

# Advanced Statistics 4 Physics Analysis

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## Course Timetable

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- **6 CFU**: 4 hours/week → 12 full weeks
  - **Wednesday**: Lab P104, 8:30 – 10:15, hands-on R laboratory sessions
  - **Thursday**: Aula C, 12:30 – 14:15, theory lecture
- Course MOODLE Web Pages:
  - <https://elearning.unipd.it/dfa/course/view.php?id=1061>

Week		Mon	Tue	Wed	Thu	Fri
1	Monday, 1 March 2021				Stat01	
2	Monday, 8 March 2021			R01	R02	
3	Monday, 15 March 2021			R03	R04	
4	Monday, 22 March 2021			R05	Stat02	
5	Monday, 29 March 2021			RLab01	Stat03	
6	Monday, 5 April 2021			RLab02	Stat04	
7	Monday, 12 April 2021			RLab03	Stat05	
8	Monday, 19 April 2021			RLab04	Stat06	
9	Monday, 26 April 2021			RLab05	Stat07	
10	Monday, 3 May 2021			RLab06	Stat08	
11	Monday, 10 May 2021			RLab07	Stat09	
12	Monday, 17 May 2021			RLab08	R06	
13	Monday, 24 May 2021			R07	Stat10	
14	Monday, 31 May 2021			Stat11	?	
15	Monday, 7 June 2021			?	?	

# Course Program and Structure

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## → Part I:

- introduction to deductive logic and plausible reasoning
- review of discrete probability distributions
- review of continuous probability distributions
- sampling of random variables and Monte Carlo methods

## → Part II:

- statistical models and inference: parameter estimation
- linear models
- model selections
- Markov Chain Monte Carlo and Gibbs sampling
- Bayesian Networks

## → Part III (in parallel to I and II):

- R language structure and R libraries will be presented and used to solve exercises complementing the theory part

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## Laboratory Assignments and Exam

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- during **each laboratory session**, a **set of exercises** will be **assigned**
- you will have to **complete the assignments** at home and **deliver them** in due time (within **2 weeks after each laboratory session**)

### Exam

- the final exam is made of two parts:
  - a **written test** with questions and small R exercises
  - a R computational problem will be assigned to each group of two-three students and the used techniques and the obtained results will be discussed in an **oral group presentation**
- the **final vote** will be a combination of three parts:

$$\text{Final Mark} = \frac{1}{3}\text{LaboratoryAssignments} + \frac{1}{3}\text{WrittenTest} + \frac{1}{3}\text{GroupProjectOralPresentation}$$

- all **lectures** and **laboratory sessions** will be given in presence
  - aula C for the theory/R lectures
  - Lab P104 for the R and Laboratory sessions
- **participation from remote will be possible through ZOOM**
- **lectures will be recorded** and made accessible offline

## Coronavirus - teaching resumes via electronic mode, research and services open to the public

The University of Padua will postpone the semester courses until March 9 and start the quarterly courses electronically starting from Monday, March 2. While exams and degrees electronically resume, University study rooms and libraries will remain closed by the moment. Library services are available online.



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## Statistics and Probability

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What is the meaning of Statistics ?

### Descriptive Statistics

- it refers to methods for summarizing and organizing the information in a data set
- it uses numbers, graphs and tables to describe data sets, as a first step of data analysis

### Probability Theory

- Probability theory is the branch of mathematics concerned with probability
- as a mathematical foundation for statistics, probability theory is essential to many activities involving quantitative analysis of data
- Methods of probability theory also apply to descriptions of complex systems given only partial knowledge of their state, as in statistical mechanics

### Inference

- statistical inference consists of methods for estimating and drawing conclusions about population characteristics based on the information contained in a subset (sample) of that population

→ **learning by data**

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# Probability and Inference

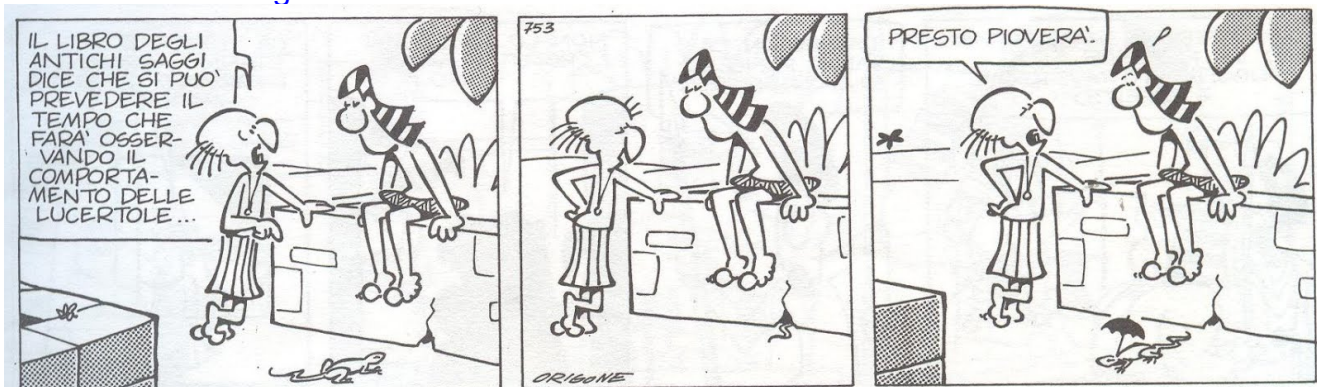
- probability theory is the **doctrine of chances**
  - a branch of mathematics that tells us how often different kind of events will happen:
    - what are the chances of a fair coin coming up heads 10 times in a row ?
    - if two six sided dice are rolled, how likely is to get 1-1 ?
  - all these probabilistic questions start with a **known model of the world** and we use the model to perform some calculations
  - **in probability theory, the model is known but data are not**
  - statistical questions work the other way around:  
we do not know the truth about the world, and we want to know it from the data:
    - I flip a coin 10 times and get 10 heads, is the coin fair ?
    - while drawing 5 cards from a deck I get all hearts, how likely is that the deck had been shuffled ?
- **statistical inference** questions are not the same as **probability** questions, but they are **deeply connected to one another**

