Regression Analysis

ECE 341: Random Processes

Lecture #19

note: All lecture notes, homework sets, and solutions are posted on www.BisonAcademy.com

Linear Estimation of Y given X:

Problem: Given measurement Y, estimate X.

- You want to know something that is difficult to measure. You estimate this based upon something that is easier to measure.
  - Fan speed ≈ thrust for a jet engine (GE)
  - Pressure drop ≈ thrust (Pratt & Whitney)

Since the estimate is different from the 'true' value, denote

$\hat{x}$ The estimate of x

x The 'true' value of x

$\bar{x}$ The mean of x

B Basis matrix: functions of x

Form an estimate based upon Y using a linear curve fit:

$$\hat{y} = ax + b$$

Least Squares

Procedure to find the parameters 'a' and 'b' given n data points:

Step 1) Write this in matrix form:

$$\begin{bmatrix} y_1 \\ y_2 \\ y_3 \\ \vdots \end{bmatrix} = \begin{bmatrix} x_1 & 1 \\ x_2 & 1 \\ x_3 & 1 \\ \vdots & \vdots \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix}$$

or

$$Y = BA$$

You can't invert matrix B since it's not square. To make it square, multiply by B transpose:

$$B^T Y = B^T B \cdot A$$

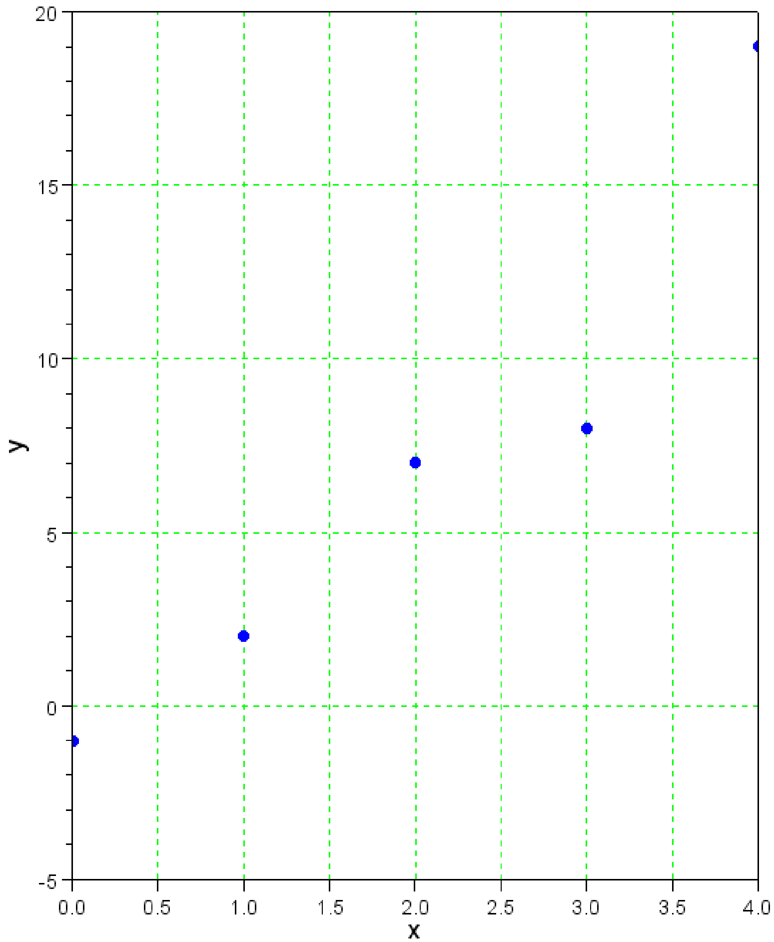
$B^T B$ is square and is usually invertable. Solve for A:

$$A = \left(B^T B\right)^{-1} B^T Y$$

This is the least squares solution for a and b.

Example: Find the least squares curve fit for the following data points (x,y)

x	y
0.	-1.
1.	2.
2.	7.
3.	8.
4.	19.



Solution: Create matrix B that defines your basis functions:

```
B = [x, x.^0]
     0.    1.
     1.    1.
     2.    1.
     3.    1.
     4.    1.
```

Determine 'a' and 'b'

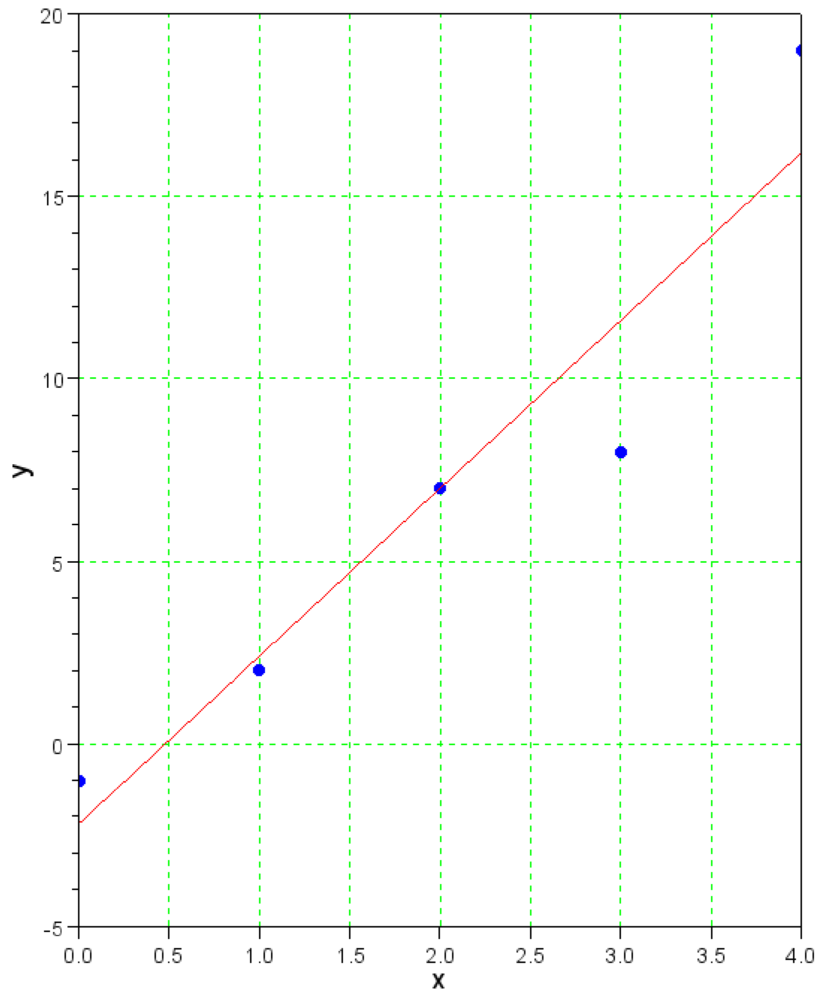
```
A = inv(B'*B)*B'*y
     4.6      times x
   - 2.2      times 1

plot(x, y, 'b.', x, y, 'r-');
```

So, the least squares estimate for y(x) is:

$$\hat{y} \approx 4.6x - 2.2$$

This minimizes the sum-squared error

$$J = \sum (y_i - \hat{y}_i)^2$$



Weighted Least squares:

If you 'trust' some data points more than others, you can weight the data. For example, suppose you weight (trust) the 4th data point 10.6 times more than the rest.

```
x   y    q (weight)
0.  - 1.   1
1.    2.   1
2.    7.   1
3.    8.   10.6
4.    19.  1
```

Create a diagonal matrix, Q, which has the weight for each element:

```
Q = diag([1,1,1,10.6,1])

    1.    0.    0.    0.      0.
    0.    1.    0.    0.      0.
    0.    0.    1.    0.      0.
    0.    0.    0.    10.6    0.
    0.    0.    0.    0.      1.
```

Return to the equation for X and Y in matrix form:

$$Y = B\ A$$

Multiply by Q

$$QY = QB\ A$$

Multiply by X transpose

$$B^T\ QY = B^T QB\ A$$

Invert

$$(B^T QB)^{-1}\ B^T\ QY = A$$

The results is the least squares solution with weighting Q:

$$J = \sum q_i (y_i - \hat{y}_i)^2$$

Going back to our example:

