SIAM Review
Vol. 59, No. 4, pp. 803–846
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Interactive Information Complexity*

Mark Braverman†

Abstract. The primary goal of this paper is to define and study the interactive information complexity of functions. Let $f(x, y)$ be a function, and suppose Alice is given x and Bob is given y. Informally, the interactive information complexity $\mathsf{IC}(f)$ of f is the least amount of information Alice and Bob need to reveal to each other to compute f. Previously, information complexity has been defined with respect to a prior distribution on the input pairs (x, y). Our first goal is to give a definition that is independent of the prior distribution. We show that several possible definitions are essentially equivalent. We establish some basic properties of the interactive information complexity $\mathsf{IC}(f)$. In particular, we show that $\mathsf{IC}(f)$ is equal to the amortized (randomized) communication complexity of f. We also show a direct sum theorem for $\mathsf{IC}(f)$ and give the first general connection between information complexity and (nonamortized) communication complexity. This connection implies that a nontrivial exchange of information is required when solving problems that have nontrivial communication complexity. We explore the information complexity of two specific problems: equality and disjointness. We show that only a constant amount of information needs to be exchanged when solving equality with no errors, while solving disjointness with a constant error probability requires the parties to reveal a linear amount of information to each other.

This paper originally appeared in [*SIAM J. Comput.*, 44 (2015), pp. 1698–1739]. The present version has been slightly updated with some recent developments.

Key words. information complexity, information theory, communication complexity

AMS subject classifications. 68Q05, 94A17, 94A29

DOI. 10.1137/17M1139254

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*Published electronically November 6, 2017. This paper originally appeared in *SIAM Journal on Computing*, Volume 44, Number 6, 2015, pages 1698–1739. An extended abstract of this paper appeared in STOC'12.

http://www.siam.org/journals/sirev/59-4/M113925.html

Funding: Research supported in part by an NSERC Discovery Grant, NSF awards DMS-1128155, CCF-1525342, and CCF-1149888, a Turing Centenary Fellowship, a Packard Fellowship in Science and Engineering, and the Simons Collaboration on Algorithms and Geometry.

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1. Introduction.

1.1. Information Theory for One-Way Communication. Shannon [67] originally developed his information theory in order to understand the *one-way* data transmission problem over a channel. For a noiseless channel, an important early result in information theory is that the cost of transmitting a (random) message X over the channel is closely related to the entropy $H(X)$ of the message. Recall that $H(X)$ is defined as $H(X) := \mathbf{E}_{x\sim X}[-\log_2 P_X(x)]$. Shannon's noiseless coding theorem, also known as Shannon's source coding theorem, states that the cost of sending a signal distributed according to X is essentially $H(X)$.

THEOREM 1.1 (Shannon's noiseless coding theorem; Huffman coding). *Let $C(X)$ denote the expected number of bits that the optimal lossless scheme for sending a sample distributed according to X needs to send across the channel. Then, for all X, $H(X) \le C(X) < H(X) + 1$.*

As a corollary, if we denote by $C_n := C(X^n)$—the cost of sending n independent samples distributed according to X—then we see that

$$\lim_{n\to\infty} \frac{C_n}{n} = H(X). \tag{1}$$

Thus the entropy approximately measures the cost of sending a single message, and

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exactly measures the amortized cost of sending many independent messages from the distribution. The noiseless coding theorem connects the communication cost of sending a message from one player to another to the information content of the message.

An example of a more subtle one-way transmission scenario where the information-theoretic bound is asymptotically tight is given by the Slepian–Wolf theorem [72]. We give one of the interpretations of the result here. Consider the following task: Alice is given an input A which she needs to transmit to Bob. Bob has an input B which is correlated with A, thus giving Bob partial information about A. Clearly this task is not harder than the task of transmitting A on its own, and thus $H(A)$ is an upper bound on the amortized transmission cost of this task (i.e., the cost of this task when it is repeated many times). Can the players do better? For example, in the extreme case where A is a deterministic function $A = F(B)$, clearly the number of bits that need to be sent is 0. It turns out that information theory again gives the precise answer to this question.

THEOREM 1.2 (Slepian–Wolf coding theorem [72]). *The amortized communication cost of transmitting the message A to a player that has prior information B is given by the conditional entropy $H(A|B) := H(AB) - H(B)$.*

Remark 1.3. Unlike Shannon's theorem, Theorem 1.2 gives only the upper bound in the amortized sense—when one needs to solve multiple copies of the transmission problem, and the number of copies goes to infinity. In [12] a one-shot version of the theorem was proved—i.e., the transmission problem is solved in $\approx H(A|B) + o(H(A|B))$ bits of transmission—but the protocol solving it is interactive, rather than a transmission protocol.

These two examples, Shannon's noiseless coding theorem and the Slepian–Wolf theorem, demonstrate the tight connection between the communication cost of *one-way* transmission problems and their inherent information costs. Based on these theorems one can argue that information-theoretic quantities are the "right" tools to study the transmission complexity of these problems. The goal of this paper is to develop the "right" information-theoretic notions for *two-way* interactive communication problems. Most importantly, we develop and study the *information complexity* of two-party problems.

Communication complexity studies the communication cost of functions. In the two-player setting, the main question it tries to answer is, "How many bits does Alice and Bob need to transmit to each other in order to solve a given problem?" Informally, information complexity tries to answer the question, "How much information does Alice and Bob need to reveal to each other in order to solve a given problem?" While, as discussed below, information theory has been used as a tool in the study of communication complexity, it was only recently that the information complexity of interactive problems has been considered in its full generality. The main goal of this paper is to work out the definition of the (two-party) interactive information complexity and to initiate the study of its properties.

1.2. Information Tools in Communication Complexity. The past decade has seen information theory become an important tool in the study of communication complexity lower bounds and their applications to lower bounds for data structures. Interestingly, the first time an expression known today as the internal information complexity of a problem was defined was in the context of understanding secure two-party computation (Alice and Bob trying to compute a function while leaking as little information as possible) [2, 49]. Information-theoretic tools had been used

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to prove communication complexity bounds even before information complexity had been formally defined. For example, Ablayev [1] used information theory to prove a lower bound for Index,[1] Nayak [59] used it in the quantum setting, and Klauck et al. [51] used it for pointer jumping.

Interactive communication, which is the way the information theory community looks at communication complexity, has been studied by the information theorists, starting with Orlitsky's work in the 1990s [60, 61]. A later paper along this line of work by Ma and Ishwar [56] gives an alternative (but closely related) way of looking at the interactive information complexity of problems and amortized communication.

Chakrabarti et al. [22] were the first to define the external information cost explicitly for the purpose of studying communication complexity. In [22], which defined what is known today as external information complexity, information theory is used to prove a direct sum theorem for problems with one simultaneous round of communication. Direct sum theorems (and the related direct product theorems) are theorems giving lower bounds for the complexity of n copies of a certain problem in terms of the complexity of one copy. In the context of communication complexity, direct sum theorems in various contexts have been the focus of much work [26, 22, 66, 39, 31, 4, 50, 33]. More recently, information-theoretic quantities have been studied in the context of differential privacy as well [57].

Information-theoretic tools have also been useful in contexts where the problem is not merely a repetition of multiple copies but some other aggregation function. A notable example is set disjointness $DISJ_n$, where the players are given two subsets of $\{1, \ldots, n\}$ and need to determine whether the sets are disjoint or not. If we represent the sets by their indicator strings $(x_1, \ldots, x_n)$ and $(y_1, \ldots, y_n)$, then the disjointness function can be written as

$$DISJ_n((x_1, \ldots, x_n), (y_1, \ldots, y_n)) := \neg \bigvee_{i=1}^{n} (x_i \wedge y_i). \tag{2}$$

Here the basic function is the conjunction in $x_i \wedge y_i$, and n copies of the conjunction are combined by the big disjunction over all i. A linear communication lower bound for the problem is known [46, 65]. While $DISJ_n$ is not a direct sum over the $(x_i \wedge y_i)$'s, similar analysis can be adapted, and information-theoretic techniques yield a linear lower bound on this problem [3]; we will see an extension of these techniques to information complexity in section 7. Razborov's simplified proof can also be cast in this framework. The information-theoretic techniques have recently been applied to more complicated composition functions rather than just the AND function [45, 55, 36]. Information-theoretic reasoning has also been successfully applied in the simpler deterministic setting [25].

The internal information cost for protocols over distributions of inputs was defined implicitly in [3] and explicitly in [4]. As in our earlier works, we will refer to internal information cost as simply information cost in this paper. It is the tool that allows one to obtain the only known direct sum results for the general randomized communication complexity. If f is a function and $R(f)$ is its randomized communication complexity, it has been shown in [4] that the randomized communication complexity of n copies of f satisfies $R(f^n) = \tilde{\Omega}(\sqrt{n} \cdot R(f))$. In the follow-up work [12] a tight relationship between the amortized distributional communication complexity of a function and its internal information cost has been established. We further extend this relationship to the nondistributional randomized setting in section 5.2.

[1] Index is a function where one player holds a string S in $0, 1^n$ and the other player holds an index $j \in 1, \ldots, n$, the goal being to output the bit $S[j]$.

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1.3. Other Related Work. Information theory has played a prominent role in a number of works involving interactive scenarios. In [19, 20] the interactive complexity of an *individual* transmission problem with a prior is studied using Kolmogorov complexity. In [49], Klauck introduces several notions of information complexity with the goal of understanding which computations can be performed *privately*, both in the classical and the quantum settings. One of the main definitions in the classical setting of [49], accounting for the amount of information learned by the parties, coincides with the notion of the (distributional) information complexity.

As noted above, interactive information-theoretic quantities have also recently been a subject of study in the information theory community. In [56], Ma and Ishwar study the amortized communication complexity of intersection and other functions using information-theoretic tools.

1.4. Main Contributions.

Interactive Information Complexity. In [3, 4], the information cost $\mathsf{IC}_\mu(\pi)$ of executing a protocol π over an a priori distribution μ of inputs is defined. This immediately yields a definition of the information cost of a function f with respect to a distribution μ: we simply look for a protocol π for f that minimizes $\mathsf{IC}_\mu(\pi)$. It turns out that there is a tight connection between the distributional information cost of f over μ and the amortized *distributional* communication complexity of f^n over μ^n [12].

Our first goal is to obtain a definition of the information cost of a function that does not depend on the prior distribution μ. Let f be a two-party function, and let $\rho < 1/3$ be an error parameter. Consider the following three quantities:

1. $I_1 = I_1(f, \rho)$ is such that for each $I > I_1$ there is a protocol π_I that on each input computes f except with error $\leq \rho$, and for each prior distribution μ reveals at most I bits of information about the inputs *to the players*. We later denote this quantity by $\mathsf{IC}(f, \rho)$.
2. $I_2 = I_2(f, \rho)$ is such that for each $I > I_2$ and for each prior distribution μ on inputs there is a protocol $\pi_{\mu,I}$ that computes f correctly except with probability $\leq \rho$ with respect to the distribution μ, and that reveals at most I bits of information about the inputs to the players. We later denote this quantity by $\mathsf{IC}_\mathsf{D}(f, \rho)$.
3. $I_3 = I_3(f, \rho)$ is the amortized randomized communication complexity of f as the number of copies goes to ∞: $I_3 = \lim_{n\to\infty} \frac{R^n_\rho(f^n)}{n}$. Here $R^n_\rho(f^n)$ denotes the communication complexity of computing n copies of f, where the protocol is allowed to err at most a ρ-fraction of the time on each input. This operationally defined quantity turns out to be equal to $\mathsf{IC}(f, \rho)$.

Note that the difference between I_1 and I_2 is in the order of quantifiers, and clearly $I_2 \leq I_1$. We prove that $I_1 = \Theta(I_2)$ (Theorem 3.5); more precisely, we show that

$$I_2(f, \rho) \leq I_1(f, \rho) \leq 2 \cdot I_2(f, \rho/2).$$

In the special case when $\rho = 0$ we show that $I_1(f, 0) = I_2(f, 0)$ (Theorem 3.6). We then establish the equality $I_3(f, \rho) = I_1(f, \rho)$ (Theorem 6.7), showing that the prior-free information complexity in the nondistributional case is equal to the amortized randomized communication complexity. These equivalences establish I_1 as the "right" notion of the interactive information complexity of f, which we denote by $\mathsf{IC}(f, \rho) := I_1 = I_3$.

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Properties of the Interactive Information Complexity. We establish some properties of the interactive information complexity. The first one is that the interactive information complexity is *additive* (Theorem 4.2). The theorem holds for tasks. A task can be, for example, computing a function f with an error bounded by ρ. We show that if T_1 and T_2 are two tasks, and $T := T_1 \times T_2$ is the task comprised of performing one copy of each of the two tasks, then the information complexity satisfies $\mathsf{IC}(T) = \mathsf{IC}(T_1) + \mathsf{IC}(T_2)$. Thus a direct sum statement holds *perfectly* for information complexity.[2]

Next, we establish a lower bound for the information complexity of any problem in terms of the communication complexity of the problem. The bound is given by Theorem 5.3. For a constant ρ the bound is of the form $\mathsf{IC}(f) = \Omega(\log R(f))$. Such a bound has been previously shown for *product* prior distributions in [41, 43]. This is a fairly weak bound, as one may expect $\mathsf{IC}(f) = \Theta(R(f))$ to hold in many cases. Nonetheless, this is the first general bound on the information revealed by *any* protocol for a problem in terms of its communication complexity.

The Interactive Information Complexity of Specific Functions. We consider two specific functions that have been studied extensively in the literature: the equality function $EQ(x, y) = \mathbf{1}_{x=y}$ and the disjointness function $DISJ_n$ that we discussed earlier. It turns out that the information complexity, or EQ, is constant, even when one does not allow the protocol to err at all: $\mathsf{IC}(EQ, 0) = O(1)$ (Proposition 3.22). This result is in sharp contrast with the fact that the zero-error randomized communication complexity of the equality function over n-bit strings is $\Omega(n)$.

On the other hand, the information complexity of $DISJ_n$ turns out to be linear (Theorem 7.2):

$$\mathsf{IC}(DISJ_n, 1/2 - \varepsilon) = \Omega(n) \text{ for all } 0 < \varepsilon < 1/2.$$

This result already follows from the proof of [3], which, in the language of this paper, gives a lower bound of $\mathsf{IC}_{\mathsf{D}}(DISJ_n, \rho)$, which in turn is a lower bound on $\mathsf{IC}_{\mathsf{D}}(DISJ_n, \rho)$. We give two proofs for this fact, which we believe to be instructive. The first one is through a reduction to the result about the communication complexity of disjointness—this reduction approach has proved fruitful in several subsequent works [11, 9]—while the second one is a more direct information-theoretic proof, which is a somewhat streamlined version of the argument in [3].

Directions and Open Problems. The notion of interactive information complexity gives rise to several research directions and many open problems surrounding its properties (e.g., the relationship between information complexity, communication complexity, and quantum communication complexity), as well as the information complexity of specific problems and generalizing information complexity to the multiparty setting. These, along with an overview of subsequent developments, are discussed in section 8.

2. Preliminaries.

In an effort to make the paper as self-contained as possible, we provide some background on information theory and communication complexity here. Additional details may be found in [12]. A more thorough treatment of the subject may be found in the textbooks on the respective subjects [24, 52]. We note that throughout the paper our protocols will make use of both public and private randomness.

[2]In fact, we prove a slightly stronger statement in the case where the permissible set of prior distributions is restricted.

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Notation. We reserve capital letters for random variables and distributions, calligraphic letters for sets, and lowercase letters for elements of sets. Throughout this paper, we often use the notation $|b$ to denote conditioning on the event $B = b$. Thus $A|b$ is shorthand for $A|B = b$.

We use the standard notion of *statistical/total variation* distance between two distributions.

DEFINITION 2.1. *Let D and F be two random variables taking values in a set $\mathcal{S}$. Their* statistical distance *is*

$$|D - F| \stackrel{\text{def}}{=} \max_{\mathcal{T} \subseteq \mathcal{S}} (|\Pr[D \in \mathcal{T}] - \Pr[F \in \mathcal{T}]|) = \frac{1}{2} \sum_{s \in \mathcal{S}} |\Pr[D = s] - \Pr[F = s]|.$$

*If $|D - F| \leq \varepsilon$, we shall say that D is ε-*close *to F. We shall also use the notation $D \stackrel{\varepsilon}{\approx} F$ to mean D is ε-close to F.*

2.1. Information Theory.

DEFINITION 2.2 (entropy). *The* entropy *of a random variable X is*

$$H(X) \stackrel{\text{def}}{=} \sum_x \Pr[X = x] \log(1/\Pr[X = x]).$$

The conditional entropy *$H(X|Y)$ is defined to be $\mathbf{E}_{y \in_R Y} [H(X|Y = y)]$.*

FACT 2.3. *$H(AB) = H(A) + H(B|A)$.*

DEFINITION 2.4 (mutual information). *The* mutual information *between two random variables A, B, denoted $I(A; B)$, is defined to be the quantity*

$$H(A) - H(A|B) = H(B) - H(B|A).$$

The conditional mutual information *$I(A; B|C)$ is $H(A|C) - H(A|BC)$.*

In analogy with the fact that $H(AB) = H(A) + H(B|A)$, we have the following proposition.

PROPOSITION 2.5 (chain rule). *Let C_1, C_2, D, B be random variables. Then*

$$I(C_1C_2; B|D) = I(C_1; B|D) + I(C_2; B|C_1D).$$

We also use the notion of *divergence* (also known as Kullback–Leibler distance or relative entropy), which is a different way to measure the distance between two distributions.

DEFINITION 2.6 (divergence). *The informational divergence between two distributions is*

$$\mathbf{D}(A||B) \stackrel{\text{def}}{=} \sum_x A(x) \log(A(x)/B(x)).$$

For example, if B is the uniform distribution on $\{0, 1\}^n$, then $\mathbf{D}(A||B) = n - H(A)$.

PROPOSITION 2.7. *Let A, B, C be random variables in the same probability space. For every a in the support of A and c in the support of C, let B_a denote $B|A = a$ and B_{ac} denote $B|A = a, C = c$. Then $I(A; B|C) = \mathbf{E}_{a,c \in_R A,C} [\mathbf{D}(B_{ac}||B_c)]$.*

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LEMMA 2.8.

$$\mathbf{D}\left(P_1 \times P_2 || Q_1 \times Q_2\right) = \mathbf{D}\left(P_1 || Q_1\right) + \mathbf{D}\left(P_2 || Q_2\right).$$

We will use the following two simple corollaries of the chain rule many times throughout the paper.

