Algorithmic information, plane Kakeya sets, and conditional dimension

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Abstract

We formulate the conditional Kolmogorov complexity of x given y at precision r, where x and y are points in Euclidean spaces and r is a natural number. We demonstrate the utility of this notion in two ways.

1. We prove a point-to-set principle that enables one to use the (relativized, constructive) dimension of a single point in a set E in a Euclidean space to establish a lower bound on the (classical) Hausdorff dimension of E. We then use this principle, together with conditional Kolmogorov complexity in Euclidean spaces, to give a new proof of the known, two-dimensional case of the Kakeya conjecture. This theorem of geometric measure theory, proved by Davies in 1971, says that every plane set containing a unit line segment in every direction has Hausdorff dimension 2.

2. We use conditional Kolmogorov complexity in Euclidean spaces to develop the lower and upper conditional dimensions dim(x|y) and Dim(x|y) of x given y, where x and y are points in Euclidean spaces. Intuitively these are the lower and upper asymptotic algorithmic information densities of x conditioned on the information in y. We prove that these conditional dimensions are robust and that they have the correct information-theoretic relationships with the well-studied dimensions dim(x) and Dim(x) and mutual dimensions mdim(x : y) and Mdim(x : y).

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1 Introduction

This paper concerns the fine-scale geometry of algorithmic information in Euclidean spaces. It shows how new ideas in algorithmic information theory can shed new light on old problems in geometric measure theory. This introduction explains these new ideas, a general principle for applying these ideas to classical problems, and an example of such an application. It also describes a newer concept in algorithmic information theory that arises naturally from this work.

Roughly fifteen years after the mid-twentieth century development of the Shannon information theory of probability spaces [27], Kolmogorov recognized that Turing’s mathematical theory of computation could be used to refine the Shannon theory to enable the amount of information in individual data objects to be quantified [16]. The resulting theory of Kolmogorov complexity, or algorithmic information theory, is now a large enterprise with many applications in computer science, mathematics, and other sciences [19]. Kolmogorov proved the first version of the fundamental relationship between the Shannon and algorithmic theories of information in [16], and this relationship was made exquisitely precise by Levin’s coding theorem [17, 18]. (Solomonoff and Chaitin independently developed Kolmogorov complexity at around the same time as Kolmogorov with somewhat different motivations [28, 6, 7].)

At the turn of the present century, the first author recognized that Hausdorff’s 1919 theory of fractal dimension [15] is an older theory of information that can also be refined using Turing’s mathematical theory of computation, thereby enabling the density of information in individual infinite data objects, such as infinite binary sequences or points in Euclidean spaces, to be quantified [20, 21]. The resulting theory of effective fractal dimensions is now an active enterprise with a growing array of applications [11]. The paper [21] proved a relationship between effective fractal dimensions and Kolmogorov complexity that is as precise as — and uses — Levin’s coding theorem.

Most of the work on effective fractal dimensions to date has concerned the (constructive) dimension $\dim(x)$ and the dual strong (constructive) dimension $\Dim(x)$ [1] of an infinite data object $x$, which for purposes of the present paper is a point in a Euclidean space $\mathbb{R}^n$ for some positive integer $n$. The inequalities

$$0 \leq \dim(x) \leq \Dim(x) \leq n$$

hold generally, with, for example, $\Dim(x) = 0$ for points $x$ that are computable and $\dim(x) = n$ for points that are algorithmically random in the sense of Martin-Löf [Mart66].

How can the dimensions of individual points—dimensions that are defined using the theory of computing—have any bearing on classical problems of geometric measure theory? The problems that we have in mind here are problems

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1These constructive dimensions are $\Sigma^0_1$ effectivizations of Hausdorff and packing dimensions [12]. Other effectivizations, e.g., computable dimensions, polynomial time dimensions, and finite-state dimensions, have been investigated, but only the constructive dimensions are discussed here.
in which one seeks to establish lower bounds on the classical Hausdorff dimensions \( \dim_H(E) \) (or other fractal dimensions) of sets \( E \) in Euclidean spaces. Such problems involve global properties of sets and make no mention of algorithms.