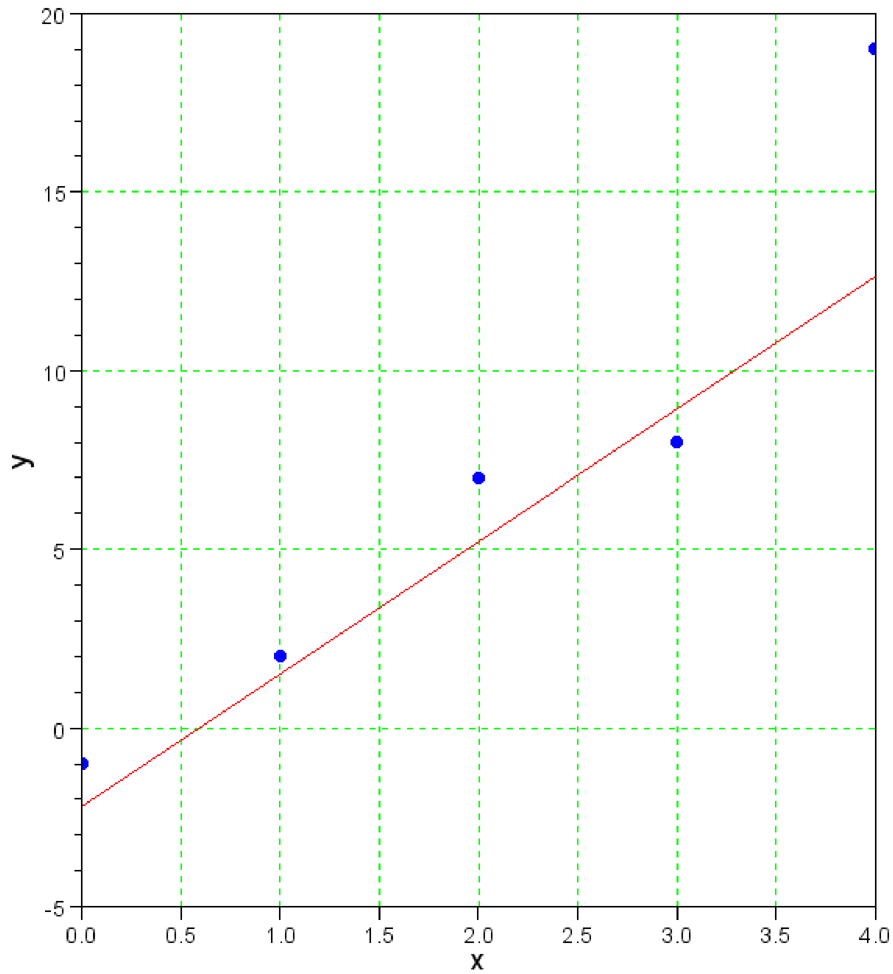
```
-->Q = diag([1,1,1,10.6,1])
-->A = inv(B'*Q*B)*B'*Q*Y

    3.7092784
  - 2.2
```

so now the estimate for y should be:

$$\hat{y} = 3.70927x - 2.2$$

Checking by plotting this vs. your data:

```
-->y1 = 3.7092784*x1 - 2.2;
-->plot(x,y,'.',x1,y1,'-r')

-->xlabel('x')
-->ylabel('y')
```



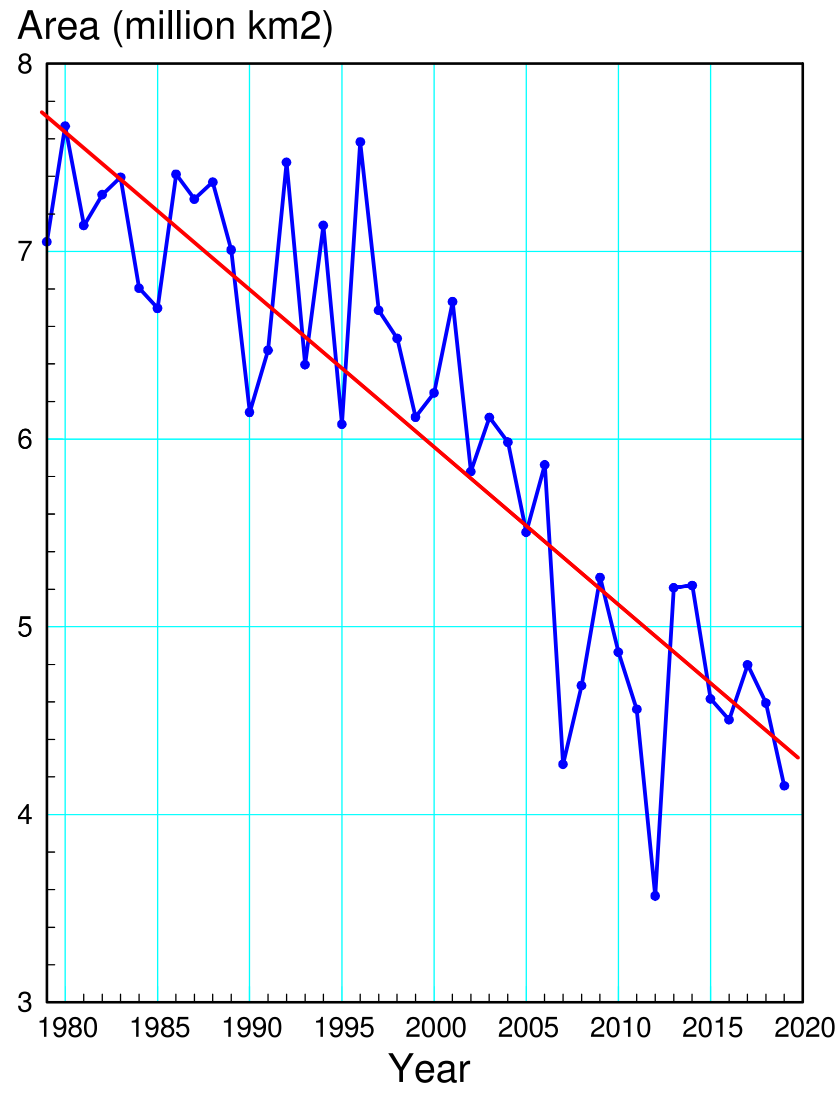
Note that the line is closer to the 4th data point (3,8) due to its weight of 10.6.

Example: Arctic Sea Ice

- Source: National Sea and Ice Data Center

```
 B = [year, year.^0];
 Y = [ice];

 A = inv(B'*B)*B'*Y

  - 0.0844726
    174.68702

plot(y,a,'b.-',y,X*A,'r')
```

$$Area \approx -0.0844 \cdot year + 174.68$$



Data Analysis

When will the Arctic be ice free?

- First time in 5 million years
- Find the zero crossing

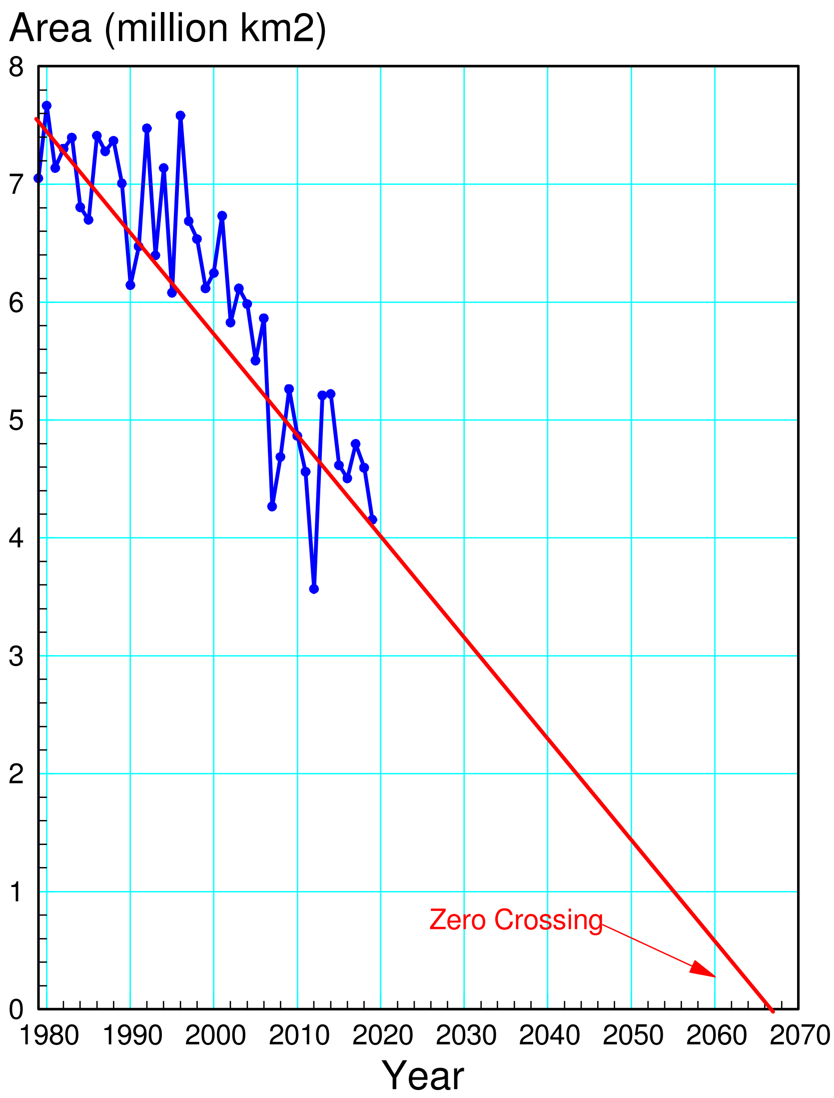
$$Area \approx 0 = -0.0844 \cdot year + 174.68$$