PROPOSITION 2.9. *Let A, B, C, D be four random variables such that $I(B; D|AC) = 0$. Then*

$$I(A; B|C) \geq I(A; B|CD).$$

Proof. We apply the chain rule twice:

$$\begin{aligned} I(A; B|CD) &= I(AD; B|C) - I(D; B|C) \\ &= I(A; B|C) + I(D; B|AC) - I(D; B|C) \\ &= I(A; B|C) - I(D; B|C) \\ &\leq I(A; B|C). \end{aligned}$$ ∎

PROPOSITION 2.10. *Let A, B, C, D be four random variables such that $I(B; D|C) = 0$. Then*

$$I(A; B|C) \leq I(A; B|CD).$$

Proof. Once again, we apply the chain rule twice:

$$\begin{aligned} I(A; B|CD) &= I(AD; B|C) - I(D; B|C) \\ &= I(AD; B|C) = I(A; B|C) + I(D; B|AC) \geq I(A; B|C). \end{aligned}$$ ∎

2.2. Communication Complexity. Let $\mathcal{X}, \mathcal{Y}$ denote the set of possible inputs to the two players, whom we name Alice and Bob. We view a *private coin protocol* for computing a function $f : \mathcal{X} \times \mathcal{Y} \to \mathbb{Z}_K$ as a rooted tree with the following structure:

- Each nonleaf node is *owned* by Alice or by Bob.
- Each nonleaf node owned by a particular player has a set of children that are owned by the other player. Each of these children is labeled by a binary string, in such a way that this coding is prefix free: no child has a label that is a prefix of another child.
- Every node is associated with a function mapping $\mathcal{X}$ to distributions on children of the node and a function mapping $\mathcal{Y}$ to distributions on children of the node.
- The leaves of the protocol are labeled by output values.

On input x, y, the protocol π is executed as in Figure 1.

Generic Communication Protocol
1. Set v to be the root of the protocol tree.
2. If v is a leaf, the protocol ends and outputs the value in the label of v. Otherwise, the player owning v samples a child of v according to the distribution associated with her input for v and sends the label to indicate which child was sampled.
3. Set v to be the newly sampled node and return to the previous step.

Fig. 1 *A communication protocol.*

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A public coin protocol is a distribution on private coin protocols, run by first using shared randomness to sample an index r and then running the corresponding private coin protocol π_r. Every private coin protocol is thus a public coin protocol. The protocol is called deterministic if all distributions labeling the nodes have support size 1.

DEFINITION 2.11. *The* communication cost *(or communication complexity) of a public coin protocol π, denoted $\mathsf{CC}(\pi)$, is the maximum number of bits that can be transmitted in any run of the protocol.*

DEFINITION 2.12. *The* number of rounds *of a public coin protocol is the maximum depth of the protocol tree π_r over all choices of the public randomness.*

Given a protocol π, $\pi(x, y)$ denotes the concatenation of the public randomness with all the messages that are sent during the execution of π. We call this the *transcript* of the protocol. When referring to the random variable denoting the transcript, rather than a specific transcript, we will use the notation $\Pi(x, y)$; thus $\pi(x, y) \in_R \Pi(x, y)$. When x and y are random variables themselves, we will denote the transcript by $\Pi(X, Y)$, or just Π. We shall use the notation $\pi(x, y)_j$ or π_j to refer to the jth transmitted message in the protocol. We write $\pi(x, y)_{\leq j}$ to denote the concatenation of the public randomness in the protocol with the first j message bits that were transmitted in the protocol. Given a transcript, or a prefix of the transcript, v, we write $\mathsf{CC}(v)$ to denote the number of message bits in v (i.e., the length of the communication).

DEFINITION 2.13 (communication complexity notation). *For a function $f : \mathcal{X} \times \mathcal{Y} \to \mathbb{Z}_K$, a distribution μ supported on $\mathcal{X} \times \mathcal{Y}$, and a parameter $\rho > 0$, $D^{\mu}_{\rho}(f)$ denotes the communication complexity of the cheapest deterministic protocol for computing f on inputs sampled according to μ with error ρ. $R_{\rho}(f)$ denotes the cost of the best randomized public coin protocol for computing f with error at most ρ on* every *input.*

We should mention the following theorem due to Yao [78], which we will extend in this paper to information cost.

THEOREM 2.14 (Yao's min-max). $R_{\rho}(f) = \max_{\mu} D^{\mu}_{\rho}(f)$.

It is proved by viewing the setup as a two-player zero-sum game where one player designs a protocol to solve f and the other tries to foil him by choosing a hard input distribution. The theorem then follows by applying von Neumann's classic minimax theorem [76]. We will use an extension of this approach several times throughout the paper.

2.3. Information + Communication: The Information Cost of a Protocol. In the sections that follow we will develop the information complexity theory for interactive communication. The most basic definition is that of the information cost of a protocol. This notion is implicit in [3] and was explicitly defined in [4] (see also [12]).

DEFINITION 2.15. *The information cost of a protocol π over inputs from $\mathcal{X} \times \mathcal{Y}$ is given by*

$$\mathsf{IC}_{\mu}(\pi) := I(\Pi; X|Y) + I(\Pi; Y|X).$$

Intuitively, Definition 2.15 captures what the two parties learn about each other's inputs from the execution transcript of the protocol π. The first term captures what the second player learns about X from Π—the mutual information between the input

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X and the transcript Π given the input Y. Similarly, the second term captures what the first player learns about Y from Π.

Note that the information of a protocol π depends on the prior distribution μ, as the mutual information between the transcript Π and the inputs depends on the prior distribution on the inputs. To give an extreme example, if μ is a singleton distribution, i.e., one with $\mu(\{(x,y)\}) = 1$ for some $(x,y) \in \mathcal{X} \times \mathcal{Y}$, then $\mathsf{IC}_\mu(\pi) = 0$ for all possible π, as no protocol can reveal anything to the players about the inputs that they do not already know a priori. Similarly, $\mathsf{IC}_\mu(\pi) = 0$ if $\mathcal{X} = \mathcal{Y}$ and μ is supported on the diagonal $\{(x,x) : x \in \mathcal{X}\}$.

As expected, one can show that the communication cost $\mathsf{CC}(\pi)$ of π is an upper bound on its information cost over *any* distribution μ.

LEMMA 2.16 (see [12]). *For any distribution μ, $\mathsf{IC}_\mu(\pi) \le \mathsf{CC}(\pi)$.*

On the other hand, as demonstrated by the simple examples above, the converse need not hold. Moreover, while $\mathsf{CC}(\pi)$ is a combinatorial property that depends only on the protocol, $\mathsf{IC}_\mu(\pi)$ depends on μ. One of our first goals it to make the study of information cost independent of the prior distribution.

3. The Prior-Free Information Complexity of a Problem.

Given a distribution μ on a two-player input space $\mathcal{X} \times \mathcal{Y}$, a function $f : \mathcal{X} \times \mathcal{Y} \to \{0,1\}$, and an error parameter ε, the *information complexity* $\mathsf{IC}_\mu(f,\varepsilon)$ is defined to be the *infimum* of the information cost over all (randomized) protocols π that achieve an error of $\le \varepsilon$ with respect to μ.

Remark 3.1. We state all our results for boolean functions. In fact, we do not need f to be binary or even a function. All our results hold if the goal is to implement a general relation F that accepts inputs in $\mathcal{X} \times \mathcal{Y}$ and for which a protocol is said to succeed if in the end the two players reach an acceptable pair of states. In the case of a boolean function f there is only one acceptable pair of states in which each player outputs "the answer is $f(x,y)$."

DEFINITION 3.2.

$$\mathsf{IC}_\mu(f,\varepsilon) := \inf_{\pi:\ \mathbf{P}_{(x,y)\sim\mu}[\pi(x,y)\neq f(x,y)]\le\varepsilon} \mathsf{IC}_\mu(\pi).$$

Clearly, $\mathsf{IC}_\mu(f,\varepsilon)$ is monotone nondecreasing in ε—i.e., a lower error ε requires higher information cost. We note that the definition of $\mathsf{IC}_\mu(f,0)$, the zero-error information complexity, also makes sense. By Lemma 2.16, it is easy to see that the information costs are smaller than the corresponding (distributional) communication costs.

Information-theoretic quantities, such as the mutual information between the parties' inputs and the protocol's transcript, only make sense with respect to a prior distribution on inputs. Nonetheless, at least syntactically, we can factor out the distribution by taking the maximum over all possible distributions.

DEFINITION 3.3. *The max-distributional information complexity of a function f with error ε is*

$$\mathsf{IC}_\mathsf{D}(f,\varepsilon) := \max_{\mu \text{ a distribution on } \mathcal{X}\times\mathcal{Y}} \mathsf{IC}_\mu(f,\varepsilon).$$

Note that we are justified in using a max in place of sup since the set of all possible distributions over $X \times Y$ is compact and $\mathsf{IC}_\mu(f,\varepsilon)$ can be shown to be continuous in μ (and ε).

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It is not immediately apparent that the definition of $\mathsf{IC}_{\mathsf{D}}(f,\varepsilon)$ is an interesting one. While it gives an upper bound on the information cost for each distribution, this upper bound may be attained by a different protocol $\pi = \pi(\mu)$ for each distribution μ. We will show that the quantifiers may "almost" be reversed: there is a single (randomized) protocol π that achieves a low information cost *and* a low error with respect to *any* distribution μ. In fact, we define the *prior-free* information complexity of a problem in terms of such a protocol. A similar notion—presented in the form of an appropriately chosen channel capacity—has been previously considered and used in the context of simultaneous-message and one-way protocols by [34].

DEFINITION 3.4. *The information complexity of a function f with error ε is*

$$\mathsf{IC}\,(f,\varepsilon) := \inf_{\pi \text{ is a protocol with } \mathbf{P}[\pi(x,y)\neq f(x,y)]\leq\varepsilon \text{ for all } (x,y)} \max_{\mu} \ \mathsf{IC}_{\mu}(\pi).$$

Clearly, $\mathsf{IC}\,(f,\varepsilon) \geq \mathsf{IC}_{\mathsf{D}}(f,\varepsilon)$. The opposite direction is our main result connecting the prior-free information complexity with the distributional information complexity.

THEOREM 3.5. *Let $f : \mathcal{X}\times\mathcal{Y} \to \{0,1\}$ be any function, and let $\varepsilon \geq 0$ be an error parameter. For each value of the parameter $0 < \alpha < 1$ we have*

$$\mathsf{IC}\left(f,\frac{\varepsilon}{\alpha}\right) \leq \frac{\mathsf{IC}_{\mathsf{D}}(f,\varepsilon)}{1-\alpha}.$$

In other words, there is a protocol π such that

1. *for each $(x,y)\in\mathcal{X}\times\mathcal{Y}$, $\mathbf{P}[\pi(x,y)\neq f(x,y)] \leq \frac{\varepsilon}{\alpha}$, i.e., the protocol π makes an error of at most ε/α on each input;*
2. *for each distribution μ on $\mathcal{X}\times\mathcal{Y}$, $\mathsf{IC}_{\mu}(\pi) \leq \frac{\mathsf{IC}_{\mathsf{D}}(f,\varepsilon)}{1-\alpha}$, i.e., for* every *distribution the protocol π reveals not too much information to the participants.*

By selecting $\alpha = \frac{1}{2}$ we can ensure that both the error and the information cost increase by a factor of at most 2.

For the zero-error case, we similarly obtain the following zero-error version of Theorem 3.5.

THEOREM 3.6. *Let $f : \mathcal{X}\times\mathcal{Y} \to \{0,1\}$ be any function. Then we have*

$$\mathsf{IC}\,(f,0) = \mathsf{IC}_{\mathsf{D}}(f,0).$$

In other words, there is a protocol π such that

1. *for each $(x,y)\in\mathcal{X}\times\mathcal{Y}$, $\pi(x,y) = f(x,y)$, i.e., the protocol π always works correctly;*
2. *for each distribution μ on $\mathcal{X}\times\mathcal{Y}$, $\mathsf{IC}_{\mu}(\pi) \leq \mathsf{IC}_{\mathsf{D}}(f,0)$.*

3.1. Proofs of Theorems 3.5 and 3.6.

Proof of Theorem 3.5. We prove the theorem using a minimax argument. For the remainder of the proof fix f and ε, and denote $I := \mathsf{IC}_{\mathsf{D}}(f,\varepsilon)$. Define the following two-player zero-sum game. Alice will come up with a (randomized) two-party protocol $\pi(x,y)$ taking inputs in $\mathcal{X}\times\mathcal{Y}$. Bob will come up with a distribution μ on inputs (x,y). Bob's payoff is given by

$$P_B(\pi,\mu) := (1-\alpha)\cdot\frac{\mathsf{IC}_{\mu}(\pi)}{I} + \alpha\cdot\frac{\mathbf{P}_{\mu}[\pi(x,y)\neq f(x,y)]}{\varepsilon}.$$

As the game is a zero-sum game, the payoff of Alice is given by $P_A(\pi,\mu) := -P_B(\pi,\mu)$. Thus Alice comes up with a protocol for f, and Bob comes up with a distribution

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that tries to highlight the mistakes of π, and also make it reveal information about the inputs to the participants. We denote the game by $\mathcal{G}$. Our first goal is to show that the value of $\mathcal{G}$ to Bob is bounded by 1.

CLAIM 3.7. *The value* $V_B(\mathcal{G}) \leq 1$.

Proof. Let ν_B be a probability distribution representing a mixed strategy for Bob. Thus ν_B is a distribution on probability distributions μ over $X \times Y$. We will actually show that $V_B(\mathcal{G}) < 1 + \delta$ for each $\delta > 0$. To show that $V_B(\mathcal{G}) < 1 + \delta$ it suffices to show that there is a protocol π such that $\mathbf{E}_{\mu\sim\nu_B}[P_B(\pi,\mu)] < 1 + \delta$. Let $\bar{\mu}$ be a distribution on $\mathcal{X} \times \mathcal{Y}$ that is obtained by taking the average of $\mu \sim \nu_B$. Formally,

$$\bar{\mu}(x,y) := \mathbf{E}_{\mu\sim\nu_B}\mu(x,y).$$

By the definition of $I = \mathsf{IC}_{\mathsf{D}}(f,\varepsilon)$, we know that there is a protocol π such that $\mathbf{P}_{\bar{\mu}}[\pi(x,y) \neq f(x,y)] \leq \varepsilon$ and $\mathsf{IC}_{\bar{\mu}}(\pi) < I \cdot (1+\delta)$. We claim that

$$\mathbf{E}_{\mu\sim\nu_B}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);X|Y)\right] \leq I_{(X,Y)\sim\bar{\mu}}(\pi(X,Y);X|Y). \tag{3}$$

In other words, the average amount of information revealed by π with respect to the different distributions $\mu \sim \nu_B$ is smaller than or equal to the amount of information revealed with respect to $\bar{\mu}$—the concavity works in the "right" direction.

To establish (3), consider the following four random variables. Let M be a random variable representing the distribution μ. Then M is distributed according to ν_B. Let X and Y be the inputs to the two parties in π such that (X,Y) is distributed according to μ. Finally, let $\Pi = \pi(X,Y)$ be the transcript of the protocol executed on X and Y. Π is randomized even conditioned on (X,Y) due to the public and private randomness used in the execution of the protocol. In this language, we have

$$\mathbf{E}_{\mu\sim\nu_B}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);X|Y)\right] = I(\Pi;X|YM)$$

and

$$I_{(X,Y)\sim\bar{\mu}}(\pi(X,Y);X|Y) = I(\Pi;X|Y).$$

Since the distribution of Π depends only on X and Y, we have $I(\Pi;M|XY) = 0$. By substituting $A = X$, $B = \Pi$, $C = Y$, and $D = M$ into Proposition 2.9 we get

$$I(X;\Pi|Y) \geq I(X;\Pi|YM), \tag{4}$$

proving (3). Similarly to (3) the following symmetric inequality is established:

$$\mathbf{E}_{\mu\sim\nu_B}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);Y|X)\right] \leq I_{(X,Y)\sim\bar{\mu}}(\pi(X,Y);Y|X). \tag{5}$$

Together, (3) and (5) imply

$$\mathbf{E}_{\mu\sim\nu_B}\left[\mathsf{IC}_{\mu}(\pi)\right] \leq \mathsf{IC}_{\bar{\mu}}(\pi). \tag{6}$$

Using (6) we obtain

$$\begin{aligned}
\mathbf{E}_{\mu\sim\nu_B}\left[P_B(\pi,\mu)\right] &= \mathbf{E}_{\mu\sim\nu_B}\left[(1-\alpha)\cdot\frac{\mathsf{IC}_{\mu}(\pi)}{I} + \alpha\cdot\frac{\mathbf{P}_{\mu}[\pi(x,y)\neq f(x,y)]}{\varepsilon}\right] \\
&= (1-\alpha)\cdot\mathbf{E}_{\mu\sim\nu_B}\left[\frac{\mathsf{IC}_{\mu}(\pi)}{I}\right] + \alpha\cdot\frac{\mathbf{P}_{\bar{\mu}}[\pi(x,y)\neq f(x,y)]}{\varepsilon} \\
&\leq (1-\alpha)\cdot\frac{\mathsf{IC}_{\bar{\mu}}(\pi)}{I} + \alpha\cdot\frac{\mathbf{P}_{\bar{\mu}}[\pi(x,y)\neq f(x,y)]}{\varepsilon} \\
&< (1-\alpha)\cdot(1+\delta) + \alpha\cdot 1 \\
&\leq 1+\delta.
\end{aligned}$$

This proves Claim 3.7. ∎

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By the minimax theorem, Claim 3.7 implies that there is a mixed strategy for Alice such that for each response by Bob, the value of the game for Bob is at most 1. A mixed strategy for Alice is a distribution ν_A on protocols. In other words,

$$\mathbf{E}_{\pi\sim\nu_A} P_B(\pi,\mu) \leq 1 \text{ for all } \mu. \tag{7}$$

Let $\bar{\pi}$ be the randomized protocol obtained by publicly sampling $\pi \sim \nu_A$, and then applying π to the inputs. We claim that $\bar{\pi}$ is the protocol we are looking for. In other words, the randomized protocol $\bar{\pi}$ has the desired payoff properties that will translate into information cost/error properties.

