Entropy and Guessing: Old and New Results

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Guessing

The problem of guessing discrete random variables has found a variety of applications in

- Shannon theory,
- coding theory,
- cryptography,
- searching and sorting algorithms,

etc.

The central object of interest:

The distribution of the number of guesses required to identify a realization of a random variable, taking values on a finite or countably infinite set.

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- A guessing function is a 1-to-1 function $g \colon \mathcal{X} \to \mathcal{X}$ where the number of guesses is equal to $g(x)$ if $X = x \in \mathcal{X}$.
- For $\rho > 0$, $\mathbb{E}[g^\rho(X)]$ is minimized by selecting g to be a ranking function g_X, for which $g_X(x) = k$ if $P_X(x)$ is the k-th largest mass.

Guessing and Shannon Entropy (Massey, ISIT '94)

Average number of successive guesses with an optimal strategy satisfies

$$\mathbb{E}[g_X(X)] \geq \tfrac{1}{4} \exp\big(H(X)\big) + 1$$

provided $H(X) \geq 2$ bits. It is tight within a factor of $\frac{4}{\mathrm{e}}$ when X is geometrically distributed.

Guessing and Shannon Entropy (McEliece and Yu, ISIT '95)

If X takes no more than $M < \infty$ possible values, then

$$\mathbb{E}[g_X(X)] \leq \left(\frac{M-1}{2 \log M}\right) H(X)$$

This upper bound on the number of guesses is tight if and only if X is equiprobable with $P_X(x) = \frac{1}{M}$ for each x, or if X is deterministic.

Can we Get Bounds on the ρ-th Moments ($\rho > 0$) by Using a Generalized Information-Theoretic Measure of Shannon's Entropy ?

1961

ON MEASURES OF ENTROPY AND INFORMATION

ALFRÉD RÉNYI

Rényi entropy

$$H_\alpha(X) = \frac{1}{1-\alpha} \log \sum_{x \in \mathcal{A}} P_X^\alpha(x), \quad \alpha \in (0,1) \cup (1,\infty)$$

$$H_1(X) = H(X), \qquad \tfrac{\alpha}{1-\alpha} \log \|P_X\|_\alpha$$

$$H_\infty(X) = \min_{x \in \mathcal{A}} \log \frac{1}{P_X(x)}$$

$$H_0(X) = \log |\{x \in \mathcal{A} \colon P_X(x) > 0\}|$$

$$H_2(X) = \log \frac{1}{\sum_{x \in \mathcal{A}} P_X^2(x)}$$

Applications of Rényi Entropy

- Random search (Rényi, 1965).
- Statistical physics (Tsallis, 1988).
- Secret-key generation (Renner-Wolf, 2005).
- Data compression (Campbell, 1965).
- Hypothesis testing and coding theorems (Csiszár, 1995).
- Guessing (Arikan, 1996).

$H_\alpha(X)$ and Guessing Moments

Theorem (Arikan '96)

Let X be a discrete random variable taking values on $\mathcal{X} = \{1, \ldots, M\}$. Let $g_X(\cdot)$ be a ranking function of X. Then, for $\rho > 0$,

$$\frac{1}{\rho} \log \mathbb{E}\big[g_X^\rho(X)\big] \geq H_{\frac{1}{1+\rho}}(X) - \log(1 + \log_{\mathrm{e}} M),$$

$$\frac{1}{\rho} \log \mathbb{E}\big[g_X^\rho(X)\big] \leq H_{\frac{1}{1+\rho}}(X).$$

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$$\tfrac{1}{\rho} \log \mathbb{E}\big[g_X^\rho(X)\big] \leq H_{\frac{1}{1+\rho}}(X).$$

Arikan's result yields an asymptotically tight error exponent:

$$\lim_{n\to\infty} \tfrac{1}{n} \log \mathbb{E}\big[g_{X^n}^\rho(X^n)\big] = \rho H_{\frac{1}{1+\rho}}(X), \quad \forall\, \rho > 0$$

when $X_1, \ldots, X_n$ are i.i.d. $\quad [X^n := (X_1, \ldots, X_n)]$.

Bounds on Guessing Moments with Side Information

- Having side information $Y = y$ on X, we refer to the conditional ranking function $g_{X|Y}(\cdot|y)$.
- $\mathbb{E}[g^{\rho}_{X|Y}(X|Y)]$ is the ρ-th moment of the number of guesses required for correctly identifying the unknown object X on the basis of Y.

