Review of Probability Theory

Mário A. T. Figueiredo

Instituto Superior Técnico & Instituto de Telecomunicações

Lisboa, **Portugal**

LxMLS: Lisbon Machine Learning School

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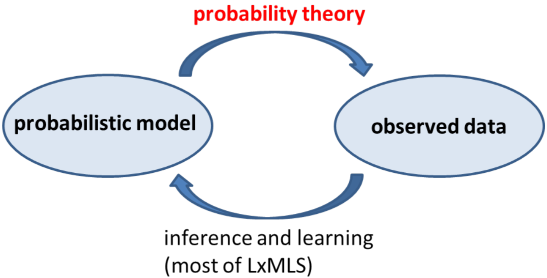
Probability theory



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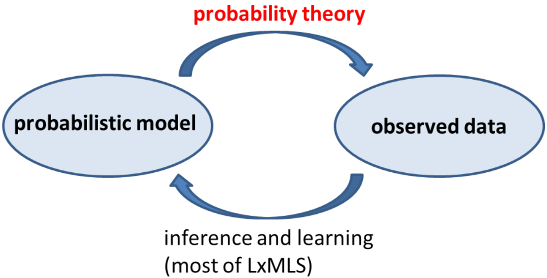

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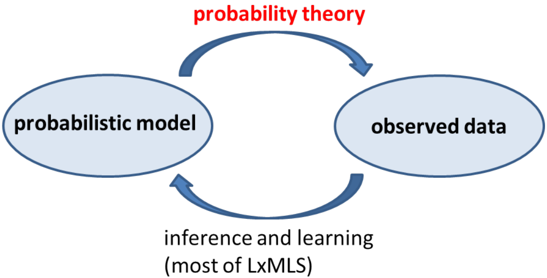

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- Great names of science: Cardano, Fermat, Pascal, Laplace, Kolmogorov, Bernoulli, Poisson, Cauchy, Boltzman, de Finetti, ...

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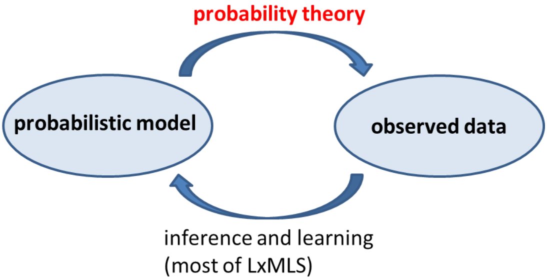

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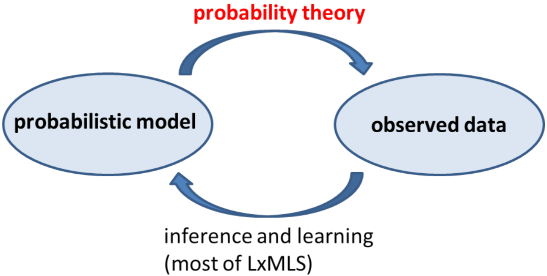

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- Great names of science: Cardano, Fermat, Pascal, Laplace, Kolmogorov, Bernoulli, Poisson, Cauchy, Boltzman, de Finetti, ...
- Natural tool to model uncertainty, information, knowledge, belief, ...
- ...thus also learning, decision making, inference, ...

What is probability?

- Classical definition: $\mathbb{P}(A) = \dfrac{N_A}{N}$

...with N mutually exclusive equally likely outcomes,
N_A of which result in the occurrence of A. *Laplace, 1814*

Example: $\mathbb{P}(\text{randomly drawn card is } \clubsuit) = 13/52$.

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- Subjective probability: $\mathbb{P}(A)$ is a degree of belief. *de Finetti, 1930s*

  ...gives meaning to $\mathbb{P}(\text{"tomorrow will rain"})$.

Key concepts: Sample space and events

- Sample space $\mathcal{X}$ = set of possible outcomes of a random experiment.

  Examples:
  - Tossing two coins: $\mathcal{X} = \{HH, TH, HT, TT\}$
  - Roulette: $\mathcal{X} = \{1, 2, ..., 36\}$
  - Draw a card from a shuffled deck: $\mathcal{X} = \{A\clubsuit, 2\clubsuit, ..., Q\diamondsuit, K\diamondsuit\}$.

