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LMD – 4<sup>e</sup> étage “dans les serres”

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## ***Program***

13/1	Elementary statistics – 1
20/1	Elementary statistics - 2
27/1	Exercises – Computer room
10/2	Fourier Analysis -1
17/2	Fourier Analysis -2, stochastic processes
24/2	Exercises – Computer room
2/3	Exercises – Computer room
9/3	Principal component analysis -1
16/3	Principal component analysis -2
23/3	Exercises – Computer room
6/4	Exercises – Computer room
13/4	Cluster analysis
27/4	Exercises – Computer room
4/5	Principal component analysis: Complements
8/6	We'll see.
??/6	Exam

## **Further reading:**

H. Von Storch and F. Zwiers. Statistical Analysis for Climate Research  
Cambridge University Press, 1999

## **Statistical software**

**R, SAS, Matlab, Python.....**

Do it yourself or use packaged routines??

**. Lesson 1.**

**Introduction to elementary statistics**

## **What exactly is statistics ?**

The purpose of statistics is to develop and apply methodology for extracting useful knowledge from both experiments and data. In addition to its fundamental role in data analysis, statistical reasoning is also extremely useful in data collection (design of experiments and surveys) and also in guiding proper scientific inference (Fisher, 1990).

Statistical data analysis can be subdivided into :

**descriptive statistics**

**inferential statistics.**

Descriptive statistics is concerned with exploring and describing a sample of data, whereas inferential statistics uses statistics from sample of data to make statements about the whole population.

We will see how we describe random variables, by their mean, variance, and p.d.f, and how we compare different random variables.

A random variable can be thought of as an unknown value that may change every time it is inspected. Thus, a random variable is a function mapping the sample space of a random process (a physical process) to the space of real numbers.

### EXAMPLES

#### **Discrete**

number of people in a car  
number of cars in a parking lot  
number of phone calls to 911

#### **Continuous**

total weight of people in a car  
distance between cars in a parking lot  
time between calls to 911.

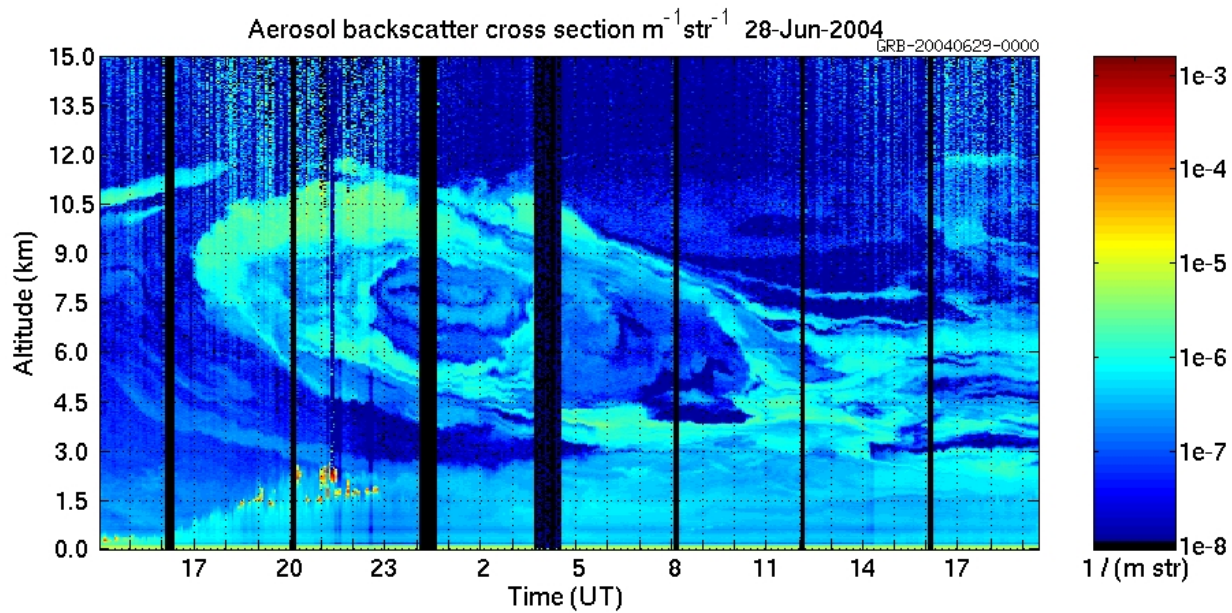
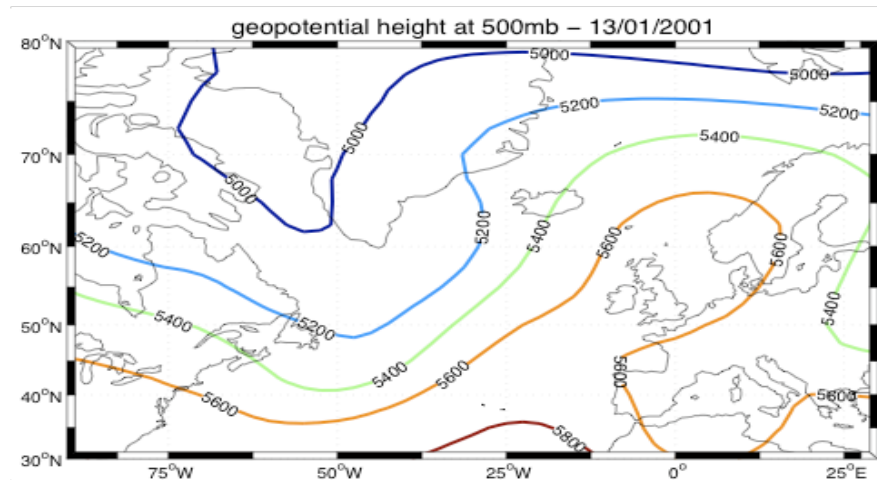
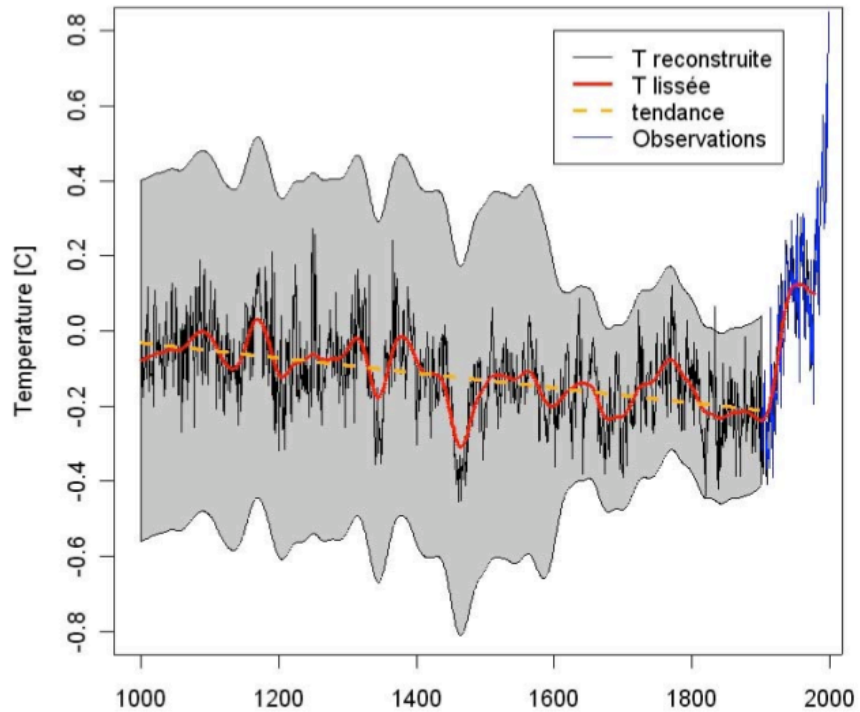
In geophysics we often have to do with data – typically with time series:

Let's call a timeseries  $x(t)$ , or, in the discrete case,  $x_i$  where  $i=1,2,\dots,N$

$x_i$  can be a scalar number, or also it can be a vector.  $\mathbf{x}_i \in \mathfrak{R}^d$

Time series analysis is a sub-field of statistics. It is declined in two main fields:

**time domain methods and frequency domain methods.**




**Scalar and vector examples**



# Descriptive vs Inference


## **Descriptive Statistics**

Gives numerical and graphic procedures to summarize a collection of data in a clear and understandable way

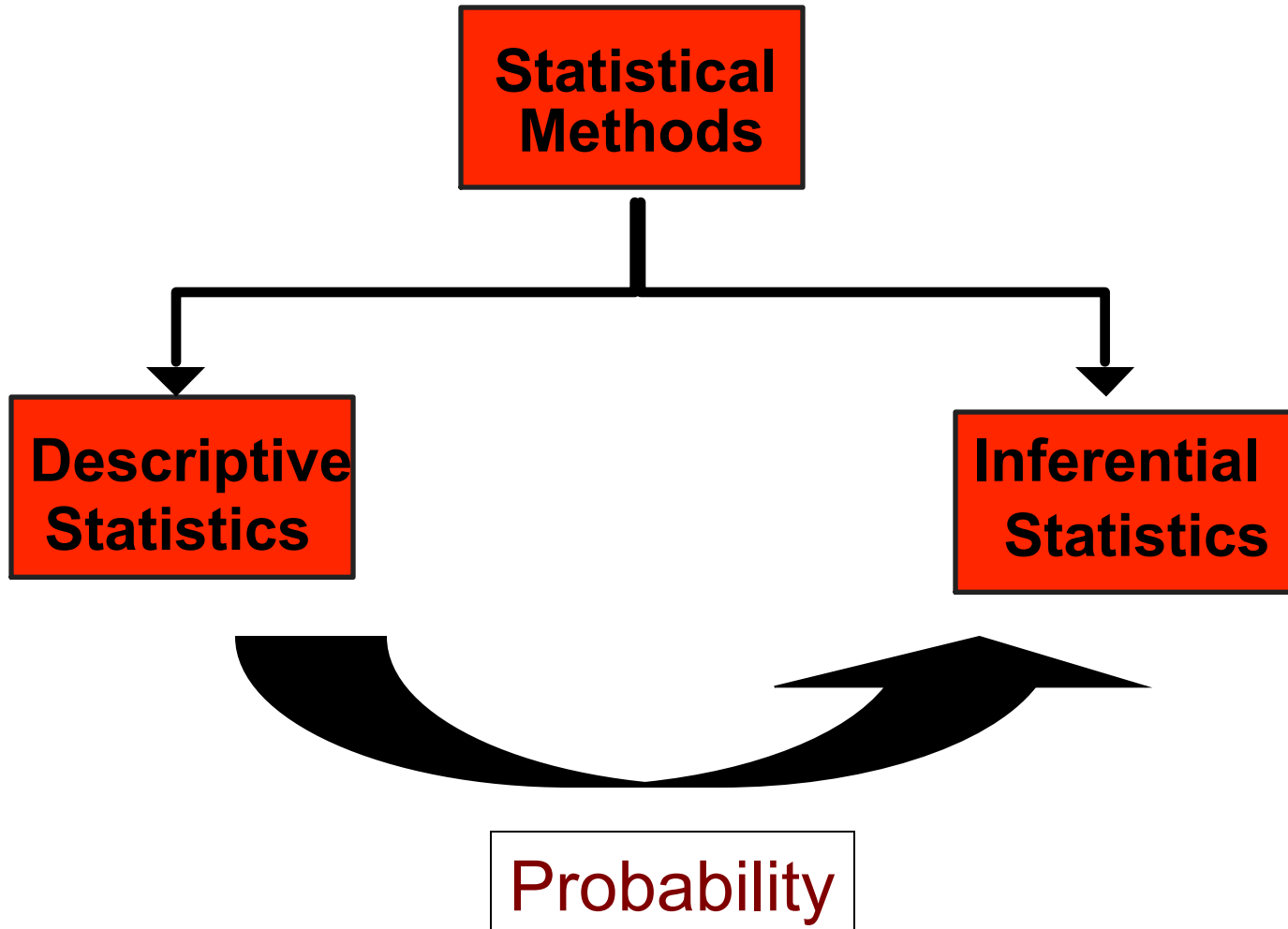
 Finding ways to summarize the important characteristics of a dataset

## **Inferential Statistics**

Provides procedures to draw inferences about a population from a sample

 How and when to generalize from a sample dataset to the larger population

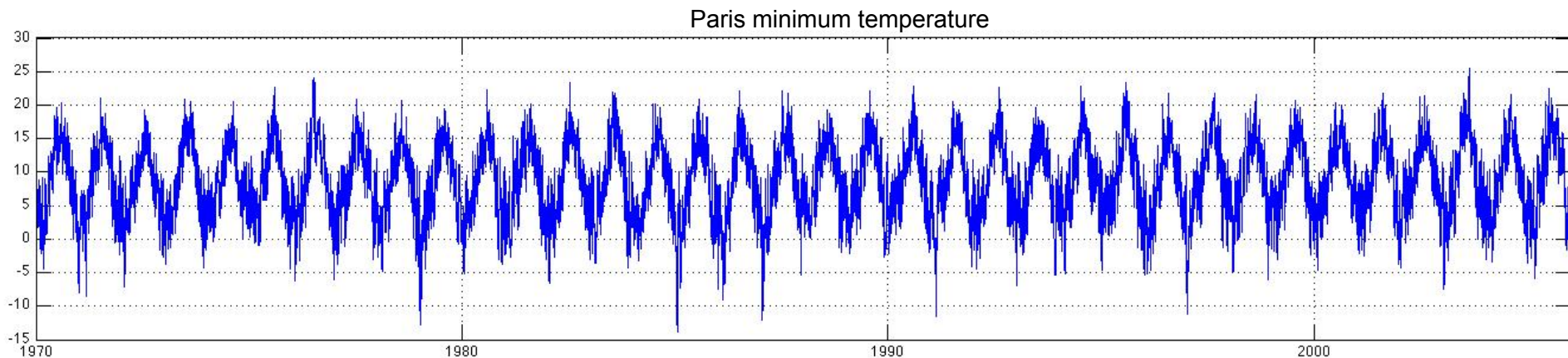
# Statistical Methods



Elementary description  
of data: the table

	Name	Height (cm)
1	Fabio	180
2	Francois	181
3	Jean-Philippe	185
4	Loic	172
5	Ara	176
6	Alvaro	172
7	Ann'Sophie	170
8	Xavier	180
9	Guillaume	183
10	Hector	171
11	Bernard	182
12	Michael	177
13	Marta	162
14	Tonia	178

The graph:



Basic attributes of data population:

$N$

**population size**

$$M(x) = \mu = \frac{1}{N} \sum_{i=1}^N x_i$$

**mean**

$$V(x) = \sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - \mu)^2$$

**variance**

$\sigma$  is the **standard deviation**

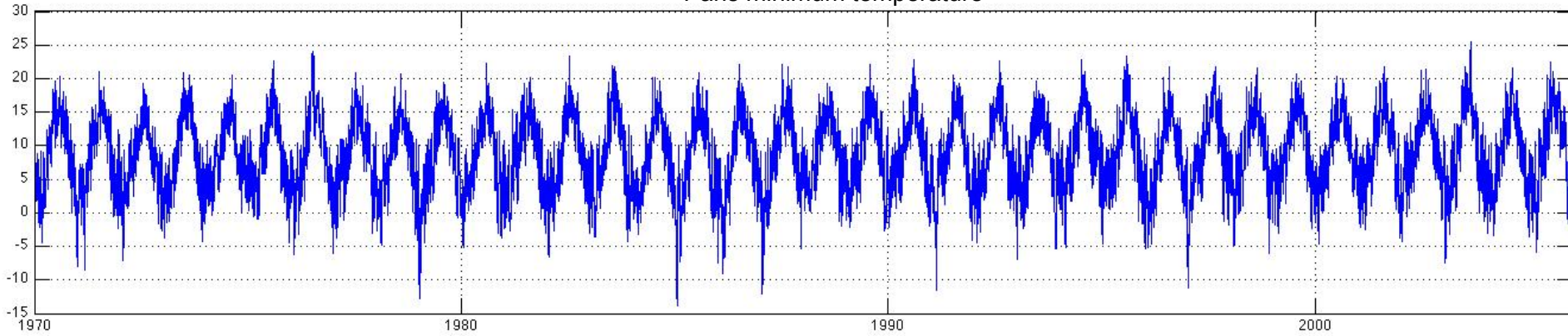
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$$N = 14$$