The key to bridging this gap is relativization. Specifically, we prove here a point-to-set principle saying that, in order to prove a lower bound \( \dim_H(E) \geq \alpha \), it suffices to show that, for every \( A \subseteq \mathbb{N} \) and every \( \varepsilon > 0 \), there is a point \( x \in E \) such that \( \dim^A(x) \geq \alpha - \varepsilon \), where \( \dim^A(x) \) is the dimension of \( x \) relative to the oracle \( A \). We also prove the analogous point-to-set principle for the classical packing dimension \( \dim_P(E) \) and the relativized strong dimension \( \text{Dim}^A(x) \).

We illustrate the power of the point-to-set principle by using it to give a new proof of a known theorem in geometric measure theory. A Kakeya set in a Euclidean space \( \mathbb{R}^n \) is a set \( K \subseteq \mathbb{R}^n \) that contains a unit line segment in every direction. Besicovitch [2, 3] proved that Kakeya sets can have Lebesgue measure 0 and asked whether Kakeya sets in the Euclidean plane can have dimension less than 2 [9]. The famous Kakeya conjecture asserts a negative answer to this and to the analogous question in higher dimensions, i.e., states that every Kakeya set in a Euclidean space \( \mathbb{R}^n \) has Hausdorff dimension \( n \).\(^2\) This conjecture holds trivially for \( n = 1 \) and was proven by Davies [9] for \( n = 2 \). For \( n \geq 3 \) it is an important open problem with deep connections to other problems in analysis [33, 30].

In this paper we use our point-to-set principle to give a new proof of Davies’s theorem. This proof does not resemble the classical proof. Instead of analyzing the set \( K \) globally, it focuses on the information content of a single, judiciously chosen point in \( K \). Given a Kakeya set \( K \subseteq \mathbb{R}^2 \), an oracle \( A \subseteq \mathbb{N} \), and a real number \( \varepsilon > 0 \), we first choose a particular line segment \( L \subseteq K \) and a particular point \( (x, mx + b) \in L \), where \( y = mx + b \) is the equation of the line containing \( L \).\(^3\) We then show that \( \dim^A(x, mx + b) \geq 2 - \varepsilon \). By our point-to-set principle this implies that \( \dim_H(K) \geq 2 \).

Our proof that \( \dim^A(x, mx + b) \geq 2 - \varepsilon \) requires us to formulate a concept of conditional Kolmogorov complexity in Euclidean spaces. Specifically, for points \( x \in \mathbb{R}^m \) and \( y \in \mathbb{R}^n \) and natural numbers \( r \), we develop the conditional Kolmogorov complexity \( K_r(x|y) \) of \( x \) given \( y \) at precision \( r \). This is a “conditional version” of the Kolmogorov complexity \( K_r(x) \) of \( x \) at precision \( r \) that has been used in several recent papers.

We are hopeful that our new proof of Davies’s theorem will open the way for using constructive fractal dimensions to make new progress in geometric measure theory.

In addition to enabling our new proof of Davies’s theorem, conditional Kolmogorov complexity in Euclidean spaces enables us to fill a gap in effective dimension theory. The fundamental quantities in Shannon information theory

\(^2\)Statements of the Kakeya conjecture vary in the literature. For example, the set is sometimes required to be compact or Borel, and the dimension used may be Minkowski instead of Hausdorff. Since the Hausdorff dimension of a set is never greater than its Minkowski dimension, our formulation is at least as strong as those variations.

\(^3\)One might naively expect that for independently random \( m \) and \( x \), the point \( (x, mx + b) \) must be random. In fact, in every direction there is a line that contains no random point [22].
are the entropy (information content) $H(X)$ of a probability space $X$, the conditional entropy $H(X|Y)$ of a probability space $X$ given a probability space $Y$, and the mutual information (shared information) $I(X;Y)$ between two probability spaces $X$ and $Y$ [8]. The analogous quantities in Kolmogorov complexity theory are the Kolmogorov complexity $K(u)$ of a finite data object $u$, the conditional Kolmogorov complexity $K(u|v)$ of a finite data object $u$ given a finite data object $v$, and the algorithmic mutual information $I(u:v)$ between two finite data objects $u$ and $v$ [19]. The above-described dimensions $\dim(x)$ and $\Dim(x)$ of a point $x$ in Euclidean space (or an infinite sequence $x$ over a finite alphabet) are analogous by limit theorems [25, 1] to $K(u)$ and hence to $H(X)$.