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- An event is a subset of $\mathcal{X}$

  Examples:

  - "exactly one H in 2-coin toss": $A = \{TH, HT\} \subset \{HH, TH, HT, TT\}$.
  - "odd number in the roulette": $B = \{1, 3, ..., 35\} \subset \{1, 2, ..., 36\}$.
  - "drawn a $\heartsuit$ card": $C = \{A\heartsuit, 2\heartsuit, ..., K\heartsuit\} \subset \{A\clubsuit, ..., K\diamondsuit\}$

Kolmogorov's Axioms for Probability

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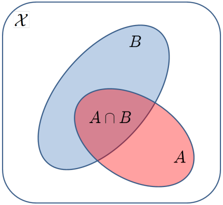
- From these axioms, many results can be derived. Examples:

  - $\mathbb{P}(\emptyset) = 0$
  - $C \subset D \;\Rightarrow\; \mathbb{P}(C) \leq \mathbb{P}(D)$
  - $\mathbb{P}(A \cup B) = \mathbb{P}(A) + \mathbb{P}(B) - \mathbb{P}(A \cap B)$
  - $\mathbb{P}(A \cup B) \leq \mathbb{P}(A) + \mathbb{P}(B)$ (union bound)



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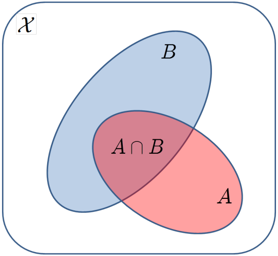

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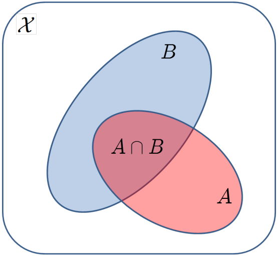

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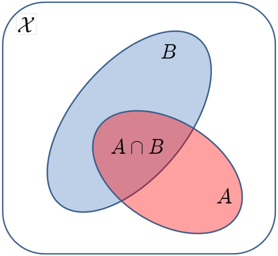

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- Relationship with conditional probabilities:

$$A \perp\!\!\!\perp B \Leftrightarrow \mathbb{P}(A|B) = \mathbb{P}(A)$$

Bayes Theorem

- Law of total probability: if $A_1, ..., A_n$ are a partition of $\mathcal{X}$

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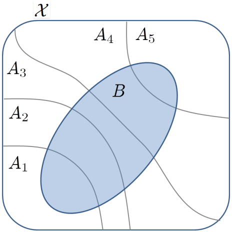

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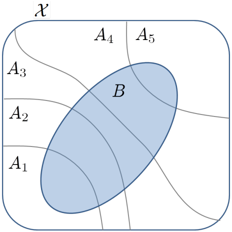

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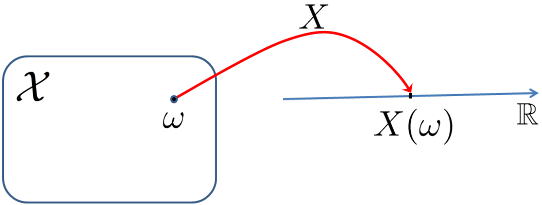
Random Variables

- A (real) random variable (RV) is a function: $X : \mathcal{X} \to \mathbb{R}$



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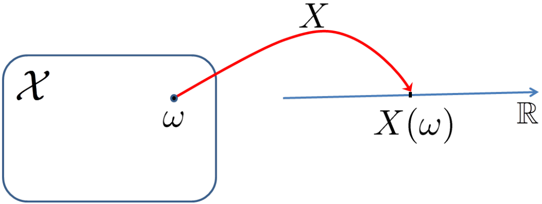

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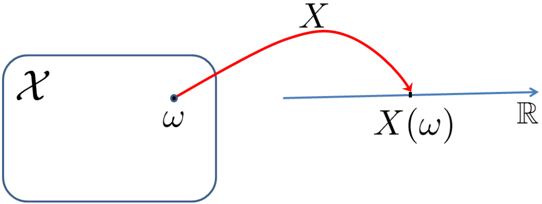

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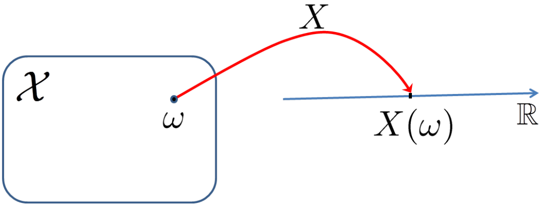