The Arimoto-Rényi Conditional Entropy

Let P_{XY} be defined on $\mathcal{X} \times \mathcal{Y}$, where X is a discrete random variable. The Arimoto-Rényi conditional entropy of order $\alpha \in [0, \infty]$ of X given Y is defined as

- If $\alpha \in (0,1) \cup (1, \infty)$, then

$$H_\alpha(X|Y) = \frac{\alpha}{1-\alpha} \log \mathbb{E}\left[\left(\sum_{x \in \mathcal{X}} P^{\alpha}_{X|Y}(x|Y) \right)^{\frac{1}{\alpha}} \right]$$

$$= \frac{\alpha}{1-\alpha} \log \sum_{y \in \mathcal{Y}} P_Y(y) \exp\left(\frac{1-\alpha}{\alpha} H_\alpha(X|Y=y) \right),$$

  where the last equality applies if Y is a discrete random variable.
- Continuous extension at $\alpha = 0, 1, \infty$ with $H_1(X|Y) = H(X|Y)$.

$H_\alpha(X|Y)$ and Guessing Moments

Theorem (Arikan '96)

Let X and Y be discrete random variables taking values on the sets $\mathcal{X} = \{1, \ldots, M\}$ and $\mathcal{Y}$, respectively. For all $y \in \mathcal{Y}$, let $g_{X|Y}(\cdot|y)$ be a ranking function of X given that $Y = y$. Then, for $\rho > 0$,

$$\frac{1}{\rho} \log \mathbb{E}\big[g^{\rho}_{X|Y}(X|Y)\big] \geq H_{\frac{1}{1+\rho}}(X|Y) - \log(1 + \log_{\mathrm{e}} M),$$

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Arikan's result yields an asymptotically tight error exponent:

$$\lim_{n\to\infty} \frac{1}{n} \log \mathbb{E}\big[g^{\rho}_{X^n|Y^n}(X^n|Y^n)\big] = \rho H_{\frac{1}{1+\rho}}(X|Y)$$

when $(X_1, Y_1), \ldots, (X_n, Y_n)$ are i.i.d. $\quad [X^n := (X_1, \ldots, X_n)]$.

Some Recent Results on Guessing

Guessing with Distributed Encoders

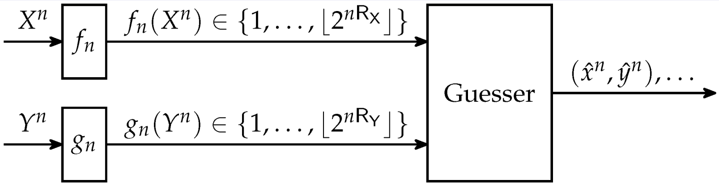

Figure: Guessing with distributed encoders f_n and g_n.

A. Bracher, A. Lapidoth and C. Pfister, "Guessing with distributed encoders," *Entropy*, March 2019.

Guessing with Distributed Encoders

Analog of Slepian-Wolf coding (distributed lossless source coding).

- Two dependent sources generate a pair of sequences $X^n := (X_1, \ldots, X_n)$ and $Y^n := (Y_1, \ldots, Y_n)$
- The pairs $\{(X_i, Y_i)\}_{i=1}^n$ are taken from a finite alphabet $\mathcal{X} \times \mathcal{Y}$.

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- The pairs $\{(X_i, Y_i)\}_{i=1}^n$ are taken from a finite alphabet $\mathcal{X} \times \mathcal{Y}$.
- Each of the two sequences is observed by a different encoder, which produces a rate-limited description to the sequence it observes:
  - The sequence X^n is described by one of $\lfloor \exp(nR_X) \rfloor$ labels.
  - The sequence Y^n is described by one of $\lfloor \exp(nR_Y) \rfloor$ labels.

$$f_n \colon \mathcal{X}^n \to \{1, \ldots, \lfloor \exp(nR_X) \rfloor\}, \quad R_X \geq 0,$$
$$g_n \colon \mathcal{Y}^n \to \{1, \ldots, \lfloor \exp(nR_Y) \rfloor\}, \quad R_Y \geq 0.$$

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$$f_n \colon \mathcal{X}^n \to \{1, \ldots, \lfloor \exp(nR_X) \rfloor\}, \quad R_X \geq 0,$$
$$g_n \colon \mathcal{Y}^n \to \{1, \ldots, \lfloor \exp(nR_Y) \rfloor\}, \quad R_Y \geq 0.$$

- The two rate-limited descriptions are provided to a guessing device, which produces guesses of the form $(\hat{x}^n, \hat{y}^n)$ until $(\hat{x}^n, \hat{y}^n) = (x^n, y^n)$.