Case and the first author have recently developed and investigated the mutual dimension $\text{mdim}(x:y)$ and the dual strong mutual dimension $\text{Mdim}(x:y)$, which are densities of the algorithmic information shared by points $x$ and $y$ in Euclidean spaces [4] or sequences $x$ and $y$ over a finite alphabet [5]. These mutual dimensions are analogous to $I(u:v)$ and $I(X;Y)$.

What is conspicuously missing from the above account is a notion of conditional dimension. In this paper we remedy this by using conditional Kolmogorov complexity in Euclidean space to develop the conditional dimension $\dim(x|y)$ of $x$ given $y$ and its dual, the conditional strong dimension $\Dim(x|y)$ of $x$ given $y$, where $x$ and $y$ are points in Euclidean spaces. We prove that these conditional dimensions are well behaved and that they have the correct information theoretic relationships with the previously defined dimensions and mutual dimensions.

The rest of this paper is organized as follows. Section 2 briefly reviews the dimensions of points in Euclidean spaces. Section 3 presents the point-to-set principles that enable us to use dimensions of individual points to prove lower bounds on classical fractal dimensions. Section 4 develops conditional Kolmogorov complexity in Euclidean spaces. Section 5 uses the preceding two sections to give our new proof of Davies’s theorem. Section 6 uses Section 4 to develop conditional dimensions in Euclidean spaces. Most proofs are deferred to the optional technical appendix.

2 Dimensions of Points in Euclidean Spaces

This section reviews the constructive notions of dimension and mutual dimension in Euclidean spaces. The presentation here is in terms of Kolmogorov complexity. Briefly, the conditional Kolmogorov complexity $K(w|v)$ of a string $w \in \{0,1\}^*$ given a string $v \in \{0,1\}^*$ is the minimum length $|\pi|$ of a binary string $\pi$ for which $U(\pi,v) = w$, where $U$ is a fixed universal self-delimiting Turing machine. The Kolmogorov complexity of $w$ is $K(w|\lambda)$, where $\lambda$ is the empty string. We write $U(\pi)$ for $U(\pi,\lambda)$. When $U(\pi) = w$, the string $\pi$ is called a program for $w$. The quantity $K(w)$ is also called the algorithmic information content of $w$. Routine coding extends this definition from $\{0,1\}^*$ to other discrete domains, so that the Kolmogorov complexities of natural numbers, rational numbers, tuples of these, etc., are well defined up to additive constants. Detailed discussions
of self-delimiting Turing machines and Kolmogorov complexity appear in the books [19, 26, 11] and many papers.

The definition of $K(q)$ for rational points $q$ in Euclidean space is lifted in two steps to define the dimensions of arbitrary points in Euclidean space. First, for $x \in \mathbb{R}^n$ and $r \in \mathbb{N}$, the Kolmogorov complexity of $x$ at precision $r$ is

$$K_r(x) = \min \{ K(q) : q \in \mathbb{Q}^n \cap B_{2^{-r}}(x) \}. \quad (2.1)$$

Second, for $x \in \mathbb{R}^n$, the dimension and strong dimension of $x$ are

$$\dim(x) = \liminf_{r \to \infty} \frac{K_r(x)}{r} \quad \text{and} \quad \text{Dim}(x) = \limsup_{r \to \infty} \frac{K_r(x)}{r}, \quad (2.2)$$

respectively.\(^4\)

Intuitively, $\dim(x)$ and $\text{Dim}(x)$ are the lower and upper asymptotic densities of the algorithmic information in $x$. These quantities were first defined in Cantor spaces using betting strategies called gales and shown to be constructive versions of classical Hausdorff and packing dimension, respectively [21, 1]. These definitions were explicitly extended to Euclidean spaces in [23], where the identities (2.2) were proven as a theorem. Here it is convenient to use these identities as definitions. For $x \in \mathbb{R}^n$, it is easy to see that

$$0 \leq \dim(x) \leq \text{Dim}(x) \leq n,$$

and it is known that, for any two reals $0 \leq \alpha \leq \beta \leq n$, there exist uncountably many points $x \in \mathbb{R}^n$ satisfying $\dim(x) = \alpha$ and $\text{Dim}(x) = \beta$ [1]. Applications of these dimensions in Euclidean spaces appear in [23, 13, 24, 10, 14].