$$\mu = 176.36$$

$$\sigma = 6.30$$

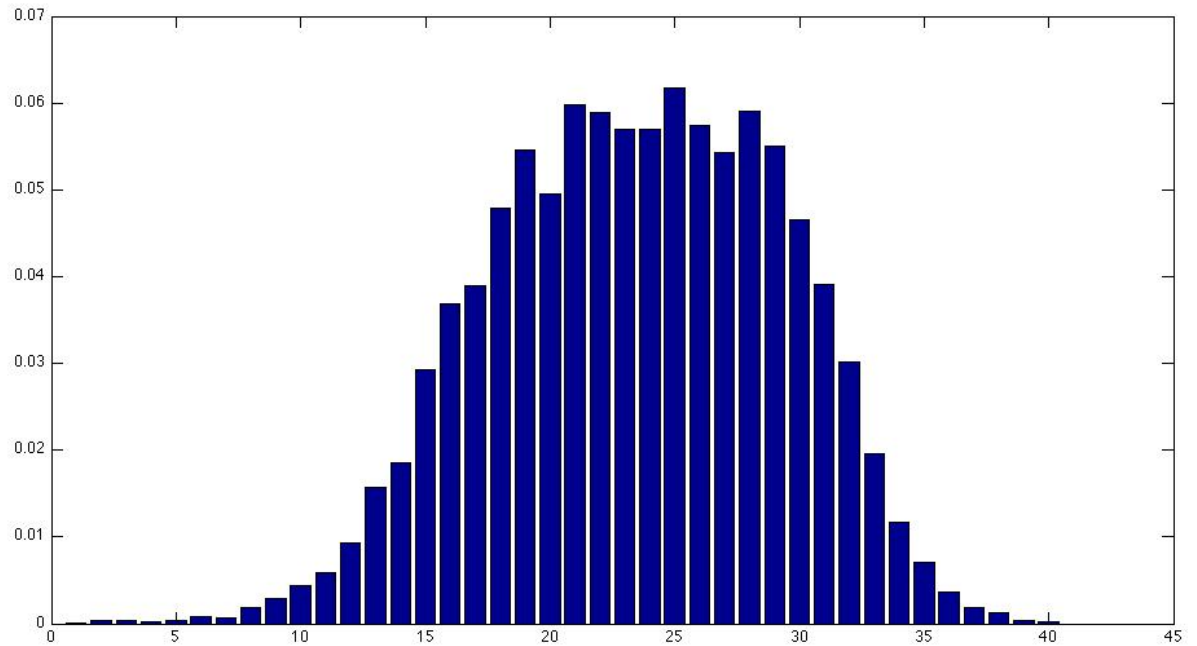
Paris minimum temperature



$$N = 13149$$

$$\mu = 8.68$$

$$\sigma = 5.70$$



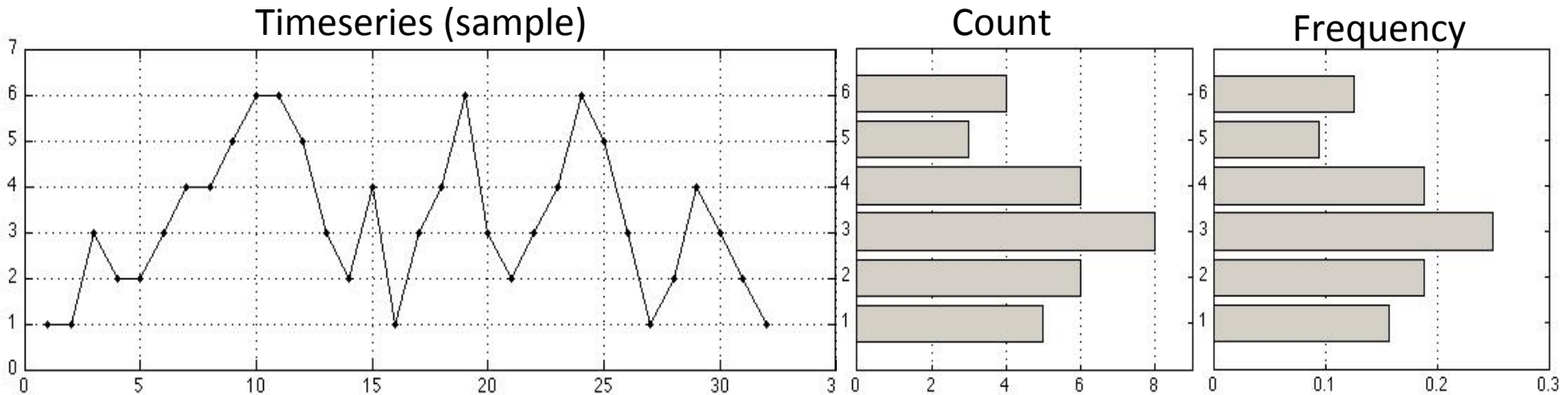
The mean:

$$M(x) = \mu = \frac{1}{N} \sum_{i=1}^N x_i$$

*Equivalent to*

The mathematical expectation, or expected value:

$$E(x) = \int_{-\infty}^{\infty} xf(x)dx$$



$$\frac{1}{N} \sum_{i=1}^N x_i = \frac{1}{N} \sum_{n=1}^6 \hat{x}_n N(\hat{x}) = \sum_{n=1}^6 \hat{x}_n f(\hat{x})$$

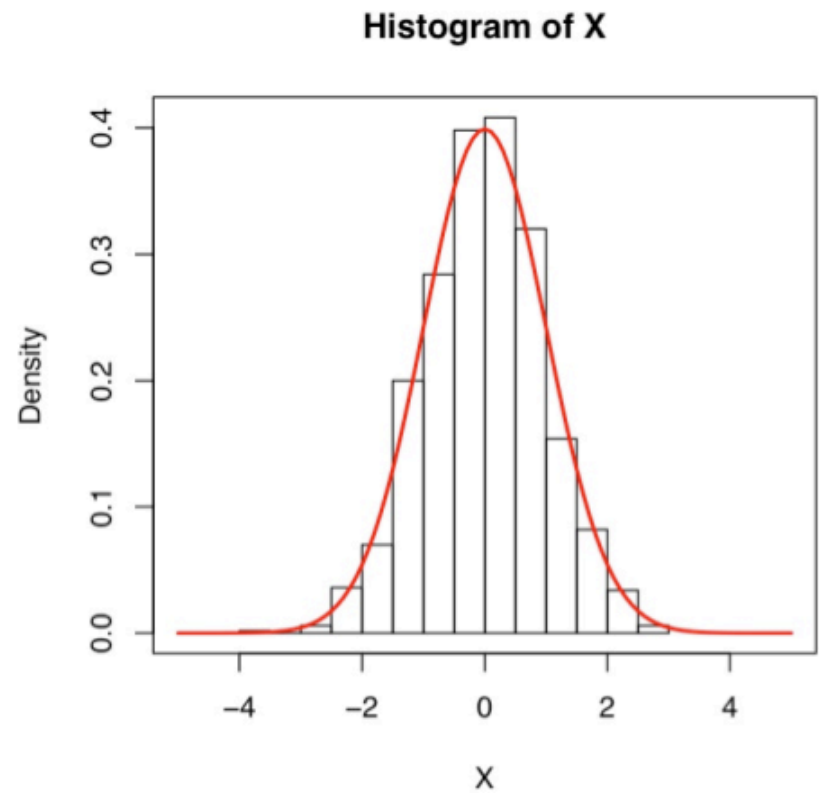
In the case of a real and continuous random variable, the probability density function (PDF) is a real function  $f$  for which:

$$P(a \leq x \leq b) = \int_a^b f(x) dx$$

It has the properties of a distribution, hence:

$$\int_{-\infty}^{\infty} f(x) dx = 1$$

$$\forall x ; f(x) \geq 0$$





In the same way as the mathematical expectation, or mean:

The second moment is the the variance:

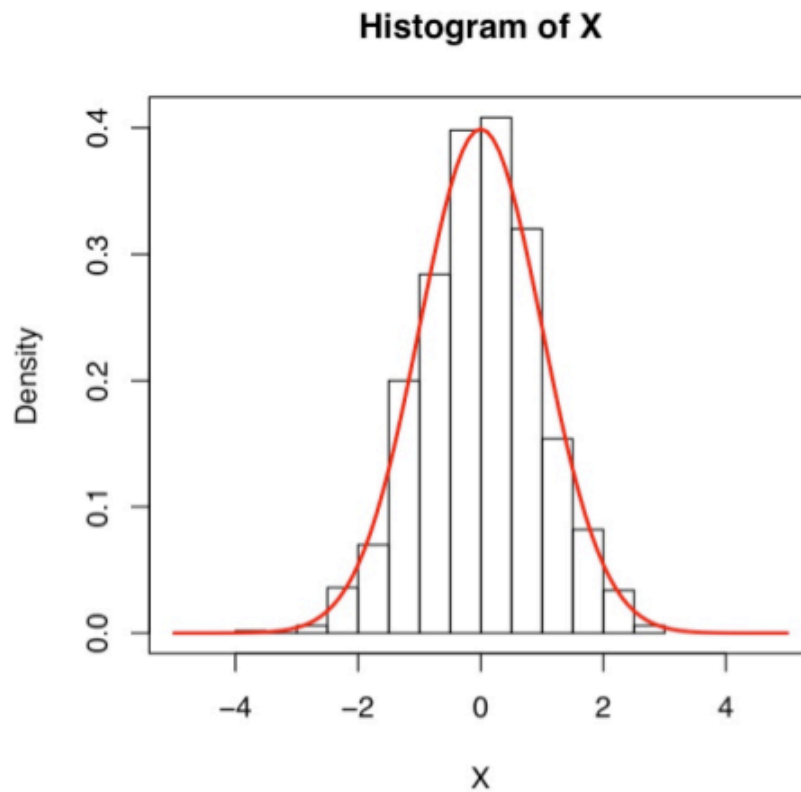
$$\text{var}(x) = E((x - E(x))^2) = \int_{-\infty}^{\infty} (x - E(x))^2 f(x) dx$$

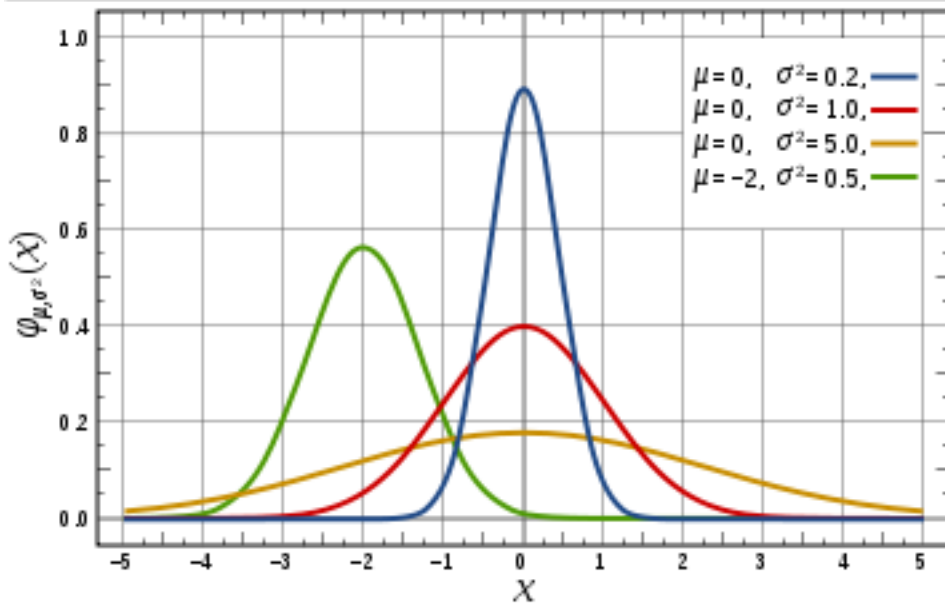
In the discrete case:

$$\text{var}(x) = \sigma^2 = \frac{1}{N} \sum_{i=1}^N (x_i - E(x))^2$$

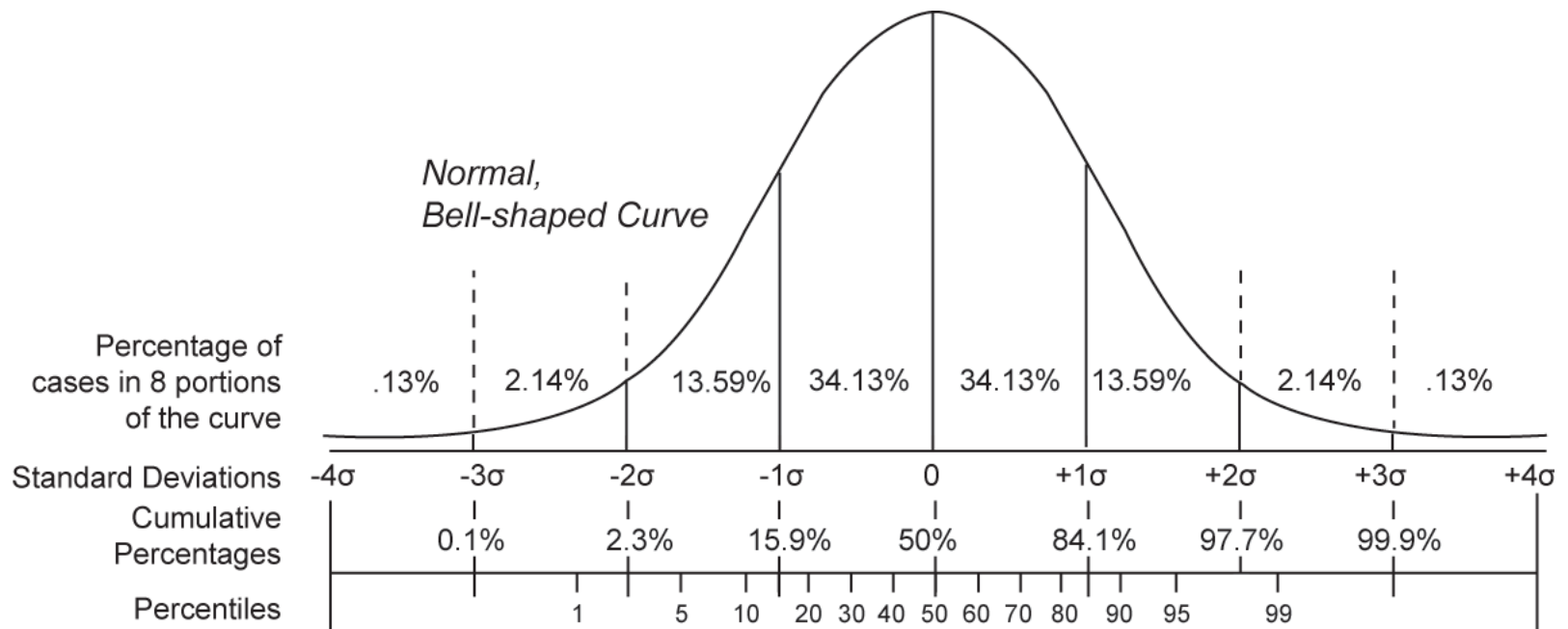
Normal distribution, or Gaussian distribution.

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





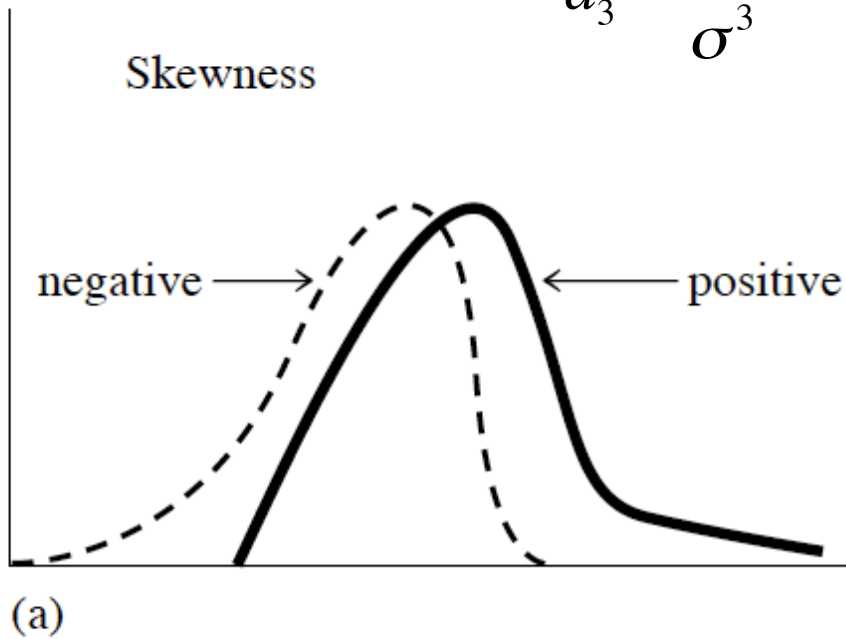
$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



### Higher order moments

$$m_r = \frac{1}{N} \sum_{i=1}^N (x_i - \mu)^r$$

$$a_3 = \frac{m_3}{\sigma^3}$$



$$a_4 = \frac{m_4}{\sigma^4}$$

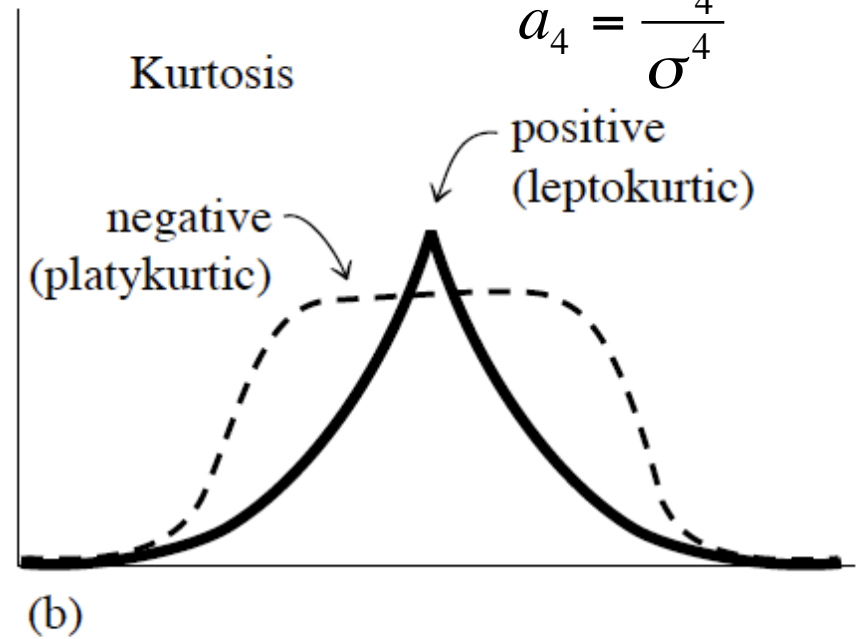
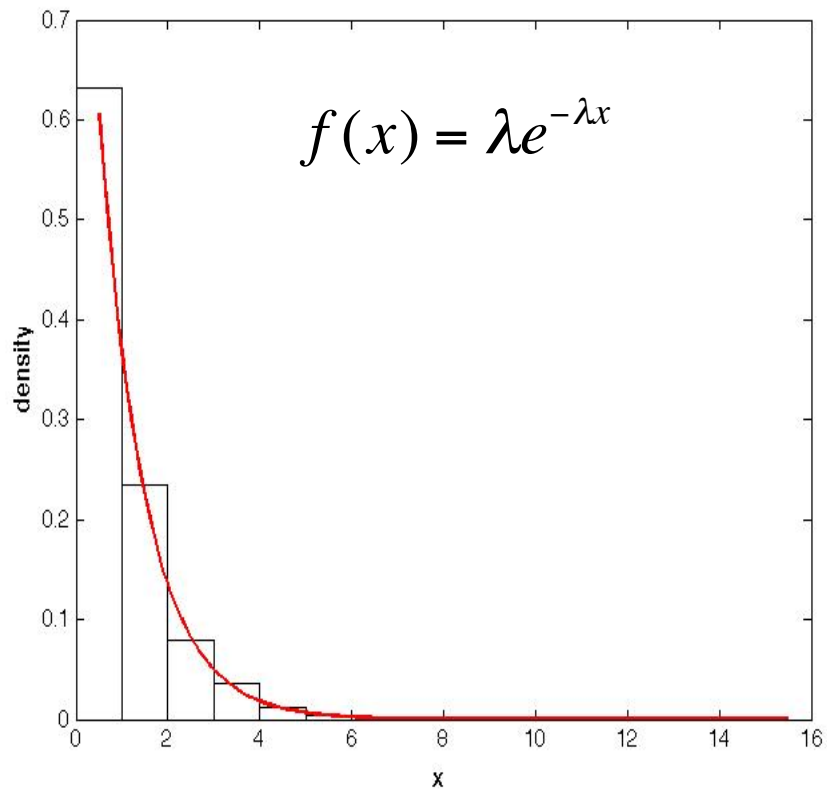