$$year = \left(\frac{174.68}{0.0844}\right) = 2067.97$$

roots() also works

```
roots(A)
    2067.9729
```

Using a linear curve fit, the data predicts that the Arctic will be ice free for the first time in 5 million years in the year 2067.



Example: Fargo Temperatures

Source: Hector Airport

- Mean Temperature in April
- Is there a trend?

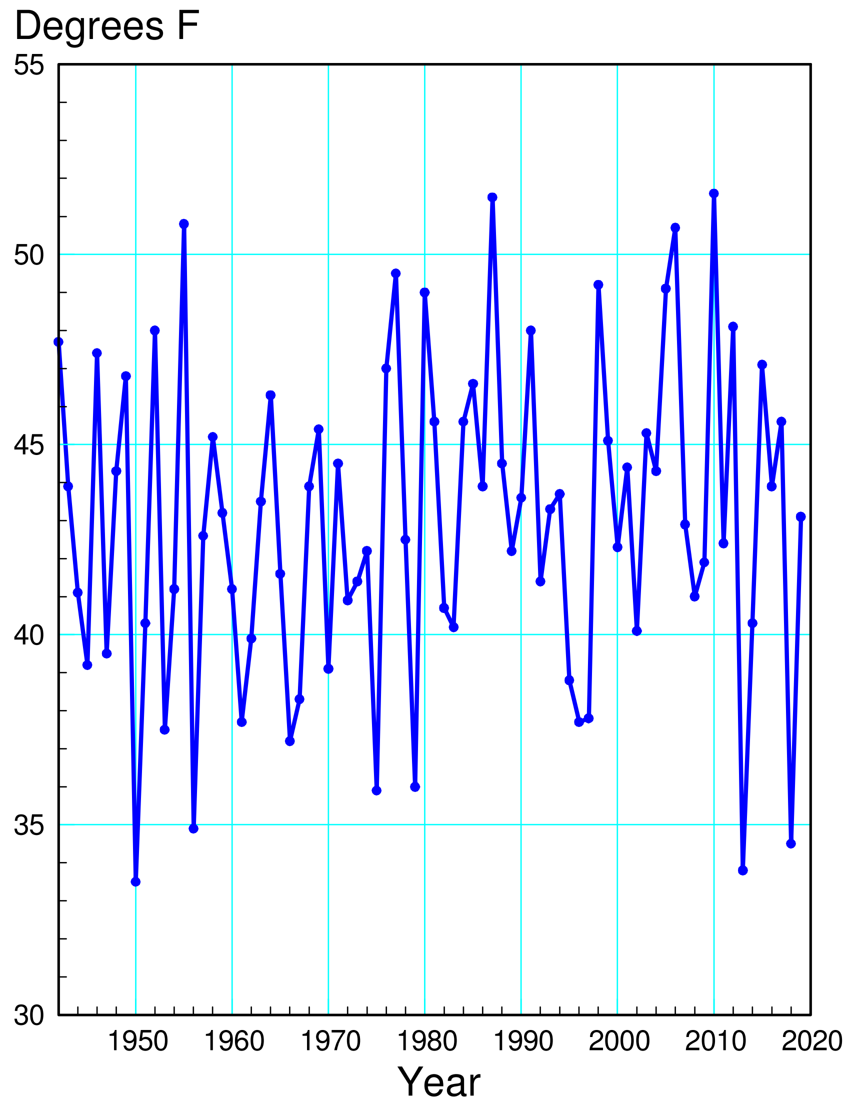
Express this in the form of

$$F = ay + b$$

where

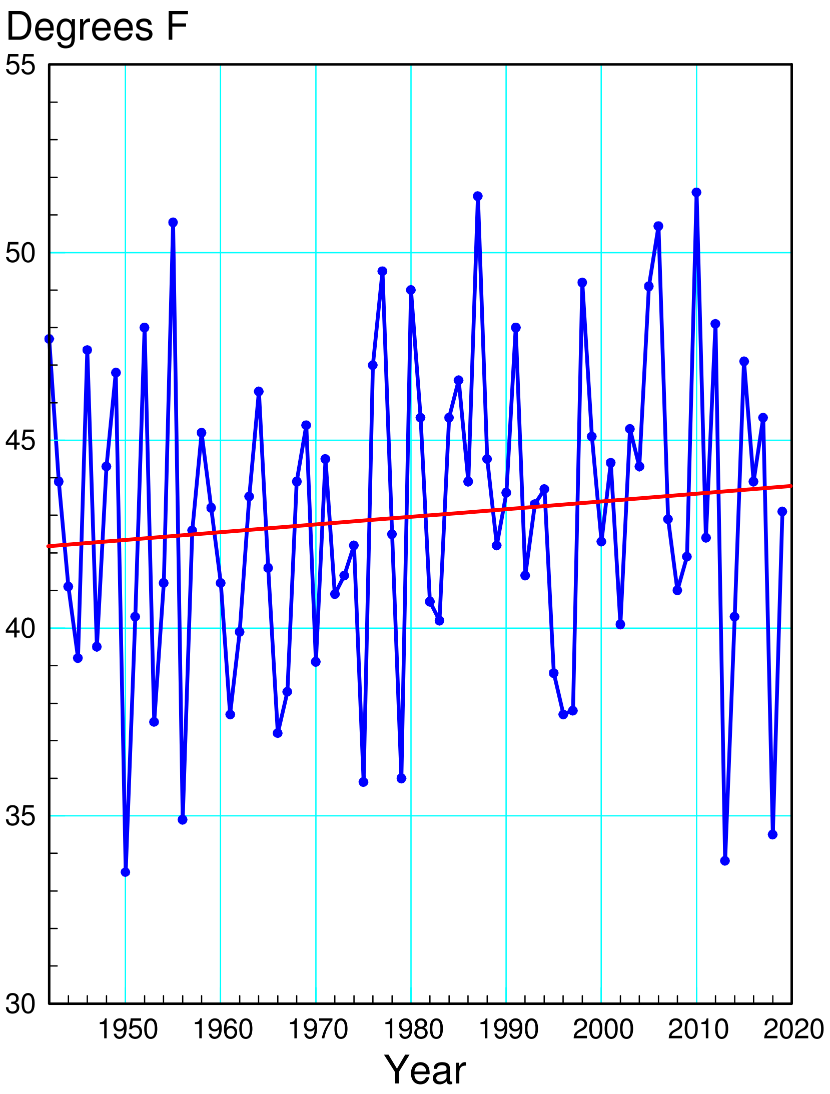
- F is the mean temperature and

y is the year.