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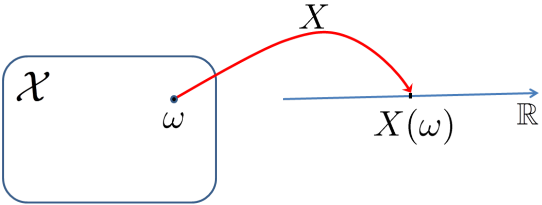

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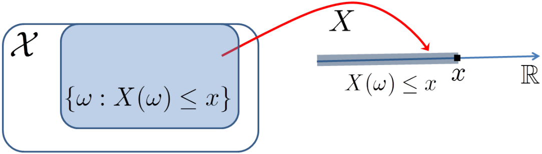
  - Example: distance traveled by a tossed coin; range of $X = \mathbb{R}_+$.

Random Variables: Distribution Function

- Distribution function: $F_X(x) = \mathbb{P}(\{\omega \in \mathcal{X} : X(\omega) \leq x\})$



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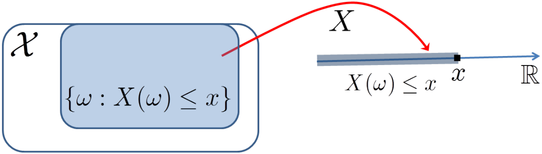

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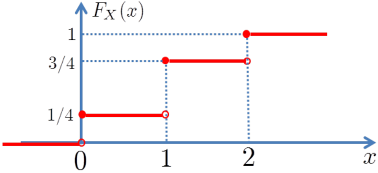

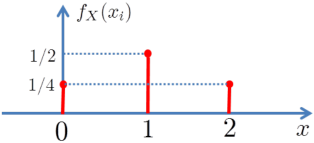

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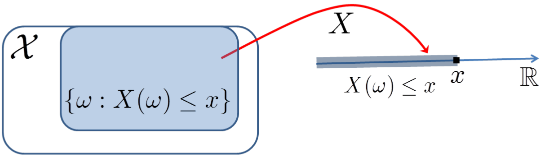

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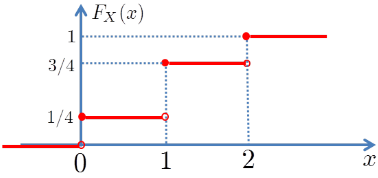

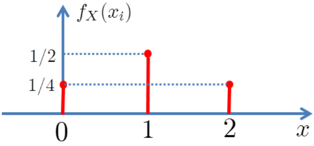

- Probability mass function (discrete RV): $f_X(x) = \mathbb{P}(X = x)$,

$$F_X(x) = \sum_{x_i \leq x} f_X(x_i).$$

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- Binomial RV: $X \in \{0, 1, ..., n\}$ (sum on n Bernoulli RVs)

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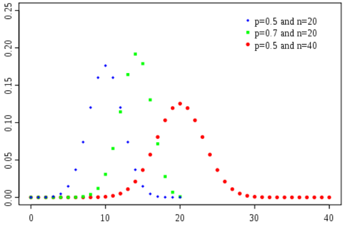
  Binomial coefficients ("n choose x"):

  $$\binom{n}{x} = \frac{n!}{(n-x)!\, x!}$$



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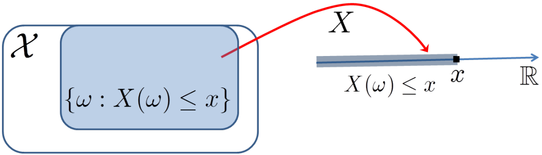

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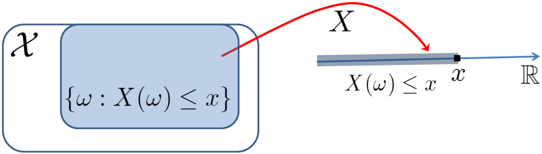
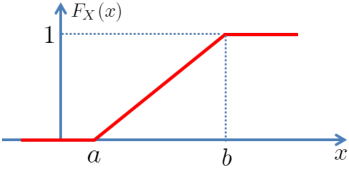
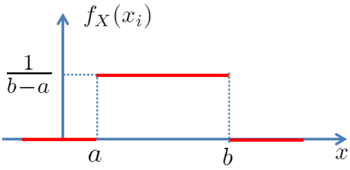


- Example: continuous RV with uniform distribution on $[a,\ b]$.