\section*{3 From Points to Sets}

The central message of this paper is a useful point-to-set principle by which the existence of a single high-dimensional point in a set $E \subseteq \mathbb{R}^n$ implies that the set $E$ has high dimension.

To formulate this principle we use relativization. All the algorithmic information concepts in Sections 2 and 6 above can be relativized to an arbitrary oracle $A \subseteq \mathbb{N}$ by giving the Turing machine in their definitions oracle access to $A$. Relativized Kolmogorov complexity $K_A^r(x)$ and relativized dimensions $\dim_A^r(x)$ and $\text{Dim}_A^r(x)$ are thus well defined. Moreover, the results of Section 2 hold relative to any oracle $A$.

We first establish the point-to-set principle for Hausdorff dimension. Let $E \subseteq \mathbb{R}^n$. For $\delta > 0$, define $U_\delta(E)$ to be the collection of all countable covers of $E$

\[^4\]We note that $K_r(x) = K(x \mid r) + o(r)$, where $x \mid r$ is the binary expansion of $x$, truncated $r$ bits to the right of the binary point. However, it has been known since Turing’s famous correction [31] that binary notation is not a suitable representation for the arguments and values of computable functions on the reals. (See also [32].) Hence, in order to make our definitions useful for further work in computable analysis, we formulate complexities and dimensions in terms of rational approximations, both here and later.
by sets of positive diameter at most $\delta$. That is, for every cover $\{U_i\}_{i \in \mathbb{N}} \in \mathcal{U}_\delta(E)$, we have $E \subseteq \bigcup_{i \in \mathbb{N}} U_i$ and $|U_i| \in (0, \delta]$ for all $i \in \mathbb{N}$, where for $X \in \mathbb{R}^n$, $|X| = \sup_{p,q \in X} |p - q|$. For $s \geq 0$, define

$$H^s_\delta(E) = \inf \left\{ \sum_{i \in \mathbb{N}} |U_i|^s : \{U_i\}_{i \in \mathbb{N}} \in \mathcal{U}_\delta(E) \right\}.$$ 

Then the $s$-dimensional Hausdorff outer measure of $E$ is

$$H^s(E) = \lim_{\delta \to 0^+} H^s_\delta(E),$$

and the Hausdorff dimension of $E$ is

$$\dim_H(E) = \inf \{ s > 0 : H^s(E) = 0 \}.$$ 

More details may be found in standard texts, e.g., [29, 12].

**Theorem 1.** (Point-to-set principle for Hausdorff dimension) For every set $E \subseteq \mathbb{R}^n$,

$$\dim_H(E) = \min_{A \subseteq \mathbb{N}} \sup_{x \in E} \dim^A(x).$$

Three things should be noted about this principle. First, while the left-hand side is the classical Hausdorff dimension, which is a global property of $E$ that does not involve the theory of computing, the right-hand side is a pointwise property of the set that makes essential use of relativized algorithmic information theory. Second, as the proof shows, the right-hand side is a minimum, not merely an infimum. Third, and most crucially, this principle implies that, in order to prove a lower bound $\dim_H(E) \geq \alpha$, it suffices to show that, for every $A \subseteq \mathbb{N}$ and every $\varepsilon > 0$, there is a point $x \in E$ such that $\dim^A(x) \geq \alpha - \varepsilon$.

**Proof of Theorem 1.** Let $E \subseteq \mathbb{R}^n$, and let $d = \dim_H(E)$. Fix $s > d$. Then $H^s(E) = 0$, so there is a sequence $\{\{U_i^{t,s}\}_{i \in \mathbb{N}}\}_{t \in \mathbb{N}}$ of countable covers of $E$ such that $|U_i^{t,s}| \leq 2^{-t}$ for every $i, t \in \mathbb{N}$, and for every sufficiently large $t$ we have

$$\sum_{i \in \mathbb{N}} |U_i^{t,s}|^s < 1. \quad (3.1)$$

Let $D = \mathbb{N}^3 \times (\mathbb{Q} \cap (d, \infty)) \to \mathbb{Q}^n$. Our oracle $A$ encodes functions $f_A : D \to \mathbb{Q}^n$ and $g_A : D \to \mathbb{Q}$ such that for every $(i, t, r, s) \in D$, we have

$$f_A(i, t, r, s) \in B_{2^{-r-1}}(u)$$

for some $u \in U_i^{t,s}$ and

$$|g_A(i, t, r, s) - |U_i^{t,s}|| < 2^{-r-4}. \quad (3.2)$$

We will show for every $x \in E$ that $\dim^A(x) \leq s$. 