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## Logic, Probability and Uncertainty

- **most of the situations** we deal with in **everyday life** are **not** completely **predictable**
  - Q: will it rain today, at 14:30, when I will be done with my lecture and go home for lunch ?
  - A: **gather information** : weather forecast, look at the sky, ...
  - despite the forecast I could get soaked going home
- ▷ but ... **there is always uncertainty**
- therefore, since **we cannot eliminate uncertainty, we need to model it**
- when faced with uncertainty, we use **plausible reasoning**
- we adjust our **belief about something**, based on **the occurrence or non-occurrence of something**



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# Plausible Reasoning

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- the policeman, the gentleman, and the jewelry shop broken window

[E. T. Jaynes, *Probability Theory, The Logic of Science*, Cambridge Univ. Press., 2003]

- after having seen the masked gentleman, with a bag, crawling out of a broken jewelry shop window, the policeman thinks - with no doubts - that the gentleman is a thief

- BUT ... the policeman's conclusion is NOT logical deduction from evidence

- there may be a perfectly innocent explanations:

- the gentleman owns the jewelry shop
- he just came home from a masquerade party and he had left his shop keys at home
- a truck just passed and threw a stone on the window shop, breaking it

→ the gentleman was just protecting his own property

- the policeman's reasoning process was not logical deduction, but it had a certain degree of validity

→ the evidence did not make the gentleman's dishonesty certain, but it did make it extremely plausible

# Plausible Reasoning

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- the formulation of plausible conclusions is a very subtle process
- we have examples of contrast between deductive reasoning and plausible reasoning

weak syllogisms:

if A is true, then B is true

but, if B is true, therefore A becomes more plausible

- in other words:
  - the evidence does not prove that A is true
  - verification of one of its consequences does give us more confidence in A

## Example

- A  $\equiv$  it will start to rain today by 14:30 at the latest
- B  $\equiv$  the sky will become cloudy before 14:30
- observing clouds at 14:15 does not give us a logical certainty that rain will follow
- nevertheless our commons sense induce us to take an umbrella, or stay inside, if the clouds are sufficiently dark

# Plausible reasoning

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- in spite of the apparent weakness of its argument, we recognize that **the policeman's conclusion has a very strong convincing power**
- ➔ **our brain**, in doing plausible reasoning, **evaluates the degree of plausibility**, in some way
- the plausibility of **rain at 14:30** depends very much on the **darkness of the clouds at 14:15**
- the brain makes use of old information as well as specific new data ➔ before deciding what to do, we try to recall our past experience with clouds and rain (and of last night's weather forecast on the news)
- the policeman was also making use of the **past experience of policemen** in general

*In our reasoning we depend very much on prior information to help us evaluating the degree of plausibility in a new problem. This reasoning process goes on unconsciously, almost instantaneously, and we conceal how complicated it really is by calling it **common sense*** .

[E. T. Jaynes, *Probability Theory, The Logic of Science*, Cambridge Univ. Press., 2003]

- ➔ **we also learn with new situations and data**

## Decision theory and *uncertainty*

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- **we are uncertain whenever we do not know what to do**
- we may be uncertain because we do not have enough information to know just what we should do
- sometimes we learn new information and decide that if we had this piece of information at the time, we would have acted differently
- some people say "if the outcome was unsatisfactory, the decision was obviously wrong". Their point is the following: **"whether a decision was RIGHT or WRONG, is to be decided entirely on the results of the decision and not on the basis of the information available at the time the decision was taken"**

### Example

- you get the following offer:
  - you pick up a coin from your pocket and toss it ten times
  - if you get at least one Head you get 200 € , if not you pay 1 €
- you accept the bet and you lose. Was it a wrong decision ?
- given the chance, would you make the same wrong decision again ?