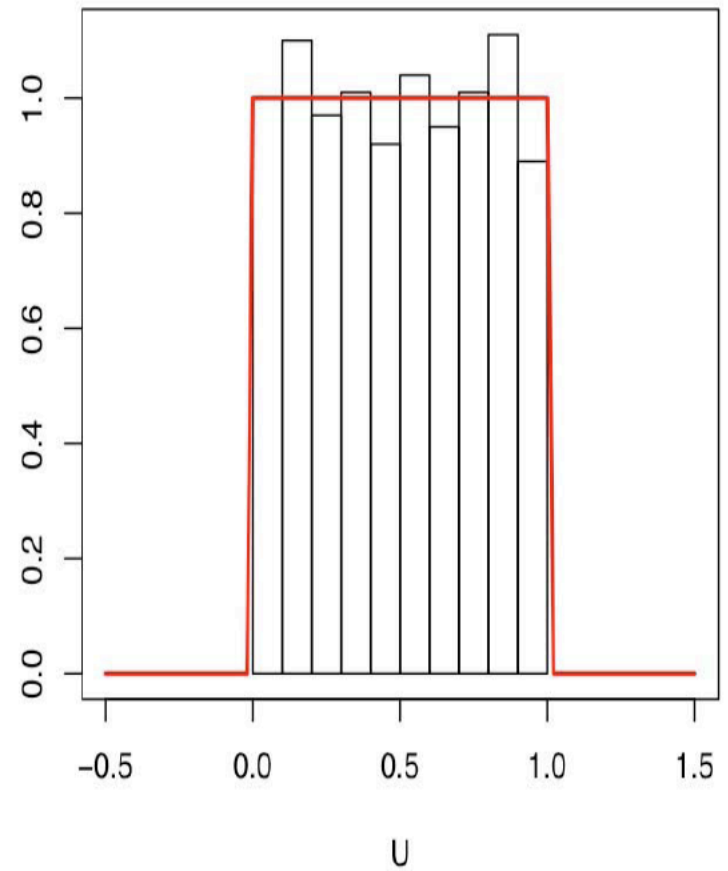
Figure 14.1.1. Distributions whose third and fourth moments are significantly different from a normal (Gaussian) distribution. (a) Skewness or third moment. (b) Kurtosis or fourth moment.

# Other distributions:

## Exponential



## Flat



Interpretation of probability:

- 1) Inverse of the number of possible ways of happening of an event (classical interpretation)
- 2) Frequency of a repeated event (frequentist interpretation)
- 3) Non-frequentist subjective interpretation - Bayes
- 4) Mathematical definition (Kolmogorov)

An event A is a set (or group) of possible outcomes of an uncertain process

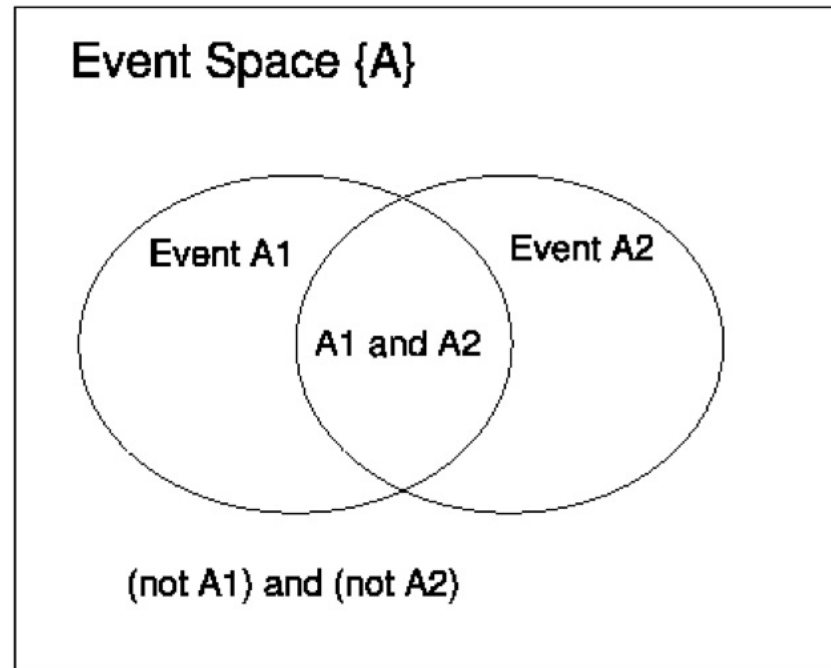
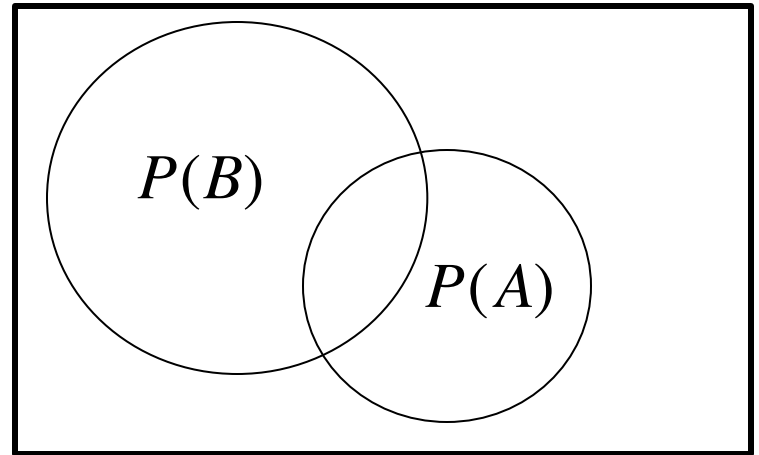


Figure 3.1: Euler diagram showing event space for 2 events.

A random variable,  $X$ , is a label allocated to a random event  $A$ . The probability is a function defined on the event space,

$$P(A) = P(X = x) \in [0,1]$$



Some properties of probability

$$1) P(\neg A) = P(A^c) = 1 - P(A)$$

$$2) P(A \cup B) = P(A) + P(B) - P(A \cap B)$$

$$3) P(A \cap B) = P(A | B)P(B)$$

$$P(A \cap B) = P(A)P(B)$$

From (3), we can also write: (Bayes Theorem)

$$P(A | B)P(B) = P(B | A)P(A)$$





## Exercise

The probability of a New York teenager owning a skateboard is 0.37, of owning a bicycle is 0.81, and of owning both is 0.36.

If a New York teenager is chosen at random, what is the probability that he/she does not own neither a skateboard nor a bicycle?

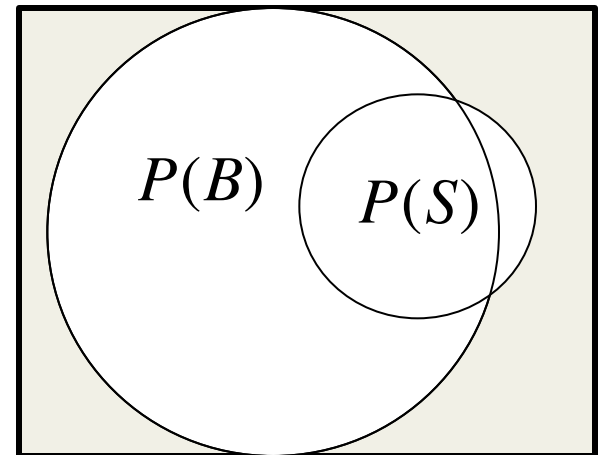
## Exercise

The probability of a New York teenager owning a skateboard is 0.37, of owning a bicycle is 0.81, and of owning both is 0.36.

If a New York teenager is chosen at random, what is the probability that he/she does not own neither a skateboard nor a bicycle?

$$\begin{aligned} P(S \cup B) &= P(S) + P(B) - P(S \cap B) = \\ &= 0.37 + 0.81 - 0.36 = 0.82 \end{aligned}$$

$$\begin{aligned} P(\overline{S \cup B}) &= 1 - P(S \cup B) = \\ &= 1 - 0.82 = 0.18 \end{aligned}$$



## A medical example of the Bayes theorem.

- 1) If an individual has the disease, the test is positive 99% of the times
- 2) If an individual doesn't have the disease, the test is positive 1% of the times
- 3) The population as a whole has probability 0.01% of having the disease

1)  $P(B|A) = 0.99$  (*correct positive*)

A: event "having the disease"

2)  $P(B|A^c) = 0.01$  (*false positive*)

B: event "test is positive"

3)  $P(A) = 0.0001$  (*one person out of 10000 has the disease*)

If you go to the doctor and you test positive, what is the probability that you have the disease? i.e., what is  $P(A|B)$  ?

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} = \frac{P(B|A)P(A)}{P(B|A)P(A) + P(B|A^c)P(A^c)} = \frac{0.99 \times 0.0001}{0.99 \times 0.0001 + 0.01 \times 0.9999} = 0.0098 \approx 1\%$$

**Don't worry and repeat the test a few times!**

*(if you take the test again and you are positive, the probability is 50%, if you take a third, and are positive again, it's 99%...)*

## Exercise

Among the clients of a gas station, 35% buy normal gasoline. 40% unleaded gasoline and 25% super-enhanced gasoline. Of those using normal gasoline, 60% systematically get a full tank-up, while of the others, only 30% and 50% respectively do it.

Compute:

1. The probability that next client will get a full tank-up of unleaded gasoline
2. The probability that the next client will get a full tank-up
3. If the next client gets a full tank-up, compute the probability that it is of normal gasoline

## Exercise

Among the clients of a gas station, 35% buy normal gasoline. 40% unleaded gasoline and 25% super-enhanced gasoline. Of those using normal gasoline, 60% systematically get a full tank-up, while of the others, only 30% and 50% respectively do it.

$$\begin{array}{lll} P(N) = 0.35, & P(U) = 0.4, & P(S) = 0.25 \\ P(F|N) = 0.6, & P(F|U) = 0.3, & P(F|S) = 0.5 \end{array}$$

Compute:

1. The probability that next client will get a full tank-up of unleaded gasoline

$$P(F|U) P(U) = 0.4 * 0.3 = 0.12$$

1. The probability that the next client will get a full tank-up

$$P(F|U) P(U) + P(F|N) P(N) + P(F|S) P(S) = 0.4 * 0.3 + 0.6 * 0.35 + 0.5 * 0.25 = 0.455$$

1. If the next client gets a full tank-up, compute the probability that it is of normal gasoline

$$P(F|N) P(N) = P(N|F) P(F) \dots \text{etc etc}$$

If you choose an answer to this question at random, what is the chance you will be correct?

A) 25%

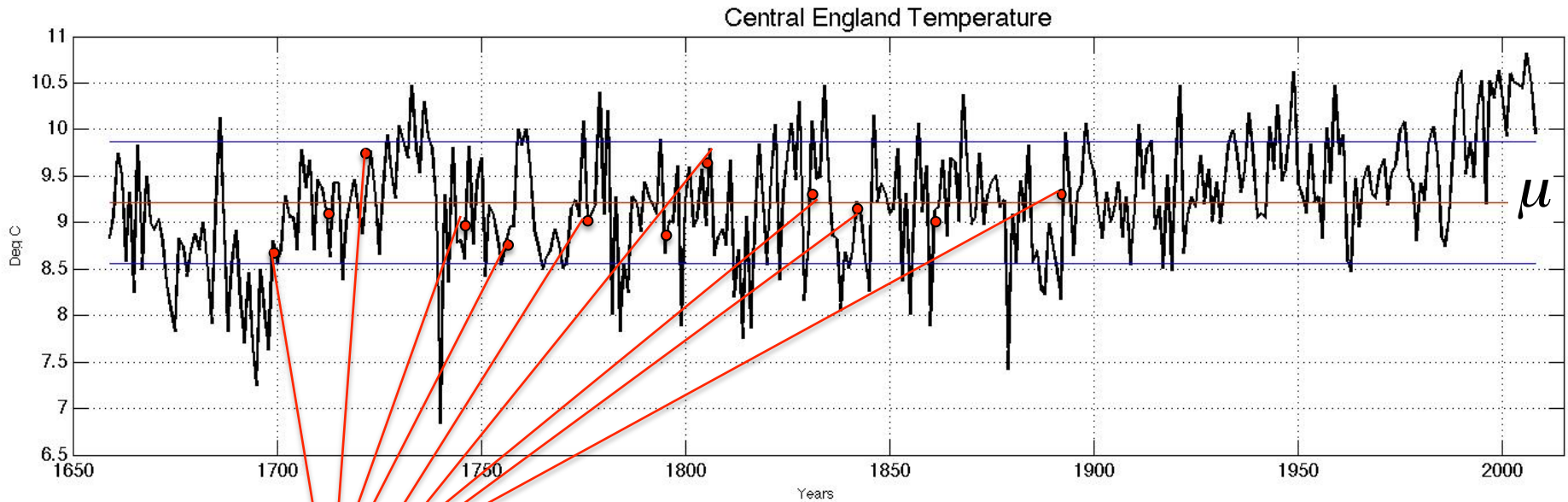
B) 50%

C) 60%

D) 25%

**sampling theory**

# Sampling distributions.

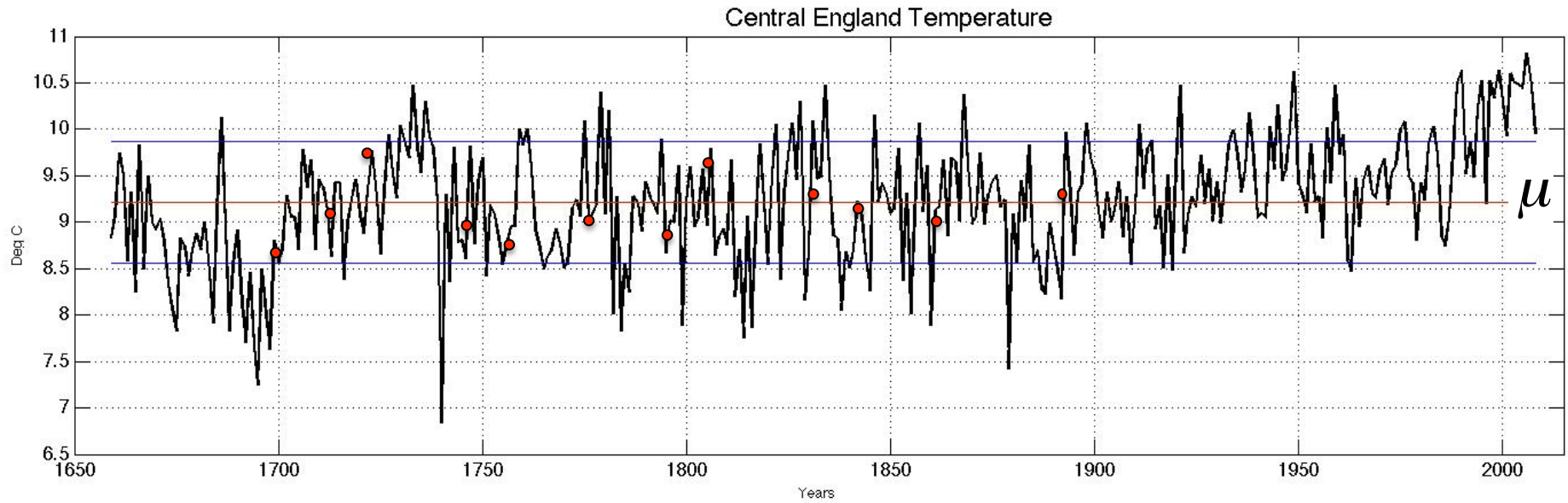


$$\bar{x} = \frac{1}{N} \sum_{i=1}^N x_i$$

Can we say that  $\bar{x} = \mu$  ?