Achievable Rate Pairs

For a fixed $\rho > 0$, a rate pair $(R_X, R_Y) \in \mathbb{R}_+^2$ is called achievable if there exists a sequence of distributed encoders and guessing functions $\{f_n, g_n, G_n\}$ such that the ρ-th moment of the number of guesses tends to 1 as we let n tend to infinity.

$$\lim_{n\to\infty} \mathbb{E}\big[G_n\big(X^n, Y^n \,|\, f_n(X^n), g_n(Y^n)\big)^{\rho}\big] = 1.$$

Exact Characterization of the Rate Region

Let $\{X_i, Y_i\}_{i=1}^{\infty}$ be i.i.d. according to P_{XY}. Consider the rate region $\mathcal{R}(\rho)$ which is defined to be the set of rate tuples (R_X, R_Y) such that

$$\begin{aligned} R_X &\geq H_{\frac{1}{1+\rho}}(X|Y), \\ R_Y &\geq H_{\frac{1}{1+\rho}}(Y|X), \\ R_X + R_Y &\geq H_{\frac{1}{1+\rho}}(X,Y). \end{aligned}$$

Then, all rate pairs in the interior of $\mathcal{R}(\rho)$ are achievable, while those outside $\mathcal{R}(\rho)$ are not achievable.

An Important Difference From Slepian-Wolf Coding

- Slepian-Wolf coding allows separate encoding with the same sum-rate as with joint encoding, $H(X,Y)$.
- This is not necessarily true in the setting of guessing with distributed encoders.
- Specifically, for $\rho > 0$, if

$$H_{\frac{1}{1+\rho}}(X|Y) + H_{\frac{1}{1+\rho}}(Y|X) > H_{\frac{1}{1+\rho}}(X,Y),$$

  then the single-rate constraints on R_X and R_Y together impose a stronger constraint on the sum-rate than the third constraint on $R_X + R_Y$. It then requires a larger sum-rate than joint encoding.

Improving Arikan's Bounds in the Non-Asymptotic Setting

Result (I.S. & S. Verdú, IEEE T-IT, June 2018)

Theorem

Given a discrete random variable X taking values on a set $\mathcal{X}$, an arbitrary non-negative function $g\colon \mathcal{X} \to (0, \infty)$, and a scalar $\rho \neq 0$, then

$$\begin{aligned}
&\sup_{\beta \in (-\rho, +\infty) \setminus \{0\}} \frac{1}{\beta} \left[H_{\frac{\beta}{\beta+\rho}}(X) - \log \sum_{x \in \mathcal{X}} g^{-\beta}(x) \right] \\
&\leq \frac{1}{\rho} \log \mathbb{E}[g^{\rho}(X)] \\
&\leq \inf_{\beta \in (-\infty, -\rho) \setminus \{0\}} \frac{1}{\beta} \left[H_{\frac{\beta}{\beta+\rho}}(X) - \log \sum_{x \in \mathcal{X}} g^{-\beta}(x) \right].
\end{aligned}$$

Theorem: Consequence of the Result

Let $g\colon \mathcal{X} \to \mathcal{X}$ be an arbitrary guessing function. Then, for every $\rho \neq 0$,

$$\frac{1}{\rho} \log \mathbb{E}\big[g^{\rho}(X)\big] \geq \sup_{\beta \in (-\rho, \infty) \setminus \{0\}} \frac{1}{\beta} \Big[H_{\frac{\beta}{\beta+\rho}}(X) - \log u_M(\beta)\Big]$$

where $u_M(\beta)$ is an upper/ lower bound on $\sum_{n=1}^{M} \frac{1}{n^{\beta}}$ for $\beta > 0$ or $\beta < 0$, respectively.