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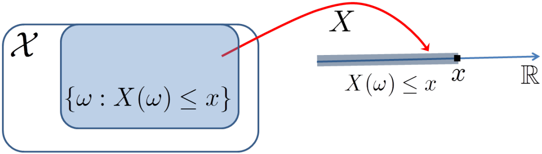

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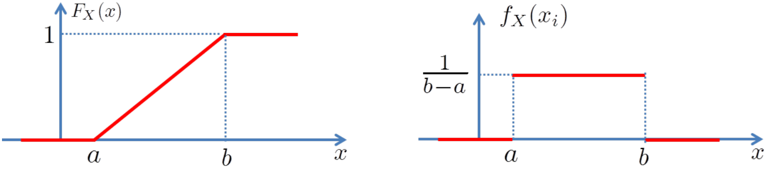

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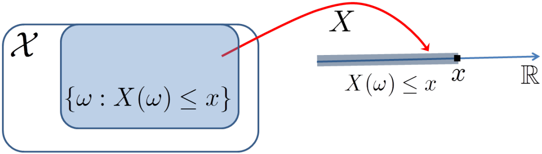

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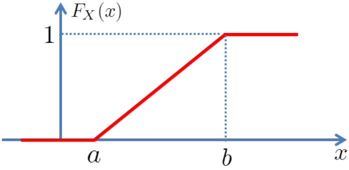

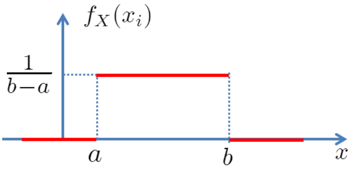

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$$F_X(x) = \int_{-\infty}^{x} f_X(u)\, du,$$

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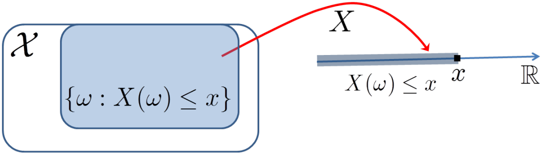
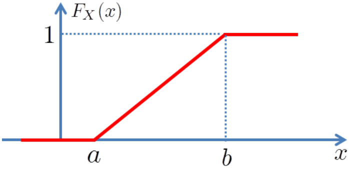
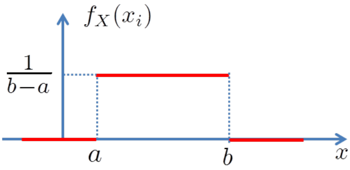


- Example: continuous RV with uniform distribution on $[a, b]$.





- Probability density function (pdf, continuous RV): $f_X(x)$

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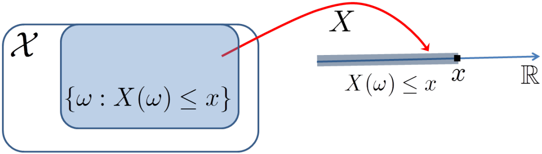

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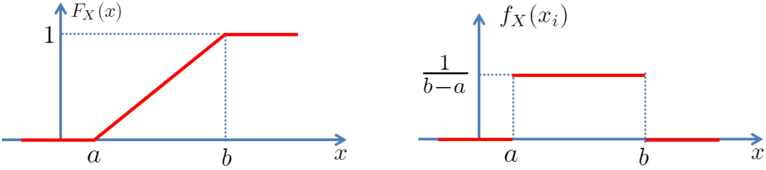

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Important Continuous Random Variables

- Uniform: $f_X(x) = \text{Uniform}(x; a, b) = \left\{ \begin{array}{ccc} \frac{1}{b-a} & \Leftarrow & x \in [a,\ b] \\ 0 & \Leftarrow & x \notin [a,\ b] \end{array} \right.$ (previous slide).

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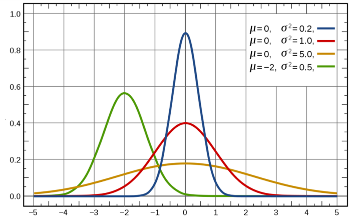

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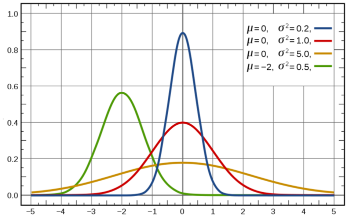