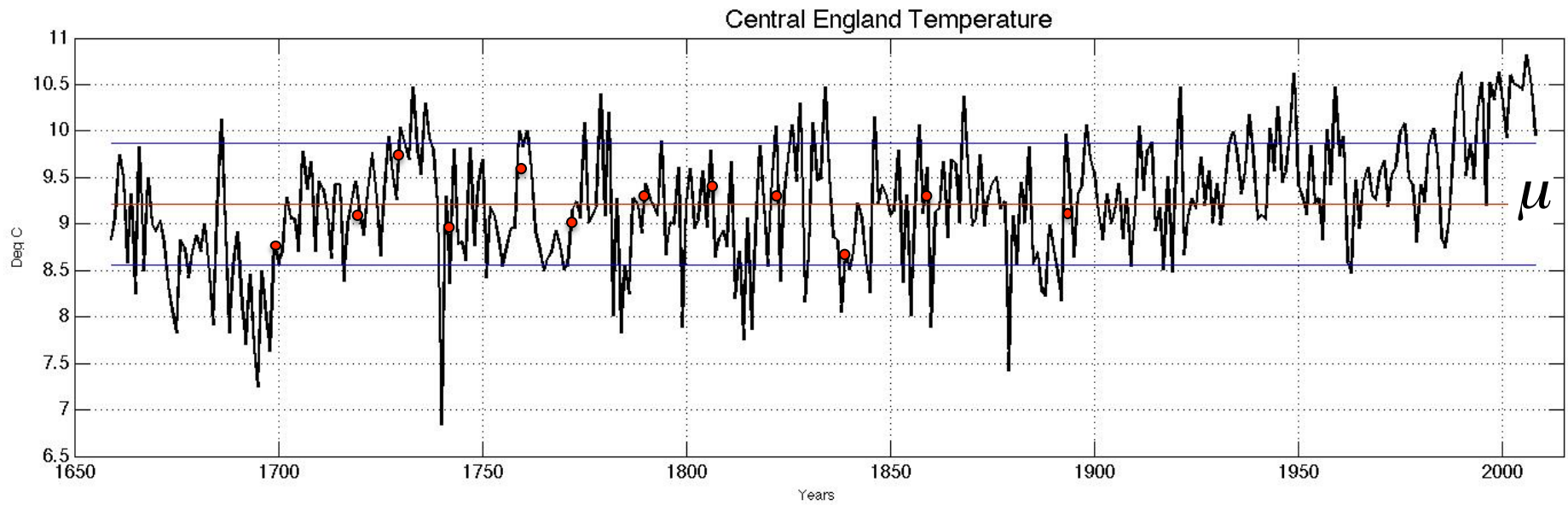


# Sampling distributions.



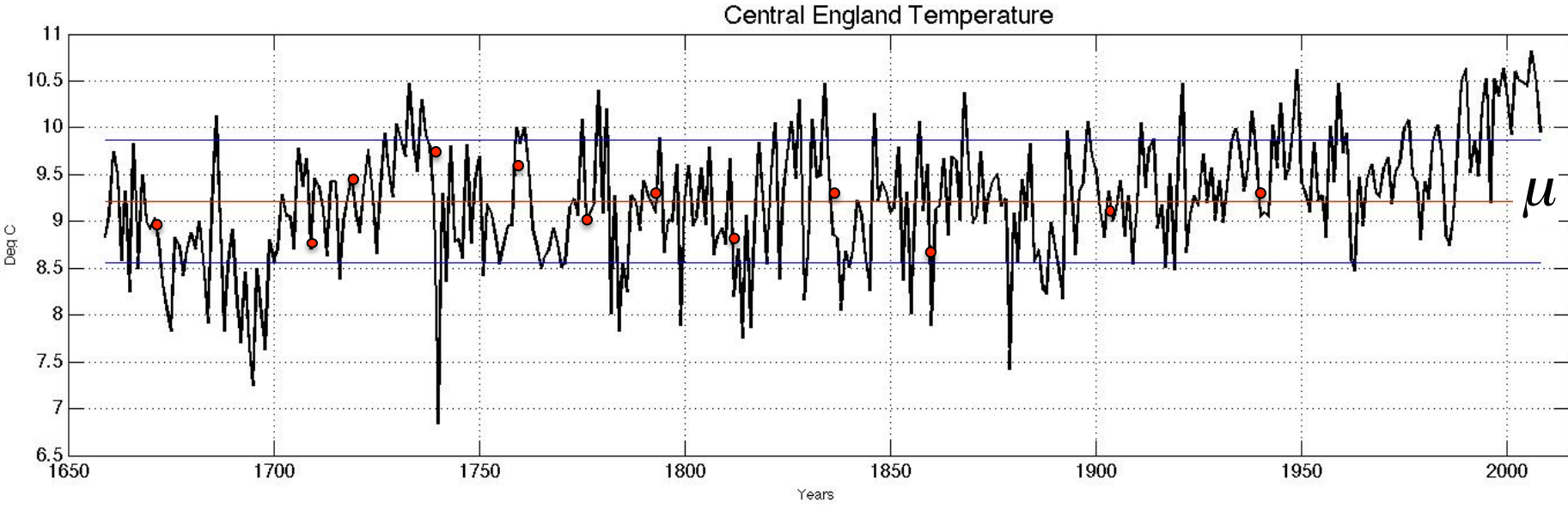
$$(\bar{x})_1$$

# Sampling distributions.



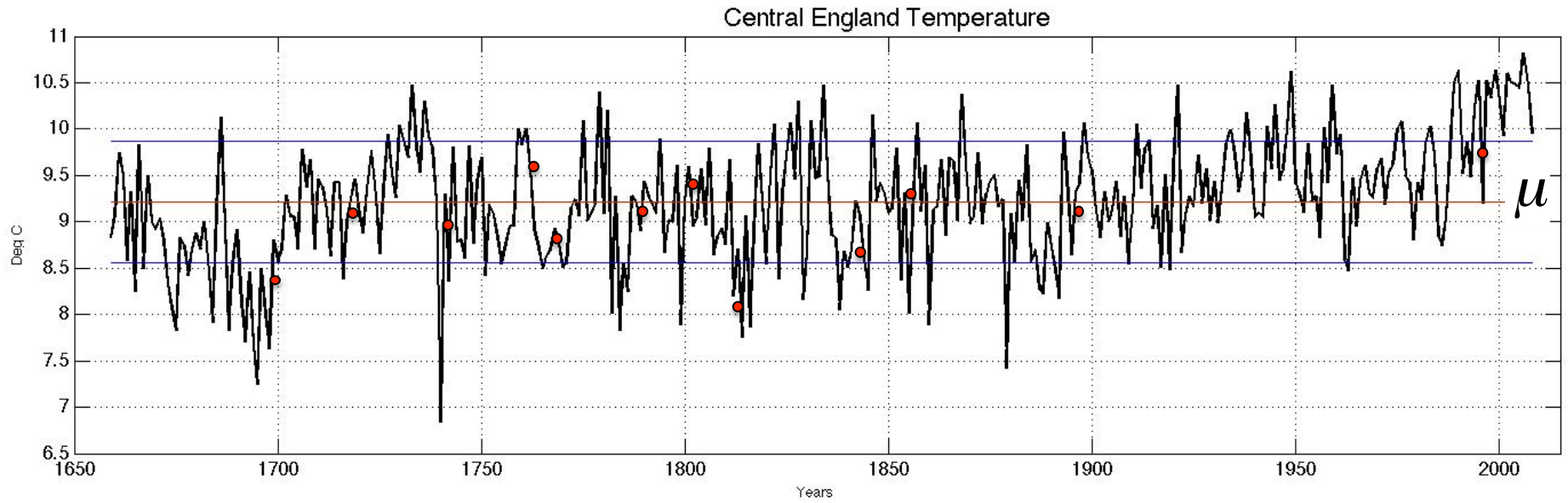
$$(\bar{x})_2$$

# Sampling distributions.



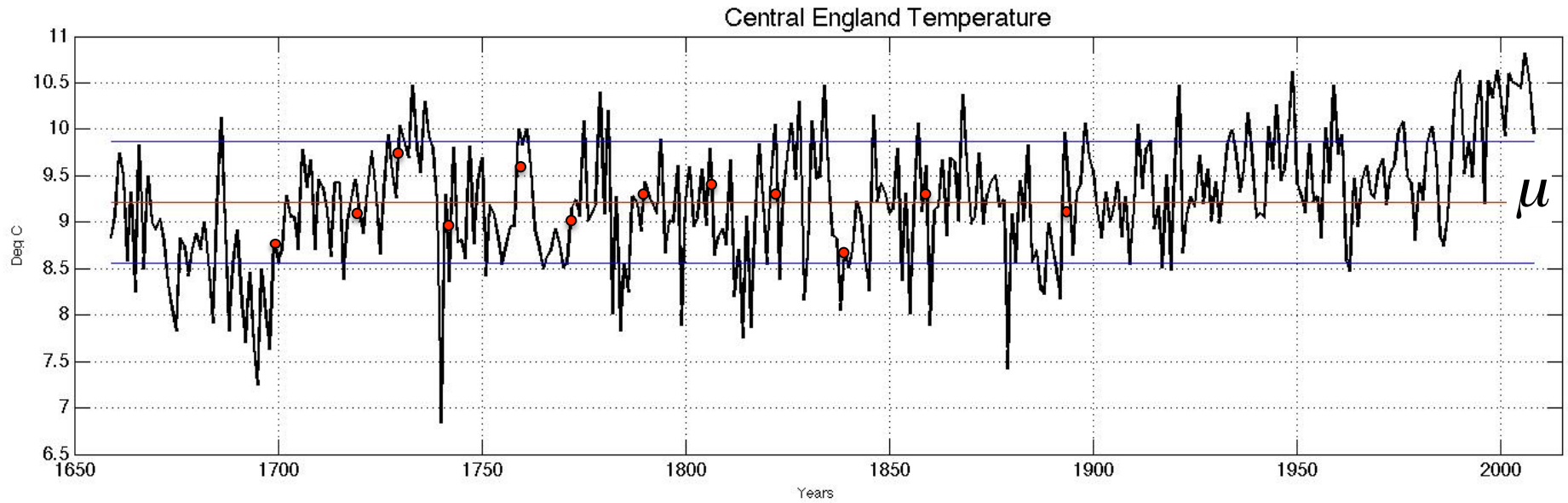
$$(\bar{x})_3$$

# Sampling distributions.



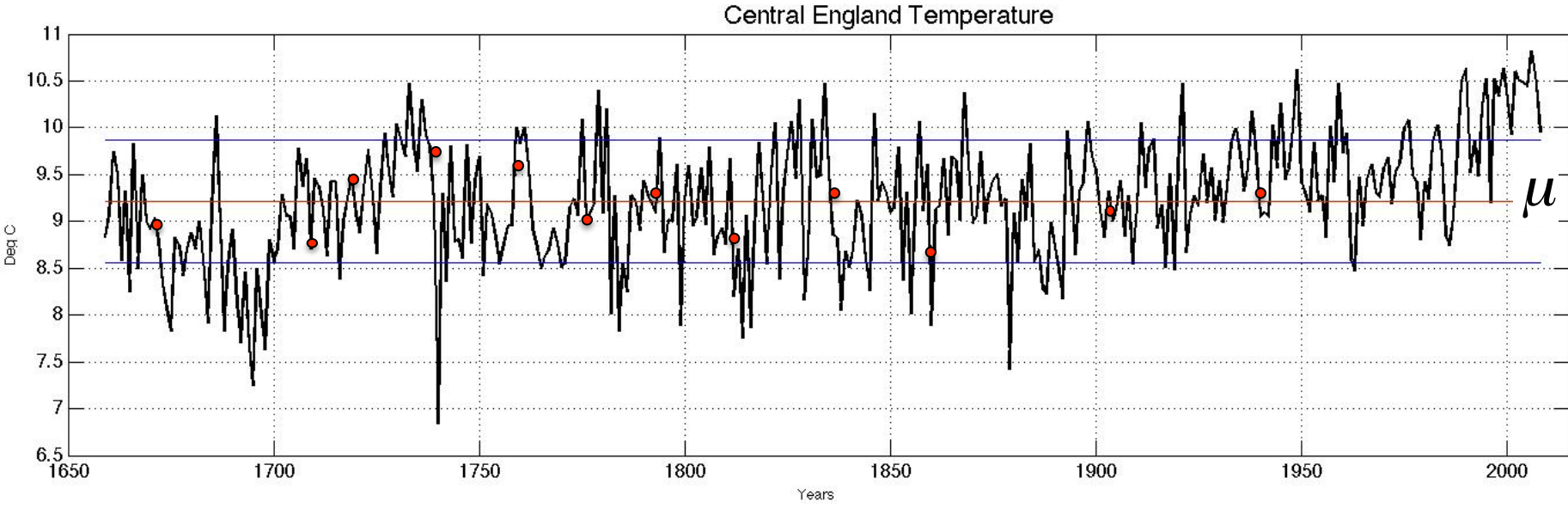
$$(\bar{x})_4$$

# Sampling distributions.



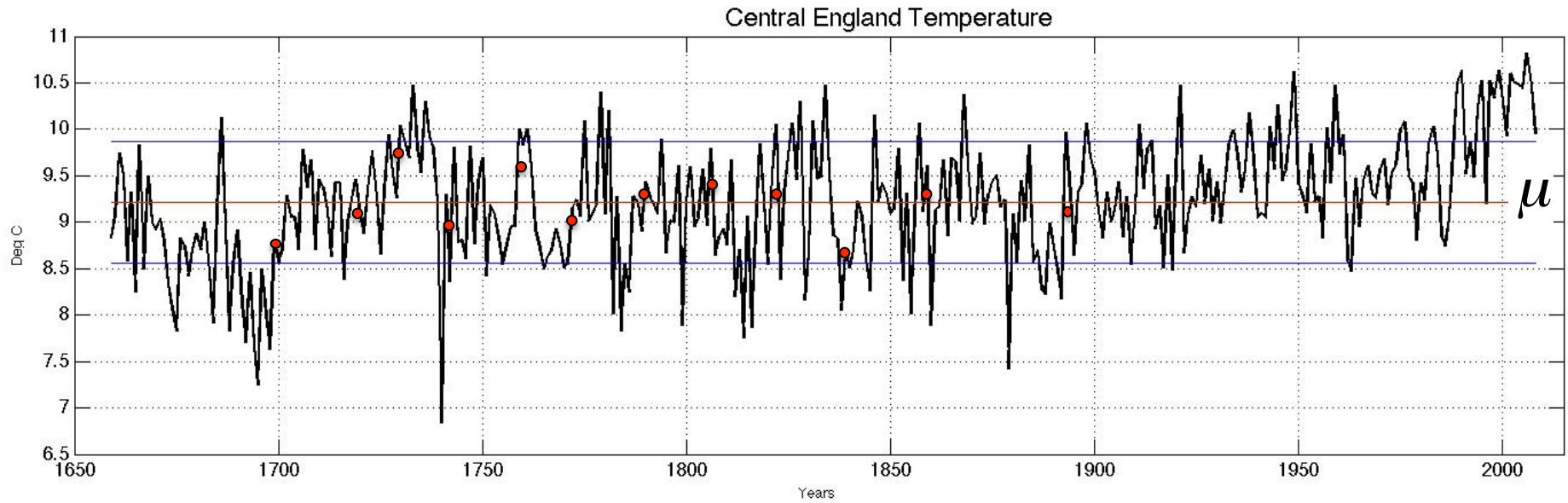
$$(\bar{x})_5$$

# Sampling distributions.



$$(\bar{x})_6$$

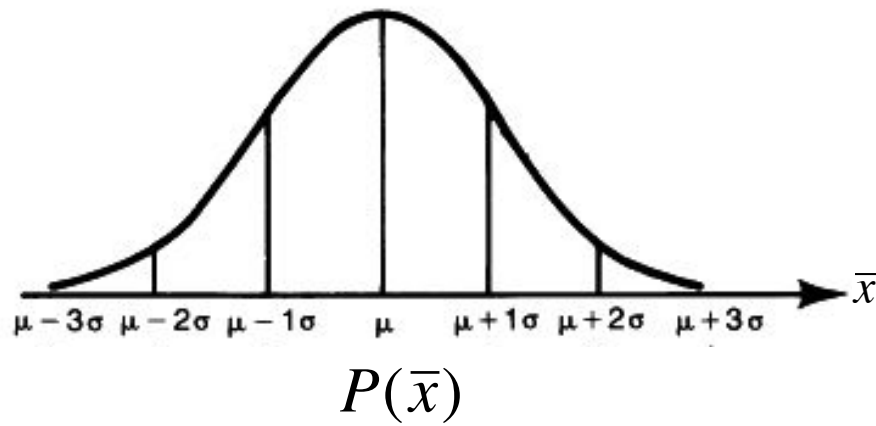
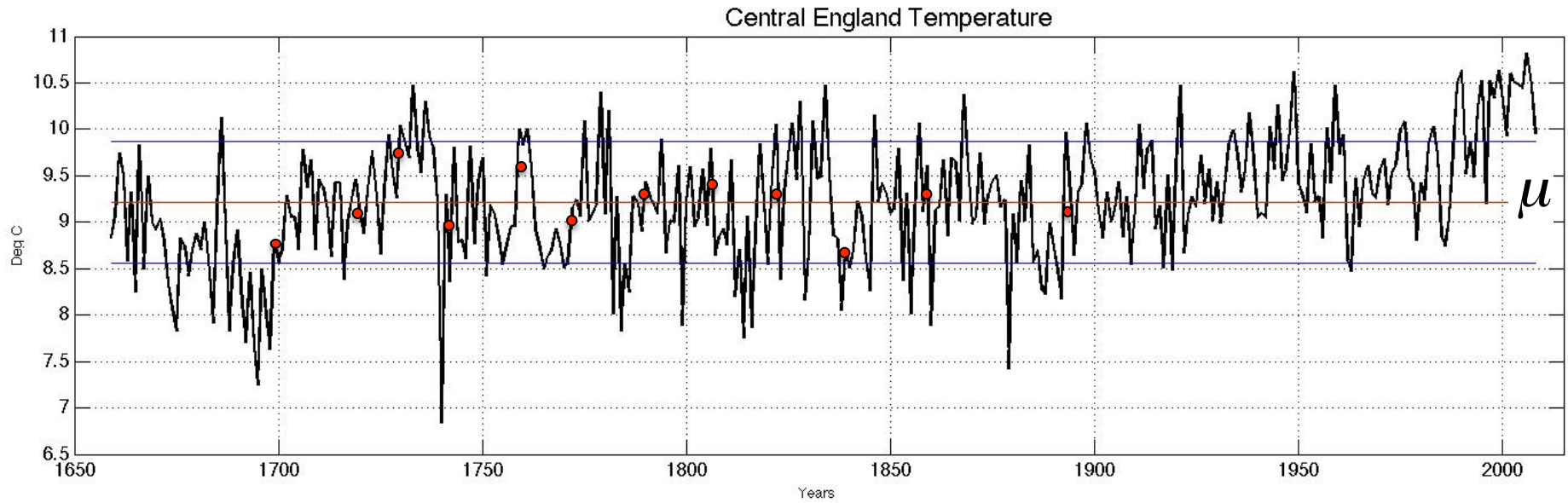
# Sampling distributions.



