i=0}^N \prod_{k \neq i} \frac{x - x_k}{x_i - x_k} y_i$$

As an example, 2nd order polynomial for 3 data points  $x_0, x_1, x_2$

$$P_2(x) = \frac{(x - x_1)(x - x_2)}{(x_0 - x_1)(x_0 - x_2)} y_0 + \frac{(x - x_0)(x - x_2)}{(x_1 - x_0)(x_1 - x_2)} y_1 + \frac{(x - x_0)(x - x_1)}{(x_2 - x_0)(x_2 - x_1)} y_2$$

**Ex 1.** Consider the following data table and show the  $f(x = 4) = 20$

x	2	3	5	8	12
f(x)	10	15	25	40	60

**Ex 2.** To understand what is going on, take a smaller data set

x	0	10	20	30
f(x)	-250	0	50	-100

Each term in Lagrange formula i.e. coefficient of  $y_i$

$$\begin{aligned}
i = 0 & \quad \frac{(x-10)(x-20)(x-30)}{(0-10)(0-20)(0-30)} = -\frac{x^3}{6000} + \frac{x^2}{100} - \frac{11x}{60} + 1 \\
i = 1 & \quad \frac{(x-0)(x-20)(x-30)}{(10-0)(10-20)(10-30)} = \frac{x^3}{2000} - \frac{x^2}{40} + \frac{3x}{10} \\
i = 2 & \quad \frac{(x-0)(x-10)(x-30)}{(20-0)(20-10)(20-30)} = -\frac{x^3}{2000} + \frac{x^2}{50} - \frac{3x}{20} \\
i = 3 & \quad \frac{(x-0)(x-10)(x-20)}{(30-0)(30-10)(30-20)} = \frac{x^3}{6000} - \frac{x^2}{200} + \frac{x}{30}
\end{aligned}$$

Multiply each line with the corresponding  $f(x_i)$  and add together the terms of like power to obtain

$$y(x) \equiv P_3(x) = -x^2 + 35x - 250$$

Lagrange's formula gives a simple **quadratic** description of the data.

If required, we can calculate, say,  $f(x = 15) = 50$  either using the quadratic formula or directly from Lagrange's formula.

**DIY** : Find both way  $f(x = 1969)$  from the data

x	1951	1961	1971
f(x)	2.8	3.2	4.5

Navigation icons: back, forward, search, etc.

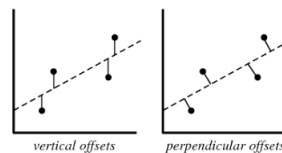
## Least square fitting

Set of data points generated  $(x_i, y_i)$  are expected to be described by a **known** function  $f(x)$  but with undetermined coefficients.

**Examples** – stress-strain data points within elastic limit, voltage-current data points. Task is to determine modulus of elasticity and Resistance of the material under consideration.

$$V = R i \quad \text{and} \quad \text{stress} = k \times \text{strain}$$

Least square fitting is a way to do this and for that we need *sum of squares of the offset (residual)* of the data points from the curve  $f(x)$ . Offsets can be either *vertical* or *perpendicular*



Vertical offsets allow uncertainties of data points along  $x$ ,  $y$ -axes to be independent of each other.

Why squares and not absolute values?

Squares permit offsets to be treated as continuous differentiable quantities.

Absolute values result in discontinuous derivatives.

Fit  $N$  data points  $(x_i, y_i, \sigma_i)$  to a model  $f(x_i; a_1, a_2, \dots, a_M)$  with  $M$  parameters ( $M < N$ ). Least square suggests to minimize squares of weighted offsets with respect to the parameters  $a_k$ 's

$$\chi^2 = \sum_{i=1}^N \left( \frac{y_i - f(x_i; a_1, a_2, \dots, a_M)}{\sigma_i} \right)^2 \rightarrow \frac{\partial \chi^2}{\partial a_j} = 0$$

Linear regression : model the data points with a straight line

$$f(x) = a_1 + a_2 x \Rightarrow \chi^2 = \sum_{i=1}^N \left( \frac{y_i - a_1 - a_2 x_i}{\sigma_i} \right)^2$$

Minimizing  $\chi^2$  w.r.t.  $a_1, a_2$  yields

$$\frac{\partial \chi^2}{\partial a_1} = -2 \sum_{i=1}^N \frac{y_i - a_1 - a_2 x_i}{\sigma_i^2} = 0$$

$$\frac{\partial \chi^2}{\partial a_2} = -2 \sum_{i=1}^N \frac{x_i (y_i - a_1 - a_2 x_i)}{\sigma_i^2} = 0$$

Introducing a shorthand symbol  $\sum_{i=1}^N \equiv \sum_i$ , we ended up with

$$\begin{aligned}\sum_i \frac{y_i}{\sigma_i^2} &= a_1 \sum_i \frac{1}{\sigma_i^2} + a_2 \sum_i \frac{x_i}{\sigma_i^2} & \mathcal{S}_y &= a_1 \mathcal{S} + a_2 \mathcal{S}_x \\ &\equiv \\ \sum_i \frac{x_i y_i}{\sigma_i^2} &= a_1 \sum_i \frac{x_i}{\sigma_i^2} + a_2 \sum_i \frac{x_i^2}{\sigma_i^2} & \mathcal{S}_{xy} &= a_1 \mathcal{S}_x + a_2 \mathcal{S}_{xx}\end{aligned}$$

If the **data errors**  $\sigma_i$  are not given, take  $\sigma_i = 1$ . However, your code must include  $\sigma_i$  in case they are provided.