Claim 3.8. *For each distribution μ, $P_B(\bar{\pi},\mu) \leq 1$.*

Proof. The proof proceeds similarly to the proof of Claim 3.7. We will prove first that

$$I_{(X,Y)\sim\mu}(\bar{\pi}(X,Y);X|Y) \leq \mathbf{E}_{\pi\sim\nu_A}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);X|Y)\right]. \tag{8}$$

In other words, the amount of information revealed by $\bar{\pi}$ is bounded by the average amount of information revealed by π that is drawn according to ν_A—once again, the concavity works in the "right" direction.

To establish (8), consider the following four random variables. Let S be a "selector" random variable that picks the protocol π to run according to the distribution ν_A. Let X and Y be inputs distributed according to μ independently of S. Finally, let $\Pi = \pi(X,Y)$ be the transcript of the selected protocol executed on X and Y. We have

$$\mathbf{E}_{\pi\sim\nu_A}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);X|Y)\right] = I(\Pi;X|YS)$$

and

$$I_{(X,Y)\sim\mu}(\bar{\pi}(X,Y);X|Y) = I(\Pi;X|Y).$$

Since the protocol π is selected independently of the inputs, we have $I(X;S|Y)=0$. By substituting $A=\Pi$, $B=X$, $C=Y$, and $D=S$ into Proposition 2.10 we get

$$I(\Pi;X|Y) \leq I(\Pi;X|YS), \tag{9}$$

establishing (8). Similarly to (8), the following symmetric inequality is established:

$$I_{(X,Y)\sim\mu}(\bar{\pi}(X,Y);Y|X) \leq \mathbf{E}_{\pi\sim\nu_A}\left[I_{(X,Y)\sim\mu}(\pi(X,Y);Y|X)\right]. \tag{10}$$

Together, (8) and (10) imply

$$\mathsf{IC}_\mu(\bar{\pi}) \leq \mathbf{E}_{\pi\sim\nu_A}\left[\mathsf{IC}_\mu(\pi)\right]. \tag{11}$$

Finally, (11) implies that

$$\begin{aligned}
P_B(\bar{\pi},\mu) &= (1-\alpha)\cdot\frac{\mathsf{IC}_\mu(\bar{\pi})}{I} + \alpha\cdot\frac{\mathbf{P}_\mu[\bar{\pi}(x,y)\neq f(x,y)]}{\varepsilon}\\
&= (1-\alpha)\cdot\frac{\mathsf{IC}_\mu(\bar{\pi})}{I} + \mathbf{E}_{\pi\sim\nu_A}\left[\alpha\cdot\frac{\mathbf{P}_\mu[\pi(x,y)\neq f(x,y)]}{\varepsilon}\right]\\
&\leq (1-\alpha)\cdot\mathbf{E}_{\pi\sim\nu_A}\left[\frac{\mathsf{IC}_\mu(\pi)}{I}\right] + \mathbf{E}_{\pi\sim\nu_A}\left[\alpha\cdot\frac{\mathbf{P}_\mu[\pi(x,y)\neq f(x,y)]}{\varepsilon}\right]\\
&= \mathbf{E}_{\pi\sim\nu_A}\left[P_B(\pi,\mu)\right]\\
&\leq 1,
\end{aligned}$$

completing the proof of Claim 3.8. ∎

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To complete the proof of Theorem 3.5, we observe that the randomized protocol $\bar{\pi}$ satisfies the conclusions of the theorem. For each distribution μ we know that $P_B(\bar{\pi}, \mu) \leq 1$, and thus

$$\mathsf{IC}_\mu(\bar{\pi}) \leq \frac{I}{1-\alpha} \quad \text{and} \quad \mathbf{P}_\mu[\bar{\pi}(x,y) \neq f(x,y)] \leq \frac{\varepsilon}{\alpha}.$$

The first inequality is exactly the second requirement in Theorem 3.5. We obtain the second requirement by letting μ be the atomic distribution on $\{(x,y)\}$. ∎

Remark 3.9. Note that the statement of Theorem 3.5 contains a gap in the following sense. We are unable to simultaneously achieve the goals of low information and low error with the same parameters as in the distributional setting. Instead we lose factors of $\frac{1}{1-\alpha}$ and $\frac{1}{\alpha}$. An interesting open problem would be in determining whether this analysis is actually tight, i.e., whether $\mathsf{IC}(f,\varepsilon) = \mathsf{IC}_\mathsf{D}(f,\varepsilon)$. It is quite possible that there is, in fact, a gap between the two quantities.

Proof of Theorem 3.6. The proof is very similar to the proof of Theorem 3.5. The key difference is that now we only deal with zero-error protocols. Denote $I := \mathsf{IC}_\mathsf{D}(f,0)$. We define the following zero-sum two-player game $\mathcal{G}_0$. Alice will come up with a (randomized) two-party protocol $\pi(x,y)$ taking inputs in $\mathcal{X} \times \mathcal{Y}$. The protocol is required to always be correct: for any pair of inputs (x,y), $\pi(x,y) = f(x,y)$ with probability 1 with respect to the random coin tosses within π. Bob will come up with a distribution μ on inputs (x,y). Note that the protocol π has to be correct even on inputs outside of the support of μ. Bob's payoff is given by

$$P_B(\pi,\mu) := \frac{\mathsf{IC}_\mu(\pi)}{I}.$$

Once again, we first need to establish that the value of the game for Bob is bounded by 1.

Claim 3.10. *The value* $V_B(\mathcal{G}_0) \leq 1$.

Proof. The proof is quite similar to the proof of Claim 3.7, with one minor twist: by the assumption, for each distribution μ there is a zero-error protocol π_μ whose information cost with respect to μ is $< (1+\delta)\cdot I$. The problem is that π_μ only has to be zero-error *on the support of* μ. This problem is easily overcome by modifying μ very slightly to ensure that it has full support.

We will actually show that $V_B(\mathcal{G}_0) < 1+\delta$ for each $\delta > 0$. Let ν_B be a probability distribution representing a mixed strategy for Bob. Thus ν_B is a distribution on probability distributions μ over $\mathcal{X} \times \mathcal{Y}$. We modify ν_B to select the distribution μ_u uniform on $\mathcal{X} \times \mathcal{Y}$ with probability $\delta/4$ to obtain ν'_B. Bob's payoff is always nonnegative. Hence, if there is a strategy π for Alice that guarantees that B's payoff with respect to ν'_B is $< 1+\delta/2$, then using the same strategy will guarantee that B's payoff with respect to ν_B is $< 1+\delta$. Otherwise, B's payoff with respect to ν'_B would be at least

$$(1+\delta)\cdot(1-\delta/4) = 1 + 3\delta/4 - \delta^2/4 > 1+\delta/2.$$

Thus we need to show that there is a zero-error protocol π such that $\mathbf{E}_{\mu\sim\nu'_B}[\mathsf{IC}_\mu(\pi)] < (1+\delta/2)\cdot I$. Let $\bar{\mu}$ be a distribution on $\mathcal{X}\times\mathcal{Y}$ that is obtained by taking the average of $\mu \sim \nu'_B$. Formally,

$$\bar{\mu}(x,y) := \mathbf{E}_{\mu\sim\nu_B}\mu(x,y).$$

Note that since one of the distributions in ν'_B is the uniform distribution on $\mathcal{X}\times\mathcal{Y}$, $\bar{\mu}$ has full support.

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By the definition of $I = \mathsf{IC}_{\mathsf{D}}(f, 0)$, we know that there is a protocol π that achieves zero-error with respect to $\bar{\mu}$ such that $\mathsf{IC}_{\bar{\mu}}(\pi) < I \cdot (1 + \delta/2)$. Since $\bar{\mu}$ has full support, π is a feasible strategy for Alice. Following the analysis in Claim 3.7 we obtain that (6) still holds here:

$$\mathbf{E}_{\mu \sim \nu'_B} [\mathsf{IC}_{\mu}(\pi)] \leq \mathsf{IC}_{\bar{\mu}}(\pi).$$

Thus

$$\mathbf{E}_{\mu \sim \nu_B} [P_B(\pi, \mu)] = \mathbf{E}_{\mu \sim \nu'_B} [\mathsf{IC}_{\mu}(\pi)] / I \leq \mathsf{IC}_{\bar{\mu}}(\pi)/I < 1 + \delta/2,$$

completing the proof of Claim 3.10. ∎

The rest of the proof of Theorem 3.6 is identical to the proof of Theorem 3.5. There is a distribution ν_A of strategies for Alice such that each protocol in ν_A is a zero-error protocol, and for each distribution μ the expected payoff $\mathbf{E}_{\pi \sim \nu_A}[P_B(\pi, \mu)] \leq 1$. If we let $\bar{\pi}$ be the randomized protocol obtained by sampling π according to ν_A and then running it, then exactly as in Claim 3.8 above we obtain

$$\mathsf{IC}_{\mu}(\bar{\pi}) \leq \mathbf{E}_{\pi \sim \nu_A}[\mathsf{IC}_{\mu}(\bar{\pi})] = I \cdot \mathbf{E}_{\pi \sim \nu_A}[P_B(\pi, \mu)] \leq I. \quad ∎$$

3.2. External Information Complexity. We next turn our attention to the *external information complexity* of a problem. Recall that the regular (internal) information cost of a problem is the amount of information the participating parties have to learn about the inputs to solve the problem. By analogy, the external information cost is the amount of information an observer necessarily has to learn when the parties perform the computation.

We start by defining the external information cost of a protocol π.

DEFINITION 3.11. *Let π be a two-party communication protocol over inputs in $\mathcal{X} \times \mathcal{Y}$. Let μ be a distribution over $\mathcal{X} \times \mathcal{Y}$. We denote by (X, Y) the (random) pair of inputs given to the players that are distributed according to μ. Let $\Pi = \Pi(X, Y)$ denote the random variable that is the transcript of the protocol. Then the external information cost of π with respect to μ is given by*

$$\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) := I(XY; \Pi).$$

We note that the external information cost is always greater than or equal to the internal information cost of a protocol.

PROPOSITION 3.12. *For each protocol π and distribution μ,*

$$\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) \geq \mathsf{IC}_{\mu}(\pi).$$

Moreover, the two quantities are equal if $\mu = \mu_{\mathcal{X}} \times \mu_{\mathcal{Y}}$ is a product distribution on $\mathcal{X} \times \mathcal{Y}$.

Proof. The proposition is only true because π is a protocol; it is not hard to see that it would fail if Π were a general random variable that is correlated with the inputs X and Y. Denote by $\Pi_1, \Pi_2, \ldots, \Pi_N$ the messages sent in the protocol π. We assume that Π_i is sent by Alice (who holds X) for odd i's and by Bob for even i's. N itself is also a random variable here.

By the chain rule, we have

$$\begin{aligned}\mathsf{IC}_{\mu}(\pi) &= I(X; \Pi | Y) + I(Y; \Pi | X) \\ &= \sum_{i=1}^{N} [I(X; \Pi_i | \Pi_1, \ldots, \Pi_{i-1} Y) + I(Y; \Pi_i | \Pi_1, \ldots, \Pi_{i-1} X)]\end{aligned}$$

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and

$$\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) = I(XY;\Pi) = \sum_{i=1}^{N} I(XY;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}).$$

We will prove the inequality term-wise. Let i be an index. Without loss of generality assume that i is odd, so that Π_i is a message sent by Alice. This means that, conditioned on prior communications and on X, Π_i is independent of Y:

$$I(\Pi_i;Y|\Pi_1,\ldots,\Pi_{i-1}X) = 0. \tag{12}$$

We can now write

$$\begin{aligned} I(XY;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}) &= I(X;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}) + I(Y;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}X) \\ &\geq I(X;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}Y) + I(Y;\Pi_i|\Pi_1,\ldots,\Pi_{i-1}X), \end{aligned}$$

where the last inequality follows from (12) and Proposition 2.9 by taking $A = X$, $B = \Pi_i$, $C = \Pi_1,\ldots,\Pi_{i-1}$, and $D = Y$.

It remains to prove the converse inequality in the case when μ is a product distribution. This direction actually holds when Π is any random variable. If μ is a product distribution, then X and Y are independent, and thus $I(X;Y) = 0$. We have

$$\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) = I(XY;\Pi) = I(X;\Pi) + I(Y;\Pi|X) \leq I(X;\Pi|Y) + I(Y;\Pi|X) = \mathsf{IC}_{\mu}(\pi),$$

where the inequality holds by Proposition 2.10 with $A = \Pi$, $B = X$, $C = \emptyset$, and $D = Y$. ∎

We can now define the natural analogues of Definitions 3.2, 3.3, and 3.4 for external information, starting with the distributional external information complexity.

Definition 3.13.

$$\mathsf{IC}^{\mathsf{ext}}_{\mu}(f,\varepsilon) := \inf_{\pi:\ \mathbf{P}_{(x,y)\sim\mu}[\pi(x,y)\neq f(x,y)]\leq\varepsilon} \mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi).$$

Definition 3.14. *The max-distributional external information complexity of a function f with error ε is*

$$\mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f,\varepsilon) := \max_{\mu \text{ a distribution on } \mathcal{X}\times\mathcal{Y}} \mathsf{IC}^{\mathsf{ext}}_{\mu}(f,\varepsilon).$$

Definition 3.15. *The external information complexity of a function f with error ε is*

$$\mathsf{IC}^{\mathsf{ext}}(f,\varepsilon) := \inf_{\pi \text{ is a protocol with } \mathbf{P}[\pi(x,y)\neq f(x,y)]\leq\varepsilon \text{ for all } (x,y)} \max_{\mu} \mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi).$$

Proposition 3.12 implies that for all μ, $\mathsf{IC}^{\mathsf{ext}}_{\mu}(f,\varepsilon) \geq \mathsf{IC}_{\mu}(f,\varepsilon)$, and also $\mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f,\varepsilon) \geq \mathsf{IC}_{\mathsf{D}}(f,\varepsilon)$ and $\mathsf{IC}^{\mathsf{ext}}(f,\varepsilon) \geq \mathsf{IC}(f,\varepsilon)$.

Finally, the analogues of Theorems 3.5 and 3.6 for external information cost are proved in the exact same way. We formulate the theorems here.

Theorem 3.16. *Let $f : \mathcal{X}\times\mathcal{Y} \to \mathbb{Z}_K$ be any function, and let $\varepsilon \geq 0$ be an error parameter. For each value of the parameter $0 < \alpha < 1$ we have*

$$\mathsf{IC}^{\mathsf{ext}}\left(f,\frac{\varepsilon}{\alpha}\right) \leq \frac{\mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f,\varepsilon)}{1-\alpha}.$$

In other words, there is a protocol π such that

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1. *for each* $(x, y) \in \mathcal{X} \times \mathcal{Y}$, $\mathbf{P}[\pi(x, y) \neq f(x, y)] \leq \frac{\varepsilon}{\alpha}$, *i.e., the protocol* π *makes an error of at most* ε/α *on each input;*
2. *for each distribution* μ *on* $\mathcal{X} \times \mathcal{Y}$, $\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) \leq \frac{\mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f,\varepsilon)}{1-\alpha}$, *i.e., for* every *distribution the protocol* π *reveals not too much information to the observer.*

THEOREM 3.17. *Let* $f : \mathcal{X} \times \mathcal{Y} \to \mathbb{Z}_K$ *be any function. Then we have*

$$\mathsf{IC}^{\mathsf{ext}}(f, 0) = \mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f, 0).$$

In other words, there is a protocol π *such that*

1. *for each* $(x, y) \in \mathcal{X} \times \mathcal{Y}$, $\pi(x, y) = f(x, y)$, *i.e., the protocol* π *always works correctly;*
2. *for each distribution* μ *on* $\mathcal{X} \times \mathcal{Y}$, $\mathsf{IC}^{\mathsf{ext}}_{\mu}(\pi) \leq \mathsf{IC}^{\mathsf{ext}}_{\mathsf{D}}(f, 0)$.

The only difference between the proofs of Theorem 3.5 and of its external version, Theorem 3.16, is that equations (4) and (9) are slightly different. The external version of (4) is

$$I(XY; \Pi) \geq I(XY; \Pi | M), \tag{13}$$

which still follows from Proposition 2.9 with $A = XY$, $B = \Pi$, $C = \emptyset$, $D = M$, and the fact that $I(\Pi; M|XY) = 0$. The external version of (9) is

$$I(\Pi; XY) \leq I(\Pi; XY|S), \tag{14}$$

which follows from Proposition 2.10 with $A = \Pi$, $B = XY$, $C = \emptyset$, $D = S$, and the fact that $I(XY; S) = 0$.

3.3. The Information Complexity Is Convex in the Error Parameter. In this section we prove that the information complexity $\mathsf{IC}(f, \varepsilon)$ is convex in the error parameter ε. Note that this function is trivially nonincreasing.

THEOREM 3.18. *For any* f, *the function* $I(\varepsilon) := \mathsf{IC}(f, \varepsilon)$ *is convex on the interval* $\varepsilon \in [0, 1]$.

Since a convex function on an interval must be continuous, the following is an immediate corollary of Theorem 3.18.

COROLLARY 3.19. *For any* f, *the function* $I(\varepsilon) := \mathsf{IC}(f, \varepsilon)$ *is continuous on the interval* $\varepsilon \in (0, 1)$.

Remark 3.20. A statement analogous to Theorem 3.18, with a very similar proof, holds for the max-distributional information complexity $\mathsf{IC}_{\mathsf{D}}(f, \varepsilon)$.

Remark 3.21. The continuity in Corollary 3.19 extends to the point $\varepsilon = 0$, although this fact does not follow directly from convexity and requires a proof [11].