In Matlab:

```
DATA = [
    control V (paste the data)
    ];
 y = DATA(:,1);
 F = DATA(:,8);
 plot(y,F,'.-')

 B = [y, y.^0];
 A = inv(B'*B)*B'*F

    0.0297
  -15.7381

 plot(y,F,'.-',y,B*A,'r')
```



Meaning

- Fargo is warming 0.0297F per year
- +2.37F over 80 years

Example: Atmospheric CO2 Levels

Source: NOAA Mauna Loa Observatory

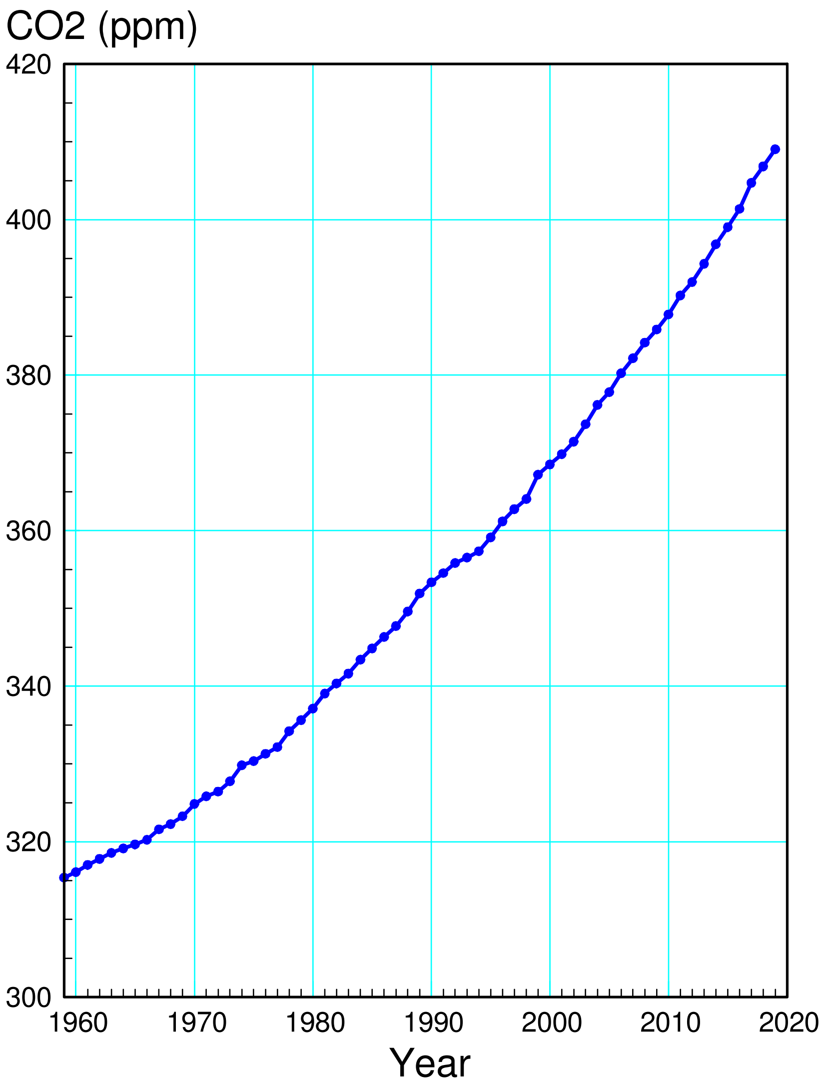
Measured since 1959

$$CO2 = ay^2 + by + c$$

Determine a parabolic curve fit

Estimate when CO2 levels will reach 2000ppm

- Same as what triggered the Permian extinction
- 251 million years ago
- Nearly wiped out all life

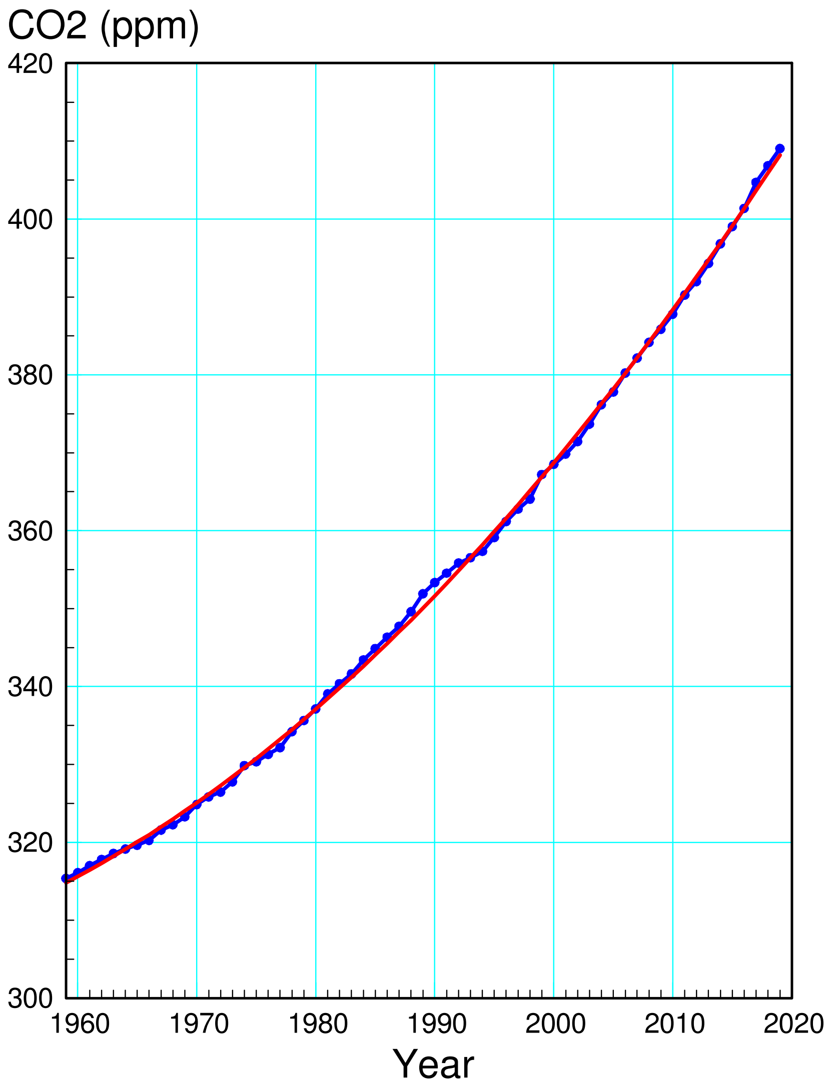


Least Squares Curve Fit

Use a parabolic curve fit:

$$CO2 = ay^2 + by + c$$

```
DATA = [
   paste in the data you just copied
   ];

y = DATA(:,1);
CO2 = DATA(:,2);
B = [y.^2, y, y.^0];
A = inv(B'*B)*B'*CO2

 1.0e+004 *

   0.0000
  -0.0047
   4.5111

plot(y,CO2,'b.-',y,B*A,'r')
xlabel('Year');
ylabel('CO2 ppm');
```



Data Analysis

When will CO2 levels reach 2000 ppm?