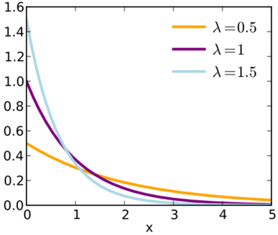

- Exponential: $f_X(x) = \text{Exp}(x; \lambda) = \begin{cases} \lambda e^{-\lambda\, x} & \Leftarrow \quad x \geq 0 \\ 0 & \Leftarrow \quad x < 0 \end{cases}$

Expectation of Random Variables

- Expectation: $\mathbb{E}(X) = \begin{cases} \displaystyle\sum_i x_i \, f_X(x_i) & X \in \{x_1, ...x_K\} \subset \mathbb{R} \\ \displaystyle\int_{-\infty}^{\infty} x \, f_X(x) \, dx & X \text{ continuous} \end{cases}$

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- Linearity of expectation:
  $\mathbb{E}(X+Y) = \mathbb{E}(X) + \mathbb{E}(Y); \quad \mathbb{E}(\alpha\, X) = \alpha\mathbb{E}(X), \;\; \alpha \in \mathbb{R}$

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- Probability as expectation of indicator, $\mathbf{1}_A(x) = \begin{cases} 1 & \Leftarrow & x \in A \\ 0 & \Leftarrow & x \notin A \end{cases}$

$$\mathbb{P}(X \in A) = \int_A f_X(x)\, dx = \int \mathbf{1}_A(x)\, f_X(x)\, dx = \mathbb{E}(\mathbf{1}_A(X))$$

Two (or More) Random Variables

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Conditionals and Bayes' Theorem

- Conditional pmf (discrete RVs):
  $$f_{X|Y}(x|y) = \mathbb{P}(X = x|Y = y) = \frac{\mathbb{P}(X = x \wedge Y = y)}{\mathbb{P}(Y = y)} = \frac{f_{X,Y}(x,y)}{f_Y(y)}.$$

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- Also valid in the mixed case (*e.g.*, X continuous, Y discrete).

Joint, Marginal, and Conditional Probabilities: An Example

- A pair of binary variables $X, Y \in \{0, 1\}$, with joint pmf:

$f_{X,Y}(x,y)$	$Y = 0$	$Y = 1$
$X = 0$	1/5	2/5
$X = 1$	1/10	3/10

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- Conditional probabilities:

$f_{X\|Y}(x\|y)$	$Y=0$	$Y=1$
$X=0$	2/3	4/7
$X=1$	1/3	3/7

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An Important Multivariate RV: Multinomial

- Multinomial: $X = (X_1, ..., X_K)$, $X_i \in \{0, ..., n\}$, such that $\sum_i X_i = n$,

$$f_X(x_1, ..., x_K) = \begin{cases} \binom{n}{x_1\ x_2\ \cdots\ x_K} p_1^{x_1}\, p_2^{x_2}\ \cdots\ p_k^{x_K} & \Leftarrow \quad \sum_i x_i = n \\ 0 & \Leftarrow \quad \sum_i x_i \neq n \end{cases}$$

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- Generalizes the binomial from binary to K-classes.

- Example: tossing n independent fair dice, $p_1 = \cdots = p_6 = 1/6$.
  x_i = number of outcomes with i dots. Of course, $\sum_i x_i = n$.

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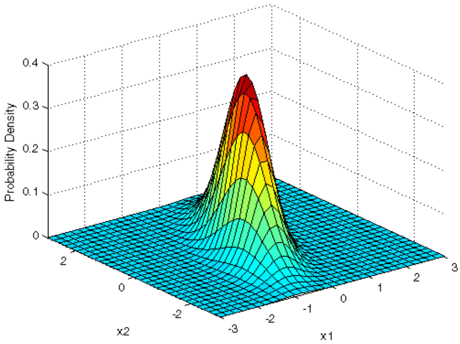

Covariance, Correlation, and all that...

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- Covariance of Gaussian RV, $f_X(x) = \mathcal{N}(x; \mu, C) \;\;\Rightarrow\;\; \text{cov}(X) = C$

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- In the Bayesian philosophy, all the knowledge about X is carried by

$$f_{X|Y}(x|y) = \frac{f_{Y|X}(y|x)\; f_X(x)}{f_Y(y)} = \frac{f_{Y,X}(y,x)}{f_Y(y)}$$

...the posterior (or a posteriori) pdf/pmf.

