INFORMATION THEORY & CODING

Differential Entropy 2

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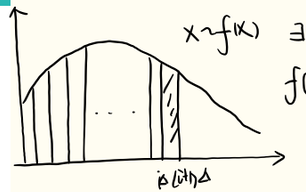
December 27, 2022

Differential Entropy - 2

- Definitions
- AEP for Continuous Random Variables
- Relation of differential entropy to discrete entropy
- Joint and Conditional Differential Entropy
- Relative Entropy and Mutual Information
- Estimation Counterpart of Fano's Inequality



$h(X) = h(f) = -\int_{-\infty}^{+\infty} f(x) \log f(x) dx$

$\exists x_i \in [i\Delta, (i+1)\Delta]$ $f(x_i)\Delta = \int_{i\Delta}^{(i+1)\Delta} f(x)dx$.

$f(x_0), f(x_1), \cdots, f(x_i), \cdots$

$\Pr[X^\Delta = x_i] = f(x_i)\Delta \triangleq p_i = \int_{\Delta}^{(i+1)\Delta} f(x)dx$

$\Delta \to 0 \quad X^\Delta \to X$

$H(X^\Delta) = -\sum_i p_i \log p_i = -\sum_i f(x_i)\Delta \log(f(x_i)\Delta) = -\sum_i \Delta f(x_i) \log f(x_i) - \sum_i \Delta f(x_i) \log \Delta$

$= -\sum_i \Delta f(x_i) \log f(x_i) - \sum_i \Delta f(x_i) \log \Delta = -\sum_i \Delta f(x_i) \log f(x_i) - \log \Delta \sum_i \Delta f(x_i)$

$= -\sum_i \Delta f(x_i) \log f(x_i) - \log \Delta$

$\Delta \to 0 \to = -\int_{-\infty}^{+\infty} f(x) \log f(x) dx - \log \Delta = h(X) - \log \Delta$

$\Delta \to 0 \quad \log \Delta \to -\infty$.

Joint and conditional differential entropy

Joint Entropy

Definition

The joint differential entropy of $X_1, X_2, ..., X_n$ with pdf $f(x_1, x_2, \ldots, x_n)$ is

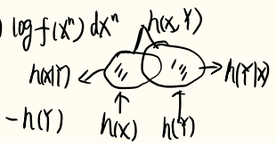
$$h(X_1, X_2, \ldots, X_n) = -\int f(x^n) \log f(x^n) \mathrm{d}x^n.$$

Definition

If X, Y have a joint pdf $f(x, y)$, the conditional differential entropy $h(X|Y)$ is

$$h(X|Y) = -\int f(x, y) \log f(x|y) \mathrm{d}x\mathrm{d}y = h(X, Y) - h(Y).$$

$X_1 \cdots X_n \sim h(X_1, \cdots X_n) = h(f) = -\int f(x^n) \log f(x^n)\, dx^n$, $f(x_1, \cdots x_n)$



$h(X|Y) = -\int f(x,y) \log f(x|y)\, dx dy = h(X,Y) - h(Y)$

$X_1 \cdots X_n \sim N(0, k)$ $\quad k = E\begin{pmatrix} X_1 \\ \vdots \\ X_n \end{pmatrix}(X_1 \cdots X_n)$

$\phi_k(x_1 \cdots x_n) = \frac{1}{(\sqrt{2\pi})^n |K|^{\frac{1}{2}}} \exp\left[-\frac{1}{2}(\vec{x}-u)^T K^{-1} (\vec{x}-u)\right]$ $\quad \vec{x} = (x_1 \cdots x_n)^T$

$h(X_1 \cdots X_n) = -\int \phi(x^n) \log \phi(x^n)\, dx^n = -\int \phi(x^n) \left[-\log(\sqrt{2\pi})^n |K|^{\frac{1}{2}} - \frac{1}{2}\log e\, (\vec{x}-u)^T K^{-1} (\vec{x}-u)\right]$

$= \frac{1}{2}\log\left[(2\pi)^n |K|\right] + \frac{\log e}{2} \int \phi(x^n) (\vec{x}-u)^T K^{-1} (\vec{x}-u)\, dx^n$

$= \frac{1}{2}\log\left[(2\pi)^n |K|\right] + \frac{\log e}{2} E\,(\vec{x}-u)^T K^{-1} (\vec{x}-u)$

$= \frac{1}{2}\log\left[(2\pi)^n |K|\right] + \frac{\log e}{2} E\left\{\mathrm{tr}\,(\vec{x}-u)(\vec{x}-u)^T K^{-1}\right\}$

Entropy of a multivariate Gaussian

Definition (Multivariate Gaussian Distribution)

If the joint pdf of $X_1, X_2, \ldots, X_n$ satisfies

$$f(\mathbf{x}) = f(x_1, \ldots, x_n) = \frac{1}{(\sqrt{2\pi})^n |K|^{1/2}} \exp\left(-\frac{1}{2}(\mathbf{x}-\mu)^T K^{-1}(\mathbf{x}-\mu)\right),$$

then $X_1, X_2, \ldots, X_n$ are multivariate/joint Gaussian/normal distributed with mean μ and covariance matrix K. Denote as $(X_1, X_2, \ldots, X_n) \sim \mathcal{N}_n(\mu, K)$.