$$(\bar{x})_7$$



# Sampling distributions.





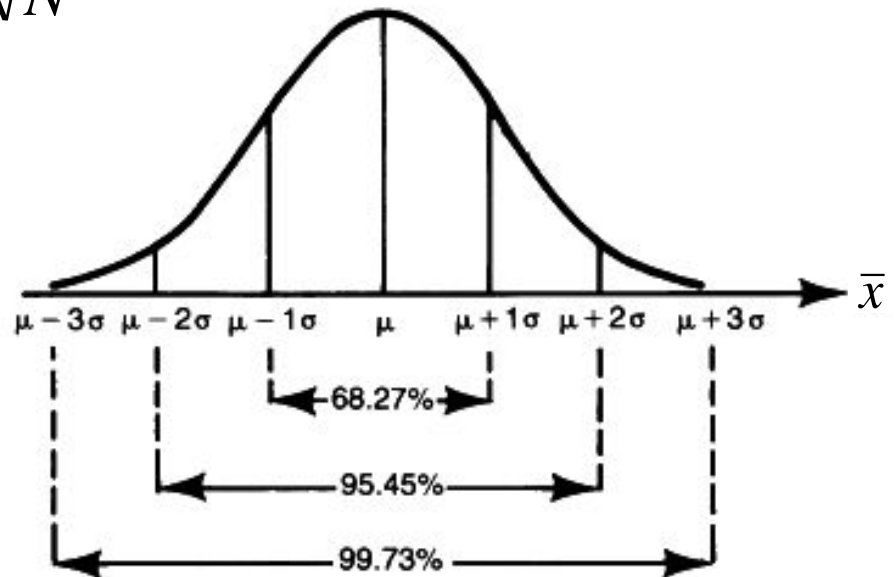
## Central limit theorem

The sampling distribution tends to a normal distribution with mean equal to  $\mu$  and variance equal to  $\sigma^2 / N$  ,

independently of the distribution of the variable

Consequently, whenever you have a sample of length N, it will

be affected by a standard error of  $\frac{\sigma}{\sqrt{N}}$



## Proof of the central limit theorem.

NB, this is a “crude” proof. For anything more formal ask your mathematicians friends (or look at a book).

i) mean  $E(\bar{x}) = \mu$

$$\begin{aligned} E(\bar{x}) &= E\left(\frac{1}{N} \sum_{i=1}^N x_i\right) = \\ &= \frac{1}{N} \sum_{i=1}^N E(x_i) = \frac{1}{N} \sum_{i=1}^N \mu = \\ &= \mu \end{aligned}$$

ii) variance  $E((\bar{x} - \mu)^2) = \frac{\sigma^2}{N}$

$$\begin{aligned} E((\bar{x} - \mu)^2) &= E\left(\left[\frac{1}{N} \sum_{i=1}^N x_i - \mu\right]^2\right) = E\left(\left[\frac{1}{N} \sum_{i=1}^N (x_i - \mu)\right]^2\right) = \\ &= \frac{1}{N^2} E\left(\left[\sum_{i=1}^N (x_i - \mu)\right]^2\right) = \\ &= \frac{1}{N^2} \sum_{i=1}^N E\left(\left[(x_i - \mu)\right]^2\right) = \\ &= \frac{1}{N^2} N \text{var}(x) = \frac{\sigma^2}{N} \end{aligned}$$

Now we can prove that the correct estimator of the variance of a sample is

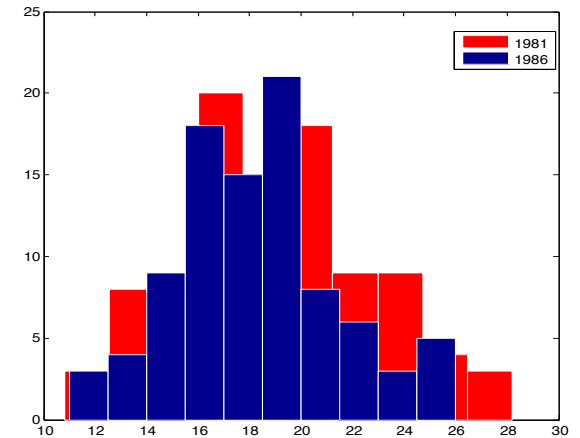
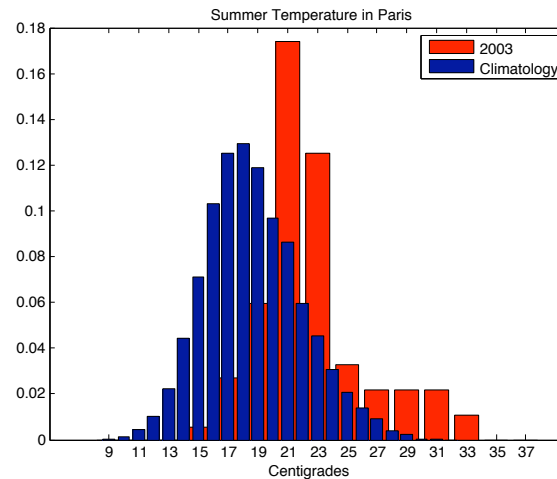
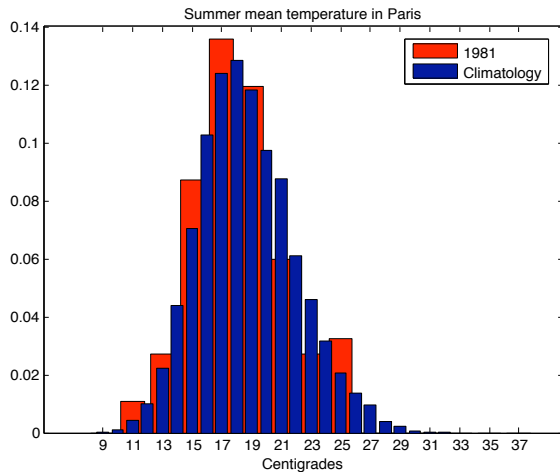
$$\sigma^2 = \frac{1}{N-1} \sum_{i=1}^N (x_i - \bar{x})^2$$

$$\begin{aligned} \sum_{i=1}^N (x_i - \bar{x})^2 &= \\ &= \sum_{i=1}^N (x_i - \mu - (\bar{x} - \mu))^2 = \\ &= \sum_{i=1}^N (x_i - \mu)^2 + N(\bar{x} - \mu)^2 - 2(\bar{x} - \mu) \sum_{i=1}^N (x_i - \mu) = \\ &= \sum_{i=1}^N (x_i - \mu)^2 + N(\bar{x} - \mu)^2 - 2N(\bar{x} - \mu)^2 = \\ &= \sum_{i=1}^N (x_i - \mu)^2 - N(\bar{x} - \mu)^2 = N\sigma^2 - N\frac{\sigma^2}{N} = (N-1)\sigma^2 \end{aligned}$$

## Comparing two set of data:

1) Are two samples issued from the same population?

Ex. Is the mean temperature in Paris for summer 2003 statistically different from climatology?



**People at LMD are taller on average than the rest of the population of Paris - Or are they?**



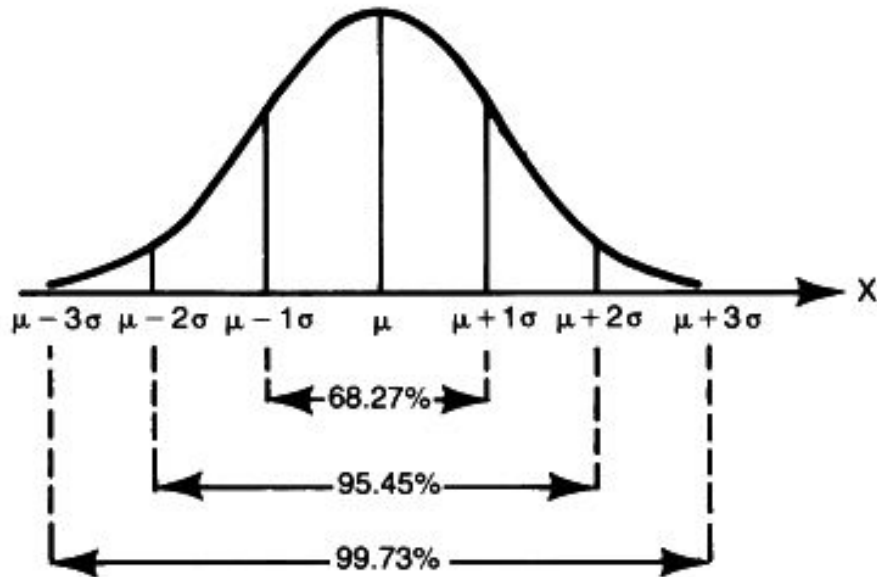
**Ronald Fisher**

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13	Pauline	175
14	Riwal	177

An example of hypothesis testing:

- 1) Set up a Null Hypothesis
- 2) Chose a test statistic
- 3) Chose a level of significance
- 4) Compute the level of probability of the sample, from the test statistic
- 5) If that is lower than the level of significance, reject the null hypothesis.

**People at LMD are taller than the rest of the population of Paris.  
Or are they?**



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9	Guillaume	183
10	Hector	171
11	Marie-Christine	165
12	Michael	177
13	Pauline	175
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Paris:  $\mu_0 = 170, \sigma_0 = 14$

LMD  $\mu = 174.7, \sigma = \sigma_0 / \sqrt{N}$

An example of hypothesis testing:

- 1) Set up a Null Hypothesis
- 2) Chose a test statistic
- 3) Chose a level of significance
- 4) Compute the level of probability of the sample, from the test statistic
- 5) If that is lower than the level of significance, reject the null hypothesis.

## hypothesis testing:

1) Set up a Null Hypothesis

The sample is issued from the same statistics  
People at LMD are not taller than the rest.

2) Chose a test statistic

The sample mean distribution

4) Chose a level of significance

95%, i.e. 2 standard errors,  $p \leq 5\%$

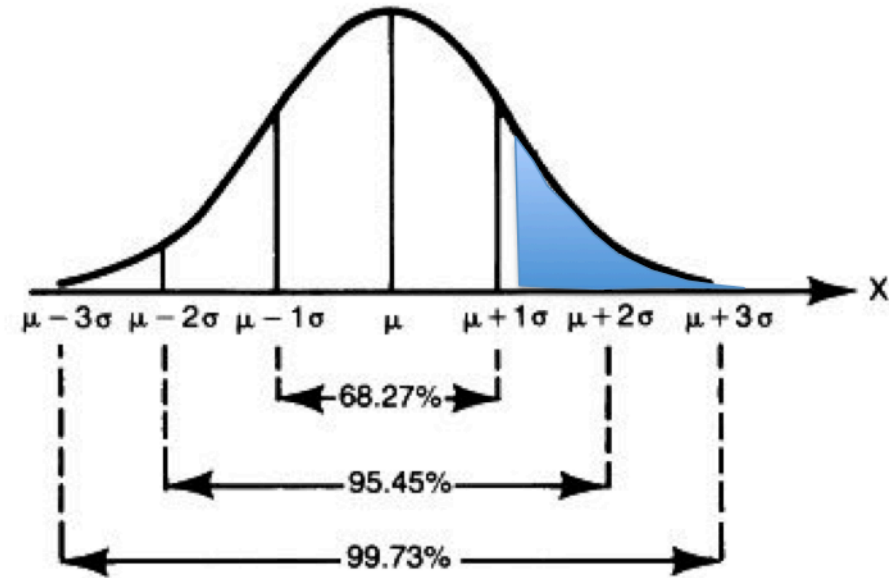
4) Compute the level of probability of the sample, from the test statistic

$$\frac{(\mu - \mu_0)}{\sigma/\sqrt{N}} = \frac{(174.7 - 170)}{14/\sqrt{14}} = 1.26$$

$$p = P(\|h\| \geq \mu) \approx 14 - 15\%$$

5) If that is lower than the level of significance, reject the null hypothesis.

CANNOT REJECT

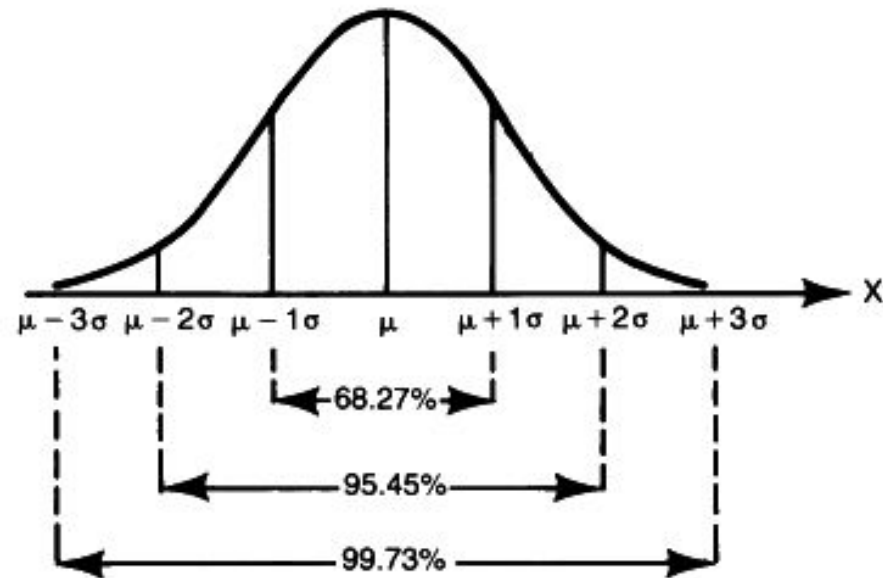
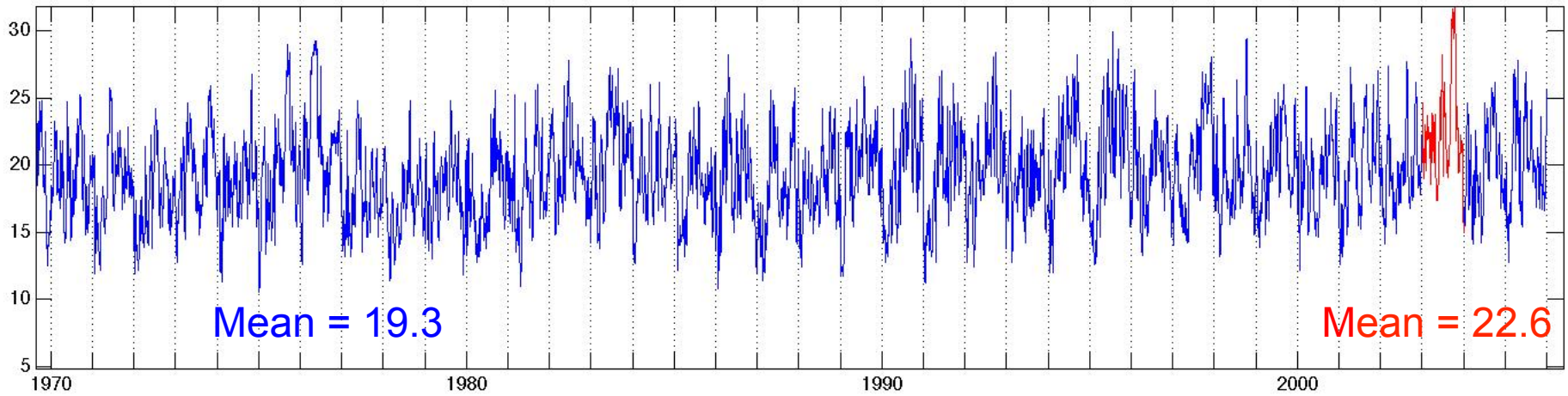


(difference of means in std error units)



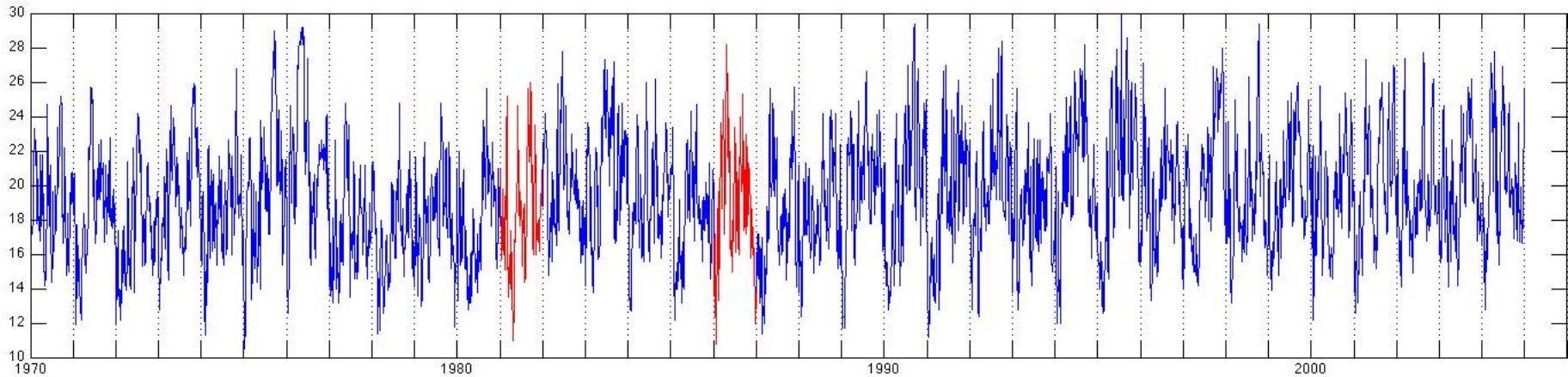
# Back to the initial question

Paris

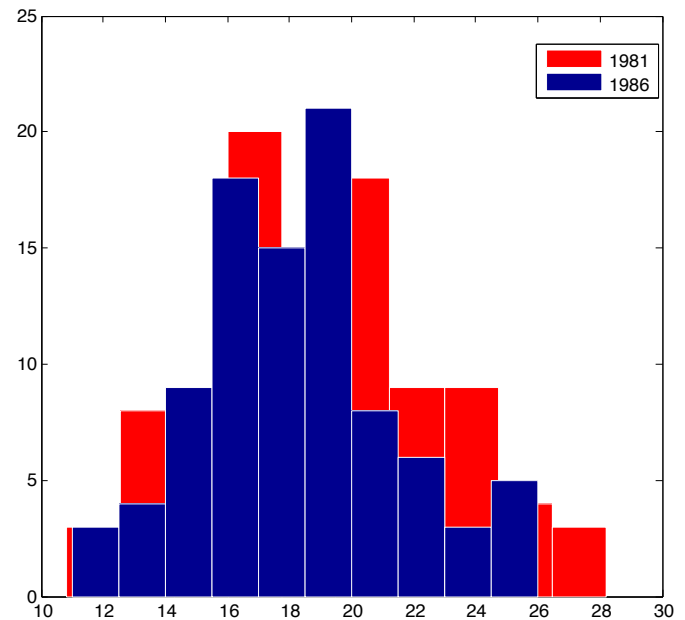


$$\frac{(\mu - \mu_0)}{\sigma/\sqrt{N}} = \frac{(22.6 - 19.3)}{3.4/\sqrt{92}} = 9.4$$

# Comparing two samples



Are the mean of these two samples different? I.e. are they issued from two distinct populations?