$$ay^2 + by + c = 2000$$

Rewrite as

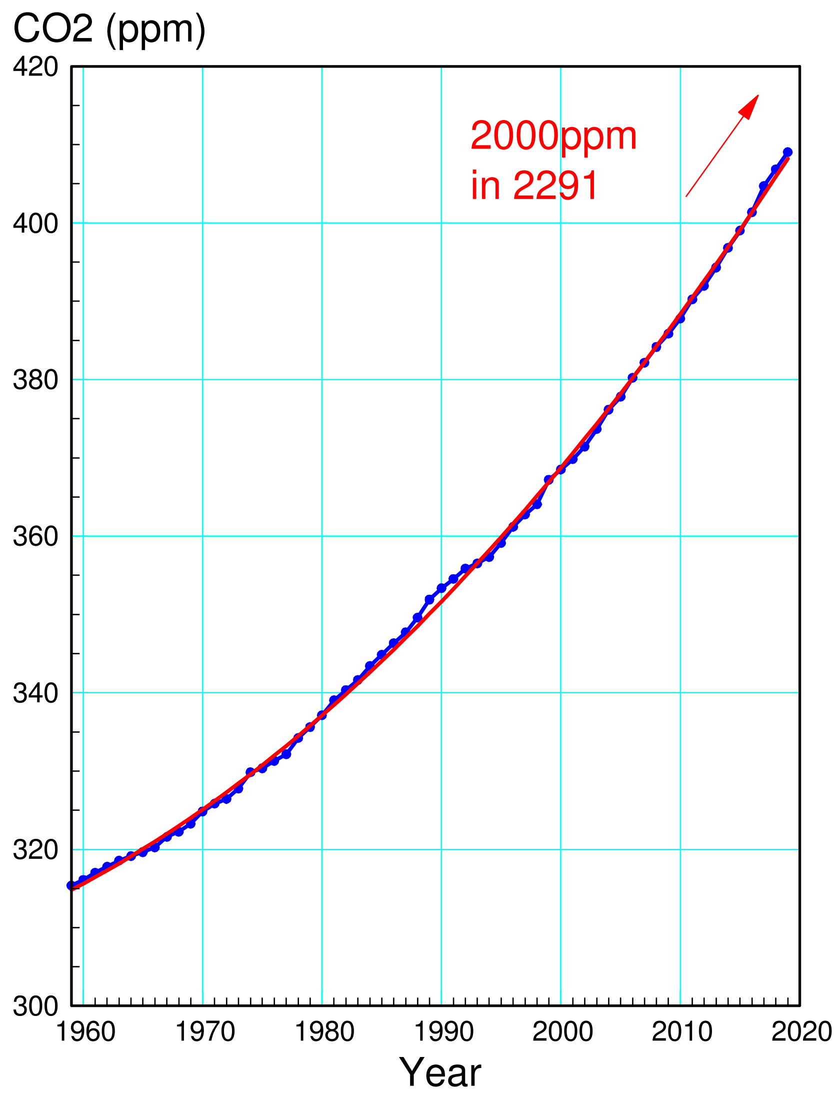
$$ay^2 + by + c - 2000 = 0$$

$$roots\left(\begin{bmatrix} a \\ b \\ c \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ 2000 \end{bmatrix}\right)$$

```
roots(A - [0;0;2000])
```

```
2291.9
1564.3
```

If nothing changes, we should hit 2000ppm of CO2 in the year 2291.



Covariance and Correlation Coefficient

The correlation between X and Y tells you how closely the two are related

- Correlation of zero means they are independent
- Correlation of +1.000 means that as X increases, Y increases.
- Correlation of -1.000 means that as X increases, Y decreases.

Correlation doesn't care about cause and affect: it just tells you whether the two behave the same way.

- Useful in jet engines: measure something highly correlated with thrust
- Useful in Wall Street: measure something that his highly correlated with stock prices 1 year in the future.

To determine the correlation coefficient, you first need to determine the covariance between X and Y.

Covariance:

The covariance between X and Y is defined as

$$Cov[X,Y] = E[(x-\bar{x})(y-\bar{y})]$$

Doing some algebra

$$Cov[X,Y] = E[(x-\bar{x})(y-\bar{y})]$$
$$= E[xy] - \bar{x}\cdot\bar{y}$$

The correlation coefficient is defined as

$$\rho_{X,Y} = \frac{Cov[X,Y]}{\sqrt{\sigma_X^2 \cdot \sigma_Y^2}}$$

- $\rho = \pm 1$ x and y are 100% correlated. If you know x you know y with no error.
- $\rho = 0$ x and y have no correlation. Knowing x tells you nothing about y.

Some other useful relationships are

1st moment (m1)

$$m_1 = mean(x)$$

2nd moment (m2)

$$m_2 = mean(x^2)$$

Variance

$$\sigma^2 = m_2 - m_1^2$$

Covariance:

$$Cov(X, Y) = mean(xy) - mean(x)\ mean(y)$$

Correlation coefficient

$$\rho_{X,Y} = \left(\frac{Cov(X,Y)}{\sqrt{\sigma_x^2 \sigma_y^2}} \right)$$

Examples: Let

- x0 be a variable in the range if (0,10)
- n be noise: random variable with a uniform distribution over (0,10)

Let x be 0% to 100% noise

$$x = \alpha x_0 + (1 - \alpha)\eta$$

Let y be related to x as

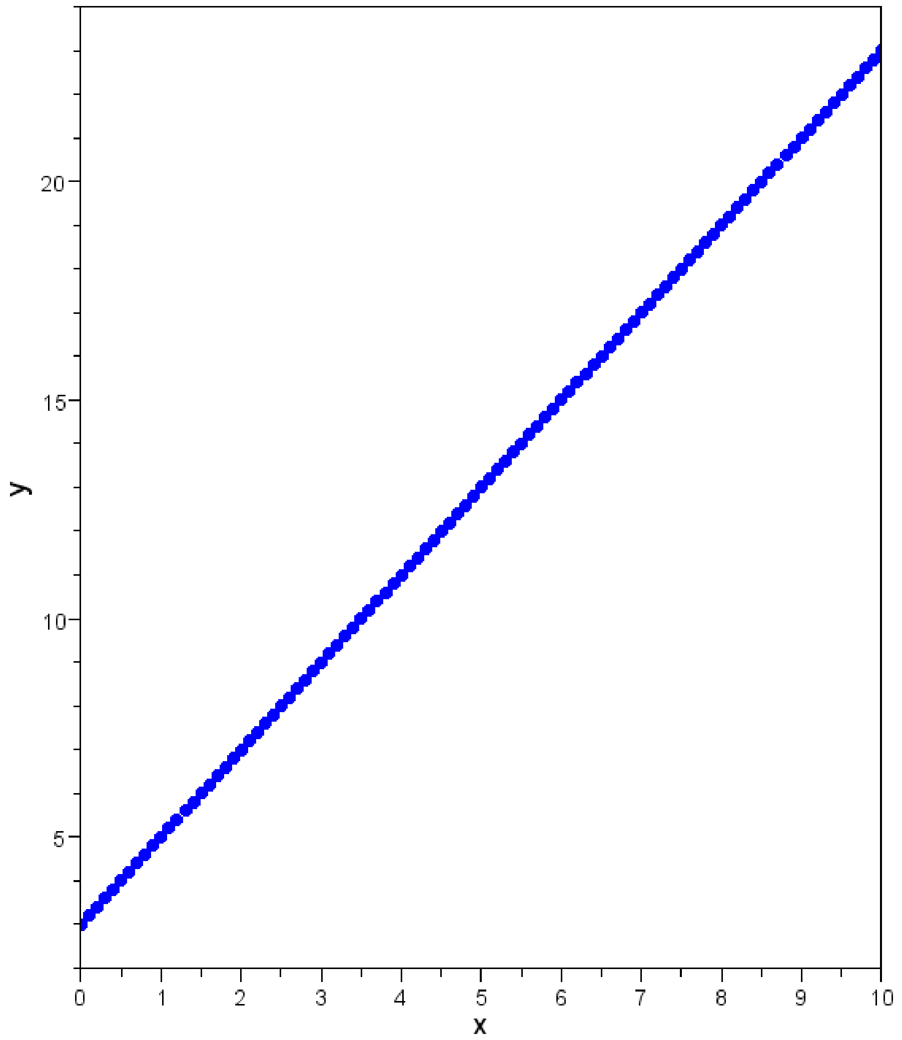
$$y = 2x + 3$$

Determine how the correlation coefficient varies with alpha.

No Noise

- $\rho^2 = 1.000$

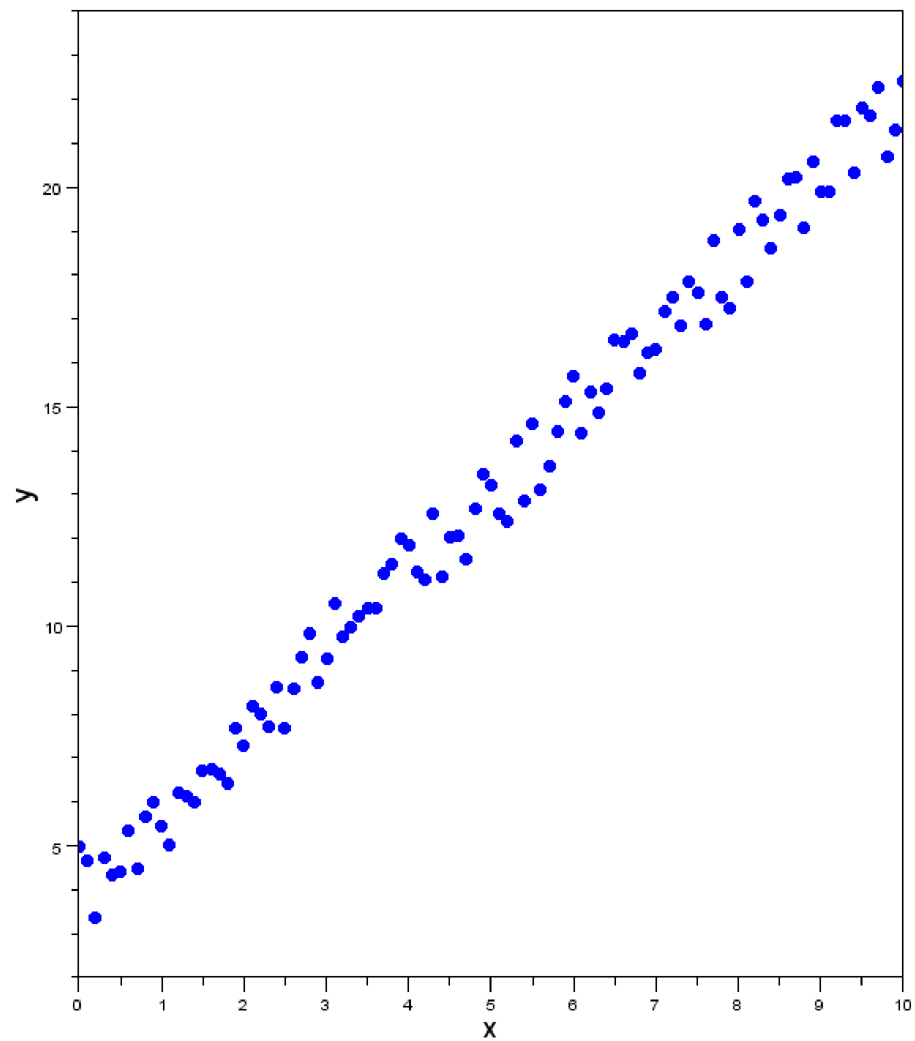
```
x = [0:0.1:10]';
n = 10*rand(length(x),1);

x0 = 1.0*x + 0.0*n;
y = 2*x0 + 3;
plot(x, y, 'b.');

s2x = mean(x.^2) - mean(x)^2;
s2y = mean(y.^2) - mean(y)^2;
Cov = mean(x.*y) - mean(x)*mean(y)
p2 = Cov / sqrt(s2x*s2y)

Cov =   17.0000

p2 =    1.0000
```