Proof of Theorem 3.18. Let $0 \leq \varepsilon_1 < \varepsilon_2 \leq 1$ be two values, and let $\alpha \in (0, 1)$ be a parameter. Set $\varepsilon := \alpha \cdot \varepsilon_1 + (1 - \alpha) \cdot \varepsilon_2$. Our goal is to show that

$$I(\varepsilon) \leq \alpha \cdot I(\varepsilon_1) + (1 - \alpha) \cdot I(\varepsilon_2).$$

Let $\delta > 0$ be a parameter that tends to 0. By the definition of $\mathsf{IC}(f, \varepsilon)$, there is a pair of protocols π_1 and π_2 that attain an error of at most ε_1 and ε_2, respectively, on each input (x, y), and such that for each distribution μ,

$$\mathsf{IC}_{\mu}(\pi_1) < I(\varepsilon_1) + \delta \quad \text{and} \quad \mathsf{IC}_{\mu}(\pi_2) < I(\varepsilon_2) + \delta.$$

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Let π be a protocol that publicly tosses a coin to select between π_1 and π_2 and then runs the selected protocol. π_1 is selected with probability α, and π_2 is selected with probability $(1-\alpha)$. For each pair of inputs (x, y) we have

$$\mathbf{P}[\pi(x,y) \neq f(x,y)] = \alpha \cdot \mathbf{P}[\pi_1(x,y) \neq f(x,y)] + (1-\alpha) \cdot \mathbf{P}[\pi_2(x,y) \neq f(x,y)] \leq \varepsilon.$$

Following the same proof as the proof of (11) in Claim 3.8, we can obtain for each μ

$$\mathsf{IC}_\mu(\pi) \leq \alpha \cdot \mathsf{IC}_\mu(\pi_1) + (1-\alpha) \cdot \mathsf{IC}_\mu(\pi_2) < \alpha \cdot I(\varepsilon_1) + (1-\alpha) \cdot I(\varepsilon_2) + \delta.$$

This implies that $I(\varepsilon) < \alpha \cdot I(\varepsilon_1) + (1-\alpha) \cdot I(\varepsilon_2) + \delta$ for each $\delta > 0$, and hence

$$I(\varepsilon) \leq \alpha \cdot I(\varepsilon_1) + (1-\alpha) \cdot I(\varepsilon_2). \qquad \square$$

3.4. Example: The Information Complexity of Equality. As an instructive illustration, consider the information complexity of the equality function. The equality function $EQ : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}$ is given by $EQ(x,y) = 1$ if and only if $x = y$. We show that the zero-error information complexity of the equality function is a constant.

PROPOSITION 3.22. $\mathsf{IC}(EQ, 0) = O(1)$.

It is well known that the deterministic communication complexity of EQ is $n+1$, while the randomized communication complexity if one allows error ε is bounded by $O(\log 1/\varepsilon)$ (assuming the parties have access to public randomness). Moreover, if the protocol is allowed to be randomized but is required to always be correct, its expected communication cost is still linear in n. Proposition 3.22 exposes a large gap between zero-error communication complexity and information complexity. Moreover, it also shows that when subconstant error is considered there is a gap between the randomized communication complexity and information complexity.

Discussion. Proposition 3.22, together with our other results, sheds interesting light onto the results by Feder et al. [26] on the (violation of) direct sum for randomized communication complexity. Feder et al. [26] give EQ as an example that appears to violate direct sum for randomized communication complexity. It is not hard to see that the randomized communication complexity of EQ with error ε, $R_\varepsilon(EQ)$, equals $\Omega(\log 1/\varepsilon)$. On the other hand, the (nontrivial) algorithm from [26] shows that the amortized communication complexity of EQ, $R_\varepsilon(EQ^n)/n$, equals $O(1)$, even for relatively small $n = \log^2 1/\varepsilon$. This shows that there is no hope for a direct sum theorem to hold if one regards the error ε as a parameter. Combining Proposition 3.22 with the "$\geq$" direction of the general Theorem 6.7 gives an alternative proof of this fact for any $\varepsilon > 0$. Thus, intuitively, the gap between the randomized and the amortized communication complexity of equality for small values of ε is caused by the gap between the randomized communication complexity (which depends on ε) and the inherent information cost of the problem (which is constant, even in the extreme case when $\varepsilon = 0$). At the same time, in light of this explanation, it is not clear whether this gap sheds any light on the situation with constant ε. We will revisit these points in the discussion of Theorem 6.7.

Proof. We present a zero-error protocol π for equality that will have low information cost with respect to any prior distribution. Note that to prove the proposition it would have been sufficient to produce such a protocol π_μ for each given prior distribution μ, as Theorem 3.6 would guarantee the existence of a protocol π that simul-

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A Zero-Error Constant-Information Complexity Protocol for EQ

1. The parties use public randomness to sample a uniformly random nonsingular matrix $A \in \mathbb{F}_2^n$. Denote the rows of A by $a_1, a_2, \ldots, a_n$.
2. At step i, the first player sends $a_i \cdot x$ to the second player. If $a_i \cdot x \neq a_i \cdot y$, the second player responds "not equal" and the protocol terminates with $EQ(x, y) = 0$.
3. If the protocol hasn't terminated after n steps, the protocol terminates with $EQ(x, y) = 1$.

Fig. 2 *The protocol for equality.*

taneously has low information cost with respect to all distributions μ. The protocol is presented in Figure 2.

Correctness. The protocol terminates on each input after at most n rounds. Both parties always output the same answer. If the protocol terminates and returns 0, then there is an a_i with $a_i \cdot x \neq a_i \cdot y$, and thus $x \neq y$. If the protocol terminates and outputs 1, then $Ax = Ay$. Since A is always chosen to be nonsingular, this implies $x = y$.

Information Cost. First of all, note that the protocol is essentially symmetric with respect to the two players: at each round the two players learn whether $a_i \cdot x = a_i \cdot y$, and only continue if this is the case. Let μ be any distribution on inputs (x, y). It suffices to show that $I_\mu(X; \pi(X, Y)|Y) = O(1)$, where $(X, Y) \sim \mu$. Let R be the public randomness used by the protocol to sample the matrix A, and let π_R be the deterministic protocol that uses this randomness. It is a simple fact (see, e.g., [12]) that $I_\mu(X; \pi|Y) = \mathbf{E}_R[I_\mu(X; \pi_R|Y)]$. In fact, we will show that

$$\mathbf{E}_R[H_\mu(\pi|Y)] = O(1),$$

which would suffice since $\mathbf{E}_R[I_\mu(X; \pi_R|Y)] \leq \mathbf{E}_R[H_\mu(\pi|Y)]$.

Given an input y to the second player, and given the matrix A that is publicly sampled, the possible protocol transcripts are of two kinds:

1. If $x \neq y$, then the protocol may last anywhere from 1 to n rounds, and the transcript will only depend on the number i of rounds. Let $p_i = p_i(R, y, \mu)$ denote the probability that the protocol lasts exactly i rounds and $x \neq y$.
2. If $x = y$, then the protocol lasts n rounds, and its transcript is completely determined by A and y. Let $p_0 = p_0(R, y, \mu)$ denote the probability that the protocol outputs $x = y$.

Denote by $\bar{p}_i(y, \mu) := \mathbf{E}_R p_i(R, y, \mu)$. We can now calculate $\mathbf{E}_R[H_\mu(\pi|Y)]$:

$$\begin{aligned}
\mathbf{E}_R[H_\mu(\pi|Y)] &= \mathbf{E}_R \mathbf{E}_{y \sim \mu_y} \sum_{i=0}^{n} p_i(R, y, \mu) \log \frac{1}{p_i(R, y, \mu)} \\
&= \mathbf{E}_{y \sim \mu_y} \mathbf{E}_R \sum_{i=0}^{n} p_i(R, y, \mu) \log \frac{1}{p_i(R, y, \mu)} \\
&\leq \mathbf{E}_{y \sim \mu_y} \sum_{i=0}^{n} \bar{p}_i(y, \mu) \log \frac{1}{\bar{p}_i(y, \mu)},
\end{aligned}$$

where the last inequality follows from the concavity of the $x \log(1/x)$ function. Next, note that for each $i \geq 2$, $\bar{p}_i(y, \mu) \leq 2^{-i+1}$, since the probability over R that the

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protocol will last for at least i rounds for each fixed pair $x \neq y$ is bounded by 2^{-i+1}. Thus for each y and for each $i \geq 3$,

$$\bar{p}_i(y,\mu) \log \frac{1}{\bar{p}_i(y,\mu)} \leq 2^{-i+1} \cdot (i-1).$$

In addition, it is always the case that $\bar{p}_i(y,\mu) \log \frac{1}{\bar{p}_i(y,\mu)} \leq 1$, and thus

$$\mathbf{E}_R[H_\mu(\pi|Y)] \leq \mathbf{E}_{y\sim\mu_y} \sum_{i=0}^{n} \bar{p}_i(y,\mu) \log \frac{1}{\bar{p}_i(y,\mu)} < 3 + \sum_{i=3}^{\infty} 2^{-i+1} \cdot (i-1) = 4.5 = O(1). \quad \square$$

4. The Additivity of Information Complexity. In this section we will show that information complexity is additive. That is, the information complexity of performing two independent tasks is the sum of the information complexities of each individual task. This is a more general (though closely related) statement than a direct sum theorem that states that n copies of the *same* task cost n times as much as one copy [12]. In contrast with the information complexity, we do not know such a statement to be true for communication complexity, and it is known to be false in other settings. See [4] for a further discussion on direct sum problems.

We formulate the result in terms of tasks. A task is just a (possibly partial) relation $R(x, y, O_x, O_y)$, along with a required success criterion. Here O_x and O_y correspond to the outputs of the two players. For example, if the task is to compute a function f with probability $> 1 - \varepsilon$, then $R(x, y, O_x, O_y) = 1$ if and only if $O_x = O_y = f(x, y)$, and the success criterion is that $R(x, y, O_x, O_y) = 1$ with probability $> 1 - \varepsilon$. Another example of a task is computing n independent copies of a function f such that the probability of success on each copy is $> 1 - \varepsilon$. In this way, a task is essentially "anything that can be solved by a communication protocol."

The information cost of a task $T(x, y)$ is defined similarly to the information cost of a function. To be concrete and to avoid cumbersome notation, we assume that the inputs (x, y) belong to $\mathcal{U} := \{0,1\}^n$. Let $\mathcal{M}$ be a set of distributions on $\mathcal{U} \times \mathcal{U}$. Then the information cost of T with respect to $\mathcal{M}$ is defined as follows.

DEFINITION 4.1. $\mathsf{IC}(T, \mathcal{M}) := \inf_{\pi \text{ succeeds at } T} \sup_{\mu \in \mathcal{M}} \mathsf{IC}_\mu(\pi)$, *where the infimum is taken over protocols that successfully perform the task T.*

Let $T_1(x_1, y_1)$ and $T_2(x_2, y_2)$ be two tasks. Let

$$T(x_1, x_2, y_1, y_2) := T_1 \times T_2$$

be the task that consists of performing T_1 and T_2 in parallel on two pairs of inputs. A protocol is successful at T if it is successful at each of the two subtasks separately.

Next, we consider two products of sets of distributions. Let $\mathcal{M}_1$ be a set of distributions of pairs (x_1, y_1), and let $\mathcal{M}_2$ be a set of distributions of pairs (x_2, y_2). Denote

$$\mathcal{M}_1 \times \mathcal{M}_2 := \{\mu_1 \times \mu_2 : \ \mu_1 \in \mathcal{M}_1, \ \mu_2 \in \mathcal{M}_2\}.$$

We also define a bigger class of distributions which are not necessarily product distributions, but whose projections fall into the sets $\mathcal{M}_1, \mathcal{M}_2$:

$$\mathcal{M}_1 \otimes \mathcal{M}_2 := \{\mu : \ \mu|_{(X_1,Y_1)} \in \mathcal{M}_1, \ \mu|_{(X_2,Y_2)} \in \mathcal{M}_2\} \supset \mathcal{M}_1 \times \mathcal{M}_2.$$

THEOREM 4.2. *Let $T_1(x_1, y_1)$ and $T_2(x_2, y_2)$ be two tasks, let $\mathcal{M}_1$ and $\mathcal{M}_2$ be any sets of distributions over (x_1, y_1) and (x_2, y_2), respectively, and let $T := T_1 \times T_2$. Then*

$$\mathsf{IC}(T, \mathcal{M}_1 \times \mathcal{M}_2) = \mathsf{IC}(T, \mathcal{M}_1 \otimes \mathcal{M}_2) = \mathsf{IC}(T_1, \mathcal{M}_1) + \mathsf{IC}(T_2, \mathcal{M}_2).$$

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Proof. We prove the theorem by establishing three nonstrict inequalities.

• $\mathsf{IC}(T, \mathcal{M}_1 \times \mathcal{M}_2) \leq \mathsf{IC}(T, \mathcal{M}_1 \otimes \mathcal{M}_2)$. This is obvious, since $\mathcal{M}_1 \otimes \mathcal{M}_2 \supset \mathcal{M}_1 \times \mathcal{M}_2$, and thus the sup in Definition 4.1 is taken over a larger set.

• $\mathsf{IC}(T, \mathcal{M}_1 \otimes \mathcal{M}_2) \leq \mathsf{IC}(T_1, \mathcal{M}_1) + \mathsf{IC}(T_2, \mathcal{M}_2)$. Let $\varepsilon > 0$ be an arbitrarily small parameter. Let π_1 and π_2 be two protocols that succeed at tasks T_1 and T_2, respectively, such that

$$\mathsf{IC}_{\mu_1}(\pi_1) < \mathsf{IC}(T_1, \mathcal{M}_1) + \varepsilon \quad \text{and} \quad \mathsf{IC}_{\mu_2}(\pi_2) < \mathsf{IC}(T_2, \mathcal{M}_2) + \varepsilon$$

for all $\mu_1 \in \mathcal{M}_1$ and $\mu_2 \in \mathcal{M}_2$. Let π be the protocol that on (the random) inputs (X_1, X_2), (Y_1, Y_2) independently runs π_1 on the pair (X_1, Y_1) and π_2 on the pair (X_2, Y_2). Then clearly the protocol π succeeds at the task $T = T_1 \times T_2$. It remains to analyze π's information cost. Let μ be a distribution in $\mathcal{M}_1 \otimes \mathcal{M}_2$. We will show that

$$\mathsf{IC}_{\mu}(\pi) < \mathsf{IC}(T_1, \mathcal{M}_1) + \mathsf{IC}(T_2, \mathcal{M}_2) + 2\varepsilon;$$

since $\varepsilon > 0$ is arbitrary, this will complete the proof. Denote $\mu_1 := \mu|_{(X_1,Y_1)} \in \mathcal{M}_1$ and $\mu_2 := \mu|_{(X_2,Y_2)} \in \mathcal{M}_2$. Let Π_1 be the random variable denoting the transcript of π_1, and similarly let Π_2 denote the transcript of π_2. We know that

$$I(X_1; \Pi_1 | Y_1) + I(Y_1; \Pi_1 | X_1) = \mathsf{IC}_{\mu_1}(\pi_1) < \mathsf{IC}(T_1, \mathcal{M}_1) + \varepsilon,$$

and similarly

$$I(X_2; \Pi_2 | Y_2) + I(Y_2; \Pi_2 | X_2) = \mathsf{IC}_{\mu_2}(\pi_2) < \mathsf{IC}(T_2, \mathcal{M}_2) + \varepsilon.$$

Next we note that the execution of π_1 depends only on the inputs X_1, Y_1 and the public/private randomness pertaining to the execution of π_1. This implies

$$\begin{aligned} I(\Pi_1; X_2 | X_1 Y_1) &= I(\Pi_1; Y_2 | X_1 Y_1) = I(\Pi_1; \Pi_2 | X_1 Y_1) = I(\Pi_1; X_2 Y_2 | X_1 Y_1) \\ &= I(\Pi_1; Y_2 \Pi_2 | X_1 Y_1) = I(\Pi_1; X_2 \Pi_2 | X_1 Y_1) = I(\Pi_1; X_2 Y_2 \Pi_2 | X_1 Y_1) = 0, \end{aligned} \tag{15}$$

and similar equalities hold for Π_2.

By Proposition 2.9 with $A = X_1$, $B = \Pi_1$, $C = Y_1$, $D = Y_2$, and the fact that $I(\Pi_1; Y_2 | X_1 Y_1) = 0$, we get

$$I(\Pi_1; X_1 | Y_1 Y_2) \leq I(\Pi_1; X_1 | Y_1). \tag{16}$$

Similarly, by Proposition 2.9 with $A = X_2$, $B = \Pi_2$, $C = Y_2$, $D = \Pi_1 Y_1$, and the fact that $I(\Pi_2; \Pi_1 Y_1 | X_2 Y_2) = 0$, we get

$$I(\Pi_2; X_2 | \Pi_1 Y_1 Y_2) \leq I(\Pi_2; X_2 | Y_2). \tag{17}$$

Putting these and (15) together, we obtain

$$\begin{aligned} I(\Pi; X_1 X_2 | Y_1 Y_2) &= I(\Pi_1 \Pi_2; X_1 X_2 | Y_1 Y_2) = I(\Pi_1; X_1 X_2 | Y_1 Y_2) + I(\Pi_2; X_1 X_2 | Y_1 Y_2 \Pi_1) \\ &= I(\Pi_1; X_1 | Y_1 Y_2) + I(\Pi_1; X_2 | X_1 Y_1 Y_2) \\ &\quad + I(\Pi_2; X_2 | Y_1 Y_2 \Pi_1) + I(\Pi_2; X_1 | X_2 Y_1 Y_2 \Pi_1) \\ &\overbrace{=}^{\text{by (15)}} I(\Pi_1; X_1 | Y_1 Y_2) + I(\Pi_2; X_2 | Y_1 Y_2 \Pi_1) \\ &\overbrace{\leq}^{\text{by (16) and (17)}} I(\Pi_1; X_1 | Y_1) + I(\Pi_2; X_2 | Y_2). \end{aligned}$$

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Similarly, $I(\Pi; Y_1Y_2|X_1X_2) \leq I(\Pi_1; Y_1|X_1) + I(\Pi_2; Y_2|X_2)$. Thus

$$\begin{aligned}\mathsf{IC}_\mu(\pi) &= I(\Pi; X_1X_2|Y_1Y_2) + I(\Pi; Y_1Y_2|X_1X_2)\\ &\leq I(\Pi_1; X_1|Y_1) + I(\Pi_2; X_2|Y_2) + I(\Pi_1; Y_1|X_1) + I(\Pi_2; Y_2|X_2)\\ &= \mathsf{IC}_{\mu_1}(\Pi_1) + \mathsf{IC}_{\mu_2}(\Pi_2) < \mathsf{IC}\,(T_1, \mathcal{M}_1) + \mathsf{IC}\,(T_2, \mathcal{M}_2) + 2\varepsilon.\end{aligned}$$

• $\mathsf{IC}\,(T_1, \mathcal{M}_1) + \mathsf{IC}\,(T_2, \mathcal{M}_2) \leq \mathsf{IC}\,(T, \mathcal{M}_1 \times \mathcal{M}_2)$. Let $\mu_1 \in \mathcal{M}_1$ and $\mu_2 \in \mathcal{M}_2$ be two distributions, and let $\varepsilon > 0$ be a parameter. We will show that there are protocols π_1 and π_2 that succeed at tasks T_1 and T_2, respectively, such that

$$\mathsf{IC}_{\mu_1}(\pi_1) + \mathsf{IC}_{\mu_2}(\pi_2) < \mathsf{IC}\,(T, \mathcal{M}_1 \times \mathcal{M}_2) + \varepsilon.$$

By the definition of $\mathsf{IC}\,(T, \mathcal{M}_1 \times \mathcal{M}_2)$, there is a protocol π that succeeds at the task $T_1 \times T_2$ such that

$$\mathsf{IC}_{\mu_1 \times \mu_2}(\pi) < \mathsf{IC}\,(T, \mathcal{M}_1 \times \mathcal{M}_2) + \varepsilon.$$

Define the protocols π_1 and π_2 as in Figure 3. From the definition of $T = T_1 \times T_2$ it follows that the protocols π_1 and π_2 succeed at T_1 and T_2, respectively. It remains to analyze their information complexity.