- of course you would bet again!
  - the odds in favor are roughly 1024 to 1
- the conclusion is that you made a **good decision**, but you had a **bad outcome**
- if a decision involves a risk, it is always possible that a **good decision** can lead to a **bad outcome**. This is the meaning of **risk**
- if all is known about a situation, our knowledge is **deterministic**
- on the other hand, if we have some uncertainties, the reasoning is **inductive**, that is, it requires **inductive logic** for finding the best solution

→ the important aspect is that **we do not know everything**, but **we do know something**

## Statistical Inference

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- it is of primary interest to physicists and engineers
  - and it allows to learn about **theory or models** from **experimental observations**
- ▷ **inference has to be based on probability theory**
- and summaries of descriptive statistics can be used in cases in which statistical sufficiency holds, i.e. when sample arithmetic average and standard deviation are used instead of the  $n$  data points



# How to Measure Plausibility

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- suppose we try to **use numbers to measure plausibility of propositions**
- when we change our plausibility for some propositions, based on the occurrence of some other proposition, we are performing an **induction**

## Properties of Plausibility Measures

- **degrees of plausibility** are represented by **non-negative real numbers**
- they qualitatively agree with common sense: **larger values mean greater plausibility**
- if a proposition can be represented in more than one way, **all representations must give the same plausibility**
- we must **always take all the relevant evidence into account**
- equivalent states of knowledge are always given the same plausibility
- a sensible way to **revise plausibility** is **by using the rules of probability**
- **probability is used as an extension of logic** to cases where deduction cannot be made

## The adopted Language

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### a **Proposition**

- must have an **unambiguous meaning**
- must be of a **simple logical type**, i.e. **true or false**
- given two propositions, **A**, and **B**

$$A \cdot B$$

- is called **logical product** or conjunction and denotes the proposition: both A and B are **true**
- the order does not matter:  $A \cdot B$  and  $B \cdot A$  say the same thing

$$A + B$$

- is called **logical sum** or disjunction and stands for at least one of the propositions A, B are **true**
- the order does not matter:  $A + B$  brings the same information of  $B + A$

$$A = B$$

- means that the proposition on the left side has **the same truth value** as that on the right side

$$\bar{A}$$

- indicated the denial of a proposition, i.e. if A is **true**,  $\bar{A}$  is **false**, and vice versa



# Probability and Random Experiments

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- we borrow examples from theory of games: in a random experiment (i.e. dice draw, coin tossing, ...) the outcome is uncertain

## Definitions

- **Random experiment** : an experiment with an outcome not completely predictable. When we repeat the experiment we may get a different result (e.g. coin tossing)
- **Outcome** : the result of a single trial of the experiment
- **Sample space** : the set of all possible outcomes of one single trial of the experiment. It is usually denoted by  $\Omega$ . The sample space containing everything we are considering in the analysis of the experiment is called **Universe**
- **Event** : any set of possible outcomes of the experiment

Given two events,  $E$  and  $F$ , we can construct

- **Union of the events** : is the set of outcomes in either  $E$  or  $F$  (inclusive or)
- **Intersection of the events** : is the set of the outcomes in both  $E$  and  $F$ , simultaneously
- **Complement of an event** : is the set of all outcomes not in  $E$

## Axiomatic Definition of Probability

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- probabilities are real numbers between 0 and 1
- the higher the probability, the more likely it is to occur
- a probability equals to 1 means the event is certain to occur
- a probability of 0 means that the event cannot possibly occur

You know it all from  
Probability Theory

The following axioms are satisfied

- 1)  $P(A|I) \geq 0$  for any event  $E$
- 2)  $P(U|I) = 1$ , is the probability of the universe (it means that some outcome occurs every time the experiment is performed)
- 3)  $P(AB|I) = P(A|B, I) \cdot P(B|I) = P(B|A, I) \cdot P(A|I)$  (PRODUCT RULE)

Other properties, derived from the Axioms

- 1)  $P(\emptyset) = 0$
- 2)  $P(\bar{A}|I) = 1 - P(A|I)$  (NORMALIZATION)
- 3)  $P(A + B|I) = P(A|I) + P(B|I) - P(AB|I)$  (SUM RULE)
- 4)  $P(A|I) = P(A, B|I) + P(A, \bar{B}|I)$  (MARGINALIZATION)

# All Probabilities are Conditional

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- whenever we talk about probability, we always use the symbol

$$P(A|I)$$

- and never  $P(A)$
- $I$  is the background condition, related to information we have
- because it makes no sense to talk about the probability of the truth of the statement  $A$  without being explicit about the conditions upon which the assignment of probability is based
- we are engaged in a chain of inductive logic and at each point where an answer is required, we shall report the best inference we can make based upon the evidence available to that point
- as new evidence becomes available, we shall use the same procedure to update our inferences
- it is therefore an iterative process until evidence is so overwhelming that it does not seem worthwhile to pursue the matter any further

## A note on the English Language

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### ► Ordinary language is not precise

one of the most ambiguous word in the language is OR

- As an example, the statement: "*This is a ceramic or a conductor*" may be represented at least in two ways.