Fix $x \in E$. If for any $i_0, t_0 \in \mathbb{N}$ we have $x \in U_{i_0}^{t_0,s}$ and $|U_{i_0}^{t_0,s}| = 0$, then $U_{i_0}^{t_0,s} = \{x\}$, so $f_{A}(i_0, t_0, r, s) \in B_{2^{-r}}(x)$ for every $r \in \mathbb{N}$. In this case, let $M$ be a prefix Turing machine with oracle access to $A$ such that, whenever $U(i) = i \in \mathbb{N}$, $U(r) = t \in \mathbb{N}$, $U(\rho) = r \in \mathbb{N}$, and $U(\sigma) = q \in \mathbb{Q} \cap (d, \infty)$,

$$M(i, t, r, q) = f_{A}(i, t, r, q).$$

Now for any $r \in \mathbb{N}$, let $i, \tau, \rho,$ and $\sigma$ be witnesses to $K(i_0), K(t_0), K(r),$ and $K(s)$, respectively. Since $i_0$, $t_0$, and $s$ are all constant in $r$ and $|\rho| = o(1)$, we have $|i, \tau, \rho, \sigma| = o(1)$. Thus $K^A_r(x) = o(r)$, and $\dim^A(x) = 0$. Hence assume that every cover element containing $x$ has positive diameter.

Fix sufficiently large $t$, and let $U_i^{t,s}$ be some cover element containing $x$. Let $M'$ be a self-delimiting Turing machine with oracle access to $A$ such that whenever $U(\kappa) = k \in \mathbb{N}$, $U(\tau) = \ell \in \mathbb{N}$, $U(\rho) = r \in \mathbb{N}$, and $U(\sigma) = q \in \mathbb{Q} \cap (d, \infty)$,

$$M'(\kappa, \tau, \rho, \sigma) = f_{A}(p, \ell, r, q),$$

where $p$ is the $k^{\text{th}}$ index $i$ such that $g_{A}(i, t, r, q) \geq 2^{-r-3}$.

Now fix $r \geq t - 1$ such that

$$|U_i^{t,s}| \in \left[2^{-r-2}, 2^{-r-1}\right].$$

Notice that $g_{A}(i, t, r, s) \geq 2^{-r-3}$. Hence there is some $k$ such that, letting $\kappa$, $\tau$, $\rho$, and $\sigma$ be witnesses to $K(k), K(t), K(r),$ and $K(s)$, respectively,

$$M'(\kappa, \tau, \rho, \sigma) \in B_{2^{-r-1}}(u),$$

for some $u \in U_i^{t,s}$. Because $|U_i^{t,s}| < 2^{-r-1}$ and $x \in U_i^{t,s}$, we have

$$M'(\kappa, \tau, \rho, \sigma) \in B_{2^{-r}}(x).$$

Thus

$$K_i^A(x) \leq K(k) + K(t) + K(r) + c,$$

where $c$ is a machine constant for $M'$. Since $s$ is constant in $r$ and $t < r$, Observation 3.2 tells us that this expression is $K(k) + o(r) \leq \log(k) + o(r)$. By (3.1), there are fewer than $2^{(r+4)s}$ indices $i \in \mathbb{N}$ such that

$$|U_i^{t,s}| \geq 2^{-r-4},$$

hence by (3.2) there are fewer than $2^{(r+4)s}$ indices $i \in \mathbb{N}$ such that $g_{A}(i, t, r, s) \geq 2^{-r-3}$, so $\log(k) \leq (r + 4)s$. Therefore $K_i^A(x) \leq rs + o(r)$.