Protocol $\pi_1(x_1, y_1)$
1. The parties jointly and publicly sample Y_2 according to $\mu_2|_{Y_2}$. 2. The first party privately samples $X_2 = X_2|Y_2$. 3. The parties run $\pi((x_1, X_2), (y_1, Y_2))$ and output the output of the task T_1.

Protocol $\pi_2(x_2, y_2)$
1. The parties jointly and publicly sample X_1 according to $\mu_1|_{X_1}$. 2. The second party privately samples $Y_1 = Y_1|X_1$. 3. The parties run $\pi((X_1, x_2), (Y_1, y_2))$ and output the output of the task T_2.

Fig. 3 *The protocols π_1 and π_2.*

We have

$$\mathsf{IC}_{\mu_1}(\pi_1) = I(\pi_1; X_1|Y_1) + I(\pi_1; Y_1|X_1) = I(\pi; X_1|Y_1Y_2) + I(\pi; Y_1|X_1X_2Y_2), \tag{18}$$

since an execution of π_1 is an execution of π where Y_2 is known to both parties and X_2 is only known to the first party. Thus π is executed with the first party knowing X_1 (input), X_2 (privately sampled), and Y_2 (publicly sampled), and the second party knowing Y_1 (input) and Y_2 (publicly sampled). Similarly,

$$\mathsf{IC}_{\mu_2}(\pi_2) = I(\pi_2; X_2|Y_2) + I(\pi_2; Y_2|X_2) = I(\pi; X_2|X_1Y_1Y_2) + I(\pi; Y_1|X_1X_2). \tag{19}$$

Putting the two equations (18) and (19) together, we get

$$\begin{aligned}&\mathsf{IC}_{\mu_1}(\pi_1) + \mathsf{IC}_{\mu_2}(\pi_2)\\ &= I(\pi; X_1|Y_1Y_2) + I(\pi; Y_1|X_1X_2Y_2) + I(\pi; X_2|X_1Y_1Y_2) + I(\pi; Y_1|X_1X_2)\\ &= I(\pi; X_1|Y_1Y_2) + I(\pi; X_2|X_1Y_1Y_2) + I(\pi; Y_1|X_1X_2) + I(\pi; Y_1|X_1X_2Y_2)\\ &= I(\pi; X_1X_2|Y_1Y_2) + I(\pi; Y_1Y_2|X_1X_2)\\ &= \mathsf{IC}_{\mu_1 \times \mu_2}(\pi) < \mathsf{IC}\,(T, \mathcal{M}_1 \times \mathcal{M}_2) + \varepsilon. \qquad \square\end{aligned}$$

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Theorem 4.2 can now be used in many different ways. Let us use it to show exact direct sum theorems for both the information cost and the distributional information cost.

THEOREM 4.3. *Let $f(x,y)$ be any function, and let $\rho \geq 0$ be an error parameter. Let f^n be the problem of computing f on n pairs of inputs such that when one considers each coordinate separately, the error is bounded by ρ. Then*

1. $\mathsf{IC}_{\mathsf{D}}(f^n,\rho) = n \cdot \mathsf{IC}_{\mathsf{D}}(f,\rho)$;
2. $\mathsf{IC}\,(f^n,\rho) = n \cdot \mathsf{IC}\,(f,\rho)$.

Proof. We note that the proofs of the two parts are quite similar; the reader may want to only read the proof of the second part, which is more important (and also simpler).

• $\mathsf{IC}_{\mathsf{D}}(f^n,\rho) \geq n \cdot \mathsf{IC}_{\mathsf{D}}(f,\rho)$. Let μ be the distribution that realizes $\mathsf{IC}_{\mathsf{D}}(f,\rho)$. Let T^n be the task of computing n copies of f such that the error on each copy when measured against the distribution μ is $\leq \rho$. Further, let $\mathcal{M}^n = \{\mu^n\}$ be the set consisting of only one product distribution. Then by the definition of μ,

$$\mathsf{IC}_{\mathsf{D}}(f,\rho) = \mathsf{IC}\left(\mathcal{M}^1, T^1\right).$$

By Theorem 4.2 we have

$$\begin{aligned}\mathsf{IC}_{\mathsf{D}}(f^n,\rho) &\geq \mathsf{IC}\,(\mathcal{M}^n, T^n)\\ &= \mathsf{IC}\left(\mathcal{M}^{n-1}, T^{n-1}\right) + \mathsf{IC}\left(\mathcal{M}^1, T^1\right) = \cdots = n \cdot \mathsf{IC}\left(\mathcal{M}^1, T^1\right) = n \cdot \mathsf{IC}_{\mathsf{D}}(f,\rho).\end{aligned}$$

• $\mathsf{IC}_{\mathsf{D}}(f^n,\rho) \leq n \cdot \mathsf{IC}_{\mathsf{D}}(f,\rho)$. Let μ be the distribution on n-tuples of inputs that realizes $\mathsf{IC}_{\mathsf{D}}(f^n,\rho)$, and let μ_i be the restriction of μ to the ith coordinate. In other words, any protocol that fails with probability $\leq \rho$ with respect to μ_i on the ith coordinate must reveal at least $\mathsf{IC}_{\mathsf{D}}(f^n,\rho)$ information with respect to μ. Let T_i be the task of computing f correctly with error $\leq \rho$ with respect to the distribution μ_i. Let $T := T_1 \times T_2 \times \cdots \times T_n$. By the definition of the task we have

$$\mathsf{IC}\,(\{\mu\}, T) \geq \mathsf{IC}_{\mathsf{D}}(f^n,\rho).$$

Let $\mathcal{M}_i := \{\mu_i\}$ and $\mathcal{M} := \mathcal{M}_1 \otimes \mathcal{M}_2 \otimes \cdots \otimes \mathcal{M}_n$. Then $\mu \in \mathcal{M}$. By Theorem 4.2 we have

$$\mathsf{IC}_{\mathsf{D}}(f^n,\rho) \leq \mathsf{IC}\,(\{\mu\}, T) \leq \mathsf{IC}\,(\mathcal{M}, T) = \mathsf{IC}\,(\mathcal{M}_1, T_1) + \cdots + \mathsf{IC}\,(\mathcal{M}_n, T_n) \leq n \cdot \mathsf{IC}_{\mathsf{D}}(f^n,\rho).$$

• $\mathsf{IC}\,(f^n,\rho) = n \cdot \mathsf{IC}\,(f,\rho)$. Let T^n be the task of computing n copies of f such that the (worst-case) probability of error on each copy is $\leq \rho$. Let $\mathcal{M}^n$ be the set of all possible distributions over n-tuples of inputs. Then, by definition,

$$\mathsf{IC}\,(f,\rho) = \mathsf{IC}\left(\mathcal{M}^1, T^1\right)$$

and

$$\mathsf{IC}\,(f^n,\rho) = \mathsf{IC}\,(\mathcal{M}^n, T^n).$$

Note that $\mathcal{M}^n = \underbrace{\mathcal{M}^1 \otimes \cdots \otimes \mathcal{M}^1}_{n \text{ times}}$ and $T^n = \underbrace{T^1 \times \cdots \times T^1}_{n \text{ times}}$, and thus by Theorem 4.2,

$$\mathsf{IC}\,(f^n,\rho) = \mathsf{IC}\,(\mathcal{M}^n, T^n) = n \cdot \mathsf{IC}\left(\mathcal{M}^1, T^1\right) = n \cdot \mathsf{IC}\,(f,\rho). \qquad \square$$

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5. Information Complexity vs. Communication Complexity. Our next goal is to give a bound on the communication complexity of a problem in terms of its information complexity. Roughly speaking, if the information complexity of a problem is I, then its communication complexity is at most $2^{O(I)}$. While the reduction incurs an exponential loss, this loss turns out to be tight [28, 29]. We note that the resulting communication protocol always runs in 2 rounds. Thus the 2-round communication complexity of any problem is at most exponential in its information complexity.

The proof relies on two main ideas. First, a (private coin) protocol induces a product structure on the probability distributions on the leaves: the probability of each leaf ℓ in the protocol tree is the product of the probability that Alice follows the path down to ℓ every time it is her turn to speak and the probability that Bob does the same when it is his turn. Alice has a prior distribution on what Bob will say when it is his turn to speak. If the information cost of a protocol is I, then for most leaves the ratio between the probability $p_B(\ell)$ that Bob will send messages consistent with ℓ and Alice's estimate $q_A(\ell)$ of this probability is at most $2^{O(I)}$. Second, in the setup as just described, one can use a new rejection-sampling-type protocol to sample according to the (approximately) correct distribution on leaves. This protocol can be viewed as an interactive three-dimensional extension of von Neumann's rejection sampling.

5.1. A New Sampling Lemma. In this section we prove a new sampling lemma. The lemma is then used to establish a new connection between the information and the communication complexity of any problem. We start with a simple claim about the information divergence of distributions. It is the classical version of the quantum substate theorem [42].

CLAIM 5.1. *Suppose that* $\mathbf{D}(\mu||\nu) \le I$. *Let* ε *be any parameter. Then*

$$\mu\left\{x:\ 2^{(I+1)/\varepsilon}\cdot\nu(x) < \mu(x)\right\} < \varepsilon.$$

Proof. Recall that $\mathbf{D}(\mu||\nu) = \sum_{x\in\mathcal{U}}\mu(x)\log\frac{\mu(x)}{\nu(x)}$. Denote $\mathcal{N} = \{x:\ \mu(x) < \nu(x)\}$—the terms that contribute a negative amount to $\mathbf{D}(\mu||\nu)$. First we observe that for all $0 < x < 1$, $x\log x > -1$, and thus

$$\sum_{x\in\mathcal{N}}\mu(x)\log\frac{\mu(x)}{\nu(x)} = \sum_{x\in\mathcal{N}}\nu(x)\cdot\frac{\mu(x)}{\nu(x)}\log\frac{\mu(x)}{\nu(x)} \ge \sum_{x\in\mathcal{N}}\nu(x)\cdot(-1) > -1.$$

Denote $\mathcal{L} = \left\{x:\ 2^{(I+1)/\varepsilon}\cdot\nu(x) < \mu(x)\right\}$; we need to show that $\mu(\mathcal{L}) < \varepsilon$. For each $x\in\mathcal{L}$ we have $\log\frac{\mu(x)}{\nu(x)} > (I+1)/\varepsilon$. Thus

$$I \ge \mathbf{D}(\mu||\nu) \ge \sum_{x\in\mathcal{L}}\mu(x)\log\frac{\mu(x)}{\nu(x)} + \sum_{x\in\mathcal{N}}\mu(x)\log\frac{\mu(x)}{\nu(x)} > \mu(\mathcal{L})\cdot(I+1)/\varepsilon - 1,$$

implying $\mu(\mathcal{L}) < \varepsilon$. ∎

We are now ready to state and prove our main sampling lemma. The lemma is tailored to apply to the scenario where $\mu = \pi_{xy}$ is the distribution of protocol transcripts (leaves of the protocol tree), ν_A is the distribution π_x of the transcripts given x (but not y), and ν_B is the distribution π_y of transcripts given y. As noted earlier, for each fixed input (x, y), π_{xy} is a product distribution. Each player can make an estimate of this distribution by averaging over the other player's inputs. The error

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of this estimate can be expressed in terms of divergence. When we apply it to this scenario in the proof of Theorem 5.3, the bound on the divergence will follow from a bound on the information cost of π combined with Claim 5.1.

LEMMA 5.2. *Let μ be any distribution over a universe $\mathcal{U}$, and let $I \geq 0$ be a parameter that is known to both A and B. Further, let ν_A and ν_B be two distributions over $\mathcal{U}$ such that $\mathbf{D}(\mu||\nu_A) \leq I$ and $\mathbf{D}(\mu||\nu_B) \leq I$. The players are each given a real function $p_A, q_A, p_B, q_B : \mathcal{U} \to [0,1]$ such that for all $\ell \in \mathcal{U}$, $\mu(\ell) = p_A(\ell) \cdot p_B(\ell)$, $\nu_A(\ell) = p_A(\ell) \cdot q_A(\ell)$, and $\nu_B(\ell) = p_B(\ell) \cdot q_B(\ell)$. Let $0 < \varepsilon < 1/16$ be an error parameter. Then there is a sampling protocol $\Pi = \Pi(p_A, p_B, q_A, q_B, I, \varepsilon)$ that communicates $2^{O((I+1)/\varepsilon)}$ bits such that the following hold:*

1. *at the end of the protocol, the players output $\ell_A \in \mathcal{U}$ and $\ell_B \in \mathcal{U}$, respectively;*
2. *there is an event $\mathcal{E}$ such that $\neg\mathcal{E} \Rightarrow \ell_A = \ell_B$ and $\mathbf{P}[\mathcal{E}] < \varepsilon$;*
3. *letting μ' be the distribution of ℓ_A conditioned on $\neg\mathcal{E}$, then $|\mu - \mu'| < \varepsilon$.*

Proof. First, Alice and Bob interpret the shared random tape as a source of points $(\ell_i, \alpha_i, \beta_i)$ uniformly distributed in $\mathcal{U} \times [0,1] \times [0,1]$. Alice and Bob consider $T = 2|\mathcal{U}| \ln 1/\varepsilon$ such points. Their goal will be to discover the first index τ such that $\alpha_\tau \leq p_A(\ell_\tau)$ and $\beta_\tau \leq p_B(\ell_\tau)$. Note that the probability of each ℓ to be such ℓ_τ is proportional to $p_A(\ell_\tau) \cdot p_B(\ell_\tau) = \mu(\ell_\tau)$. Thus the distribution of ℓ_τ is correct.

Denote $B_A := \{\ell : \ 2^{8(I+1)/\varepsilon} \cdot \nu_A(\ell) < \mu(\ell)\}$ and $B_B := \{\ell : \ 2^{8(I+1)/\varepsilon} \cdot \nu_B(\ell) < \mu(\ell)\}$. Then by Claim 5.1, $\mu(B_A), \mu(B_B) < \varepsilon/8$. Next, we note that the probability that an index t satisfies $\alpha_t \leq p_A(\ell_t)$ and $\beta_t \leq p_B(\ell_t)$ is exactly $1/|\mathcal{U}|$. Hence the probability that $\tau > T$ (i.e., that ℓ_τ is not among the T points considered) is bounded by

$$(1 - 1/|\mathcal{U}|)^T < e^{-T/|\mathcal{U}|} = e^{-2\ln 1/\varepsilon} = \varepsilon^2 < \varepsilon/16.$$

Denote by $\mathcal{A}$ the set of indices

$$\mathcal{A} := \{i \leq T : \ \alpha_i \leq p_A(\ell_i) \text{ and } \beta_i \leq 2^{8(I+1)/\varepsilon} \cdot q_A(\ell_i)\}.$$

$\mathcal{A}$ is the set of indices that are candidates to be τ from A's viewpoint. Similarly,

$$\mathcal{B} := \{i \leq T : \ \alpha_i \leq 2^{8(I+1)/\varepsilon} \cdot q_B(\ell_i) \text{ and } \beta_i \leq p_B(\ell_i)\}.$$

Assuming $\ell_\tau \notin B_A \cup B_B$, we have that $\tau \in \mathcal{A} \cap \mathcal{B}$, because $\ell_\tau \notin B_A$ implies

$$\frac{p_B(\ell_\tau)}{q_A(\ell_\tau)} = \frac{\mu(\ell_\tau)}{\nu_A(\ell_\tau)} \leq 2^{8(I+1)/\varepsilon},$$

and thus $\beta_\tau < p_B(\ell_\tau) \leq 2^{8(I+1)/\varepsilon} \cdot q_A(\ell_\tau)$, and hence $\tau \in \mathcal{A}$. In fact, τ is the first element in $\mathcal{A} \cap \mathcal{B}$. Note that for each t, $\mathbf{P}[t \in \mathcal{A}] \leq 2^{8(I+1)/\varepsilon}/|\mathcal{U}|$. Thus $\mathbf{E}[|\mathcal{A}|] \leq 2^{8(I+1)/\varepsilon} \cdot 2\ln 1/\varepsilon < 2^{9(I+1)/\varepsilon}$. Thus, by Chernoff bound,

$$\mathbf{P}[|\mathcal{A}| > 2^{10(I+1)/\varepsilon}] \ll \varepsilon/16.$$

Let the event $\mathcal{E}_1 := [\ell_\tau \in B_A \cup B_B]$, and $\mathcal{E}_2 := [\tau > T \text{ or } |\mathcal{A}| > 2^{10(I+1)/\varepsilon} \text{ or } |\mathcal{B}| > 2^{10(I+1)/\varepsilon}]$. Then by union bound, setting $\mathcal{E} := \mathcal{E}_1 \cup \mathcal{E}_2$, $\mathbf{P}[\mathcal{E}] < 2 \cdot \varepsilon/8 + 3 \cdot \varepsilon/16 < \varepsilon/2$. The distribution μ' conditioned on $\neg(\mathcal{E}_1 \cup \mathcal{E}_2)$ satisfies $|\mu' - \mu| < \varepsilon/2$, because it is the distribution μ restricted to the set $\mathcal{U} \setminus (B_A \cup B_B)$ (note that only the restriction by $\neg\mathcal{E}_1$ biases the distribution). We will show a protocol, such that assuming the event $\neg(\mathcal{E}_1 \cup \mathcal{E}_2)$ the parties succeed at outputting the same correct value of ℓ_τ with probability $> 1 - \varepsilon/2$, thus completing the proof.