Let's define:

- proposition  $A$ : "it is a ceramic"
- proposition  $B$ : "it is a conductor"

inclusive  
↓

exclusive  
↓

- the sentence can be represented by  $(A + B)$  or by  $(A\bar{B} + \bar{A}B)$
- because it is not clear if the word *or* is used in the inclusive or exclusive sense
  - if we say  $A + B$  and we mean  $(A + B)$ , the word *or* is used in the inclusive sense
  - instead if  $A + B$  is meant by  $(A\bar{B} + \bar{A}B)$ , the word *or* is used in the exclusive sense
- similarly the equal sign does not mean that two statements mean the same thing, but only that they have the same truth table

# Independent versus Mutually Exclusive Events

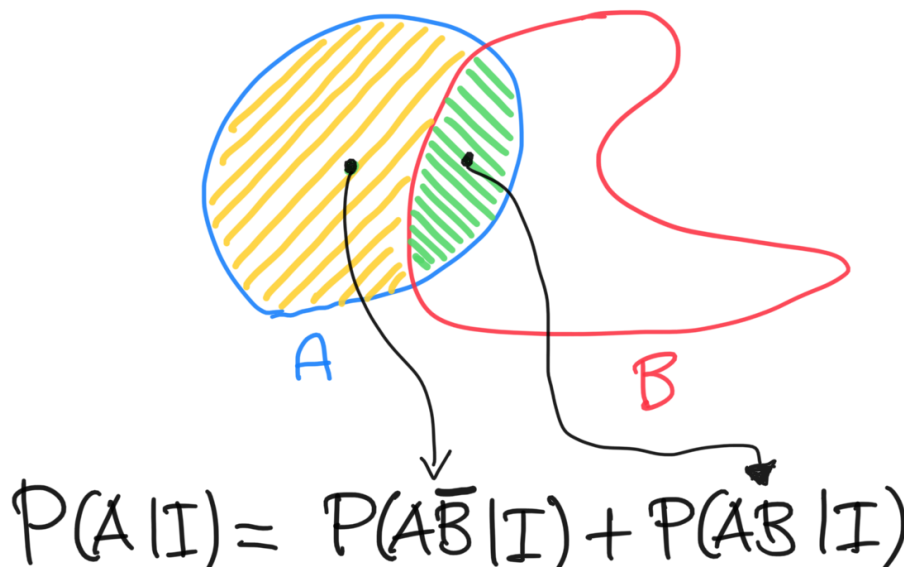
- a semantic confusion may arise because the word **independent** has several meanings
- primary meaning : **two events are independent if the occurrence of the first does not affect the occurrence or non-occurrence of the second**
- For independent events,  $P(A|B, I) = P(A|I)$ , therefore  $P(AB|I) = P(A|I)P(B|I)$
- **independence of two events is not a property of the events themselves**, but it comes from the probabilities of the events and their intersection
- if  $A$  and  $B$  are **mutually exclusive events**, (i.e. they have no outcome in common),  $P(A + B|I) = P(A|I) + P(B|I)$
- **mutually exclusive events** contain no elements in common, and this **is a property of the events**

## Laplace's "Bayes Theorem"

### Marginal Probability

- The marginal probability of one event is found by summing its disjoint parts:

$$P(A|I) = P(AB|I) + P(A\bar{B}|I)$$



# Laplace's "Bayes Theorem"

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## Marginal Probability

- The marginal probability of one event is found by summing its disjoint parts:

$$P(A|I) = P(AB|I) + P(A\bar{B}|I)$$

## Bayes' Theorem : 1

- from the definition of the probability of the intersection of two events

$$P(AB|I) = P(A|B, I)P(B|I) = P(B|A, I)P(A|I)$$

- we can re-write one of the two equalities as:

$$P(B|A, I) = \frac{P(AB|I)}{P(A|I)}$$

- and making use of the marginalized expression for  $P(A|I)$

$$P(B|A, I) = \frac{P(AB|I)}{P(AB|I) + P(A\bar{B}|I)}$$

# Laplace's "Bayes Theorem" : 2

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- we now use the product rule to find each of the joint probabilities

$$P(B|A, I) = \frac{P(A|B, I)P(B|I)}{P(A|B, I)P(B|I) + P(A|\bar{B}, I)P(\bar{B}|I)}$$

- Bayes' theorem is a restatement of the original product rule in terms of the  $P(B|A)$  probability, where
  - 1) the probability of  $A$  is found as the sum of the probabilities of its disjoint parts  $AB$  and  $A\bar{B}$
  - 2) each of the joint probabilities are found using the multiplication rule
- it is important to notice that:
  - 1) the union of  $B$  and  $\bar{B}$  is the whole universe
  - 2) and they are disjoint

# Partition and Marginalization

- let's imagine that we have a set of more than two events that partition the universe:

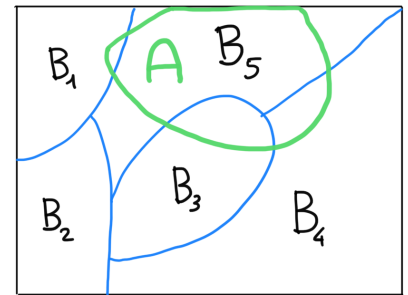
$$U = B_1 \cup B_2 \cup \dots \cup B_n$$