90% data, 10% noise

- $\rho^2 = 0.9943$

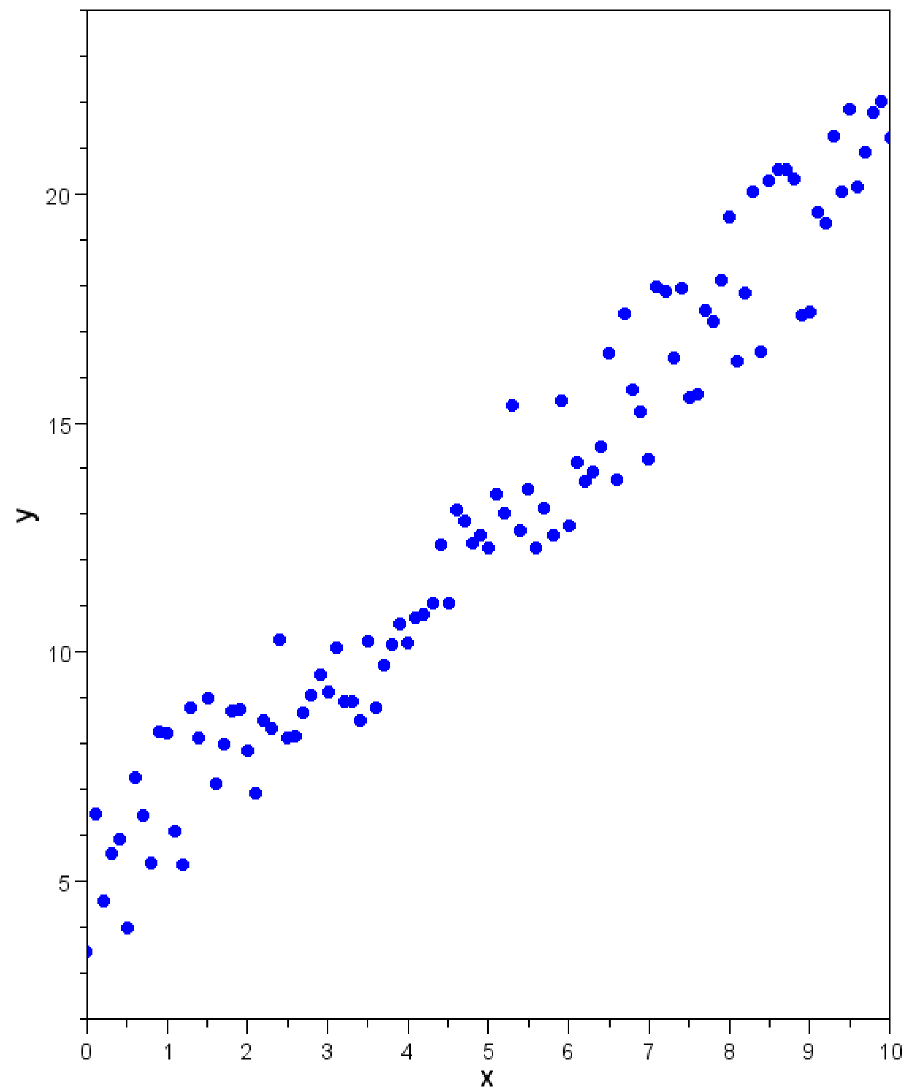
```
x = [0:0.1:10]';
n = 10*rand(size(x0));

P = zeros(100,1);

x0 = 0.9*x + 0.1*n;

y = 2*x0 + 3;
s2x = mean(x.^2) - mean(x)^2;
s2y = mean(y.^2) - mean(y)^2;
Cov = mean(x.*y) - mean(x)*mean(y)
p2 = Cov / sqrt(s2x*s2y)

Cov =    15.5010

p2 =     0.9943
```



80% data / 20% noise

- $\rho^2 = 0.9700$

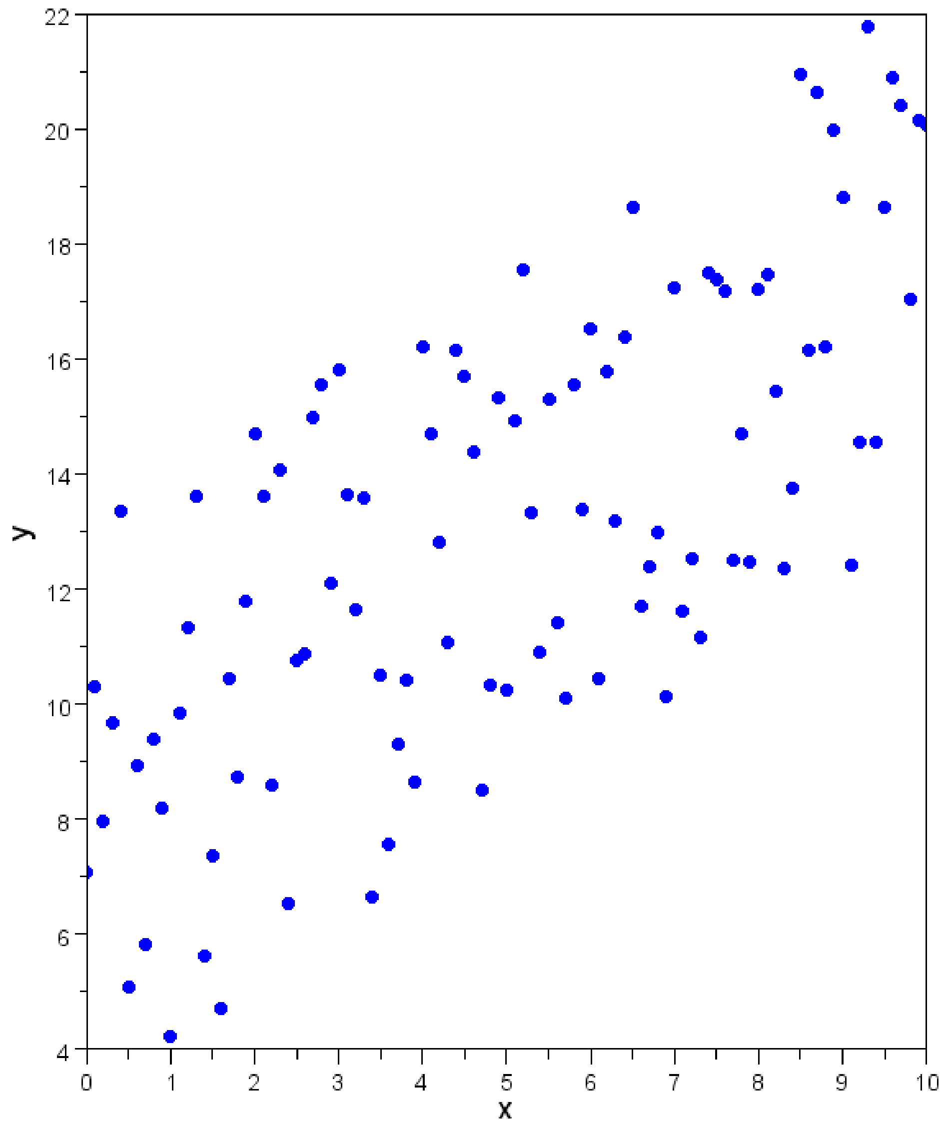
```
x = [0:0.1:10]';
n = 10*rand(size(x0));

x0 = 0.8*x + 0.2*n;

y = 2*x0 + 3;
s2x = mean(x.^2) - mean(x)^2;
s2y = mean(y.^2) - mean(y)^2;
Cov = mean(x.*y) - mean(x)*mean(y)
p2 = Cov / sqrt(s2x*s2y)

plot(x,y,'.')

Cov =   13.8326

p2 =    0.9700
```