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We have reduced the problem to that of finding and outputting the first element in $\mathcal{A} \cap \mathcal{B}$, where $|\mathcal{A}|, |\mathcal{B}| \leq 2^{10(I+1)/\varepsilon}$. The communication complexity of the protocol will be $2^{O((I+1)/\varepsilon)}$. We note that the protocol can be organized in such a way that only Alice needs to communicate that many bits, while Bob communicates only $O((I+1)/\varepsilon)$ bits. The protocol is presented in Figure 4.

Information-Cost Only Sampling Protocol
1. Alice computes the set $\mathcal{A}$. If $\lvert\mathcal{A}\rvert > 2^{10(I+1)/\varepsilon}$, the protocol fails. 2. Bob computes the set $\mathcal{B}$. If $\lvert\mathcal{B}\rvert > 2^{10(I+1)/\varepsilon}$, the protocol fails. 3. For each $a \in \mathcal{A}$, Alice computes $d = \lceil 20(I+1)/\varepsilon + \log 1/\varepsilon + 2 \rceil$ random hash values $h_1(a), \ldots, h_d(a)$, where the hash functions are evaluated using public randomness. 4. Alice sends the values $\{h_j(a_i)\}_{a_i \in \mathcal{A},\ 1 \leq j \leq d}$ to Bob. 5. Bob finds the first index i such that there is a $b \in \mathcal{B}$ for which $h_j(b) = h_j(a_i)$ for $j = 1, \ldots, d$ (if such an i exists). Bob outputs ℓ_b and sends the index i to Alice. 6. Alice outputs ℓ_{a_i}.

Fig. 4 *The main sampling protocol from Lemma 5.2.*

First note that the number of bits communicated by Alice is bounded by $2^{10(I+1)/\varepsilon} \cdot d = 2^{O((I+1)/\varepsilon)}$. The number of bits communicated by Bob is bounded by $\log |\mathcal{A}| \leq 10(I+1)/\varepsilon$. To see that the protocol works, observe that for $a \in \mathcal{A}$ and $b \in \mathcal{B}$ such that $a \neq b$, the probability (over possible choices of the hash functions) that $h_j(a) = h_j(b)$ for $j = 1, \ldots, d$ is bounded by $2^{-d} < \frac{\varepsilon}{4|\mathcal{A}| \cdot |\mathcal{B}|}$. Thus, by union bound, the probability that there is an $a \in \mathcal{A}$, $b \in \mathcal{B}$ such that $a \neq b$ but the hashes match is bounded by $\varepsilon/4$. Assuming there are no such a and b, and there is a $\tau \in \mathcal{A} \cap \mathcal{B}$, the protocol is guaranteed to find it, completing the proof. ∎

5.2. Information vs. Communication. In the language of communication complexity, Lemma 5.2 implies the following.

THEOREM 5.3. *Let $f : \mathcal{X} \times \mathcal{Y} \to \mathbb{Z}_K$ be any function, and let $\rho, \varepsilon > 0$ be error parameters:*

1. *For any distribution μ, $D^{\mu}_{\rho+\varepsilon}(f) = 2^{O(1/\varepsilon + \mathsf{IC}_{\mu}(f,\rho)/\varepsilon^2)}$.*
2. *$R_{\rho+\varepsilon}(f) = 2^{O(1/\varepsilon + \mathsf{IC}(f,\rho)/\varepsilon^2)}$.*

Theorem 5.3 can be used as a generic (if weak) tool to obtain unconditional lower bounds on the information complexity of problems. For example, the fact that $R_{1/3}(DISJ_n) = \Omega(n)$ immediately implies that $\mathsf{IC}\,(DISJ_n, 1/6) = \Omega(\log n)$. In section 7 we will see that in fact $\mathsf{IC}\,(DISJ_n, 1/6) = \Omega(n)$.

Proof. We begin with the first part of the theorem. Let μ be any distribution over the inputs. Let π be a protocol that realizes the value $I_\mu := \mathsf{IC}_\mu(f, \rho)$. In other words, π has an error rate of at most ρ and information cost of at most I_μ with respect to μ. Denote by π_{xy} the random variable that represents that transcript π given the inputs (x, y), and by π_x (resp., π_y) the protocol conditioned on only the input x (resp., y). We denote by π_{XY} the transcripts where (X, Y) are also a pair of random variables. We know that

$$I_\mu = I(X; \pi_{XY}|Y) + I(Y; \pi_{XY}|X) = \mathbf{E}_{(x,y)\sim\mu}[\mathbf{D}\,(\pi_{xy}||\pi_x) + \mathbf{D}\,(\pi_{xy}||\pi_y)].$$

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Thus by Markov's inequality, with probability at least $1-\varepsilon/2$ (with respect to μ) we will have $\mathbf{D}(\pi_{xy}||\pi_x) \le 2I_\mu/\varepsilon$ and $\mathbf{D}(\pi_{xy}||\pi_y) \le 2I_\mu/\varepsilon$. Let us now run the sampling algorithm from Lemma 5.2, with the distribution μ in Lemma 5.2 taken to be π_{xy}, the distribution ν_A taken to be π_x, the distribution ν_B taken to be π_y, I taken to be $2I_\mu/\varepsilon$, and the error parameter taken to be $\varepsilon/4$.

At each node v of the protocol tree that is owned by player X let $p_0(v)$ and $p_1(v) = 1 - p_0(v)$ denote the probabilities that the next bit sent by X is 0 and 1, respectively. For nodes owned by player Y, let $q_0(v)$ and $q_1(v) = 1 - q_0(v)$ denote the probabilities that the next bit sent by Y is 0 and 1, respectively, *as estimated by player X given the input x*. For each leaf ℓ let $p_X(\ell)$ be the product of all the values of $p_b(v)$ from the nodes that are owned by X along the path from the root to ℓ; let $q_X(\ell)$ be the product of all the values of $q_b(v)$ from the nodes that are owned by Y along the path from the root to ℓ. The values $p_Y(\ell)$ and $q_Y(\ell)$ are defined similarly. For each ℓ we have $\mathbf{P}[\pi_{xy} = \ell] = p_X(\ell) \cdot p_Y(\ell)$, $\mathbf{P}[\pi_x = \ell] = p_X(\ell) \cdot q_X(\ell)$, and $\mathbf{P}[\pi_y = \ell] = p_Y(\ell) \cdot q_Y(\ell)$. Thus we can apply Lemma 5.2, to successfully obtain a sample transcript T such that the statistical distance $|T - \pi_{xy}| < \varepsilon/2$. T is obtained using $2^{O(1/\varepsilon + I_\mu/\varepsilon^2)}$ communication. Let T_{out} be the final output of the transcript T, and let π_{out} be the final output of the original protocol. $|T - \pi_{xy}| < \varepsilon/2$ implies that $\mathbf{P}[T_{out} \ne \pi_{out}] < \varepsilon/2$.

It remains to bound the error probability of our new protocol. In other words, we need to show that

$$\mathbf{P}_{(x,y)\sim\mu,\text{protocol randomness}}[T_{out} \ne f(x,y)] < \rho + \varepsilon.$$

The protocol above only works for pairs (x,y) where $\mathbf{D}(\pi_{xy}||\pi_x) \le 2I_\mu/\varepsilon$ and $\mathbf{D}(\pi_{xy}||\pi_y) \le 2I_\mu/\varepsilon$. Call such pairs "good." We saw that $\mathbf{P}_{(x,y)\sim\mu}[(x,y) \text{ is good}] > 1 - \varepsilon/2$. Thus we have

$$\begin{aligned}\mathbf{P}[T_{out} \ne f(x,y)] &\le \mathbf{P}[(x,y) \text{ not good}] + \mathbf{P}[T_{out} \ne \pi_{out} | (x,y) \text{ is good}] \\ &\quad + \mathbf{P}[\pi_{out} \ne f(x,y)] \\ &< \varepsilon/2 + \varepsilon/2 + \rho = \rho + \varepsilon.\end{aligned}$$

To prove the second part of the theorem recall that by Yao's minimax theorem there is a distribution μ such that $D^\mu_{\rho+\varepsilon}(f) = R_{\rho+\varepsilon}(f)$. Since by definition $\mathsf{IC}_\mu(f,\rho) \le \mathsf{IC}(f,\rho)$, we obtain

$$R_{\rho+\varepsilon}(f) = D^\mu_{\rho+\varepsilon}(f) = 2^{O(1/\varepsilon + \mathsf{IC}_\mu(f,\rho)/\varepsilon^2)} \le 2^{O(1/\varepsilon + \mathsf{IC}(f,\rho)/\varepsilon^2)}. \qquad \square$$

6. Information Complexity and Amortized Communication.

6.1. Preliminaries: The Distributional Case. We next turn our attention to the relationship between the information cost of a problem and its amortized communication cost—the communication cost of solving n copies of the problem as n goes to ∞. In [12] such a connection was established for the distributional setting. Here we extend the connection to the distribution-free setting. The extension is very similar to the original proof. In addition, we formulate a more careful statement of the result. This statement may be more useful in applications. For example, it will be useful in one of the proofs establishing the linear lower bound on the information cost of disjointness in section 7. We will first repeat some definitions and theorems from prior works, before stating our main results.

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Let $f : \mathcal{X} \times \mathcal{Y} \to \mathbb{Z}_K$ be any function.[3] The distributional communication cost of n copies of f has been defined in [12] as follows.

DEFINITION 6.1. *Let μ be a distribution on $\mathcal{X} \times \mathcal{Y}$ and let $0 < \rho < 1$. We denote by $D^{\mu,n}_{\rho}(f^n)$ the distributional complexity of computing f on each of n independent pairs of inputs drawn from μ, with probability of failure at most ρ on each of the inputs (when averaged over μ).*

Note that trivially $D^{\mu,n}_{\rho}(f^n) \le n \cdot D^{\mu}_{\rho}(f)$—this can be achieved by just running n copies of the protocol for f independently.

Remark 6.2. In Definition 6.1 we deliberately do not require the n-copy protocol to succeed with probability $1-\rho$ on *all* n copies. This latter task may be qualitatively more difficult. Consider, for example, a scenario based on Shaltiel's example [66], where f and μ are such that $D^{\mu}_{1/10}(f) \ll D^{\mu}_{1/100}(f)$. This may happen, for example, if 90% of the input pairs are "very easy," and thus $D^{\mu}_{1/10}(f)$ is very small, while the remaining 10% are "very hard," and thus $D^{\mu}_{1/100}(f)$ is very large. Then $D^{\mu,n}_{1/10}(f^n)$ as in Definition 6.1 will still be small. At the same time, computing f correctly on *all* n copies simultaneously (except with probability 10%) would require one to solve a lot of "very hard" instances and would have a much higher communication complexity that cannot possibly be related to $D^{\mu}_{1/10}(f)$.

A version of the following theorem, giving a connection between (distributional) information cost and amortized communication complexity, was proved in [3]. The sharper statement presented below is from [12] (cf. also Theorem 4.3 above).

THEOREM 6.3. *For every μ, f, ρ there exists a protocol τ computing f on inputs drawn from μ with probability of error at most ρ on each input (when averaged over μ) and communication at most $D^{\mu,n}_{\rho}(f^n)$ such that $\mathsf{IC}_{\mu}(\tau) \le \frac{D^{\mu,n}_{\rho}(f^n)}{n}$, and thus $\mathsf{IC}_{\mu}(f,\rho) \le \frac{D^{\mu,n}_{\rho}(f^n)}{n}$.*

Thus the amortized communication complexity gives an upper bound on the information cost of the problem. For each fixed n, we do not know whether the inequality in Theorem 6.3 is tight or not, and it probably isn't: for $n = 1$ this is equivalent to the question of whether $\mathsf{IC}_{\mu}(f,\rho) = D^{\mu}_{\rho}(f)$—which remains open. However, in [12] it has been shown that *in the limit* the inequality is tight.

THEOREM 6.4. *The distributional information cost is equal to amortized communication:*

$$\mathsf{IC}_{\mu}(f,\rho) = \lim_{n\to\infty} \frac{D^{\mu,n}_{\rho}(f^n)}{n}.$$

To prove Theorem 6.4 one needs to use a low-information protocol for one copy of f to produce a low-amortized communication cost protocol for n copies, when n is large. The main technical ingredient in the proof is the following protocol compression lemma.

LEMMA 6.5 (see [12]). *Let (x,y) be inputs to an r-round communication protocol π whose (internal) information cost is $I := \mathsf{IC}_{\mu}(\pi)$. Then for every $\varepsilon > 0$ there exists a protocol τ such that at the end of the protocol each party outputs a transcript for π. Furthermore, there is an event G with $\mathbf{P}[G] > 1 - r\varepsilon$ such that, conditioned on G, the expected communication of τ is $I + O(\sqrt{rI} + 1) + 2r\log(1/\varepsilon)$, and both parties output the same transcript distributed according to $\pi(x,y)$.*

[3] As before, our results also hold for tasks and not just functions.

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The lemma is proved in [12] using an iterated correlated sampling argument. We will return to some of the proof details in the next section. Our goal will be to establish the analogue of Theorem 6.4 for the randomized communication complexity.

6.2. The Nondistributional Case. Recall that $R_\rho(f)$ is the randomized communication complexity of f with error ρ. We know by Yao's minimax theorem that $R_\rho(f) = \max_\mu D^\mu_\rho(f)$. We now give a definition of the randomized communication complexity of n copies of f. It is the distribution-free analogue of Definition 6.1.

DEFINITION 6.6. *Let $0 < \rho < 1$. We denote by $R^n_\rho(f^n)$ the randomized communication complexity of computing f so that on each set of n inputs the probability of failure on each of the inputs is at most ρ.*

Our main result states that the prior-free information cost of f captures precisely f's amortized communication complexity.

THEOREM 6.7. *For $\rho > 0$,*

$$\mathsf{IC}\,(f,\rho) = \lim_{n\to\infty} \frac{R^n_\rho(f^n)}{n}.$$

Remark 6.8. We note that Theorem 6.7 does not hold when $\rho = 0$, i.e., when the protocol is not allowed to err. Recall (Proposition 3.22) that $\mathsf{IC}\,(EQ, 0) = O(1)$. At the same time, it is not hard to see that if the function EQ is on the space $\{0,1\}^m \times \{0,1\}^m$, then $R^n_\rho(f^n) = \Omega(m{\cdot}n)$, and thus the right-hand side in Theorem 6.7 is $\Omega(m)$. The "$\leq$" direction of Theorem 6.7 holds even for $\rho = 0$. The other direction, however, requires the use of compression, such as Lemma 6.5. Such lemmas necessarily introduce a small amount of additional error. For each fixed $\rho > 0$, the additional error introduced can be made negligible, but this does not work for $\rho = 0$.

The proof of Theorem 6.7 will consist of proving inequalities in two directions. We will actually prove a slightly stronger statement in the "$\geq$" direction—showing that low information cost implies low amortized communication complexity. Here is the precise statement that we prove.

THEOREM 6.9. *Let $f : X \times Y \to \{0,1\}$, and let $I := \mathsf{IC}\,(f,\rho)$. Then for each $\delta_1, \delta_2 > 0$ there is an $N = N(f,\rho,\delta_1,\delta_2)$ such that for each $n \geq N$ there is a protocol*

$$\pi_n = \pi_n((x_1,\ldots,x_n),(y_1,\ldots,y_n))$$

for computing n instances of f. The protocol π_n will have communication complexity $< n{\cdot}I{\cdot}(1{+}\delta_1)$ and will have error $\lesssim \rho$ on each copy. Moreover, except with probability $< \delta_2$, the protocol errors will behave as if the n evaluations were independent.

More precisely, let $Q : \{0,1\}^n \to \{0,1\}$ be any monotone function. Fix the inputs $(x_1,\ldots,x_n)$, $(y_1,\ldots,y_n)$, let $(f_1,\ldots,f_n) := (f(x_1,y_1),\ldots,f(x_n,y_n))$, and let $(p_1,\ldots,p_n)$ be the random variable representing π_n's output. Let $\mathbf{e} = (e_1,\ldots,e_n)$ be the "errors vector"—$e_i = \chi_{p_i \neq f_i}$. Let $\mathbf{b} = (b_1,\ldots,b_n)$ be a vector of independent Bernoulli variables $b_i \sim B_\rho$. Then

$$\mathbf{P}[Q(\mathbf{e}) = 1] \leq \mathbf{P}[Q(\mathbf{b}) = 1] + \delta_2.$$

Clearly, Theorem 6.9 (applied n times, each time with Q being one of the coordinate indicator functions) implies that $R^n_{\rho+\delta_2}(f^n) \leq n \cdot I \cdot (1+\delta_1)$. Taking $\delta_1 \to 0$ and $n \to \infty$, for each $\delta_2 > 0$ we get

$$\mathsf{IC}\,(f,\rho) \geq \lim_{n\to\infty} \frac{R^n_{\rho+\delta_2}(f^n)}{n}.$$

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Substituting $\rho - \delta_2$ for ρ we get

$$\mathsf{IC}\,(f, \rho - \delta_2) \geq \lim_{n\to\infty} \frac{R^n_\rho(f^n)}{n}.$$

Finally, by the continuity of $\mathsf{IC}\,(f, \rho)$ in ρ (Corollary 3.19), we have

$$\mathsf{IC}\,(f, \rho) = \lim_{\delta_2\to 0} \mathsf{IC}\,(f, \rho - \delta_2),$$

and thus

$$\mathsf{IC}\,(f, \rho) \geq \lim_{n\to\infty} \frac{R^n_\rho(f^n)}{n},$$

which proves the "$\geq$" direction of Theorem 6.7. It remains to prove the "$\leq$" direction of Theorems 6.7 and 6.9.