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with

$$u_M(\beta) = \begin{cases} \log_{\mathrm{e}} M + \gamma + \frac{1}{2M} - \frac{5}{6(10M^2+1)} & \beta = 1, \\ \min\Big\{\zeta(\beta) - \frac{(M+1)^{1-\beta}}{\beta-1} - \frac{(M+1)^{-\beta}}{2}, \, u_M(1)\Big\} & \beta > 1, \\ 1 + \dfrac{1}{1-\beta} \left[\left(M + \frac{1}{2}\right)^{1-\beta} - \left(\frac{3}{2}\right)^{1-\beta}\right] & |\beta| < 1, \\ \dfrac{M^{1-\beta} - 1}{1-\beta} + \frac{1}{2}\left(1 + M^{-\beta}\right) & \beta \leq -1. \end{cases}$$

- $\gamma \approx 0.5772$ is Euler's constant;
- $\zeta(\beta) = \sum\limits_{n=1}^{\infty} \frac{1}{n^\beta}$ is Riemann's zeta function for $\beta > 1$.

Lower Bound: Special Case

Specializing to $\beta = 1$, and using an upper bound on the harmonic sum:

$$u_M(1) = \sum_{j=1}^{M} \frac{1}{j} \leq 1 + \log_{\mathrm{e}} M, \quad M \geq 2,$$

we obtain

$$\frac{1}{\rho} \, \log \mathbb{E}\big[g^\rho(X)\big] \geq H_{\frac{1}{1+\rho}}(X) - \log\big(1 + \log_{\mathrm{e}} M\big)$$

for $\rho \in (-1, \infty)$. The latter bound was obtained for $\rho > 0$ by Arikan.

Improved Upper Bounds

We also derive improved upper bounds on the guessing moments, expressed as a function of Rényi entropies of X.

Numerical Results

Let X be geometrically distributed restricted to $\{1, \dots, M\}$ with the probability mass function

$$P_X(k) = \frac{(1-a)\, a^{k-1}}{1-a^M}, \quad k \in \{1, \dots, M\}$$

where $a = 0.9$ and $M = 32$. Table 1 compares $\mathbb{E}[g_X^3(X)]$ to its various lower and upper bounds (LBs and UBs, respectively).

Table: Comparison of $\mathbb{E}[g_X^3(X)]$ and bounds.

Arikan's LB	Improved LB	$\mathbb{E}[g_X^3(X)]$ exact value	Improved UB	Arikan's UB
268	$2,390$	$2,507$	$6,374$	$23,861$

Bounds on Guessing Moments with Side Information

- Our lower and upper bounds extend to allow side information Y for guessing the value of X.
- These bounds tighten the results by Arikan for all $\rho > 0$.
- With side information Y, all bounds stay valid by the replacement of $H_\alpha(X)$ with the Arimoto-Rényi conditional entropy $H_\alpha(X|Y)$.

New Setup

Let

- $\alpha > 0$;
- $\mathcal{X}$ and $\mathcal{Y}$ be finite sets of cardinalities
$$|\mathcal{X}| = n, \quad |\mathcal{Y}| = m, \quad n > m \geq 2;$$
without any loss of generality, let
$$\mathcal{X} = \{1, \dots, n\}, \quad \mathcal{Y} = \{1, \dots, m\};$$
- $\mathcal{P}_n$ $(n \geq 2)$ be the set of probability mass functions (pmf) on $\mathcal{X}$;
- X be a RV taking values on $\mathcal{X}$ with a pmf $P_X \in \mathcal{P}_n$;
- $\mathcal{F}_{n,m}$ be the set of deterministic functions $f \colon \mathcal{X} \to \mathcal{Y}$;
- $f \in \mathcal{F}_{n,m}$ is not one-to-one since $m < n$.

Majorization

Let

- X be a discrete RV with pmf P_X, which takes n possible values, and assume that
$$P_X(1) \geq P_X(2) \geq \ldots \geq P_X(n).$$
- $f \in \mathcal{F}_{n,m}$;
- Q_X be the pmf of $f(X)$; assume that
$$Q_X(1) \geq P_X(2) \geq \ldots \geq Q_X(m),$$
$$Q_X(m+1) = \ldots = Q_X(n) = 0.$$

Then, P_X is majorized by Q_X:

$$P_X \prec Q_X \quad \left(\sum_{i=1}^{k} P_X(i) \leq \sum_{i=1}^{k} Q_X(i), \, \forall \, k \in \{1, \ldots, n\} \right).$$

Solving the Maximum Rényi Entropy Problem

$$\max_{Q \in \mathcal{P}_m : P_X \prec Q} H_\alpha(Q)$$

with $X \in \{1, \ldots, n\}$, $m < n$, and $\alpha > 0$.