**We are comparing two series that are both the sampling of an unknown variable.**

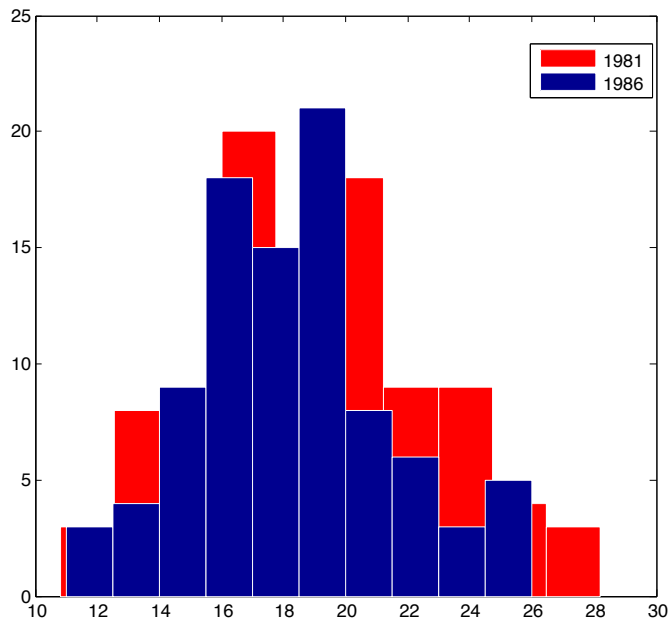
We need another test statistics

The distribution of:

$$t = \frac{\mu_a - \mu_b}{s/\sqrt{N}}, \quad \text{where} \quad s = \sqrt{\frac{(N_a - 1)\sigma_a^2 + (N_b - 1)\sigma_b^2}{N_a + N_b - 2}}$$

$$\frac{1}{N} = \left( \frac{1}{N_a} + \frac{1}{N_b} \right)$$

Is known, it is called the Student-t distribution. Its value for a given t can be found in tables, or in the most usual statistical software packages.



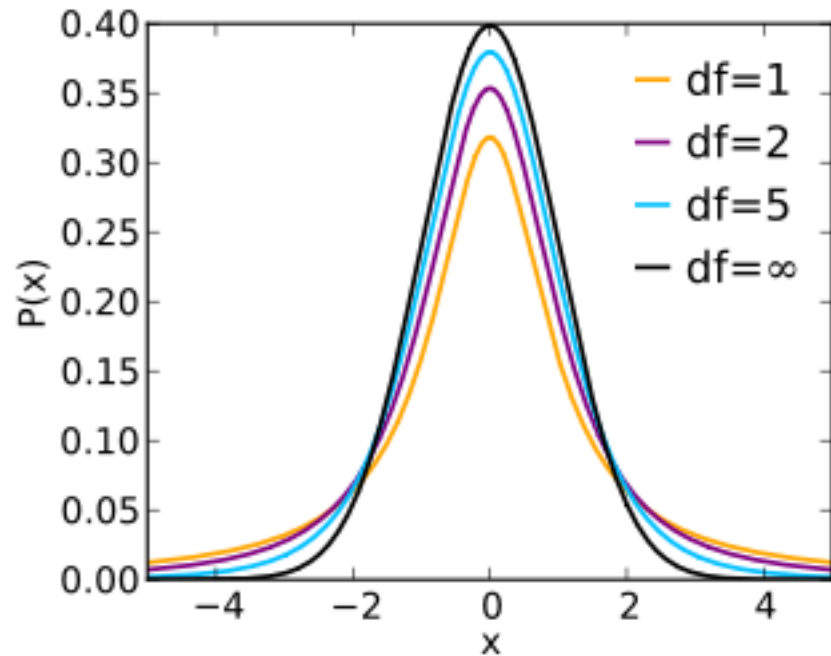
$$\mu_a - \mu_b = 0.72,$$

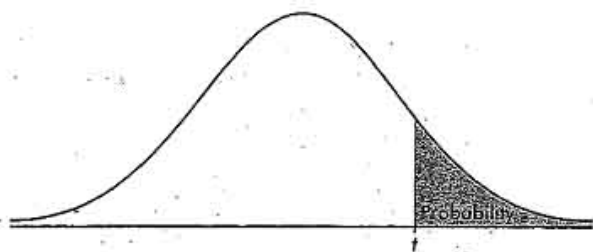
$$s = \sqrt{\frac{(N_a - 1)\sigma_a^2 + (N_b - 1)\sigma_b^2}{N_a + N_b - 2}} = 3.47$$

$$t = \frac{\mu_a - \mu_b}{s/\sqrt{N}} = 1.4$$

$$p(t) = 0.1588$$

$$df = N_a + N_b - 2$$





**TABLE B: t-DISTRIBUTION CRITICAL VALUES**

df	Tail probability $p$											
	.25	.20	.15	.10	.05	.025	.02	.01	.005	.0025	.001	.0005
1	1.000	1.376	1.963	3.078	6.314	12.71	15.89	31.82	63.66	127.3	318.3	636.6
2	.816	1.061	1.386	1.886	2.920	4.303	4.849	6.965	9.925	14.09	22.33	31.60
3	.765	.978	1.250	1.638	2.353	3.182	3.482	4.541	5.841	7.453	10.21	12.92
4	.741	.941	1.190	1.533	2.132	2.776	2.999	3.747	4.604	5.598	7.173	8.610
5	.727	.920	1.156	1.476	2.015	2.571	2.757	3.365	4.032	4.773	5.893	6.869
6	.718	.906	1.134	1.440	1.943	2.447	2.612	3.143	3.707	4.317	5.208	5.959
7	.711	.896	1.119	1.415	1.895	2.365	2.517	2.998	3.499	4.029	4.785	5.408
8	.706	.889	1.108	1.397	1.860	2.306	2.449	2.896	3.355	3.833	4.501	5.041
9	.703	.883	1.100	1.383	1.833	2.262	2.398	2.821	3.250	3.690	4.297	4.781
10	.700	.879	1.093	1.372	1.812	2.228	2.359	2.764	3.169	3.581	4.144	4.587
11	.697	.876	1.088	1.363	1.796	2.201	2.328	2.718	3.106	3.497	4.025	4.437
12	.695	.873	1.083	1.356	1.782	2.179	2.303	2.681	3.055	3.428	3.930	4.318
13	.694	.870	1.079	1.350	1.771	2.160	2.282	2.650	3.012	3.372	3.852	4.221
14	.692	.868	1.076	1.345	1.761	2.145	2.264	2.624	2.977	3.326	3.787	4.140
15	.691	.866	1.074	1.341	1.753	2.131	2.249	2.602	2.947	3.286	3.733	4.073
16	.690	.865	1.071	1.337	1.746	2.120	2.235	2.583	2.921	3.252	3.686	4.015
17	.689	.863	1.069	1.333	1.740	2.110	2.224	2.567	2.898	3.222	3.646	3.965
18	.688	.862	1.067	1.330	1.734	2.101	2.214	2.552	2.878	3.197	3.611	3.922
19	.688	.861	1.066	1.328	1.729	2.093	2.205	2.539	2.861	3.174	3.579	3.883
20	.687	.860	1.064	1.325	1.725	2.086	2.197	2.528	2.845	3.153	3.552	3.850
21	.686	.859	1.063	1.323	1.721	2.080	2.189	2.518	2.831	3.135	3.527	3.819
22	.686	.858	1.061	1.321	1.717	2.074	2.183	2.508	2.819	3.119	3.505	3.792
23	.685	.858	1.060	1.319	1.714	2.069	2.177	2.500	2.807	3.104	3.485	3.768
24	.685	.857	1.059	1.318	1.711	2.064	2.172	2.492	2.797	3.091	3.467	3.745
25	.684	.856	1.058	1.316	1.708	2.060	2.167	2.485	2.787	3.078	3.450	3.725
26	.684	.856	1.058	1.315	1.706	2.056	2.162	2.479	2.779	3.067	3.435	3.707
27	.684	.855	1.057	1.314	1.703	2.052	2.158	2.473	2.771	3.057	3.421	3.690
28	.683	.855	1.056	1.313	1.701	2.048	2.154	2.467	2.763	3.047	3.408	3.674
29	.683	.854	1.055	1.311	1.699	2.045	2.150	2.462	2.756	3.038	3.396	3.659
30	.683	.854	1.055	1.310	1.697	2.042	2.147	2.457	2.750	3.030	3.385	3.646
40	.681	.851	1.050	1.303	1.684	2.021	2.123	2.423	2.704	2.971	3.307	3.551
50	.679	.849	1.047	1.299	1.676	2.009	2.109	2.403	2.678	2.937	3.261	3.496
60	.679	.848	1.045	1.296	1.671	2.000	2.099	2.390	2.660	2.915	3.232	3.460
80	.678	.846	1.043	1.292	1.664	1.990	2.088	2.374	2.639	2.887	3.195	3.416
100	.677	.845	1.042	1.290	1.660	1.984	2.081	2.364	2.626	2.871	3.174	3.390
1000	.675	.842	1.037	1.282	1.646	1.962	2.056	2.330	2.581	2.813	3.098	3.300
$\infty$	.674	.841	1.036	1.282	1.645	1.960	2.054	2.326	2.576	2.807	3.091	3.291
	50%	60%	70%	80%	90%	95%	96%	98%	99%	99.5%	99.8%	99.9%
	Confidence level $C$											

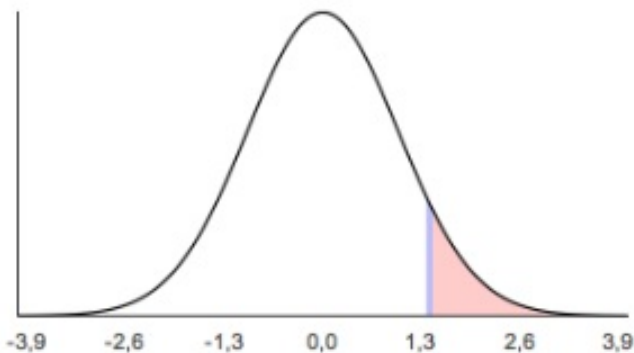
### t-Distribution: $X \sim t_{(df)}$

df = 180

x = 1.4

$P(X > x) =$

0.08162



#### Help

©2012 Matt Bognar  
Department of Statistics and Actuarial Science  
University of Iowa

Suppose we divide the class in two groups: one studies in a room with loud techno music all day long, the other group studies in a silent room. After the exams, these are the results of the two groups:

Group A (with music)	Group B (no music)	
18	15	
17	15	
13	10	
10	11	
14		
$M_a = 14.8$	$M_b = 12.75$	$M_a - M_b = 2.05$
$\text{Var}(A) = 9.7$	$\text{Var}(B) = 6.9167$	

Can we say that techno music is good for studying statistics?

$$\mu_a - \mu_b = 14.8 - 12.75 = 2.05$$

$$s = \sqrt{\frac{(N_a - 1)\sigma_a^2 + (N_b - 1)\sigma_b^2}{N_a + N_b - 2}} = \sqrt{\frac{4\sigma_a^2 + 3\sigma_b^2}{7}} = \sqrt{\frac{4 \cdot 9.7 + 3 \cdot 6.9167}{7}} = 2.9167$$

$$N = \frac{1}{\frac{1}{4} + \frac{1}{5}} = 2.222$$

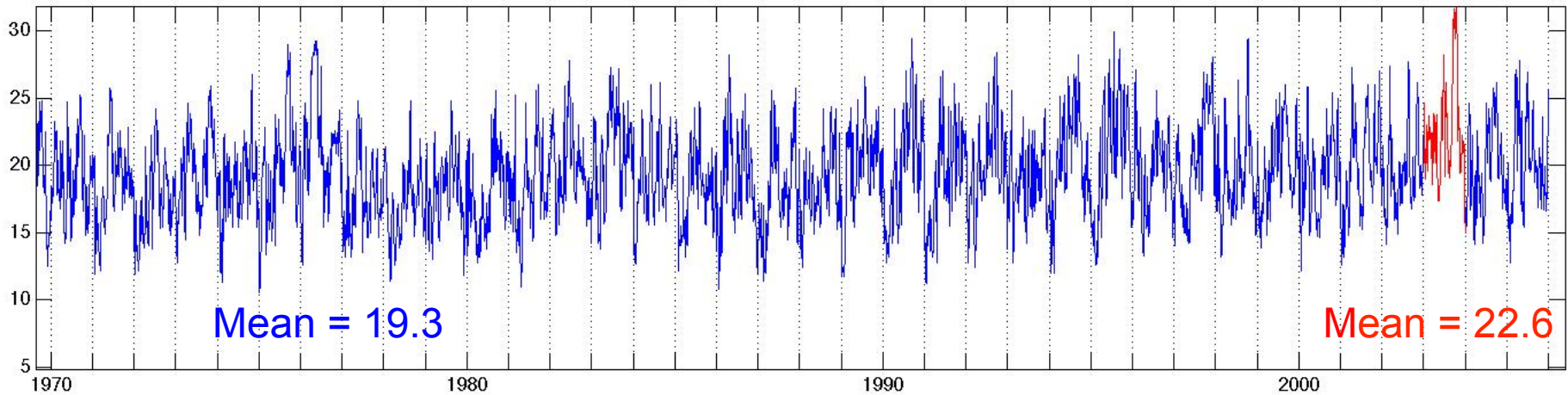
$$t = \frac{\mu_a - \mu_b}{s/\sqrt{N}} = \frac{2.05}{2.9167/\sqrt{2.222}} = 1.0477$$

$$p(t) = 0.1648$$

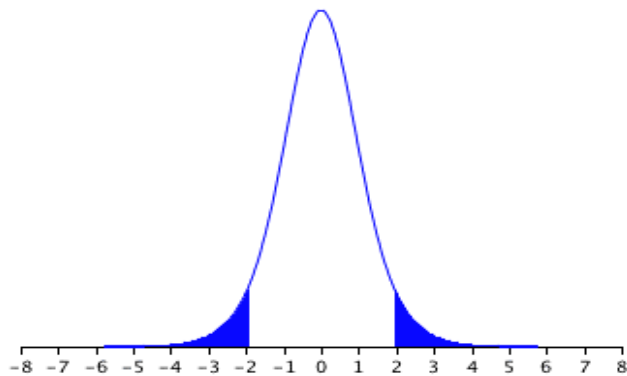


# Applying it to the long timeseries...

## Paris



t distribution with df = 8



df: 8      t: 1.96  
 One-tailed test    Two-tailed test

Shaded area: 0.0857

$$\mu_a - \mu_b = 3.3,$$

$$s = \sqrt{\frac{(N_a - 1)\sigma_a^2 + (N_b - 1)\sigma_b^2}{N_a + N_b - 2}} = 3.25$$

$$t = \frac{\mu_a - \mu_b}{s/\sqrt{N}} = 9.4,$$



Each problem its test distribution.

## 1 One-Sample tests:

1.1 mean with known variance: Z-test  $Z = \frac{\mu - \mu_0}{\sigma_0/\sqrt{n}} \sim N(0; 1)$

1.2 mean with unknown variance: T-test  $T = \frac{\mu - \mu_0}{\sigma/\sqrt{n}} \sim t_{n-1}$

## 2 Two-Samples tests:

2.1 means with unknown variances: T-test

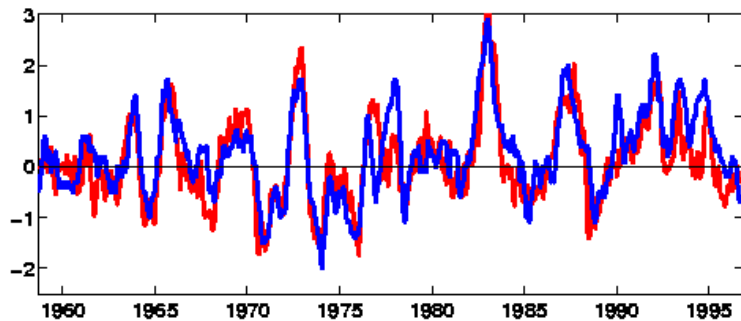
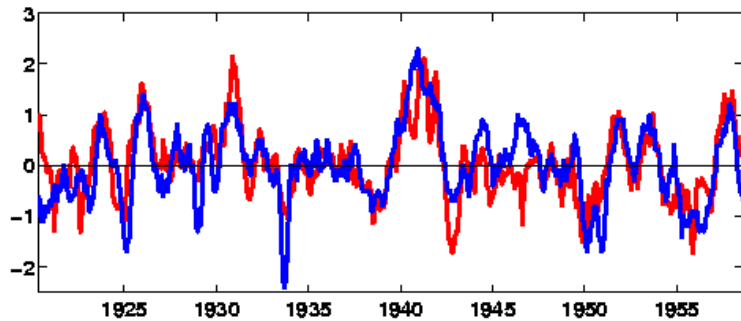
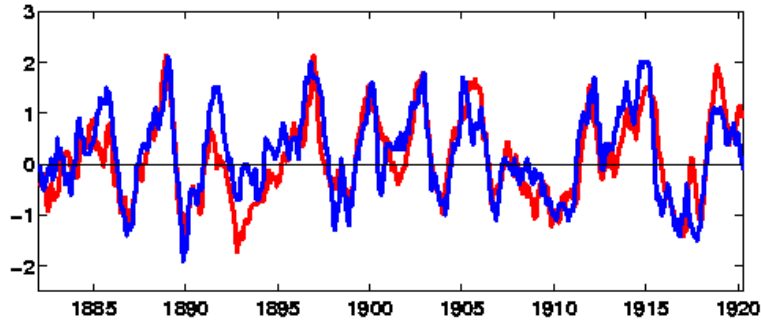
$$T = \frac{\mu_a - \mu_b}{s/\sqrt{n}} \sim t_{n_a+n_b-2}, \quad s = \sqrt{\frac{(n_a - 1)\sigma_a^2 + (n_b - 1)\sigma_b^2}{n_a + n_b - 2}}, \quad \frac{1}{n} = \frac{1}{n_a} + \frac{1}{n_b}$$

2.2 Variances: F-test,  $\chi^2$  test

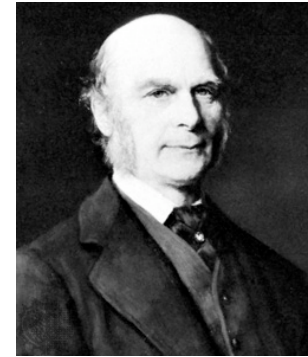
Look up your favourite statistics handbook and find your special case!!