Proof of the "$\leq$" direction of Theorem 6.7. It follows immediately from part 2 of Theorem 4.3 that

$$\mathsf{IC}\,(f, \rho) = \frac{\mathsf{IC}\,(f^n, \rho)}{n} \leq \frac{R^n_\rho(f^n)}{n}.$$

The second inequality holds because the amount of communication is always an upper bound on information cost. ∎

The proof of the other direction of Theorem 6.7, i.e., Theorem 6.9, is unfortunately fairly complicated. It is easier to give a proof of the weaker statement that $\lim_{n\to\infty} \frac{R^n_\rho(f^n)}{n} = O(\mathsf{IC}\,(f, \rho))$—if we didn't care to prove that the constant is 1. It would be interesting to see whether this proof can be simplified.

Proof of Theorem 6.9. Recall that f is a function on the space $X \times Y$. Let K be such that $|X|, |Y| \leq 2^K$. By the continuity of $\mathsf{IC}\,(f, \rho)$, there is a $\delta_3 > 0$ such that

$$\mathsf{IC}\,(f, \rho - \delta_3) < \mathsf{IC}\,(f, \rho) \cdot (1 + \delta_1/3).$$

By the definition of $\mathsf{IC}\,(f, \rho - \delta_3)$, there is a protocol π that on each pair of inputs succeeds except with probability $\leq \rho - \delta_3$, and such that for each distribution μ,

$$\mathsf{IC}_\mu(\pi) \leq \mathsf{IC}\,(f, \rho) \cdot (1 + \delta_1/3).$$

Our overall strategy will be to try and execute n copies of π in a communication-efficient way. We claim that it is possible. Set $\delta_4 := \min(\delta_2, \delta_3)/2$.

CLAIM 6.10. *For each sufficiently large n there is a protocol π_n that takes n instances of f as an input and has the following properties:*

1. *For each set of inputs, the statistical distance between the output of π_n and the output of π^n (i.e., an execution of n independent copies of π) is $< \delta_4/(2n^2)$.*
2. *The expected communication cost of π_n is $< n \cdot \mathsf{IC}\,(f, \rho) \cdot (1 + 2\delta_1/3)$.*
3. *The worst-case communication cost of π_n is $< 100nK/\delta_1$.*

The bulk of the effort will go into proving Claim 6.10. Assuming Claim 6.10, note that the execution of π_n will be very similar to the execution of π^n. In turn, the errors in the execution of π^n are dominated by n independent Bernoulli random variables $B_{\rho-\delta_3} < B_\rho$, thus almost completing the proof of the theorem.

The reason the proof is not complete is the additional complication stemming from π^n using $< n \cdot \mathsf{IC}\,(f, \rho) \cdot (1 + 2\delta_1/3)$ communication *in expectation*, while we would like an upper bound on the worst-case communication complexity of f^n. We are able to prove the theorem with n replaced with n^3 by taking n^2 independent copies of π_n. The following claim thus completes the proof of the theorem.

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CLAIM 6.11. *Let Π be the protocol that runs on n^3 pairs of inputs by dividing them into n^2 blocks of n pairs each and running π_n on each block. Further, the protocol Π is truncated (and fails) if it does not terminate after $< n^3 \cdot \mathsf{IC}(f,\rho)\cdot(1+\delta_1)$ communication. Then for each set of inputs, the statistical distance between the output of Π and the output of π^{n^3} is $< \delta_4$.*

Proof. Fix a set of n^3 inputs. There are two sources of statistical distance between the output of Π and the output of π^{n^3}: the first one is due to one of the n^2 blocks being different under π_n than under π^n; the second is from the probability that the protocol Π fails altogether by not terminating in the allotted time. The probability of the first event is bounded by $n^2 \cdot \delta_4/(2n^2) = \delta_4/2$. It remains to bound probability of the second event by $\delta_4/2$.

Let T_i for $i = 1,\dots,n^2$ denote the random variable representing the amount of communication used by the ith copy of π_n during the execution of Π. Denote $T := \sum_{i=1}^{n^2} T_i$. Our goal is to show that

$$\mathbf{P}\left[T \geq n^3 \cdot \mathsf{IC}(f,\rho)\cdot(1+\delta_1)\right] < \delta_4/2.$$

We know that T_i are independent and identically distributed, $\mathbf{E}[T_i] < n \cdot \mathsf{IC}(f,\rho)\cdot(1+2\delta_1/3)$, and

$$\mathrm{Var}(T_i) < \mathbf{E}[T_i]\cdot 100nK/\delta_1 < 200n^2K\cdot \mathsf{IC}(f,\rho)/\delta_1.$$

Hence $\mathbf{E}[T] < n^3\cdot\mathsf{IC}(f,\rho)\cdot(1+2\delta_1/3)$ and $\mathrm{Var}(T) < 200n^4K\cdot\mathsf{IC}(f,\rho)/\delta_1$. Thus, by Chebyshev's inequality, we get

$$\begin{aligned}\mathbf{P}\left[T \geq n^3\cdot\mathsf{IC}(f,\rho)\cdot(1+\delta_1)\right] &< \mathbf{P}\left[T > \mathbf{E}[T] + n^3\cdot\mathsf{IC}(f,\rho)\cdot\delta_1/3\right]\\ &< \frac{200n^2K\cdot\mathsf{IC}(f,\rho)/\delta_1}{(n^3\cdot\mathsf{IC}(f,\rho)\cdot\delta_1/3)^2}\\ &< \delta_4/2\end{aligned}$$

for a sufficiently large n. ∎

Claim 6.11 implies that for each sufficiently large n,

$$\frac{R^n_\rho(f^{n^3})}{n^3} < \mathsf{IC}(f,\rho)\cdot(1+\delta_1),$$

and, further, that the other conclusions of Theorem 6.9 hold.

It remains to prove Claim 6.10.

Proof of Claim 6.10. We first give a protocol π^n that satisfies the first condition and that has a slightly lower expected communication cost of $< n\cdot\mathsf{IC}(f,\rho)\cdot(1+3\delta_1/5)$. We then show how to modify it to satisfy the third condition without increasing the expected communication cost by too much.

Let r be the number of rounds in the protocols π, and let $\alpha > 0$ be a (small) parameter that we will set later. We let $\mathcal{G}$ be the following zero-sum game. The first player M produces a distribution μ on n-tuples of pairs of inputs. The second player T produces a (randomized) protocol τ. Let $I := \mathsf{IC}(f,\rho)$. The payoff for the first player is the sum

$$P_M(\mu,\tau) := (1-\alpha)\cdot\frac{\mathbf{E}_{\vec{x},\vec{y}\sim\mu}|\tau(\vec{x},\vec{y})|}{n\cdot I\cdot(1+\delta_1/2)} + \frac{\mathbf{E}_{\vec{x},\vec{y}\sim\mu}|\tau(\vec{x},\vec{y})-\pi^n(\vec{x},\vec{y})|}{\delta_4/(2n^2)}. \tag{20}$$

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Here $|\tau(\vec{x},\vec{y})|$ denotes the expected communication cost of τ on inputs $(\vec{x},\vec{y})$, and $|\tau(\vec{x},\vec{y}) - \pi^n(\vec{x},\vec{y})|$ denotes the statistical distance between the two protocols on a given input. We first establish that for any large enough n the value of the game is bounded by 1:

• $\mathrm{Val}_M(\mathcal{G}) < 1$: Let ν be any mixed strategy for player M. Denote by $\bar{\mu}$ the average distribution in ν: $\bar{\mu}(\vec{x},\vec{y}) = \mathbf{E}_{\mu\sim\nu}\mu(\vec{x},\vec{y})$. Since the payoff function is calculated in terms of expectations over $(\vec{x},\vec{y}) \sim \mu$, for any τ we have

$$\mathbf{E}_{\mu\sim\nu} P_M(\mu,\tau) = P_M(\bar{\mu},\tau).$$

Thus it is enough to show that for each distribution μ there is a protocol τ such that $P_M(\mu,\tau) < 1$.

Fix a distribution μ. Let $\mu_1,\ldots,\mu_n$ be the projections of μ onto its n coordinates. As in the proof of the second part of Theorem 4.2, one can see that the information revealed by the protocol π^n that applies π to each copy independently has bounded information cost:

$$\mathsf{IC}_\mu(\pi^n) \le \sum_{i=1}^{n} \mathsf{IC}_{\mu_i}(\pi) \le n \cdot I \cdot (1+\delta_1/3). \tag{21}$$

Furthermore, as π, the protocol π^n is still an r-round protocol, independently of n. Let

$$\varepsilon := \frac{\alpha \cdot \delta_4}{2n^2 r}.$$

By Lemma 6.5 the protocol π^n can be simulated by a protocol τ so that the expected communication $\mathbf{E}_{\vec{x},\vec{y}\sim\mu}|\tau(\vec{x},\vec{y})|$ is bounded by

$$n \cdot I \cdot (1+\delta_1/3) + O(\sqrt{r \cdot n \cdot I \cdot (1+\delta_1/3)} + 1) + 2r\log(1/\varepsilon) < n \cdot I \cdot (1+\delta_1/2),$$

so that the statistical distance between the execution of π^n and the execution of τ is $< r \cdot \varepsilon$. Putting the pieces together, we get

$$P_M(\mu,\tau) < (1-\alpha) \cdot \frac{n \cdot I \cdot (1+\delta_1/2)}{n \cdot I \cdot (1+\delta_1/2)} + \frac{r \cdot \varepsilon}{\delta_4/(2n^2)} = (1-\alpha) + \alpha = 1.$$

By the minimax theorem, there is a distribution ν on protocols τ, such that for each distribution μ, $\mathbf{E}_{\tau\sim\nu}[P_M(\mu,\tau)] < 1$. This implies that the randomized protocol π_n obtained by executing a protocol τ that is distributed according to ν also satisfies $P_M(\mu,\pi_n) < 1$ for all μ. This is in particular true for each singleton $\mu = 1_{(\vec{x},\vec{y})}$. Let

$$\alpha < 1 - \frac{1+\delta_1/2}{1+3\delta_1/5}.$$

Then for each $(\vec{x},\vec{y})$, $P_M(1_{(\vec{x},\vec{y})},\pi_n) < 1$ implies that the statistical distance between the output of π_n and the output of π^n is bounded by

$$P_M(1_{(\vec{x},\vec{y})},\pi_n) \cdot \frac{\delta_4}{2n^2} < \frac{\delta_4}{2n^2}.$$

At the same time, the expected running time of π_n on $(\vec{x},\vec{y})$ is bounded by

$$P_M(1_{(\vec{x},\vec{y})},\pi_n) \cdot \frac{n \cdot I \cdot (1+\delta_1/2)}{1-\alpha} < n \cdot I \cdot (1+3\delta_1/5).$$

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To finish the proof, it remains to show how to modify π_n so that its worst-case communication cost is bounded by $100nK/\delta_1$. We modify π_n as follows. We let it run as usual for $80nK/\delta_1$ bits. If the protocol π_n does not terminate in this many steps, the players will use $2nK$ bits of communication to completely exchange their inputs $(\vec{x}, \vec{y})$. They then finish the execution of the protocol π_n using private randomness but without communicating. They can do this since now they can simulate each other's internal state.

The bound on the worst-case communication cost clearly holds. To bound the expected communication, note that by Markov's inequality the probability of the protocol reaching $80nK/\delta_1$ bits of communication is bounded by

$$\frac{\text{Expected Communication}}{80nK/\delta_1} < \frac{2nI}{80nK/\delta_1} = \frac{\delta_1 I}{40K}.$$

Thus the additional contribution to the communication cost caused by the modification is bounded by

$$\frac{\delta_1 I}{40K} \cdot (2nK) = \frac{\delta_1 nI}{20}.$$

Overall, the modified protocol has expected communication complexity of less than

$$n \cdot I \cdot (1 + 3\delta_1/5) + \frac{\delta_1 nI}{20} < n \cdot I \cdot (1 + 2\delta_1/3),$$

thus still satisfying the second condition. ∎

This concludes the proof of Theorem 6.9. ∎

7. The Information Complexity of Disjointness. In this section we will consider the information complexity of disjointness and give two proofs that the information complexity of $DISJ_n$ is $\Omega(n)$. Disjointness is a natural and well-studied problem, and many communication complexity lower bounds follow through a reduction to it. While the result itself essentially follows from the proof of [3], we believe that the techniques in the two proofs are useful and worth including.

The first proof uses the "information = amortized communication" connection in a reverse direction of how it is used in proving direct sum theorems: to prove an information complexity lower bound, use a communication complexity lower bound and self-reducibility to give an amortized communication complexity lower bound. This paradigm was further developed in [11] and has recently led to a resolution of an open problem on the round-communication trade-offs in quantum communication complexity [9].

The second proof is very close to the proof of [3]. However, the exact reduction technique we use is tighter and avoids a factor-2 loss inherent in earlier reductions. This becomes important when trying to produce tight communication complexity bounds—e.g., finding the constant C_{DISJ} such that $R_{1/n}(DISJ_n) = C_{DISJ} \cdot n \pm o(n)$ [10].

7.1. A Linear Lower Bound, Proof I: Using Self-Reducibility. Our goal in this section is to prove a linear lower bound on the information complexity of the disjointness function $DISJ_n : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}$ given by

$$DISJ_n((x_1, \ldots, x_n), (y_1, \ldots, y_n)) := \neg \bigvee_{i=1}^{n} (x_i \wedge y_i).$$

In our first proof, we will rely on the following classical result on the *communication complexity* of $DISJ_n$.

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THEOREM 7.1 (see [46, 65]). $R_{1/6}(DISJ_n) = \Omega(n)$.

We do not have a general bound that would show that $\mathsf{IC}(DISJ_n, \rho) = \Omega(R_{1/6}(DISJ_n)) = \Omega(n)$ for some constant ρ. However, we are able to exploit the self-similar structure of the disjointness function to prove the linear lower bound directly.

THEOREM 7.2. $\mathsf{IC}(DISJ_n, 1/2 - \varepsilon) = \Omega(n)$ *for all* $0 < \varepsilon < 1/2$.

Proof. By Theorem 7.1 we know that there is a constant $0 < \alpha < 1$ such that

$$R_{1/6}(DISJ_n) > \alpha n \tag{22}$$

for all sufficiently large n. Assume, for the sake of contradiction, that $\mathsf{IC}\big(DISJ_n, 1/2 - \varepsilon\big) = o(n)$ for some $0 < \varepsilon < 1/2$. By repeating the same protocol a constant number of times and taking the majority we obtain $\mathsf{IC}(DISJ_n, \gamma) = o(n)$ for all constant $\gamma > 0$. We fix $\gamma := \alpha/10$. Thus for a sufficiently large $n \geq n_0$ we have $\mathsf{IC}(DISJ_n, \alpha/10) < (\alpha/10) \cdot n$.

Fix an $n \geq n_0$. We apply Theorem 6.9 to $DISJ_n$ with $\rho = \alpha/10$, $\delta_1 = 1/4$, and $\delta_2 = 1/40$. There is an N_0 such that for all $N > N_0$ there is a protocol π_N for computing N copies of $DISJ_n$. π_N has communication complexity $< N \cdot (\alpha/10) \cdot n \cdot (1 + 1/4) = (\alpha/8) \cdot (N \cdot n)$. The probability of π_N being wrong on each input is $\leq \rho + \delta_2 < 1/8$. Moreover, the stronger property in Theorem 6.9 holds. We use the protocol π_N to give a very efficient protocol for $DISJ_{N \cdot n}$, which will contradict Theorem 7.1. The protocol Π is given in Figure 5. We next analyze the protocol's complexity and failure probability.

The Protocol $\Pi((x_1, \ldots, x_{N \cdot n}), (y_1, \ldots, y_{N \cdot n}))$

The players first interpret the input as N blocks of n bits each. Denote the blocks by $(X_1, \ldots, X_N)$, $(Y_1, \ldots, Y_N)$.

1. The players run $\pi_N((X_1, \ldots, X_N), (Y_1, \ldots, Y_N))$ to obtain an output $(a_1, \ldots, a_N)$.
2. Let $i_1, \ldots, i_k$ be the indexes where $a_{i_j} = 0$.
3. If $k \geq \alpha N/4$, **return** 0 ("not disjoint").
4. Otherwise, for each $j = 1, \ldots, k$:
   (a) Run the brute force disjointness protocol on (X_{i_j}, Y_{i_j}).
   (b) If it returns 0, **return** 0 ("not disjoint").
5. If none of the executions on (X_{i_j}, Y_{i_j}) returned 0, **return** 1 ("disjoint").

Fig. 5 *The protocol* Π.

The Communication Complexity of Π. The first step of Π consists of an execution of π_N, and thus uses $< (\alpha/8) \cdot (N \cdot n)$ communication. The fourth step is only executed if $k < \alpha N/4$, in which case it is executed fewer than $\alpha N/4$ times to a total communication cost of $< (\alpha N/4) \cdot (n + 1)$. Thus the total communication cost of Π is bounded by

$$(\alpha/8) \cdot (N \cdot n) + (\alpha N/4) \cdot (n + 1) < (\alpha/2) \cdot (N \cdot n).$$

The Failure Probability of Π. Let $((x_1, \ldots, x_{N \cdot n}), (y_1, \ldots, y_{N \cdot n})) = (X_1, \ldots, X_N), (Y_1, \ldots, Y_N)$ be an input to the protocol. We need to show that the probability

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that Π computes $DISJ_{N\cdot n}$ incorrectly on this input is $< 1/6$. There are two cases to consider.

Case 1: $DISJ_{n\cdot N}((x_1,\ldots,x_{N\cdot n}),(y_1,\ldots,y_{N\cdot n})) = 0$. In this case there is a coordinate ℓ such that $DISJ_n(X_\ell, Y_\ell) = 0$. By the property of π_N we will have the first-step output $a_\ell = 0$ except with probability $< 1/8$. Assuming $a_\ell = 0$ note that the protocol Π is guaranteed to output 0, either in step 3 or in step 4 after considering the pair (X_ℓ, Y_ℓ). Thus the probability of an error in this case is $< 1/8 < 1/6$.