Solution: $R_m(P_X)$

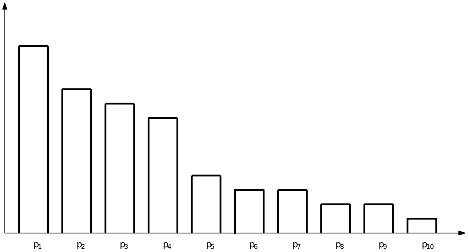
- If $P_X(1) < \frac{1}{m}$, then $R_m(P_X)$ is the equiprobable dist. on $\{1, \ldots, m\}$;
- Otherwise, $R_m(P_X) := Q_X \in \mathcal{P}_m$ with

$$Q_X(i) = \begin{cases} P_X(i), & i \in \{1, \ldots, n^*\}, \\ \dfrac{1}{m - n^*} \displaystyle\sum_{j=n^*+1}^{n} P_X(j), & i \in \{n^* + 1, \ldots, m\}, \end{cases}$$

where n^* is the max. integer i s.t. $P_X(i) \geq \frac{1}{m-i} \sum_{j=i+1}^{n} P_X(j)$.

Intuitively

p



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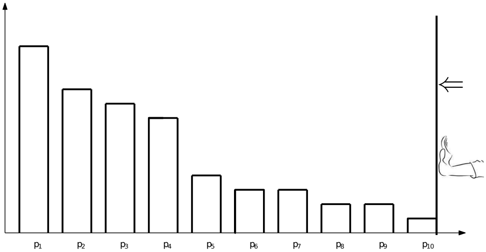

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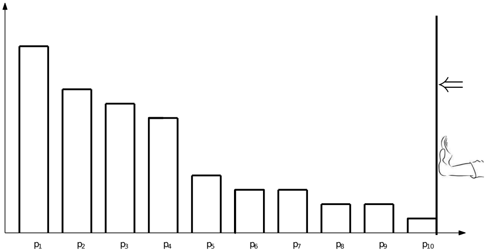
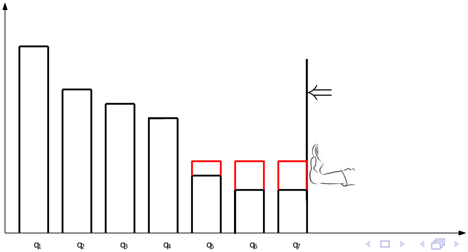


$R(\mathbf{p})$



Theorem: Guessing Moments

Let

- $\{X_i\}_{i=1}^k$ be i.i.d. with $X_1 \sim P_X$ taking values on a set $\mathcal{X}$, $|\mathcal{X}| = n$;
- $Y_i = f(X_i)$, for every $i \in \{1, \ldots, k\}$, where $f \in \mathcal{F}_{n,m}$ is a deterministic function with $m < n$;
- $$g_{X^k} \colon \mathcal{X}^k \to \{1, \ldots, n^k\}, \quad g_{Y^k} \colon \mathcal{Y}^k \to \{1, \ldots, m^k\}$$

  be, respectively, ranking functions of the random vectors

  $$X^k := (X_1, \ldots, X_k), \quad Y^k := (Y_1, \ldots, Y_k).$$

Notation

For $m \in \{2, \ldots, n\}$, let

$$\widetilde{X}_m \sim R_m(P_X).$$

Theorem: Guessing Moments (Cont.)

1. For every deterministic function $f \in \mathcal{F}_{n,m}$, and for all $\rho > 0$,

$$\frac{1}{k} \log \frac{\mathbb{E}\left[g_{X^k}^{\rho}(X^k)\right]}{\mathbb{E}\left[g_{Y^k}^{\rho}(Y^k)\right]} \geq \rho \left[H_{\frac{1}{1+\rho}}(X) - H_{\frac{1}{1+\rho}}(\widetilde{X}_m)\right] - \frac{\rho \log(1 + k \ln n)}{k}.$$

Theorem: Guessing Moments (Cont.)