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$$\widehat{x}_{\text{Bayes}} = \arg\min_{\widehat{x}} \mathbb{E}[L(\widehat{x}, X)|Y = y]$$

where

$$\mathbb{E}[L(\widehat{x}, X)|Y = y] = \begin{cases} \displaystyle\int L(\widehat{x}, x)\, f_{X|Y}(x|y)\, dx, & \text{continuous (estimation)} \\ \displaystyle\sum_x L(\widehat{x}, x)\, f_{X|Y}(x|y), & \text{discrete (classification)} \end{cases}$$

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ML = maximum likelihood criterion.

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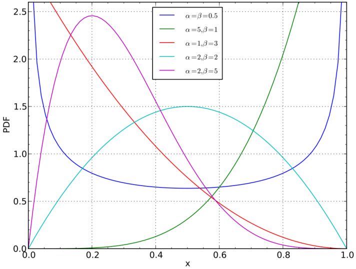

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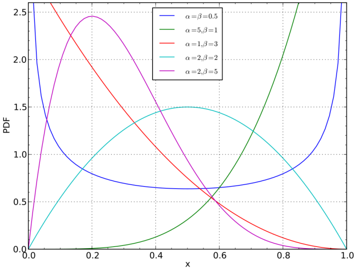

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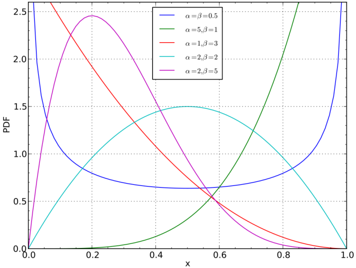

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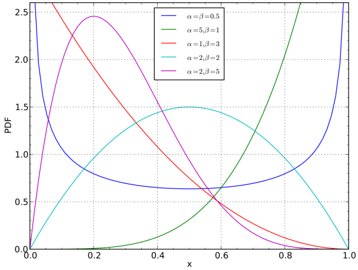

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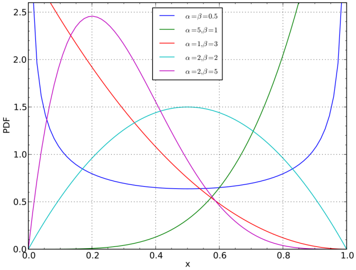

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- Does not apply to classification problems.

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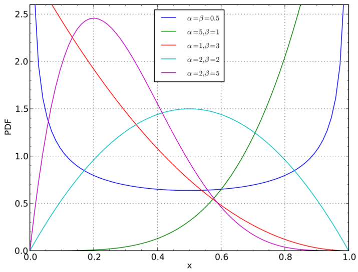

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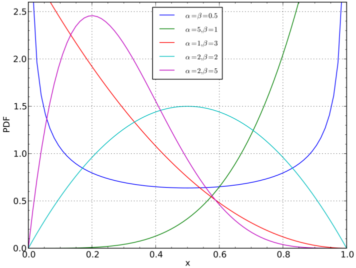

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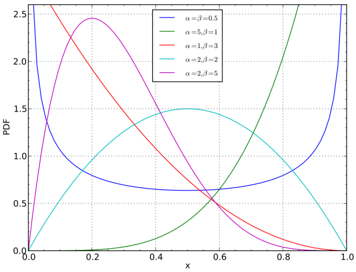

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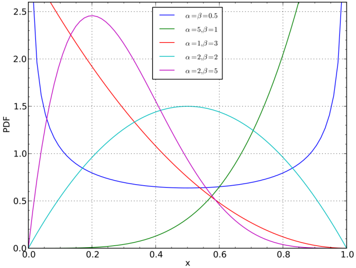


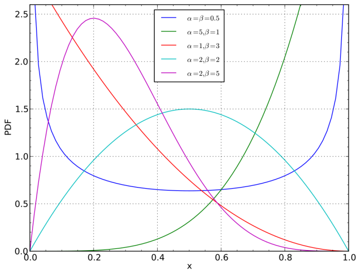
$\widehat{x}_{\text{MMSE}} \simeq 0.611 \quad \left(\text{recall that } \widehat{x}_{\text{MAP}} = 0.625, \; \widehat{x}_{\text{ML}} = 0.7\right)$

Back to the Bernoulli Example

- Observed n i.i.d. (independent identically distributed) Bernoulli RVs.