Case 2: $DISJ_{n\cdot N}((x_1,\ldots,x_{N\cdot n}),(y_1,\ldots,y_{N\cdot n})) = 1$. Let $Q : \{0,1\}^N \to \{0,1\}$ be the monotone function that returns 1 if and only if the Hamming weight of the input is at least $\alpha N/4$. Let B_ρ be a Bernoulli variable with the probability of 1 being $\rho = \alpha/10$. By Chernoff bound, for a sufficiently large N,

$$\mathbf{P}[Q(B_\rho,\ldots,B_\rho) = 1] < 1/10.$$

Thus by Theorem 6.9, the probability of π_N making at least $\alpha N/4$ errors is bounded by

$$\mathbf{P}[Q(B_\rho,\ldots,B_\rho) = 1] + \delta_2 < 1/8.$$

Thus the probability of Π outputting 0 in step 3 is $< 1/8$. Note that if Π does not output 0 in step 3, it is guaranteed to output 1, since all the pairs (X_i, Y_i) are disjoint. Thus the probability of error in this case is also $< 1/8 < 1/6$.

We proved that $R_{1/6}(DISJ_{N\cdot n}) < (\alpha/2)\cdot(N\cdot n)$ for all sufficiently large N. This contradicts our assumption (22) and completes the proof of the theorem. ∎

7.2. Proof 2: Using Information Cost Direct Sum (Sketch). The second proof will be much shorter and does not use the communication complexity lower bound for disjointness. Rather, it will use the information cost direct sum techniques as in Theorem 4.2. It will resemble the proof [65, 3] that disjointness has linear communication complexity, but will work for information cost.

Let us define the task $T(x,y)$ on two bits $x,y \in \{0,1\}$ of computing the AND function $x \wedge y$. Let μ be the distribution on $\{0,1\}^2$ that is uniform on the set $\{(0,0),(0,1),(1,0)\}$. Let μ' be the restriction of μ to one coordinate. In other words, μ' is a distribution on $\{0,1\}$ such that $\mu'(0) = 2/3$ and $\mu'(1) = 1/3$. Suppose, for contradiction, that there was a protocol Π for solving disjointness on n-bit long strings with error δ and in $< \varepsilon n$ *information* cost, where δ and ε are very small constants.

In particular we have $\mathsf{IC}_{\mu^n}(\Pi) < \varepsilon n$. Let π be the protocol obtained by restricting Π to one coordinate as in Figure 6 (cf. [12]).

Protocol $\pi(x,y)$
1. The parties jointly and publicly sample a uniformly selected index $J \in \{1,\ldots,n\}$.
2. The parties publicly sample $X_1,\ldots,X_{J-1},Y_{J+1},\ldots,Y_n$ according to μ'.
3. The first party privately samples $X_{J+1},\ldots,X_n$ and the second party privately samples $Y_1,\ldots,Y_{J-1}$ conditioned on the corresponding publicly sampled variables, so that each (X_i,Y_i) is distributed according to μ.
4. The parties run $\Pi((X_1,\ldots,X_{J-1},x,X_{J+1},\ldots,X_n),(Y_1,\ldots,Y_{J-1},y,Y_{J+1},\ldots,Y_n))$ and output the output of Π.

Fig. 6 *The protocol $\pi(x,y)$, $x,y \in \{0,1\}$.*

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The proof from [12] (and also the proof of Theorem 4.2) shows that the information cost

$$\mathsf{IC}_\mu(\pi) = \frac{1}{n} \cdot \mathsf{IC}_{\mu^n}(\Pi) < \varepsilon.$$

At the same time we note that π can be used to solve the task $T(x, y)$. For each pair of inputs (x, y), and for each possible randomized selections in the protocol π, we have

$$\begin{aligned} T(x,y) &= x \wedge y \\ &= DISJ_n((X_1, \ldots, X_{J-1}, x, X_{J+1}, \ldots, X_n), (Y_1, \ldots, Y_{J-1}, y, Y_{J+1}, \ldots, Y_n)) \\ &= \pi(x, y), \end{aligned}$$

where the last equality holds with probability $> 1 - \delta$. We note that we measure the information revealed by π only against the distribution μ, whereas π will perform correctly on all four possible pairs of inputs. This is important to achieve a contradiction, since computing $x \wedge y$ correctly on inputs in the support of μ is trivial, as the function is identically 0 on this set.

It remains to show that a protocol that reveals almost no information over the distribution μ cannot be computing $x \wedge y$ correctly. This part is very similar to previous proofs of the communication lower bounds for disjointness, and we omit the details here.

8. Recent Progress, Directions, and Open Problems.

In this section we outline some further progress surrounding information complexity, driven in part by the earlier versions of this paper. We then present some outstanding open problems concerning information complexity. We group these problems by topic. Some of the problems are very concrete, while others take the form of a potential research direction. Since a fair amount of progress has happened since the presentation of this paper in its technical report form, we try to give an update on the progress as of June 2015.

8.1. Recent Progress on Information Complexity.

Zero-Communication Protocols and Lower Bounds on Information Complexity. Techniques used in the proof of Lemma 5.2 have been generalized to prove that the discrepancy method is applicable for information complexity lower bounds [17]. In other words, low information complexity implies high discrepancy (more on the discrepancy method in communication complexity can be found in [52]). More importantly, that result was further generalized by Kerenidis et al. [47] to show that the relaxed partition bound applies to information complexity. The main idea of the construction of [47] is that a low-information cost protocol can be turned into a zero-communication protocol with abort: the protocol aborts with probability close to 1, but conditioned on not aborting, it succeeds with high probability. The relaxed partition bound rules out such protocols.

The lower bounds of [47] subsume most known communication complexity lower bounds techniques, which in turn makes it difficult to separate information complexity from communication complexity. They also imply that the linear lower bounds of [21, 75, 69] for the gap Hamming distance problem[4] apply to information complexity as well. This result was later sharpened to show that the $\Omega(n)$ bound on the information complexity of GHD_n applies even when the prior distribution is uniform [11]. Very

[4]Given two vectors x, y in $\{-1, +1\}^n$, the GHD_n problem is distinguishing between the case when $\langle x, y\rangle > \sqrt{n}$ and the case when $\langle x, y\rangle < -\sqrt{n}$.

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recently, the lower bounds of [47] have been shown [27] to not apply to the partition bound technique of Jain and Klauck [35].

Kerenidis et al. [47] also implied a polynomial lower bound on the information complexity of the vector in a subspace problem (VSP). VSP is the (promise) problem that yields an exponential separation between the one-way quantum and randomized communication complexity given by Klartag and Regev [48]. VSP_n is defined as follows. Alice is given a unit vector $u \in \mathbf{R}^n$, and Bob is given a subspace $H \subset \mathbf{R}^n$ of dimension $n/2$ with the promise that either $u \in H$ or $u \in H^\perp$. Their goal is to decide which is the case. The lower bound on the information complexity of VSP_n, coupled with the logarithmic upper bound on its quantum communication complexity, implies that in some cases the quantum communication complexity and the information complexity of problems are exponentially apart.

Exact Bounds on Communication Problems. As discussed below, a general method for computing the information complexity of a function given its truth table appears to be computationally costly. The problem is even nontrivial for specific functions, such as the AND of two bits (where Alice receives $x \in \{0,1\}$, Bob receives $y \in \{0,1\}$, and they need to output $x \wedge y$). In [10] the optimal sequence of protocols for computing the AND of two bits has been found, showing that the information complexity of AND is $C_\wedge \approx 1.4922$ bits. The same work also obtained the exact constants for the disjointness and the small set disjointness problem. In particular it sharpened the result of section 7 to show that with small error (e.g., $1/n$) the communication complexity of $DISJ_n$ is $c_{DISJ} \cdot n \pm o(n)$, where $c_{DISJ} \approx 0.4827\cdots$ is an explicitly computable constant. This result is tight in that it gave upper and lower bounds that coincide up to $o(n)$.

Direct Product Theorems. In this paper we considered *direct sum* problems of the following form: "If one copy of a problem requires C resources, do n copies of the problem require $n \cdot C$ resources?" More generally, "what lower bound can one give on the amount C_n of resources needed for the n copies?" In the specific case of computing a function with error ε, this means that C_n represents the cost of computing n independent copies of f, with error ε each. This leaves a gap in the hardness of computing f^n: as a lower bound, C_n only bounds the cost of computing f^n with success probability $\geq 1-\varepsilon$. One would expect that with $< C_n$ resources, the probability of successfully computing *all* n copies would behave as $(1-\varepsilon)^n$, or as another exponential in n. Statements asserting that if the amount of resources is too small, then the probability of success is exponentially small are known as direct product theorems. Direct product theorems are generally harder to prove than direct sum theorems. In the context of communication complexity, they have a long history, including recent developments [66, 54, 68, 44, 37, 15, 58, 14]. In particular, in [15] a generic direct product result that roughly matches the direct sum results of [4] was given. Building on that result, most recently, in [18] a direct product theorem was finally given showing that $o(n \cdot \mathsf{IC}(f, 1/3))$ communication will lead to an exponentially small success probability in computing f^n.

It is interesting to note that while no strong formal connection has been established, there is a connection between the parallel repetition problem for two-prover games and the direct product theorem for communication. Two-prover games closely correspond to constraint satisfaction problems and play a significant role in that context (in particular, the games in the "unique games conjecture" are two-prover games). The "value" of such a game is the probability that the provers can win the game, when they play optimally. Parallel repetition theorems assert that winning a number of independent instances of such games is harder than winning a single in-

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stance, and they quantify such hardness in terms of the original game's value and the number of instances [64, 62]. Indeed, progress made on work towards the direct product theorem for randomized communication complexity also translated into progress on proving the most general parallel repetition theorem for two-prover games [8]. It is an interesting question whether this connection can be formalized and developed further.

8.2. Outstanding Open Problems. Below we discuss several major outstanding open problems and research directions, along with some recent progress.

8.2.1. Properties of the Interactive Information Complexity. The first set of problems has to do with the properties of $\mathsf{IC}(f,\varepsilon)$ and its relationship with other communication complexity measures. First and foremost, we would like to understand to what extent interactive computation can be compressed. The recent results of [28, 29] show that it is not the case that for all f, $\mathsf{IC}(f,\varepsilon) = \Omega(R(f,\varepsilon))$. Moreover, more recently, it was also shown [30] that it is not the case that $\mathsf{IC}^{\mathsf{ext}}(f,\varepsilon) = \Omega(R(f,\varepsilon))$—at least for relations—and there is every reason to believe that it is not the case for functions either.

These results can be framed in terms of producing tasks that can be solved without revealing too much information, but in a way that cannot be compressed. Roughly speaking, they imply that a protocol that uses C bits of communication and reveals I bits of information cannot be compressed to fewer than $I \log C$ bits of communication. On the other hand, the best compression result of [4] yields a compression protocol to $\tilde{O}(\sqrt{I \cdot C})$ bits. Narrowing this gap remains an open problem as of 2017.

PROBLEM 1. *Given a protocol π of communication cost C and information cost I, what is the lowest $c(I,C)$ such that π can always be simulated (up to a constant error ε) by a protocol π' of communication cost $c(I,C)$?*

Improved bounds for Problem 1 will readily translate into improved bounds for the direct sum problem for randomized communication complexity. A specific question that would be interesting to answer is whether one can get $c(I,C) = \mathrm{poly}(I, \log C)$. Existing examples do not rule out this possibility, although it is quite possible that a stronger example can be constructed to rule it out. A further discussion of this problem can be found in the survey [77].

Another natural problem is the following: given a truth table of a function f and the error parameter ε, compute $\mathsf{IC}(f,\varepsilon)$.

PROBLEM 2. *What is the computational complexity of the problem of evaluating the information complexity of a function f? In other words, given a truth table of $f : \{0,1\}^n \times \{0,1\}^n \to \{0,1\}$ and a rational $\varepsilon \geq 0$, what is the complexity of evaluating $\mathsf{IC}(f,\varepsilon)$?*

Only recently, $\mathsf{IC}(f,0)$ has been shown to be computable [16]. It is very likely that the same techniques imply that $\mathsf{IC}(f,\varepsilon)$ for $\varepsilon > 0$ is computable as well. One general approach is to successively enumerate r-round protocols and find the information complexity $\mathsf{IC}^r(f,\varepsilon)$ of f when limited to r-round protocols. While, by definition, $\mathsf{IC}^r(f,\varepsilon) \searrow \mathsf{IC}(f,\varepsilon)$, the rate of convergence remains open.

PROBLEM 3. *What is the rate of convergence of $\mathsf{IC}^r(f,\varepsilon) \searrow \mathsf{IC}(f,\varepsilon)$? In other words, how big does r need to be as a function of n and $\delta > 0$ so that $\mathsf{IC}^r(f,\varepsilon) - \mathsf{IC}(f,\varepsilon) < \delta$.*

A dependence on both n and δ is needed. Braverman and Schneider [16] provides an upper bound that suffices to establish computability, but it is unknown, for ex-

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ample, whether the bound can be of the form $c(n)/\delta^{O(1)}$ for some function $c(n)$. For the two-bit AND function, the rate of convergence is $1/\sqrt{\delta}$ [10], and thus at least a polynomial dependence on δ is inevitable.

8.2.2. Quantum Information Complexity. We next turn our attention to directions of interest. These are more open-ended than the problems above. The first one has to do with extending interactive compression into the quantum communication setting. Much of the early development of information complexity was, in fact, motivated by quantum problems [38, 40]. More recently, Touchette [74] gave the "correct" quantum analogue of information complexity—one that satisfies the "information = amortized communication" relationship. More recently [9] showed an analogue of Theorem 5.3 in the (nondistributional) quantum setting: $\mathsf{QCC} < 2^{O(\mathsf{QIC})}$. Interestingly, the proof techniques are quite different from the proof of Theorem 5.3, and one ingredient that is clearly missing is that of quantum interactive compression.

PROBLEM 4. *To what extent is quantum interactive compression possible? In particular, does a compression result along the lines of* [4] *hold?*

The problem with extending the proof of [4] directly is that the classical proof relies on the ability to "rewind" a protocol if the parties learn that they have made a mistake in the past. It is not clear what the correct quantum analogue of this operation is. The current best upper bound on compression [73] shows how to compress an r-*round* protocol with quantum information cost I to a protocol of communication $I/r^2 + r^3$. No results for the unbounded-round setting are known.

8.2.3. Multiparty Information Complexity. Perhaps the most natural extension to the present work one should consider is the extension to the communication setting with more than two players. There are several models for (randomized) multiparty communication complexity. They can be broadly split into the number-in-hand and the number-on-the-forehead models.

In the number-in-hand (NIH) model, each of the k players is given an input x_i, and the players need to compute a function $f(x_1, \ldots, x_k)$. The players may be communicating either through a blackboard that is visible to all players or through private messages, depending on the model. Note that if k is constant, e.g., $k = 3$, then the two settings are equivalent up to a multiplicative constant. The NIH setting is usually very similar to the two-party setting. One communication complexity lower bound technique in this case is to partition the k players into two groups and show that a large number of bits must be exchanged between the two groups. This leads naturally to the question of extending the interactive information cost to the multiparty NIH setting.

PROBLEM 5. *What is the "right" definition of the multiparty NIH information complexity, and what are its properties?*

It is quite plausible that a straight generalization of the information cost would work. One source of difficulty is that now there are potentially different kinds of "public" randomness—e.g., randomness that is accessible by some but not all players.

The number-on-the-forehead (NOF) model is notoriously more difficult. In this model there are still k players and k inputs $x_1, \ldots, x_k$, but each player i has access to *all* inputs but x_i—as if x_i was written on her forehead. Lower bounds in this model are notoriously more difficult. There is no straightforward reduction to the two-party case. Even the disjointness problem over $[n]$ with fewer than $\log n$ players proves to be a major challenge that has been partially resolved only recently [23, 53, 70, 71, 63].

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Moreover, any explicit lower bound on the multiparty communication complexity in the NOF model with $(\log n)^{\omega(1)}$ players would yield to superpolynomial circuit lower bounds for the class $\mathbf{ACC^0}$ of bounded-depth circuits with modulo gates [79, 5, 32]. Thus proving lower bounds in the NOF model is a well-motivated problem.

PROBLEM 6. *Is there a way to define information complexity in the multiparty NOF model, and what are its properties?*

Note that in this model one has to be particularly careful since, at least when there is randomness-on-the-forehead available, one can design protocols that reveal no information to the participants except for the output of the computation [6].

8.2.4. Continuous Complexity Measures. Finally, we take a higher level view on the relationship between the (two-party) information complexity of problems and their communication complexity. One way to look at $\mathsf{IC}(f,\varepsilon)$ is as a continuous relaxation of the communication complexity $R(f,\varepsilon)$: $\mathsf{IC}(f,\varepsilon) \leq R(f,\varepsilon)$, since communication is always an upper bound of information. On the other hand, as far as we know, $\mathsf{IC}(f,\varepsilon)$ may be smaller than $R(f,\varepsilon)$. The advantage comes from the fact that when considering *information*, each communication round may carry a nonintegral amount of information—potentially much smaller than 1 bit. Thus if during the execution of a protocol a bit is sent that is not very "informative," $\mathsf{IC}(\cdot,\cdot)$ will measure the amount of information correctly, while the communication complexity of sending this bit is "rounded" to cost 1. One can argue that if $\mathsf{IC}(\cdot,\cdot)$ has nicer properties than $R(\cdot,\cdot)$—such as an exact direct sum theorem—it is because $\mathsf{IC}(\cdot,\cdot)$ is nonintegral and measures the interaction between the player more accurately.

This raises the open-ended question of whether there are reasonable (and useful) continuous "relaxations" of other classically integral complexity measures.

PROBLEM 7. *Is there a good way to define continuous relaxations of the classically integral complexity measures such as circuit complexity and branching program size?*

Such continuous measures may potentially lead to lower bounds that are currently obfuscated by the integrality of the complexity measures involved. More broadly, information-theoretic considerations may inspire lower bounds in these models. For example, the derandomization technique in [13] was inspired by information-theoretic considerations.

Acknowledgments. I would like to thank Boaz Barak, Stephen Cook, Ankit Garg, Denis Pankratov, Toni Pitassi, Anup Rao, Alexander Razborov, Michael Saks, Omri Weinstein, Avi Wigderson, and the anonymous referees for the insightful conversations and comments on earlier drafts of this paper.

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