- and every distinct pair of the events are disjoint

$$B_j \cap B_i = \emptyset, \text{ with } j \neq i$$

- an observable event  $A$  will be partitioned into parts

$$A = \bigcup_{j=1}^n (A \cap B_j)$$



- and therefore

$$P(A|I) = \sum_{j=1}^n P(AB_j|I) = \sum_{j=1}^n P(A|B_j, I)P(B_j|I)$$

- where we have used the product rule on each joint probability

## Laplace's "Bayes Theorem" : 3

- finally, the conditional probability  $P(B_j|A, I)$  is found by dividing each joint probability by the probability of the event  $A$ , partitioned over all  $B_j$

$$P(B_j|A, I) = \frac{P(A|B_j, I)P(B_j|I)}{\sum_{j=1}^n P(A|B_j, I)P(B_j|I)}$$

- this is known as [Bayes' theorem](#)
- it was published posthumously in 1763 after the death of its discoverer, Reverend Thomas Bayes
- Pierre-Simon Laplace reproduced and extended Bayes's results in 1774, apparently unaware of Bayes's work
- [The Bayesian interpretation of probability was developed mainly by Laplace](#)

### Note that

- the events  $A$  and  $B_j$ , ( $j = 1, \dots, n$ ), are not treated symmetrically :
  - $A$  is an observable event
  - $B_j$  are considered not observable. We never know which one of them occurred
- The marginal probabilities  $P(B_j)$  are assumed known before we start and are called our prior probabilities

# Interpretation of the Laplace's "Bayes Theorem"

- we often write Bayes' in its proportional form as

$$P(B_j|A, I) \propto P(A|B_j, I) \cdot P(B_j|I)$$

Diagram illustrating the components of Bayes' Theorem:

- posterior** (points to  $P(B_j|A, I)$ )
- likelihood** (points to  $P(A|B_j, I)$ )
- prior** (points to  $P(B_j|I)$ )

- this gives the relative weights for each of the events  $B_j$ , after we know  $A$  has occurred
- dividing by the sum of the relative weights it re-scales the relative weights, they now sum to 1  $\rightarrow$  making it a probability distribution

$$P(B_j|A, I) = \frac{P(A|B_j, I)P(B_j|I)}{\sum_{j=1}^n P(A|B_j, I)P(B_j|I)}$$

## Exercise 1

- a new medical diagnostic test for a specific disease comes to market
- the **sensitivity** of the test, i.e. the probability the test gives a positive response if a person has the disease is 0.95
- the **specificity**, i.e. the probability that the test gives a negative response if a person does not have the disease, is 0.90
- ↘ this allows to evaluate the **false positive rate** to 0.10 (i.e. the probability that the test gives a positive response if a person does not have the disease)
- we know that **1% of the population**, in Italy, **has the disease**
- ➔ **What is the probability that a person has the disease, given the fact that the test gives a positive response ?**

- we define the following propositions:  
 $D :=$  a person has a disease  
 $T :=$  the test gives a positive result

- and the data tell us  
 $P(T|D, I) = 0.95$   
 $P(\bar{T}|\bar{D}, I) = 0.90$   
 $P(D|I) = 0.01$

# Contingency Tables

- it's a method of **keeping track** of the various **probabilities**, and seeing how to compute one from another
- the following example shows a  $2 \times 2$  table of probabilities involving two statements **A** and **B** :

	$B$	$\bar{B}$	
$A$	$P(AB I) = \omega_1$	$P(A\bar{B} I) = \omega_2$	$P(A I) = \omega_1 + \omega_2$
$\bar{A}$	$P(\bar{A}B I) = \omega_3$	$P(\bar{A}\bar{B} I) = \omega_4$	$P(\bar{A} I) = \omega_3 + \omega_4$
	$P(B I) = \omega_1 + \omega_3$	$P(\bar{B} I) = \omega_2 + \omega_4$	1

## Exercise 1, Solution

- the initial data give:  $P(T|D, I) = 0.95$ ,  $P(\bar{T}|\bar{D}, I) = 0.90$  and  $P(D|I) = 0.01$

- we build a contingency table with the propositions:

$D$  := a person has a disease

$T$  := the test gives a positive result

	$T$	$\bar{T}$	
$D$	0.0095	0.0005	0.01
$\bar{D}$	0.099	0.891	0.99
	0.1085	0.8915	1

- we deduce:  $P(\bar{D}|I) = 1 - P(D|I) = 0.99$  and  $P(T|\bar{D}, I) = 1 - P(\bar{T}|\bar{D}, I) = 0.05$

-  $P(DT|I) = P(T|D, I) \cdot P(D|I) = 0.95 \times 0.01 = 0.0095$

-  $P(D\bar{T}|I) = P(D|I) - P(DT|I) = 0.01 - 0.0095 = 0.0005$

-  $P(\bar{D}T|I) = P(T|\bar{D}, I) \cdot P(\bar{D}|I) = P(T|\bar{D}, I)(1 - P(D|I)) = 0.1 \times 0.99 = 0.099$

-  $P(\bar{D}\bar{T}|I) = P(\bar{D}|I) - P(\bar{D}T|I) = 0.99 - 0.099 = 0.891$

- finally,

$$P(T|I) = P(DT|I) + P(\bar{D}T|I) = 0.1085 \text{ and } P(\bar{T}|I) = P(D\bar{T}|I) + P(\bar{D}\bar{T}|I) = 0.8915$$