There are infinitely many such $r$, which can be seen by replacing $t$ above with $r + 2$. We have shown

$$\dim^A(x) = \liminf_{r \to \infty} \frac{K_i^A(x)}{r} \leq s,$$

for every $s > d$, hence $\dim^A(x) \leq d$. It follows that

$$\min_{A \subseteq \mathbb{N}} \sup_{x \in E} \dim^A(x) \leq d.$$

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For the other direction, assume for contradiction that there is some oracle $A$ and $d' < d$ such that

$$\sup_{x \in E} \dim^A(x) = d'.$$

Then for every $x \in E$, $\dim^A(x) \leq d'$. Let $s \in (d', d)$. For every $r \in \mathbb{N}$, define the sets

$$B_r = \{ B_{2^{-r}}(q) : q \in \mathbb{Q} \text{ and } K^A(q) \leq rs \}$$

and

$$\mathcal{W}_r = \bigcup_{k=r}^{\infty} B_k.$$

There are at most $2^{ks+1}$ balls in each $B_k$, so for every $r \in \mathbb{N}$ and $s' \in (s, d)$,

$$\sum_{W \in \mathcal{W}_r} |W|^{s'} \geq \sum_{k=r}^{\infty} \sum_{W \in B_k} |W|^{s'} \leq \sum_{k=r}^{\infty} 2^{ks+1} (2^{1-k})^{s'} = 2^{1+s'} \sum_{k=r}^{\infty} 2^{(s-s')k},$$

which approaches 0 as $r \to \infty$. As every $\mathcal{W}_r$ is a cover for $E$, we have $H^{s'}(E) = 0$, so $\dim_H(E) \leq s' < d$, a contradiction. \hfill \Box

The **packing dimension** $\dim_P(E)$ of a set $E \subseteq \mathbb{R}^n$, defined in the appendix and standard texts, e.g., [12], is a dual of Hausdorff dimension satisfying $\dim_P(E) \geq \dim_H(E)$, with equality for very “regular” sets $E$. We also have the following.

**Theorem 2.** (Point-to-set principle for packing dimension) For every set $E \subseteq \mathbb{R}^n$,

$$\dim_P(E) = \min_{A \subseteq \mathbb{N}} \sup_{x \in E} \text{Dim}^A(x).$$

### 4 Conditional Kolmogorov Complexity in Euclidean Spaces

We now develop the conditional Kolmogorov complexity in Euclidean spaces.

For $x \in \mathbb{R}^m$, $q \in \mathbb{Q}^n$, and $r \in \mathbb{N}$, the **conditional Kolmogorov complexity** of $x$ at precision $r$ given $q$ is

$$\hat{K}_r(x|q) = \min \{ K(p|q) : p \in \mathbb{Q}^m \cap B_{2^{-r}}(x) \}.$$  \hfill (4.1)

For $x \in \mathbb{R}^m$, $y \in \mathbb{R}^n$, and $r, s \in \mathbb{N}$, the **conditional Kolmogorov complexity** of $x$ at precision $r$ given $y$ at precision $s$ is

$$K_{r,s}(x|y) = \max \{ \hat{K}_r(x|q) : q \in \mathbb{Q}^n \cap B_{2^{-s}}(y) \}.$$  \hfill (4.2)
Intuitively, the maximizing argument \( q \) is the point near \( y \) that is least helpful in the task of approximating \( x \). Note that \( K_{r,s}(x|y) \) is finite, because \( K_r(x|q) \leq K_r(x) + O(1) \). For \( x \in \mathbb{R}^m \), \( y \in \mathbb{R}^n \), and \( r \in \mathbb{N} \), the conditional Kolmogorov complexity of \( x \) given \( y \) at precision \( r \) is

\[
K_r(x|y) = K_{r,r}(x|y). \tag{4.3}
\]

**Theorem 3.** (Chain rule for \( K_r \)) For all \( x \in \mathbb{R}^m \) and \( y \in \mathbb{R}^n \),

\[
K_r(x, y) = K_r(x|y) + K_r(y) + o(r).
\]

An oracle for \( y \in \mathbb{R}^n \) is a set \( A \) encoding a function \( f_A : \mathbb{N} \to \mathbb{Q}^n \) such that for every \( r \in \mathbb{N} \),

\[
f_A(r) \in B_{2^{-r}}(y).
\]

Then the dimension of \( x \in \mathbb{R}^m \) relative to \( y \) is defined as

\[
\dim^y(x) = \sup \{ \dim^A(x) : A \text{ is an oracle for } y \}.
\]

The following lemma reflects the intuition that an oracle for \( y \) is at least as useful as any bounded-precision estimate for \( y \).