- Likelihood: $f_{Y|X}(y_1, ..., y_n|x) = \prod_{i=1}^{n} x^{y_i}(1-x)^{1-y_i} = x^{\sum_i y_i}(1-x)^{n-\sum_i y_i}$

  - In our case, the Beta pdf
    $f_X(x) \propto x^{\alpha-1}(1-x)^{\beta-1}, \quad \alpha, \beta > 0$
  - Posterior:
    $f_{X|Y}(x|y) = x^{\alpha-1+\sum_i y_i}(1-x)^{\beta-1+n-\sum_i y_i}$
  - MMSE: $\widehat{x}_{\text{MMSE}} = \frac{\alpha+\sum_i y_i}{\alpha+\beta+n}$
  - Example: $\alpha = 4$, $\beta = 4$, $n = 10$,
    $y = (1, 1, 1, 0, 1, 0, 0, 1, 1, 1)$,



$\widehat{x}_{\text{MMSE}} \simeq 0.611 \quad \left(\text{recall that } \widehat{x}_{\text{MAP}} = 0.625, \quad \widehat{x}_{\text{ML}} = 0.7\right)$

- Conjugate prior equivalent to "virtual" counts;
  often called "smoothing" in NLP and ML.

The Bernstein-Von Mises Theorem

- In the previous example, we had
  $n = 10, \;\; y = (1,1,1,0,1,0,0,1,1,1), \;$ thus $\sum_i y_i = 7$.
  With a Beta prior with $\alpha = 4$ and $\beta = 4$, we had

$$\widehat{x}_{\text{ML}} = 0.7, \quad \widehat{x}_{\text{MAP}} = \frac{3 + \sum_i y_i}{6 + n} = 0.625, \quad \widehat{x}_{\text{MMSE}} = \frac{4 + \sum_i y_i}{8 + n} \simeq 0.611$$

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- Consider $n = 100$, and $\sum_i y_i = 70$, with the same Beta(4,4) prior

$$\widehat{x}_{\text{ML}} = 0.7, \quad \widehat{x}_{\text{MAP}} = \frac{73}{106} \simeq 0.689, \quad \widehat{x}_{\text{MMSE}} = \frac{74}{108} \simeq 0.685$$

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  ... both Bayesian estimates are much closer to the ML.

- This illustrates an important result in Bayesian inference: the Bernstein-Von Mises theorem; under (mild) conditions,

$$\lim_{n\to\infty} \widehat{x}_{\text{MAP}} = \lim_{n\to\infty} \widehat{x}_{\text{MMSE}} = \widehat{x}_{\text{ML}}$$

  message: if you have a lot of data, priors don't matter.

Important Inequalities

- Markov's ineqality: if $X \geq 0$ is an RV with expectation $\mathbb{E}(X)$, then

$$\mathbb{P}(X > t) \leq \frac{\mathbb{E}(X)}{t}$$

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- Chebyshev's inequality: $\mu = \mathbb{E}(Y)$ and $\sigma^2 = \text{var}(Y)$, then

$$\mathbb{P}(|X - \mu| \geq s) \leq \frac{\sigma^2}{s^2}$$

...simple corollary of Markov's inequality, with $X = |Y - \mu|^2, \;\; t = s^2$

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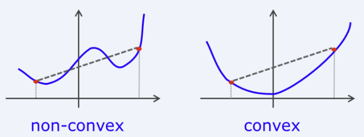
$$g(\alpha x + (1-\alpha)y) \leq \alpha g(x) + (1-\alpha)g(y)$$



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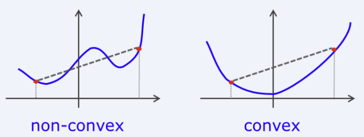

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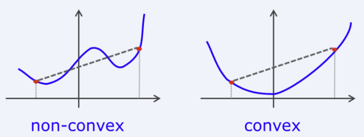

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Examples: $\mathbb{E}(X)^2 \leq \mathbb{E}(X^2) \;\Rightarrow\; \text{var}(X) = \mathbb{E}(X^2) - \mathbb{E}(X)^2 \geq 0.$
$\mathbb{E}(\log X) \leq \log \mathbb{E}(X)$, for X a positive RV.

Entropy and all that...

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- If $var(Y) = \sigma^2$, then $h(Y) \leq \frac{1}{2}\log(2\pi e \sigma^2)$

Kullback-Leibler divergence

Kullback-Leibler divergence (KLD) between two pmf:

$$D(f_X \| g_X) = \sum_{x=1}^{K} f_X(x) \log \frac{f_X(x)}{g_X(x)}$$

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Enjoy LxMLS 2013