Theorem (Entropy of a multivariate normal distribution)

Let $X_1, X_2, \ldots, X_n$ have multivariate normal distribution with mean μ and covariance matrix K. Then

$$h(X_1, X_2, \ldots, X_n) = h(\mathcal{N}_n(\mu, K)) = \frac{1}{2}\log(2\pi e)^n |K| \text{ bits},$$

where $|K|$ denotes the determinant of K.

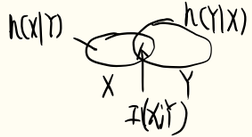
$= \frac{1}{2}\log[(2\pi)^n |K|] + \log_2 e \, tr\mathbb{E}[(\vec{x}-\vec{u})(\vec{x}-\vec{u})^T K^{-1}]$

$= \frac{1}{2}\log[(2\pi)^n |K|] + \frac{1}{2}\log e^n = \frac{1}{2}\log[(2\pi e)^n |K|]$

$f(x^n)\ g(x^n)$

Relative Entropy: $D(f\|g) = \int f(x^n)\log\frac{f(x^n)}{g(x^n)}dx^n$

mutual Info. $I(X;Y) = \int f(x,y)\log\frac{f(x,y)}{f(x)f(y)}dxdy = D(f(x,y)\|f(x)f(y))$



Relative entropy and mutual information

Definition

The relative entropy $D(f||g)$ between two pdfs f and g is

$$D(f||g) = \int f \log \frac{f}{g}.$$

Note: $D(f||g)$ is finite only if the support set of f is contained in the support set of g.

Definition

The mutual information $I(X;Y)$ between two random variables with joint pdf $f(x,y)$ is

$$I(X;Y) = \int f(x,y) \log \frac{f(x,y)}{f(x)f(y)} \mathrm{d}x\mathrm{d}y.$$

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Relative entropy and mutual information

By definition, it is clear that

$$I(X;Y) = h(X) - h(X|Y) = h(Y) - h(Y|X) = h(X) + h(Y) - h(X,Y).$$

and

$$I(X;Y) = D\Big(f(x,y)\Big|\Big|f(x)f(y)\Big).$$

Mutual information between correlated Gaussian r.v.s

- Let $(X, Y) \sim \mathcal{N}(0, K)$, where

$$K = \begin{bmatrix} \sigma^2 & \rho\sigma^2 \\ \rho\sigma^2 & \sigma^2 \end{bmatrix}.$$

- $h(X) = h(Y) = \frac{1}{2}\log(2\pi e)\sigma^2$
- $h(X, Y) = \frac{1}{2}\log(2\pi e)^2|K| = \frac{1}{2}(\log 2\pi e)^2\sigma^4(1-\rho^2)$
- $I(X;Y) = h(X) + h(Y) - h(X, Y) = -\frac{1}{2}\log(1-\rho^2)$

if $\rho = 0$, X and Y are independent, the mutual information is 0.

if $\rho \pm 1$, X and Y are perfectly correlated, the mutual information is infinite.

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Theorem

$D(f||g) \geq 0$ with equality iff $f = g$ almost everywhere.

Proof.

Let $\mathcal{S}$ be the support set of f. Then

$$
\begin{aligned}
-D(f||g) &= \int_{\mathcal{S}} f \log \frac{g}{f} \\
&\leq \log \int_{\mathcal{S}} f \frac{g}{f} \quad \text{(by Jensen's inequality)} \\
&= \log \int_{\mathcal{S}} g \\
&\leq \log 1 = 0
\end{aligned}
$$

Theorem

$D(f||g) \geq 0$ *with equality iff* $f = g$ *almost everywhere.*

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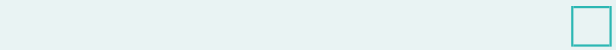

Properties of differential entropy

- $I(X;Y) \geq 0$ with equality iff X and Y are independent.
- $h(X|Y) \leq h(X)$ with equality iff X and Y are independent.

Theorem (Chain rule for differential entropy)

$$h(X_1, X_2, \ldots, X_n) = \sum_{i=1}^{n} h(X_i|X_1, X_2, ..., X_{i-1}).$$

- $h(X_1, X_2, \ldots, X_n) \leq \sum h(X_i)$, with equality iff $X_1, X_2, \ldots, X_n$ are independent.

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Properties of differential entropy

Theorem (Translation does not change the differential entropy)

$$h(X+c) = h(X).$$

Theorem

$$h(aX) = h(X) + \log|a|.$$

Proof.