# Are two timeseries correlated?

Darwin SLP NINO3 SST 1882 – 1996

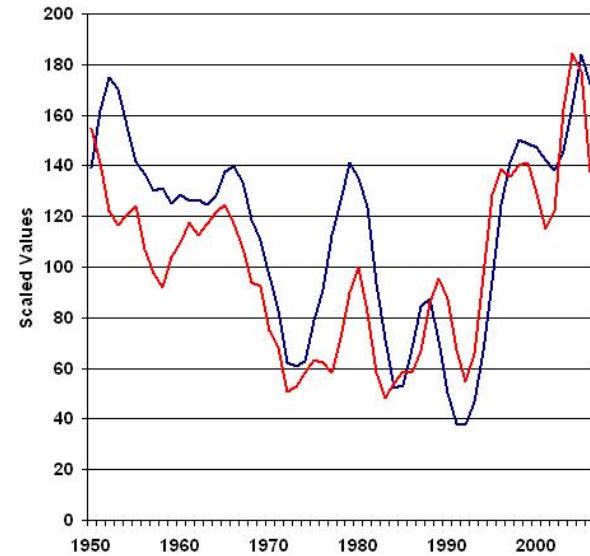


Francis Galton

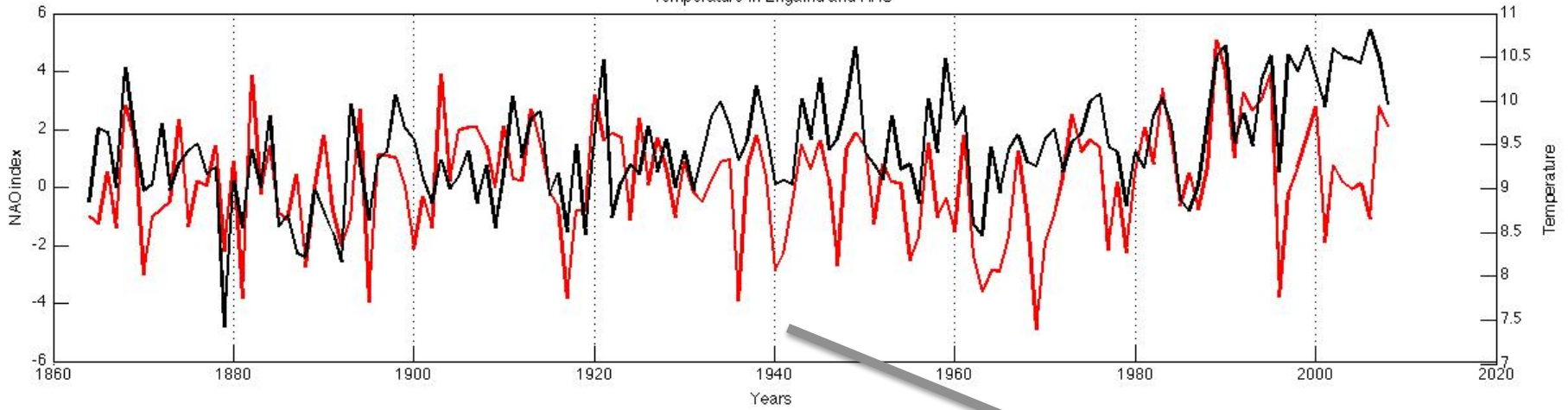


In geophysics, sometimes one wonders whether two timeseries are linked.

North Atlantic Subpolar Gyre SST and Hurricane ACE  
(1-2.3-2-1 Smoothing)

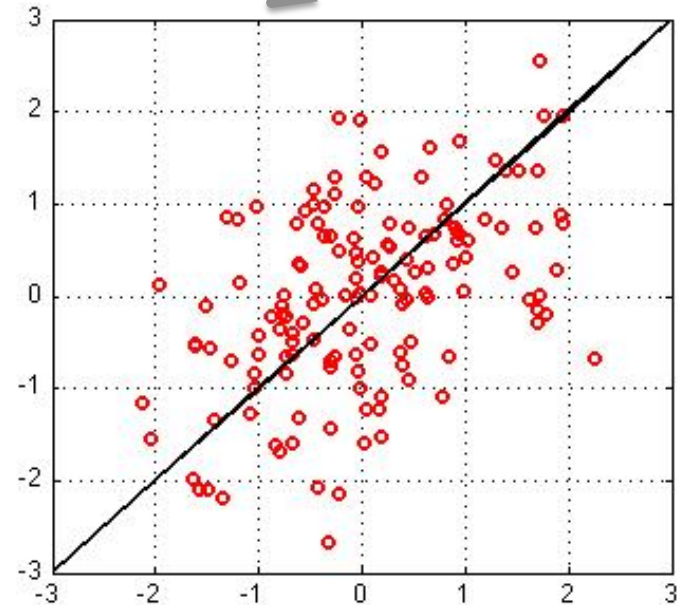
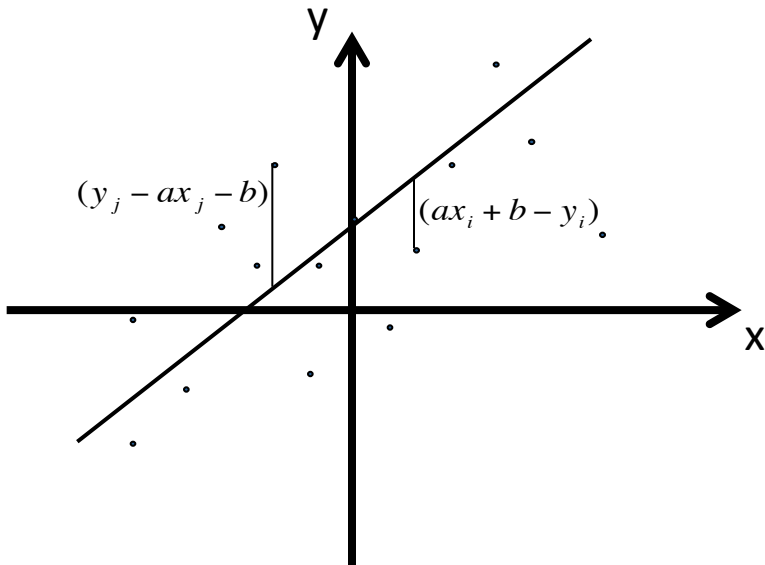


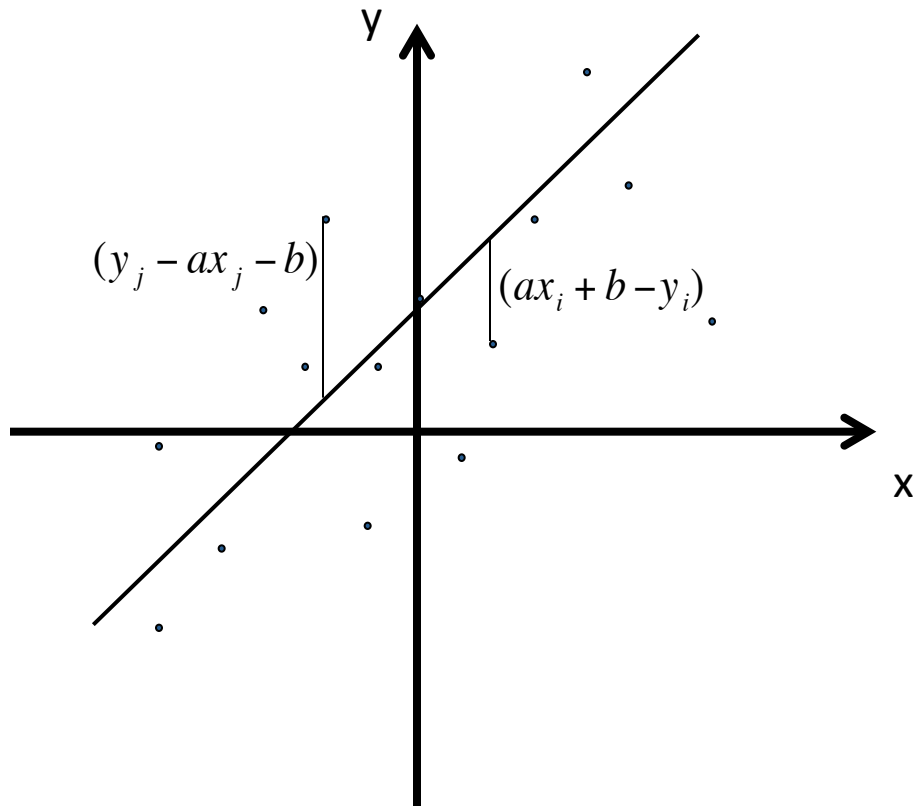
Temperature in Engalnd and NAO



One way to put it is to estimate if one series can be obtained by linear transformation from the other:

$$y_i = ax_i + b$$





We want to minimize:

$$\sum_{i=1}^N (y_i - ax_i - b)^2$$

We take the derivative with respect to  $a$  and  $b$  and we obtain the two conditions:

$$a) \quad \sum x_i (y_i - ax_i - b) = 0$$

$$b) \quad \sum (y_i - ax_i - b) = 0$$

Condition b) gives:

$$b) \quad \sum_{i=1}^N y_i - a \sum_{i=1}^N x_i - Nb = 0 \Rightarrow \boxed{b = \bar{y} - a\bar{x}}$$

Substituting b) into a) gives:

$$a) \quad \sum_{i=1}^N (y_i x_i - ax_i^2 - \bar{y}x_i - a\bar{x}x_i) = \sum_{i=1}^N (y_i' x_i' - ax_i'^2)$$

Where we have introduced the definitions :

$$x_i = \bar{x} + x', y_i = \bar{y} + y'.$$

Hence

$$a = \frac{\sum_{i=1}^N x_i' y_i'}{\sum_{i=1}^N x_i'^2}$$

Regression

$$b = \bar{y} - a\bar{x}$$

The regression is not perfect:  $\hat{y}_i = ax_i + b \neq y_i$

How good is the regression? One way to answer is to compute how much of the variance of  $y$  is explained by  $x$ .

Introducing the error  $y_i^* = y_i - \hat{y}_i$  We can write  $y_i = ax_i + b + y_i^*$

And the variance of  $y$  becomes:

$$\overline{y'^2} = \overline{a^2 x'^2} + \overline{y^{*2}} \Rightarrow \frac{\overline{a^2 x'^2} + \overline{y^{*2}}}{\overline{y'^2}} = 1$$

explained variance + unexplained variance = 1

Substituting the value of  $a$  found above we find:

$$\frac{\overline{a^2 x_i'^2}}{\overline{y_i'^2}} = \frac{(\overline{x'y'})^2}{\overline{x'^2 y'^2}} = r^2, \quad r = \frac{\overline{x'y'}}{\sigma_x \sigma_y}$$

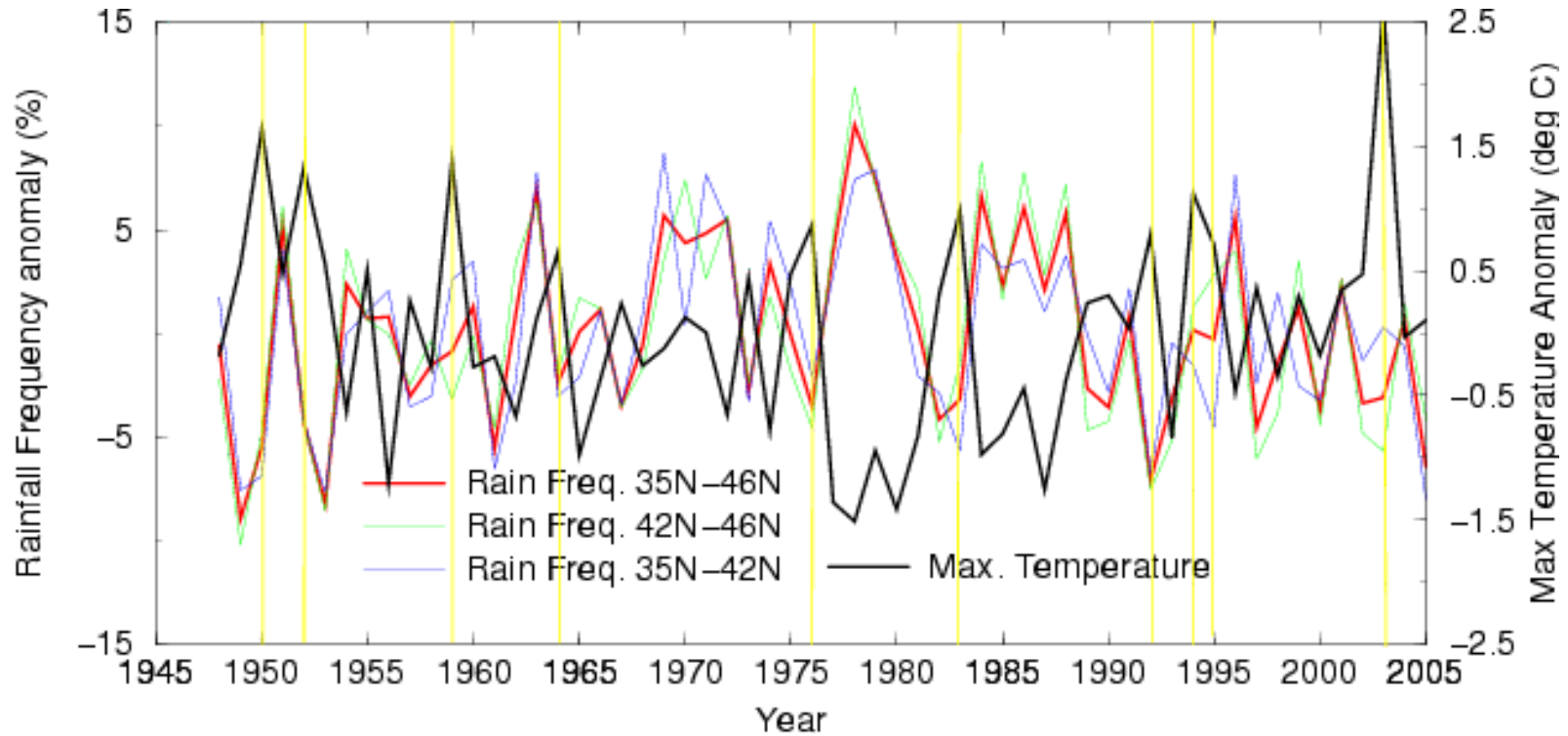
Is the (Pearson's) correlation coefficient

$$r^2 = \frac{\text{Explained Variance}}{\text{Total Variance}}; \quad 1 - r^2 = \frac{\text{Unexplained Variance}}{\text{Total Variance}}$$



Karl Pearson

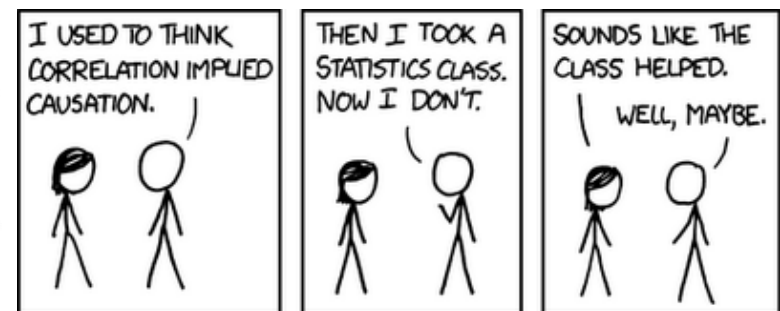
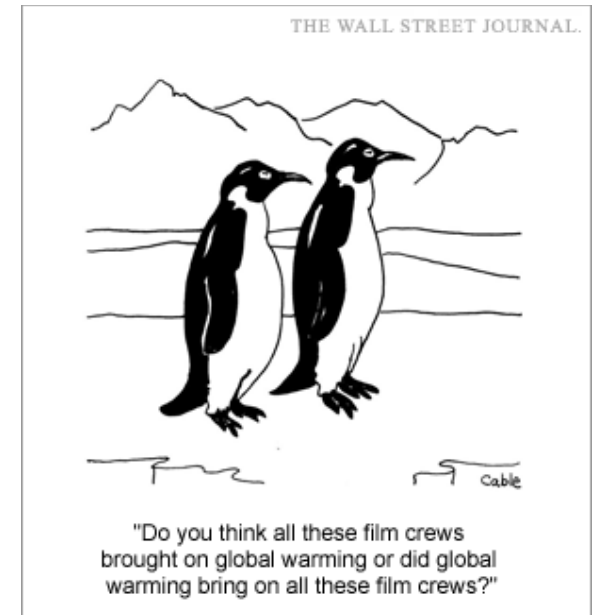
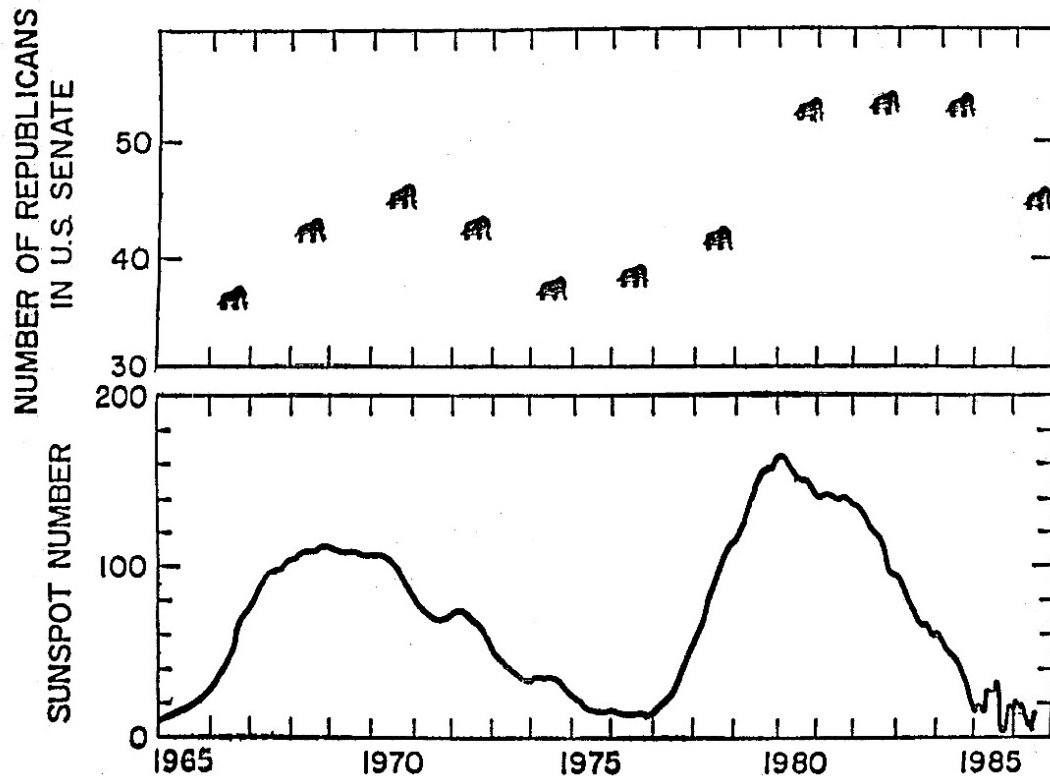
## Another example, summer heat in Europe and Mediterranean precipitations



Detrended summertime (JJA) daily maximum temperature anomalies, averaged over European stations, as a function of year (in black), together with the detrended anomaly of rainfall frequency averaged in the 35°N-46°N latitude band during preceding winter and early spring (January to May), in red. Temperature anomalies are in °C while precipitation frequencies anomalies are in % of days. The correlation between the two sets of values is  $-0.55$ . In order to assess the sensitivity of this latitude band for precipitation frequency, it is split into 2 latitude bands for which the time series are also calculated: 42°N-46°N (green) and 35°N-42°N. Yellow bars indicate the selected 10 hottest summers.