**Lemma 4.** For each \( m, n \in \mathbb{N} \) there is a constant \( c \in \mathbb{N} \) such that, for all \( x \in \mathbb{R}^m \), \( y \in \mathbb{R}^n \), and \( r, s \in \mathbb{N} \),

\[
K^y_r(x) \leq K_{r,s}(x|y) + K(s) + c.
\]

In particular, \( K^y_r(x) \leq K_r(x|y) + K(r) + c. \)

## 5 Kakeya Sets in the Plane

This section uses the results of the preceding two sections to give a new proof of the following classical theorem. Recall that a Kakeya set in \( \mathbb{R}^n \) is a set containing a unit line segment in every direction.

**Theorem 5.** (Davies [9]) Every Kakeya set in \( \mathbb{R}^2 \) has Hausdorff dimension 2.

Our new proof of Theorem 5 uses a relativized version of the following lemma.

**Lemma 6.** Let \( m \in [0, 1] \) and \( b \in \mathbb{R} \). Then for almost every \( x \in [0, 1] \),

\[
\liminf_{r \to \infty} \frac{K_r(m, b, x) - K_r(b|m)}{r} \leq \dim(x, mx + b). \tag{5.1}
\]

**Proof.** We build a program that takes as input a precision level \( r \), an approximation \( p \) of \( x \), an approximation \( q \) of \( mx + b \), a program \( \pi \) that will approximate \( b \) given an approximation for \( m \), and a natural number \( h \). In parallel, the program considers each multiple of \( 2^{-r} \) in \([0,1]\) as a possible approximate value \( u \) for the slope \( m \), and it checks whether each such \( u \) is consistent with the program’s inputs. If \( u \) is close to \( m \), then \( \pi(u) \) will be close to \( b \), so \( up + \pi(u) \) will be close
to $mx + b$. Any $u$ that satisfies this condition is considered a “candidate” for approximating $m$.

Some of these candidates may be “false positives,” in that there can be values of $u$ that are far from $m$ but for which $up + \pi(u)$ is still close to $mx + b$. Thus the program is also given an input $h$ so that it can choose the correct candidate; it selects the $h^{th}$ candidate that arises in its execution. We will show that this $h$ is often not large enough to significantly affect the total input length.

Formally, let $M$ be a Turing machine that runs the following algorithm on input $\rho \pi \sigma \eta$ whenever $U(\rho) = r \in \mathbb{N}$, $U(\eta) = h \in \mathbb{N}$, and $U(\sigma) = (p, q) \in \mathbb{Q}^2$:

$$\text{candidate} := 0$$

for $i = 0, 1, \ldots, 2^r$, in parallel:

\begin{align*}
  u_i &:= 2^{-r}i \\
  v_i &:= U(\pi, u_i)
\end{align*}

do atomically:

if $v_i \in \mathbb{R}$ and $|u_i p + v_i - q| < 2^{2-r}$, then $\text{candidate} := \text{candidate} + 1$

if $\text{candidate} = h$, then return $(u_i, v_i, p)$ and halt

Fix $m \in [0, 1]$ and $b \in \mathbb{R}$. For each $r \in \mathbb{N}$, let $m_r = 2^{-r} \lfloor m \cdot 2^r \rfloor$, and fix $\pi_r$ testifying to the value of $\hat{K}_r(b|m_r)$ and $\sigma_r$ testifying to the value of $K_r(x, mx + b)$.

Proofs of the following four claims appear in the appendix. Intuitively, Claim 1 says that no point in $B_{2^{-r}}(m)$ gives much less information about $b$ than $m_r$ does. Claim 2 states that there is always some value of $h$ that causes this machine to return the desired output. Claim 3 says that for almost every $x$, this value does not grow too quickly with $r$, and Claim 4 says that (5.1) holds for every such $x$.

Claim 1. For every $r \in \mathbb{N}$, $K_r(b|m) = \hat{K}_r(b|m_r) + o(r)$.