# Exercise 1, Solution

- the initial data give:  $P(T|D, I) = 0.95$ ,  $P(\bar{T}|\bar{D}, I) = 0.90$  and  $P(D|I) = 0.01$

- we build a contingency table with the propositions:

$D$  := a person has a disease

$T$  := the test gives a positive result

	T	$\bar{T}$	
D	0.0095	0.0005	0.01
$\bar{D}$	0.099	0.891	0.99
	0.1085	0.8915	1

- let's apply Bayes' theorem:

$$P(D|T, I) = \frac{P(T|D, I)P(D|I)}{P(T|I)}$$

- the normalization factor is

$$\begin{aligned} P(T|I) &= P(T|D, I)P(D|I) + P(T|\bar{D}, I)P(\bar{D}|I) \\ &= 0.95 \times 0.01 + 0.10 \times 0.99 = 0.1085 \end{aligned}$$

- and the final answer is:

$$P(D|T, I) = \frac{0.0095}{0.1085} = 0.0876$$

## Exercise 2

- a new medical screening procedure for a specific cancer is introduced
- the screening has:  
sensitivity = 0.90, and specificity = 0.95
- suppose the underlying rate of the cancer in the population is 0.001

→ What is the probability that a person has the disease given the results of the screening is positive ?

→ Does this show that screening is effective in detecting this cancer ?

- we define the following propositions:  
 $B$  := a person has a specific cancer  
 $A$  := the screening has positive result

- and the data tell us  
 $P(A|B, I) = 0.90$   
 $P(\bar{A}|\bar{B}, I) = 0.95$   
 $P(B|I) = 0.001$

## Exercise 2, Solution

- the initial data give:  $P(A|B, I) = 0.90$ ,  $P(\bar{A}|\bar{B}, I) = 0.95$  and  $P(B|I) = 1 \cdot 10^{-3}$

$B$  := a person has a specific cancer

$A$  := the screening has positive result

	A	$\bar{A}$	
B	$9 \cdot 10^{-4}$	$1 \cdot 10^{-4}$	$10 \cdot 10^{-4}$
$\bar{B}$	0.050	0.949	0.999
	0.051	0.949	1

### Calculations

- given sensitivity and specificity,  $P(A|\bar{B}, I) = 1 - 0.95 = 0.05$
- $P(AB|I) = P(A|B, I)P(B|I) = 0.90 \times 0.001 = 9 \cdot 10^{-4}$
- $P(\bar{A}\bar{B}|I) = P(\bar{A}|\bar{B}, I)P(\bar{B}|I) = 0.05 \times 0.999 = 0.050$

$$\begin{aligned}
 P(A|I) &= P(AB|I)P(B|I) + P(\bar{A}\bar{B}|I)P(\bar{B}|I) \\
 &= 9 \cdot 10^{-4} \times 10 \cdot 10^{-4} + 0.04995 \times 0.999 = 0.051
 \end{aligned}$$

- Bayes' theorem tells us that

$$P(B|A, I) = \frac{P(A|B, I)P(B|I)}{P(A|I)} = \frac{9 \cdot 10^{-4}}{0.05} = 0.018$$

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## Odds Ratios

- another way of dealing with uncertain events we are modeling is to form the **odds ratio** of the event:

$$\text{odds}(A|I) = \frac{P(A|I)}{P(\bar{A}|I)}$$

- since  $P(\bar{A}|I) = 1 - P(A|I)$ ,

$$\text{odds}(A|I) = \frac{P(A|I)}{1 - P(A|I)}$$

- if we are using **prior probabilities**, we get the **prior odds ratio**
- if, instead, if we are using **posterior probabilities**, we get the **posterior odds ratio**
- solving the equation for the probability of the event  $A$ , we get

$$P(A|I) = \frac{\text{odds}(A|I)}{1 + \text{odds}(A|I)}$$

# Assigning probabilities: 1

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- so far we have derived **consistent rules** that can be used **to manipulate probabilities**, associated to real numbers
- but **nothing tell us what actual numerical value we should assign** at the beginning of a problem
- Suppose we have  **$n$  propositions  $A_j, j = 1, \dots, n$** , and **at least one of them is true**
- In addition, let's suppose that they are mutually exclusive, i.e.

$$P(A_i A_j | B) = P(A_i | B) \delta_{ij}$$

- therefore

$$P(A_1 + A_2 + \dots + A_m | B) = \sum_i^m P(A_i | B), \text{ with } 1 \leq m \leq n$$

- we add the hypothesis that the propositions are also exhaustive, the background information  $B$  stipulates that one and only one of them must be true. Therefore:

$$\sum_{i=1}^n P(A_i | B) = 1$$

# Assigning probabilities: 2

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## Problem I

- we have a set of **mutually exclusive and exhaustive** propositions:  $\{A_1, \dots, A_n\}$  and we seek to evaluate  $P(A_i | B)_I$ , with  $i = 1, 2, \dots, n$
- note that the labels are arbitrary: it makes no difference which proposition is called  $A_1$  and which  $A_2$ , and so on