50% data / 50% noise

- $\rho^2 = 0.7074$

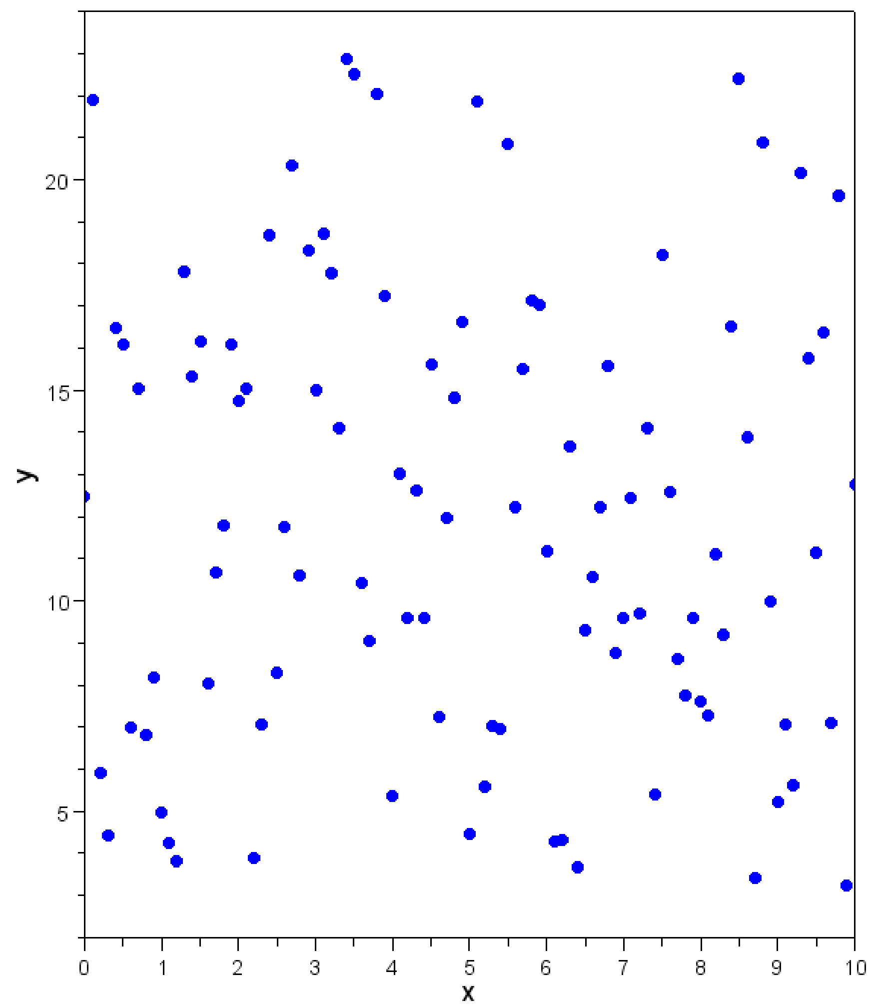
```
x = [0:0.1:10]';
n = 10*rand(size(x0));

x0 = 0.5*x + 0.5*n;

y = 2*x0 + 3;
s2x = mean(x.^2) - mean(x)^2;
s2y = mean(y.^2) - mean(y)^2;
Cov = mean(x.*y) - mean(x)*mean(y)
p2 = Cov / sqrt(s2x*s2y)

plot(x,y,'.')

Cov =     8.3611

p2 =    0.7074
```



0% Data, 100% Noise

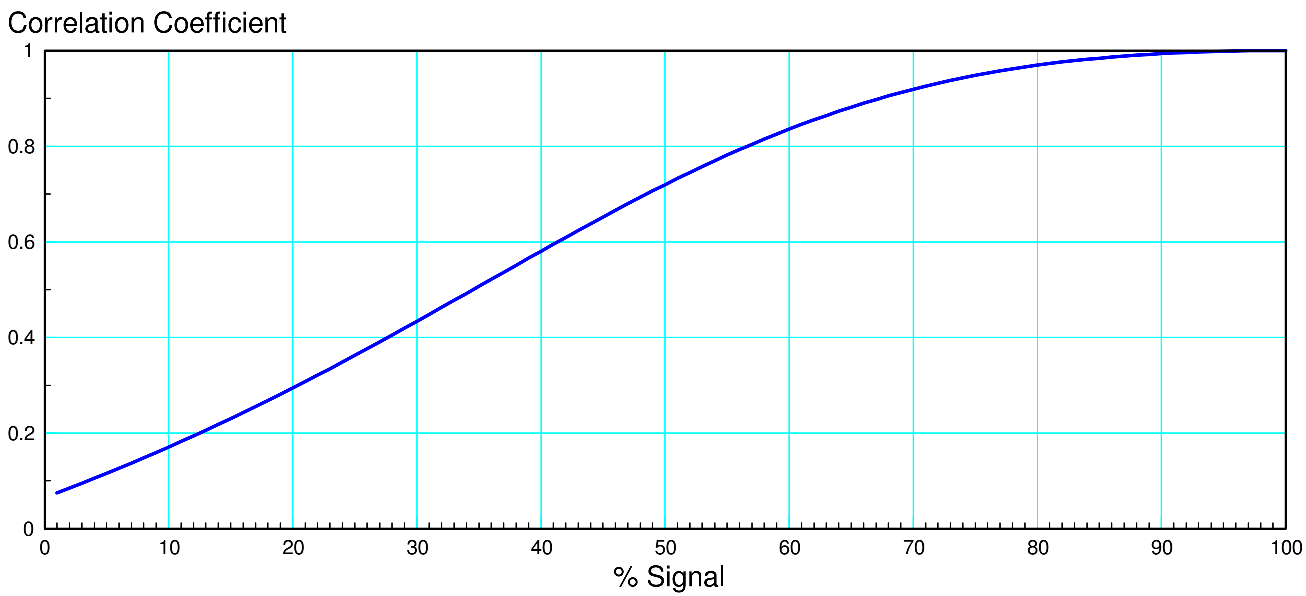
- $\rho^2 = 0.2429$

```
x = [0:0.1:10]';
n = 10*rand(size(x0));

x0 = 0.0*x + 1.0*n;

y = 2*x0 + 3;
s2x = mean(x.^2) - mean(x)^2;
s2y = mean(y.^2) - mean(y)^2;
Cov = mean(x.*y) - mean(x)*mean(y)
p2 = Cov / sqrt(s2x*s2y)

plot(x,y,'.')

Cov =     4.0005

p2 =   0.2494
```



What's the relationship between the correlation coefficient and the contribution of the signal to your measurement?