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2. For the deterministic function $f^* \in \mathcal{F}_{n,m}$, constructed by Huffman algorithm, with $Y_i = f^*(X_i)$ for all $i \in \{1, \ldots, k\}$, we have

$$I\big(X;\, f^*(X)\big) \geq \max_{f \in \mathcal{F}_{n,m}} I\big(X;\, f(X)\big) - 0.08607 \text{ bits},$$

and, for all $\rho > 0$,

$$\frac{1}{k} \log \frac{\mathbb{E}\big[g^{\rho}_{X^k}(X^k)\big]}{\mathbb{E}\big[g^{\rho}_{Y^k}(Y^k)\big]} \leq \rho \left[H_{\frac{1}{1+\rho}}(X) - H_{\frac{1}{1+\rho}}(\widetilde{X}_m) + v\left(\frac{1}{1+\rho}\right) \right] + \frac{\rho \log(1 + k \ln m)}{k}.$$

Theorem: Guessing Moments (Cont.)

3) For every $\rho > 0$, the gap between the universal lower bound and the upper bound, for $f = f^*$, is at most

$$\rho \, v\left(\frac{1}{1+\rho}\right) + \frac{2\rho \log(1 + k \log_{\mathrm{e}} n)}{k}$$

$$\approx \frac{0.08607 \, \rho}{1+\rho} + O\left(\frac{\log k}{k}\right) \text{ bits.}$$

Letting $k \to \infty$, the gap is less than 0.08607 bits for all $\rho > 0$, and the construction of the function $f^* \in \mathcal{F}_{n,m}$ does not depend on ρ.

Theorem: Guessing Moments (Cont.)

For every $\rho > 0$,

3. The gap between the universal lower bound on $\frac{1}{k} \log \frac{\mathbb{E}\left[g^{\rho}_{X^k}(X^k)\right]}{\mathbb{E}\left[g^{\rho}_{Y^k}(Y^k)\right]}$, for all $f \in \mathcal{F}_{n,m}$ (with $Y_i = f(X_i)$), and the upper bound with the specific function $f = f^* \in \mathcal{F}_{n,m}$, is at most

$$\rho\, v\left(\frac{1}{1+\rho}\right) + \frac{2\rho \log(1 + k \log_{\mathrm{e}} n)}{k} \approx \frac{0.08607\,\rho}{1+\rho} + O\left(\frac{\log k}{k}\right) \text{ bits}$$

while $f = f^*$ also almost achieves the maximal mutual information of $I\big(X; f(X)\big)$ up to a difference of 0.08607 bits.

Letting $k \to \infty$, the gap in the normalized ratio of the ρ-th guessing moments is less than 0.08607 bits for all $\rho > 0$, and the construction of the function $f^* \in \mathcal{F}_{n,m}$ does not depend on ρ.

The Algorithm Relying on Huffman Coding

1. Start from the PMF $P_X \in \mathcal{P}_n$ with $P_X(1) \geq \ldots \geq P_X(n)$;
2. Merge successively pairs of probability masses by applying the Huffman algorithm;
3. Stop the process in Step 2 when a probability mass function $Q \in \mathcal{P}_m$ is obtained (with $Q(1) \geq \ldots \geq Q(m)$);
4. Construct the deterministic function $f^* \in \mathcal{F}_{n,m}$ by setting $f^*(k) = j \in \{1, \ldots, m\}$ for all probability masses $P_X(k)$, with $k \in \{1, \ldots, n\}$, being merged in Steps 2–3 into the node of $Q(j)$.

Journal Paper

I. S., "Tight bounds on the Rényi entropy via majorization with applications to guessing and compression," *Entropy*, vol. 20, no. 12, paper 896, pp. 1–25, November 2018.

Ongoing Activity in Guessing Problems

The topic of guessing from an IT perspective is very active these days.

- Noisy guesses (N. Merhav, arXiv:1910.00215).
- Asymptotic analysis of card guessing with feedback (P. Liu, arXiv:1908.07718).
- A unified framework for problems on guessing, source coding and task partitioning (A. Kumar et al., arXiv:1907.06889).
- Guessing individual sequences using finite-state machines (N. Merhav, arXiv:1906.10857).
- Optimal guessing under non-extensive framework and associated moment bounds (A. Ghosh, arXiv:1905.07729).
- Guessing probability in quantum key distribution (X. Wang et al., arXiv:1904.12075).
- Guessing random additive noise decoding with soft detection symbol reliability information (K. Duffey and M. Medard, arXiv:1902.03796).