## Problem II

- we have a set of **mutually exclusive and exhaustive** propositions:  $\{A'_1, \dots, A'_n\}$ , given by

$$A'_1 \equiv A_2, \quad A'_2 \equiv A_1 \text{ and } A'_k = A_k, \quad 3 \leq k \leq n$$

- and we seek to evaluate  $P(A_i | B)_{II}$ , with  $i = 1, 2, \dots, n$
- since the background information  $B$  is the same for both problems, we must have

$$P(A_1 | B)_I \equiv P(A'_2 | B)_{II} \text{ and } P(A_2 | B)_I \equiv P(A'_1 | B)_{II}$$

- **problem I and II are** not only related, but **entirely equivalent**, therefore

$$P(A_i | B)_I \equiv P(A'_i | B)_{II} \quad \forall i = 1, 2, \dots, n$$

# Assigning probabilities: 3

- since **equivalent state of knowledge must represent equivalent plausibility assignments**
- propositions  $A_1$  and  $A_2$  must be assigned equal probabilities in Problem I and II
- the argument just given is the 'baby' version of the **group invariance principle**
- more generally,  $\{A_1'', \dots, A_n''\}$  may be any permutation of  $\{A_1, \dots, A_n\}$
- if the background information  $B$  is indifferent among all propositions. we are exactly in the same state of knowledge
- we obtain  $n$  equation of the form  $P(A_i|B)_I = P(A_k|B)_I$  and the relations must hold whatever the particular permutation we used in our problem
- we come to the conclusion that all the  $P(A_i|B)$  must be equal
- using the initial assumption that the  $\{A_1, \dots, A_n\}$  are **exhaustive**, i.e.  $\sum_{i=1}^n P(A_i|B) = 1$ , the only possibility is

$$P(A_j|B) = \frac{1}{n} \text{ with } 1 \leq j \leq n$$

➤ following **Keynes (1921)**, we shall call this result the **principle of indifference**

## Boolean Algebra

- Given two propositions **A** and **B**, we define two binary operations:
- **A · B** as the **logical product** or conjunction (also called AND). This will be true, if 'both A and B are true'
- **A + B** as the **logical sum** or disjunction; it stands for 'at least one of the propositions A, B is true'
- and one unary operation:
- $\bar{A}$  indicates the denial of a proposition
- and the relation between A and  $\bar{A}$  is reciprocal:  $\overline{\bar{A}} = A$

A	B	NOT $\bar{A}$	NOT $\bar{B}$	AND $A \wedge B$	OR $A \vee B$
T	T	F	F	T	T
T	F	F	T	F	T
F	T	T	F	F	T
F	F	T	T	F	F

# Boolean Algebra: basic identities

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$A \cdot A = A$	$A + A = A$	idempotence
$A \cdot B = B \cdot A$	$A + B = B + A$	commutativity
$A (B \cdot C) = (A \cdot B) C$	$A + (B + C) = (A + B) + C$	associativity
$A (B + C) = A \cdot B + A \cdot C$	$A + B \cdot C = (A + B) (A + C)$	distributivity
$C = A \cdot B \rightarrow \overline{C} = \overline{A} + \overline{B}$	$D = A + B \rightarrow \overline{D} = \overline{A} \cdot \overline{B}$	De Morgan's
$A \implies B$	to be read as <b>A implies B</b>	implication

$A$  implies  $B$  does not assert that either  $A$  or  $B$  is true, but it means that  $A\overline{B}$  is false or that  $(\overline{A} + B)$  is true.

That is if  $A$  is true, then  $B$  must be true; or if  $B$  is false, then  $A$  must be false.

## Boolean Algebra: adequate set

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- ⤴ so far we have defined four operations by which, starting from two propositions,  $A$  and  $B$ , other propositions may be defined
- the logical product:  $A \cdot B$  (also written  $AB$ )
- the logical sum:  $A + B$
- the negation:  $\overline{A}$
- the implication:  $A \implies B$

**NOTE** : in ordinary language, 'A implies B' ( $A \implies B$ ) means that  $B$  is logically deducible from  $A$ . In formal logic, 'A implies B' means only that the propositions  $A$  and  $B$  have the same truth value

- ⤴ it is possible to demonstrate that **the three basic operations of Boolean Algebra, AND, OR and NOT constitute an 'adequate set'**, i.e. they suffice to generate all possible logic functions

# Example

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- Boolean algebra rules can be used, for instance in **enumerating all possible cases of an event**
- let's define the following propositions:
  - ▷  $E_1$  : a coin is tossed once
  - ▷  $E_2$  : a coin is tossed for a second time
  - ▷  $H_1$  : the coin lands 'tail' on the first toss
  - ▷  $H_2$  : the coin lands 'tail' on the second toss
- we can write:  $E_1 = H_1 + \overline{H_1}$  and  $E_2 = H_2 + \overline{H_2}$  using the multiplication rule:

$$\begin{aligned} E_1 E_2 &= (H_1 + \overline{H_1})(H_2 + \overline{H_2}) \\ &= H_1 H_2 + H_1 \overline{H_2} + \overline{H_1} H_2 + \overline{H_1} \overline{H_2} \end{aligned}$$