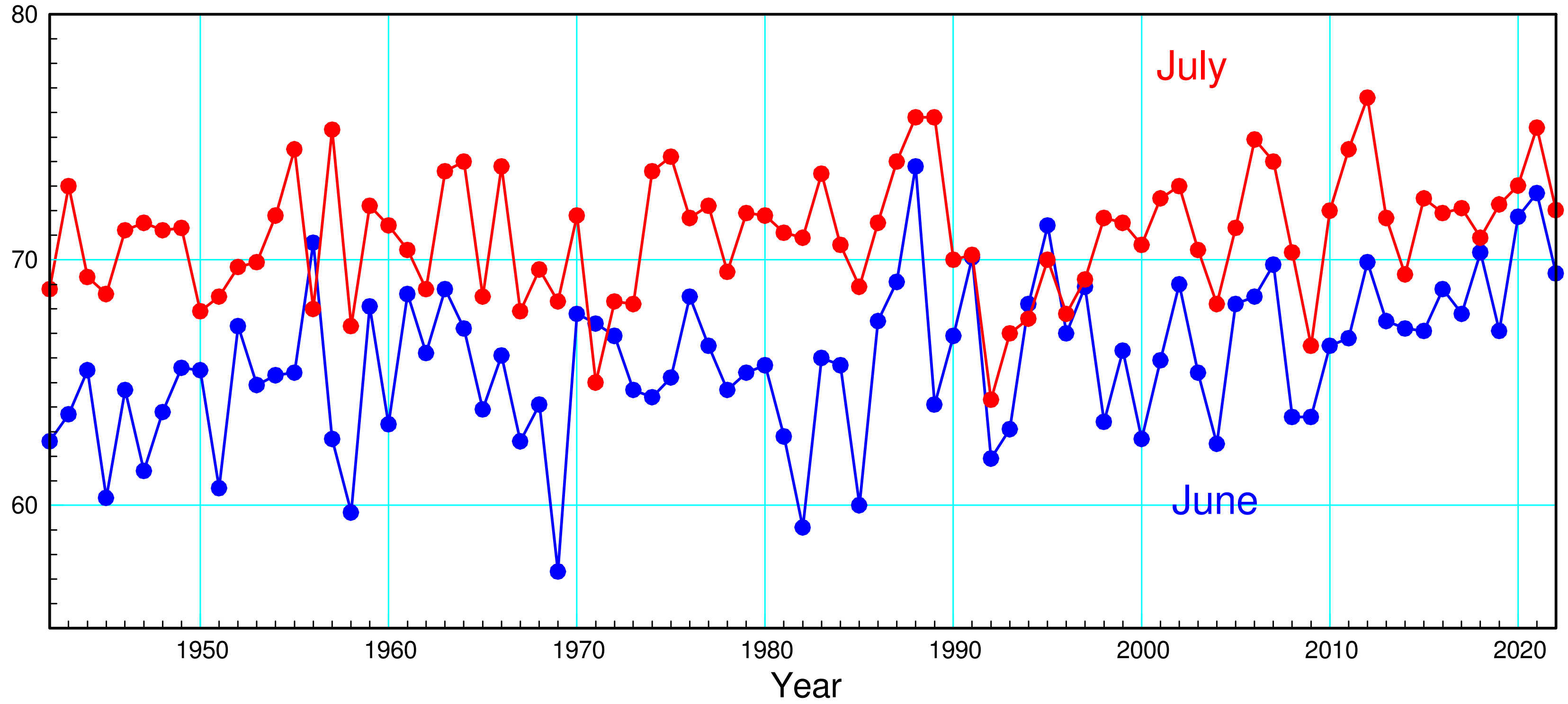
```
x = [0:0.1:10]';
n = 10*rand(size(x));
P = zeros(100,1);
for i=1:100
   a = i/100;
   x0 = a*x + (1-a)*n;
   y = 2*x0 + 3;
   s2x = mean(x.^2) - mean(x)^2;
   s2y = mean(y.^2) - mean(y)^2;
   Cov = mean(x.*y) - mean(x)*mean(y)
   p2 = Cov / sqrt(s2x*s2y)
   P(i) = p2;
   end
```



Fun with Correlation Coefficients

If June is a hot month, what's the chance that July will also be hot?

- What's the correlation between the temperature in June and July?



The average temperature in June in Fargo, ND is available at

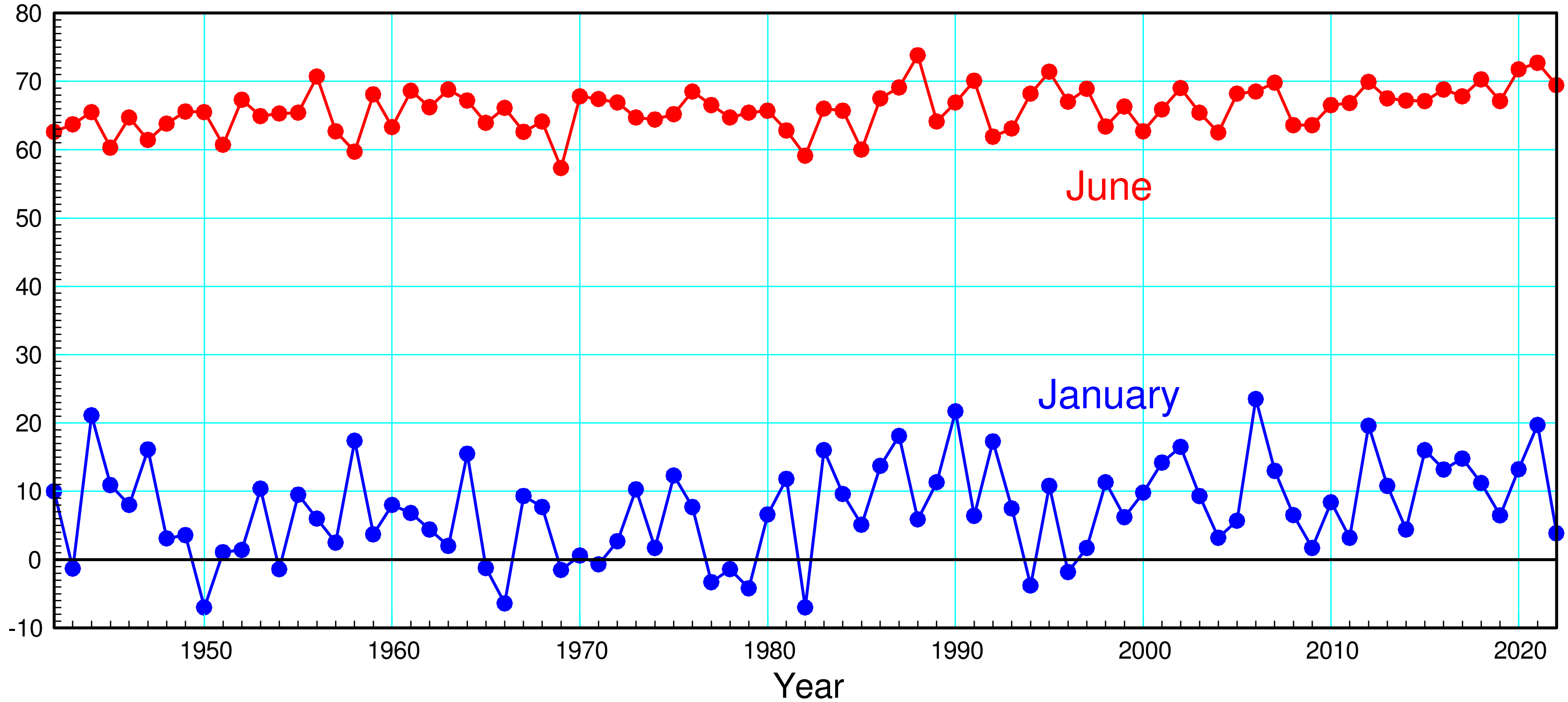
```
hector international airport
http://www.bisonacademy.com/ECE111/Code/Fargo_Weather_Monthly_Avg.txt

>> July = DATA(:,8);
>> June = DATA(:,7);

>> Cov = mean(June .* July) - mean(June) * mean(July)

Cov =    2.8057

>> correlation = Cov / ( std(June) * std(July) )

correlation =    0.3624
```

There is a 36% correlation between July and June

- If it's a hot June, there chance that July will also be hot is 36% higher than average

January vs. June

If January is warm, will June be warm?



Load data from Hector International Airport

```
http://www.bisonacademy.com/ECE111/Code/Fargo_Weather_Monthly_Avg.txt
```

Find the correlation coefficient

```
>> June = DATA(:,7);
>> January = DATA(:,2);
>> Cov = mean(June .* January) - mean(June) * mean(January)

Cov =    3.5356

>> correlation = Cov / ( std(June) * std(January) )

correlation =    0.1640
```

There is a 16.4% correlation between January and June

- If January is cold, the chance that June will also be cold is 16% higher than average

Summary

Regression analysis is basically curve fitting

Using least-squares, you can approximate data with polynomials

Correlation coefficients tell you how closely two variables change with each other

- Used in industry
- If you want to know something that is difficult to measure,
    - Find something that you can measure
    - That his highly correlated with what you want to measure