The solution of these equations are absolutely straight forward,

$$a_1 = \frac{\mathcal{S}_{xx}\mathcal{S}_y - \mathcal{S}_x\mathcal{S}_{xy}}{\Delta}, \quad a_2 = \frac{\mathcal{S}_{xy}\mathcal{S} - \mathcal{S}_x\mathcal{S}_y}{\Delta} \quad \text{where } \Delta = \mathcal{S}\mathcal{S}_{xx} - \mathcal{S}_x^2$$

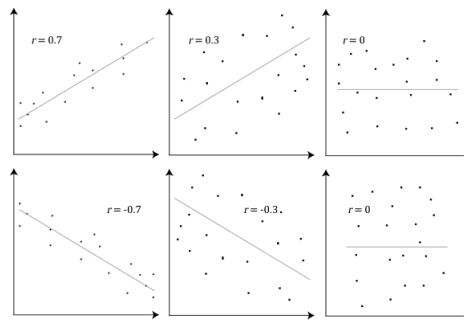
Estimating the errors  $\sigma_{a_i}$  on the parameters  $a_i$  determined above

$$\begin{aligned}\sigma_{a_i}^2 &= \sum_i \sigma_i^2 \left( \frac{\partial a_i}{\partial y_i} \right)^2 \\ \Rightarrow \quad \frac{\partial a_1}{\partial y_i} &= \frac{\mathcal{S}_{xx} - \mathcal{S}_x x_i}{\Delta \sigma_i^2}, \quad \frac{\partial a_2}{\partial y_i} = \frac{\mathcal{S} x_i - \mathcal{S}_x}{\Delta \sigma_i^2} \\ \Rightarrow \quad \sigma_{a_1}^2 &= \frac{\mathcal{S}_{xx}}{\Delta} \quad \text{and} \quad \sigma_{a_2}^2 = \frac{\mathcal{S}}{\Delta}\end{aligned}$$

To this end, in order to get some idea about how *good* is the **linear** fit we define an estimate called *Pearson's correlation coefficient*  $r$

$$r^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}} \quad \text{where } 0 \leq r^2 \leq 1$$

As  $r^2 \rightarrow 1$  fit gets better.



**NB :** But is the straight line model itself good to fit the data? To address this requires ideas of *goodness of fit*, *confidence level*, testing some *null hypothesis* against  $\chi^2$  probability distribution and so on.



The straight line model is generic enough for use in a few other models which can be reduced to straight line form usually by taking logarithms,

$$\text{exponential : } f(x) = a e^{bx} \rightarrow \log f(x) = \log a + bx$$

$$\text{logarithm : } f(x) = a + b \log x$$

$$\text{power law : } f(x) = a x^b \rightarrow \log f(x) = \log a + b \log x$$

### Least square polynomial fitting

Polynomial model  $f(x) = \sum_{k=0}^n a_k x^k$  can also be subjected to linear fitting. For simplified expressions, we put all the errors  $\sigma_i^2 = 1$  without any loss of generality. In such case,  $\chi^2 \rightarrow R^2$

$$R^2 = \sum_{i=1}^n \left[ y_i - (a_0 + a_1 x_i + \dots + a_k x_i^k) \right]^2$$

$$\frac{\partial R^2}{\partial a_0} = -2 \sum \left[ y_i - (a_0 + a_1 x_i + \dots + a_k x_i^k) \right] = 0$$

$$\frac{\partial R^2}{\partial a_1} = -2 \sum \left[ y_i - (a_0 + a_1 x_i + \dots + a_k x_i^k) \right] x_i = 0$$

...

$$\frac{\partial R^2}{\partial a_k} = -2 \sum \left[ y_i - (a_0 + a_1 x_i + \dots + a_k x_i^k) \right] x_i^k = 0$$

Set of equations for  $a_i$ 's are,

$$\begin{aligned} a_0 n + a_1 \sum x_i + \dots + a_k \sum x_i^k &= \sum y_i \\ a_0 \sum x_i + a_1 \sum x_i^2 + \dots + a_k \sum x_i^{k+1} &= \sum x_i y_i \\ &\dots \\ a_0 \sum x_i^k + a_1 \sum x_i^{k+1} + \dots + a_k \sum x_i^{2k} &= \sum x_i^k y_i \end{aligned}$$

which when written in matrix form becomes a problem of matrix inversion, and you are free to use your favorite inverter.

$$\begin{pmatrix} n & \sum x_i & \dots & \sum x_i^k \\ \sum x_i & \sum x_i^2 & \dots & \sum x_i^{k+1} \\ \vdots & \vdots & \ddots & \vdots \\ \sum x_i^k & \sum x_i^{k+1} & \dots & \sum x_i^{2k} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ \vdots \\ a_k \end{pmatrix} = \begin{pmatrix} \sum y_i \\ \sum x_i y_i \\ \vdots \\ \sum x_i^k y_i \end{pmatrix}$$

$$\Rightarrow X \cdot a = Y \rightarrow a = X^{-1}Y$$

## DIY fitting

1. A time versus angular velocity data set on deceleration of a rotating disc is in the file `fit1.dat`. Fit it with the following functions (i)  $\omega(t) = \omega_0 + \omega_c t$  and (ii)  $\omega(t) = \omega_0 e^{-\omega_c t}$ . Determine  $\omega_0$ ,  $\omega_c$  and the quality of fit for both the functions by *Pearson's  $r$* .
2. Distance ( $r$ ) versus height ( $h$ ) of the trajectory of a test missile is given in the datafile `fit2.dat`. Try quadratic fit  $h = a_0 + a_1 r + a_2 r^2$  and determine the highest point reached by the missile.