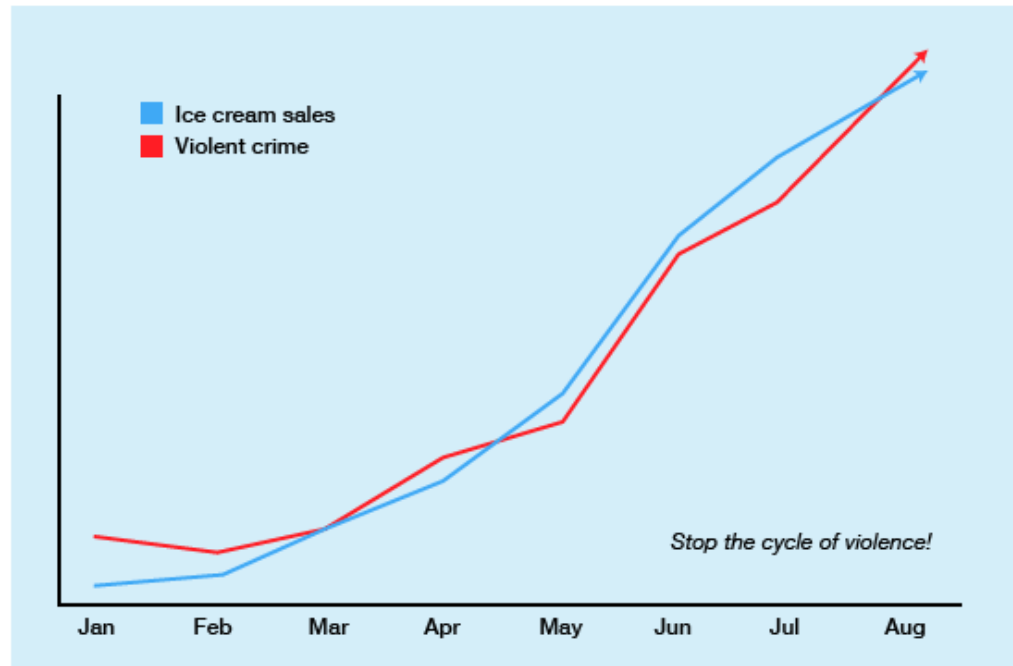
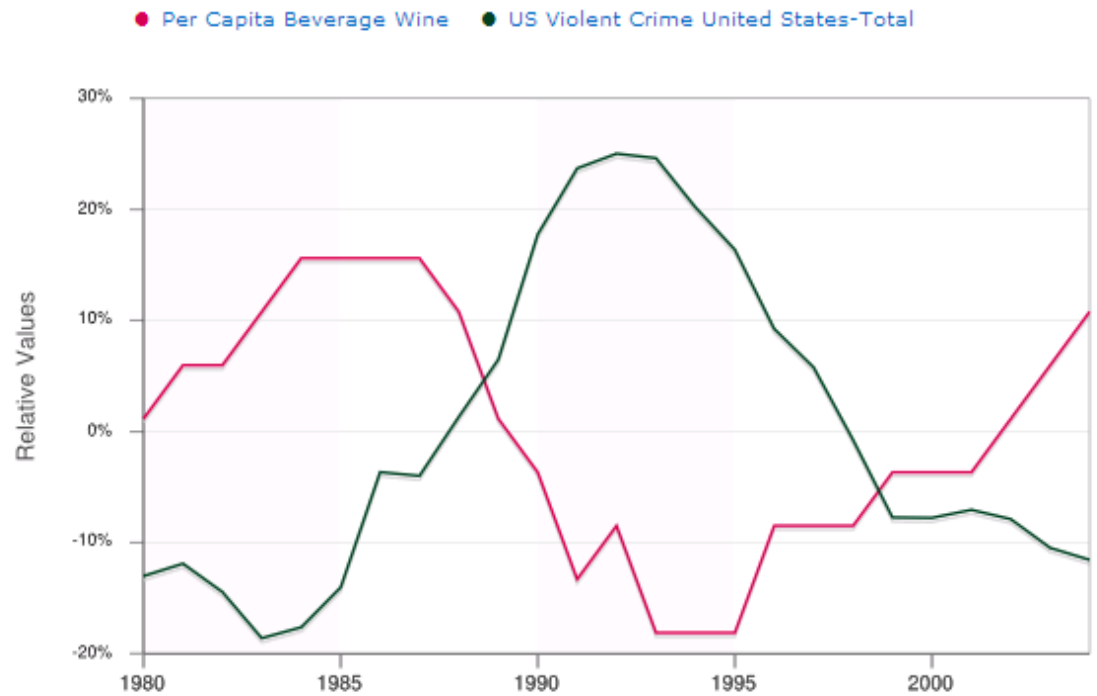
## Two cautionary notes

1. One should always check the statistical significance of the correlations one computes.
2. High correlation does NOT imply causality.



Reduce Violent crimes?

Drink wine and stop that  
Ice cream!





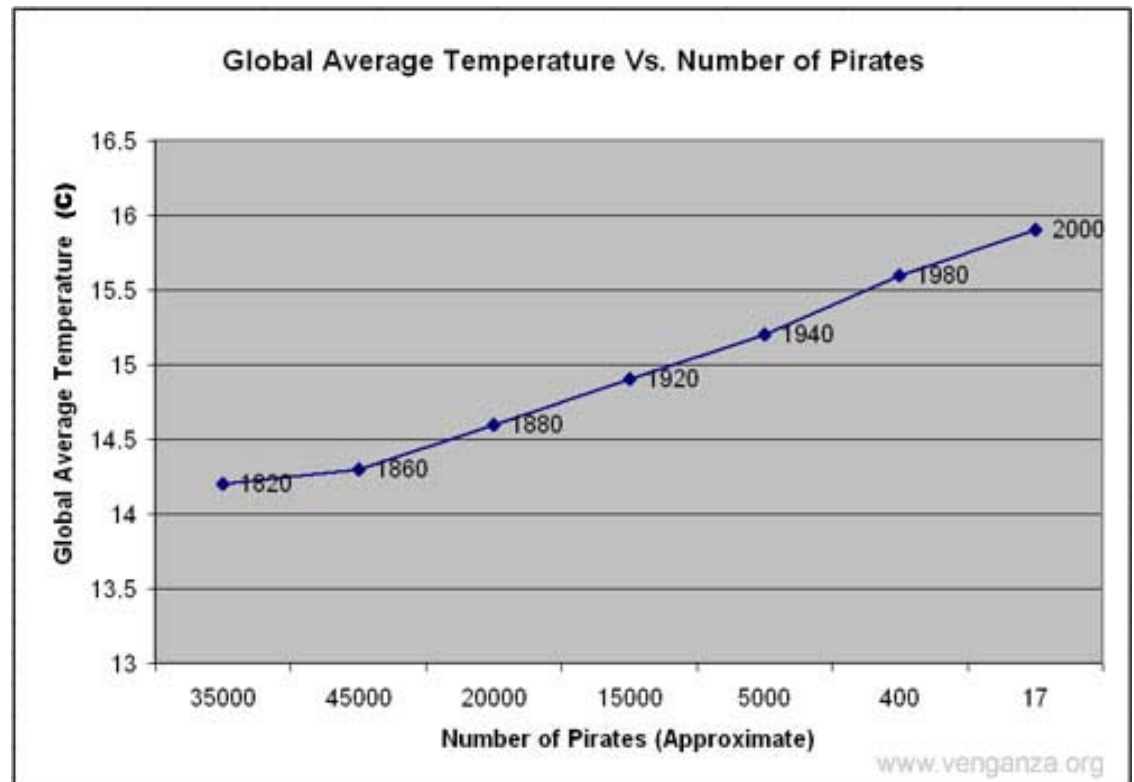
hypothesis testing:

- 1) Set up a Null Hypothesis
- 2) Chose a test statistic
- 3) Chose a level of significance
- 4) Compute the level of probability of the sample, from the test statistic
- 5) If that is lower than the level of significance, reject the null hypothesis.

In particular beware of trends:



Church of the Flying Spaghetti Monster  
<http://www.venganza.org/>

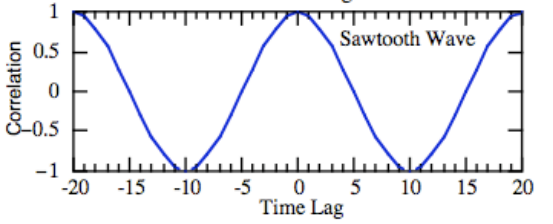
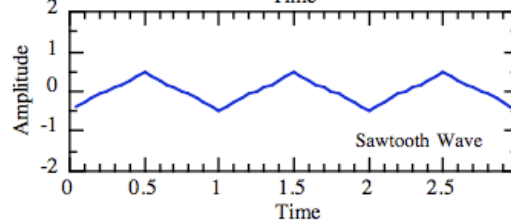
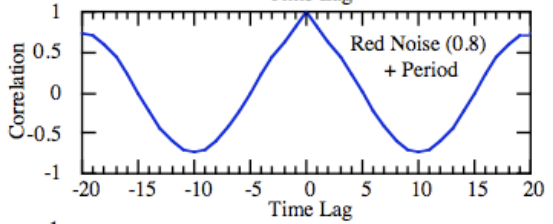
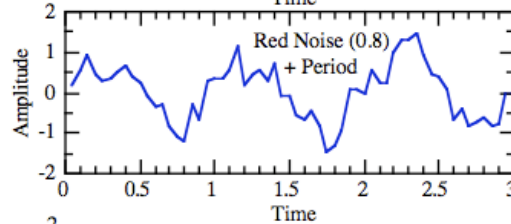
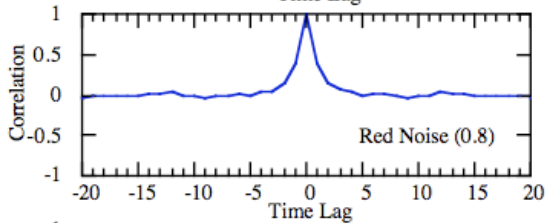
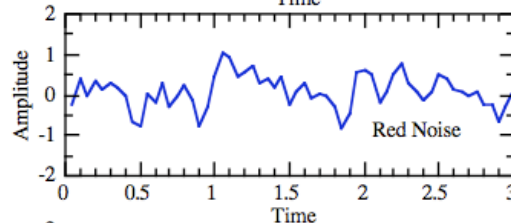
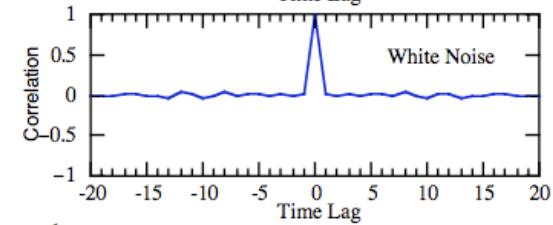
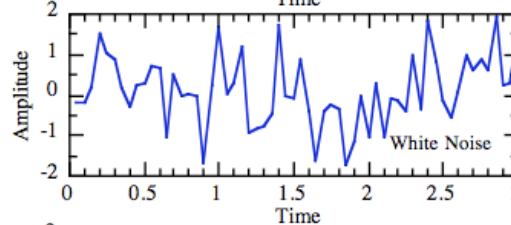
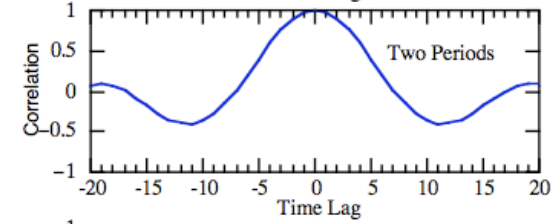
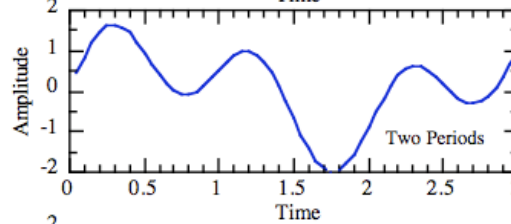
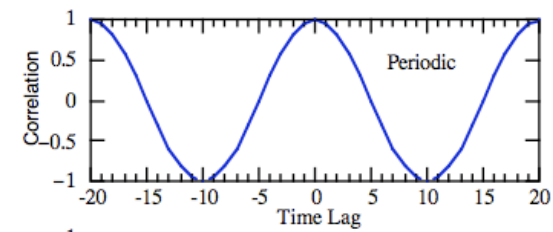
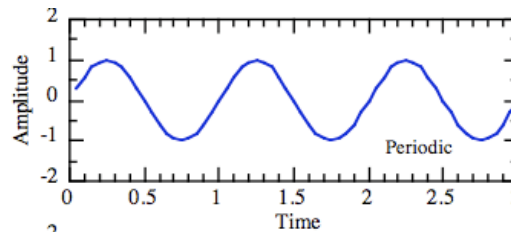


# AUTOCORRELATION

Correlation of a time series with itself.

$$\phi(L) = \frac{1}{N - 2L} \sum_{k=L}^{N-L} x'_k x'_{k+L} = \overline{x'_k x'_{k+L}}$$

$$L = 0, \pm 1, \pm 2, \dots$$



**Montecarlo methods** are a class of computational algorithms that rely on repeated random sampling to computer their results.

It is useful when one doesn't know a priori the PDF of the statistical parameter to be tested.

Example, test the correlation of two timeseries.

1) Set up null hypothesis

*The two series are not correlated*

2) Chose a test statistics

*Create 1000 random time series of the same length, mean and variance of one of the two series, estimate PDF from it.*

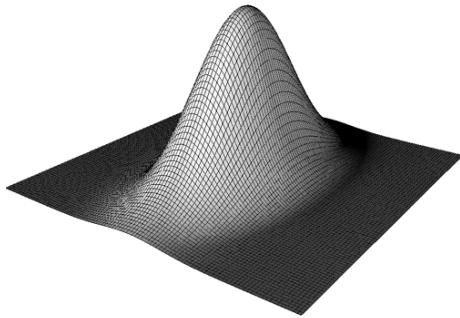
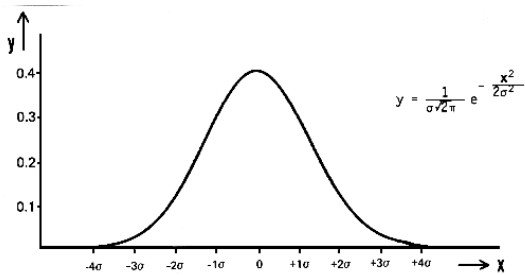
3) Chose a level of significance

4) Compute the probability of the sample

*Compare the value of the correlation of the two series with the correlation of one series with all the random ones.*

5) Reject or accept the null hypothesis.

# Analysing a vector series $\mathbf{x}(t)$



Everybody is familiar with scalar time series statistics. Mean, variance, correlation, etc.

What happens with vector time series?

The mean is easy. Let's suppose  $\bar{\mathbf{x}} = 0$

But what takes the place of variance?

The covariance matrix:  $\overline{\mathbf{x}\mathbf{x}^T}$

$$C = \begin{pmatrix} \overline{x_1x_1} & \overline{x_1x_2} & \dots & \dots & \overline{x_1x_N} \\ \overline{x_2x_1} & \overline{x_2x_2} & \dots & \dots & \overline{x_2x_N} \\ \vdots & & \ddots & & \vdots \\ \vdots & & & \ddots & \vdots \\ \overline{x_Nx_1} & \overline{x_Nx_2} & \dots & \dots & \overline{x_Nx_N} \end{pmatrix}$$

$C$  gives the variance of the sample in any given direction in phase space.  
So if  $\mathbf{e}$  is a unitary vector,

$$\mathbf{e}^T C \mathbf{e}$$

is the variance in the direction  $\mathbf{e}$ .