## Boolean Algebra: alternative adequate set

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- it is possible to demonstrate that there are operations which, alone, would constitute an adequate set: these are **NAND and NOR**

➤ NAND is the negation of AND:

$$A \uparrow B \equiv \overline{AB} = \overline{A} + \overline{B}$$

➤ and it can generate the other operations:

✓  $\overline{A} = A \uparrow A$

✓  $AB = (A \uparrow B) \uparrow (A \uparrow B)$

✓  $A + B = (A \uparrow A) \uparrow (B \uparrow B)$

➤ NOR is the negation of OR:

$$A \downarrow B \equiv \overline{A + B} = \overline{A} \overline{B}$$

➤ and it can generate the other operations:

✓  $\overline{A} = A \downarrow A$

✓  $A + B = (A \downarrow B) \downarrow (A \downarrow B)$

✓  $AB = (A \downarrow A) \downarrow (B \downarrow B)$

- $\overline{A} = A \uparrow A$   $\square$  NAND  
since  $\overline{A} = \overline{A \cdot A}$  using idempotence
- $AB = \overline{\overline{A} \overline{B}}$  since  $\overline{\overline{A}} = A$   
 $\downarrow$   
 $= \overline{\overline{A \cdot B} \cdot \overline{A \cdot B}}$  using idempotence  
 $\downarrow$   
 $= (A \uparrow B) \uparrow (A \uparrow B) \quad \square$
- $A + B = \overline{\overline{A + B}} = \overline{\overline{A} \cdot \overline{B}}$  using De Morgan's  
 $\downarrow$   
 $= \overline{\overline{A \cdot A} \cdot \overline{B \cdot B}}$  using idempotence  
 $\downarrow$   
 $= (A \uparrow A) \uparrow (B \uparrow B) \quad \square$

## The Extended Sum Rule

$$\begin{aligned}
 P(A + B|C) &= 1 - P(\overline{A + B}|C) = 1 - P(\overline{A} \cdot \overline{B}|C) \\
 &= 1 - P(\overline{A}|C) \cdot P(\overline{B}|\overline{A}C) = 1 - P(\overline{A}|C) [1 - P(B|\overline{A}C)] \\
 &= 1 - P(\overline{A}|C) + P(\overline{A}|C) P(B|\overline{A}C) \\
 &= P(A|C) + P(\overline{A}B|C) = P(A|C) + P(B|C) P(\overline{A}|BC) \\
 &= P(A|C) + P(B|C) [1 - P(A|BC)] \\
 &= P(A|C) + P(B|C) - P(B|C) P(A|BC) \\
 &= P(A|C) + P(B|C) - P(AB|C)
 \end{aligned}$$



# Summary of our mathematical tools

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PRODUCT  
RULE

$$P(AB|C) = P(A|BC)P(B|C) = P(B|AC)P(A|C)$$

SUM RULE

$$P(A|B) + P(\bar{A}|B) = 1$$

EXTENDED  
SUM RULE

$$P(A + B|C) = P(A|C) + P(B|C) - P(AB|C)$$

BAYES'  
THEOREM

$$P(B_j|A, I) = \frac{P(A|B_j, I)P(B_j|I)}{\sum_{j=1}^n P(A|B_j, I)P(B_j|I)}$$

PRINCIPLE of  
INDIFFER-  
ENCE

Given  $H_1, \dots, H_n$ , mutually exclusive and exhaustive. If  $B$  does not favor any of them:  
 $P(H_j|B) = 1/n$

## Some useful transformations

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- given  $P(A|B)$ , three probability transformations are particularly useful and will be employed later in our calculations:

- Odds :

$$O(A|E) = P(A|E)/P(\bar{A}|E)$$

- Evidence :

$$ev(A|E) = K \ln(O(A|E)) = K(\ln(P(A|E)) - \ln(P(\bar{A}|E)))$$

- Surprisal :

$$u(A|E) = -K \ln(P(A|E))$$

# Useful formulas

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definition	range	denial rule	joint rule
Probability $p(A C)$	$[0,1]$	$P(\bar{A} C) = 1 - P(A C)$	$P(AB C) = P(A BC)P(B C)$
Odds $O(A C) = \frac{P(A C)}{P(\bar{A} C)}$	$[0, \infty]$	$O(\bar{A} C) = \frac{1}{O(A C)}$	$O(AB C) = \frac{O(A BC)O(B C)}{1+O(A BC)+O(B C)}$
Surprisal $u(A C) = -k \ln P(A C)$	$[\infty, 0]$	$u(\bar{A} C) = -k \ln (1 - \exp \frac{-u(A C)}{k})$	$u(AB C) = u(A BC) + u(B C)$
Evidence $ev(A C) = k \ln \frac{P(A C)}{P(\bar{A} C)}$	$[-\infty, \infty]$	$ev(\bar{A} C) = -ev(A C)$	*

$$* \quad ev(AB|C) = ev(A|BC) + ev(B|C) - k \ln \left[ 1 + \exp \frac{ev(A|BC)}{k} + \exp \frac{ev(B|C)}{k} \right]$$

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