Let $Y = aX$, Then $f_Y(y) = \frac{1}{|a|} f_X(\frac{y}{a})$, and we have

$$h(aX) = -\int f_Y(y)\log f_Y(y)\mathrm{d}y = -\int \frac{1}{|a|} f_X(\frac{y}{a})\log\left(\frac{1}{|a|} f_X\left(\frac{y}{a}\right)\right)\mathrm{d}y$$

$$= -\int f_X(x)\log f_X(x)\mathrm{d}x + \log|a| = h(X) + \log|a|$$

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$$= -\int f_X(x)\log f_X(x)\mathrm{d}x + \log|a| = h(X) + \log|a|$$

Properties of differential entropy

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Corollary.

$$h(A\mathbf{X}) = h(\mathbf{X}) + \log|\det(A)|.$$

□

期望 协方差矩阵.
↑ ↑

Multivariate Gaussian maximizes the entropy

Theorem

Let the random vector $\mathbf{X} \in \mathbb{R}^n$ have zero mean and covariance $K = \mathbb{E}\mathbf{X}\mathbf{X}^t$ (i.e., $K_{ij} = \mathbb{E}X_iX_j$, $1 \le i, j \le n$). Then

$$h(\mathbf{X}) \le \frac{1}{2}\log(2\pi e)^n|K|$$

with equality iff $\mathbf{X} \sim \mathcal{N}(0, K)$.

$\phi_K \sim N(0,K)$ $g(x^n)$ 0 K. want to prove $h(\phi_K) \ge h(g)$

$0 \le D(g\|\phi_K) = \int g(x^n)\log\frac{g(x^n)}{\phi(x^n)}dx^n = -h(g) - \int g(x^n)\log\phi(x^n)dx^n$

$\int g(x^n)\log\phi(x^n)dx^n = \int g(x^n)\left[\log\frac{1}{(\sqrt{2\pi})^n|K|^{\frac{1}{2}}} - \frac{1}{2}\log e(\vec{x}-u)^T K^{-1}(\vec{x}-u)\right]dx^n$

$= \int g(x^n)\left[\log\frac{1}{(\sqrt{2\pi})^n|K|^{\frac{1}{2}}}\right]dx^n - \frac{1}{2}\log e\int g(x^n)(\vec{x}-u)^T K^{-1}(\vec{x}-u)\,dx^n$

$E_g(\vec{x}-u)^T K^{-1}(\vec{x}-u)$

$= E_g\, tr(\vec{x}-u)(\vec{x}-u)^T K^{-1}$

$= tr\, K K^{-1} = tr\, I = E_\phi(\vec{x}-u)^T K^{-1}(\vec{x}-u)$

Random variable X, estimator $\hat{X}$. The expected prediction error $\mathbf{E}(X-\hat{X})^2$.

Theorem (Estimation error and differential entropy)

For any random variable X and estimator $\hat{X}$,

$$\mathbb{E}(X-\hat{X})^2 \geq \frac{1}{2\pi e}\exp\Big(2h(X)\Big),$$

with equality iff X is Gaussian and $\hat{X}$ is the mean of X.

AWGN.

$X \to$ [AWGN] $\xrightarrow{Y=X+Z,\ Z\sim\mathcal{N}(0,\sigma^2)}$

$\max_{f(x)} I(X;Y) = C$

$E[X]=P$

$I(X;Y)=h(Y)-h(Y|X)=h(Y)-h(Z|X)=h(Y)-h(Z)$

$h(Z)=\frac{1}{2}\log 2\pi e\sigma^2$ (随机变量, $E[Z]=0$)

$E[Y^2]=E[(X+Z)^2]=E[X^2+Z^2+2XZ]=E[X^2]+E[Z^2]$

$=P+\sigma^2$

$\Rightarrow h(Y)=\frac{1}{2}\log 2\pi e(P+\sigma^2)$

$\Rightarrow I(X;Y)=h(Y)-h(Z)=\frac{1}{2}\log\left(1+\frac{P}{\sigma^2}\right)$

Theorem (Estimation error and differential entropy)

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$$\mathbb{E}(X-\hat{X})^2 \geq \frac{1}{2\pi e}\exp\Big(2h(X)\Big),$$

with equality iff X is Gaussian and $\hat{X}$ is the mean of X.

Proof.

We have

$$\begin{aligned}
\mathbb{E}(X-\hat{X})^2 &\geq \min_{\hat{X}} \mathbb{E}(X-\hat{X})^2 \\
&= \mathbb{E}(X-\mathbb{E}(X))^2 \quad \text{mean is the best estimator} \\
&= \mathsf{Var}(X) \\
&\geq \frac{1}{2\pi e}\exp\Big(2h(X)\Big). \quad \text{The Gaussian has maximum entropy}
\end{aligned}$$

Summary

- Discrete r.v. $\Rightarrow$ continuous r.v.
- entropy $\Rightarrow$ differential entropy.
- Many things similar: mutual information, relative entropy, AEP, chain rule, ...
  Some things different: $h(X)$ can be negative, maximum entropy distribution is Gaussian

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