Claim 2. For each $x \in [0, 1]$ and $r \in \mathbb{N}$, there exists an $h \in \mathbb{N}$ such that

$$M(\rho \pi_r \sigma_r \eta) \in B_{2^{2-r}}(m, b, x),$$

where $U(\rho) = r$ and $U(\eta) = h$.

For every $x \in [0, 1]$ and $r \in \mathbb{N}$, define $h(x,r)$ to be the minimal $h$ satisfying the conditions of Claim 2.

Claim 3. For almost every $x \in [0, 1]$, $\log(h(x,r)) = o(r)$.

Claim 4. For every $x \in [0, 1]$, if $\log(h(x,r)) = o(r)$, then

$$\liminf_{r \to \infty} \frac{K_r(m, b, x) - K_r(b|m)}{r} \leq \dim(x, mx + b).$$

The lemma follows immediately from Claims 3 and 4. $\square$

Proof of Theorem 5. Let $K$ be a Kakeya set in $\mathbb{R}^2$. By Theorem 1, there exists an oracle $A$ such that $\dim_H(K) = \sup_{p \in K} \dim^A(p)$.

Let $m \in [0, 1]$ such that $\dim^A(m) = 1$; such an $m$ exists by Theorem 4.5 of [21]. $K$ contains a unit line segment $L$ of slope $m$. Let $(x_0, y_0)$ be the left
endpoint of such a segment. Let \( q \in \mathbb{Q} \cap [x_0, x_0 + 1/8] \), and let \( L' \) be the unit segment of slope \( m \) whose left endpoint is \((x_0 - q, y_0)\). Let \( b = y_1 + qm \), the \( y \)-intercept of \( L' \).

By a relativized version of Lemma 6, there is some \( x \in [0, 1/2] \) such that \( \dim^{A,m,b}(x) = 1 \) and

\[
\liminf_{r \to \infty} \frac{K_{r}(m, b, x) - K_{r}(b|m)}{r} \leq \dim^{A}(x, mx + b).
\]

(This holds because almost every \( x \in [0, 1/2] \) is algorithmically random relative to \((A, m, b)\) and hence satisfies \( \dim^{A,m,b}(x) = 1 \).) Fix such an \( x \), and notice that \((x, mx + b) \in L'\). Now applying a relativized version of Theorem 3,

\[
\dim^{A}(x, mx + b) \geq \liminf_{r \to \infty} \frac{K_{r}(m, b, x) - K_{r}(b|m) + K_{r}(m)}{r}
= \liminf_{r \to \infty} \frac{K_{r}(x|b, m) + K_{r}(m)}{r}
\geq \liminf_{r \to \infty} \frac{K_{r}(x|b, m)}{r} + \liminf_{r \to \infty} \frac{K_{r}(m)}{r).
\]

By Lemma 4, \( K_{r}(x|b, m) \geq K_{r}^{A,b,m}(x) + o(r) \), so we have

\[
\dim^{A}(x, mx + b) \geq \liminf_{r \to \infty} \frac{K_{r}^{A,b,m}(x)}{r} + \liminf_{r \to \infty} \frac{K_{r}(m)}{r}
= \dim^{A,b,m}(x) + \dim^{A}(m),
\]

which is 2 by our choices of \( m \) and \( x \).

By Observation A.4,

\[
\dim^{A}(x, mx + b) = \dim^{A}(x + q, mx + b).
\]

Hence, there exists a point \((x+q, mx+b) \in K\) such that \( \dim^{A}(x+q, mx+b) \geq 2 \).

By Theorem 1, the point-to-set principle for Hausdorff dimension, this completes the proof.

\(\square\)

6 Conditional Dimensions in Euclidean Spaces

The results of Section 4, which were used in the proof of Theorem 5, also enable us to give robust formulations of conditional dimensions.

For \( x \in \mathbb{R}^m \) and \( y \in \mathbb{R}^n \), the lower and upper conditional dimensions of \( x \) given \( y \) are

\[
\dim(x|y) = \liminf_{r \to \infty} \frac{K_{r}(x|y)}{r} \quad \text{and} \quad \Dim(x|y) = \limsup_{r \to \infty} \frac{K_{r}(x|y)}{r}, \quad (6.1)
\]
respectively.

The use of the same precision bound $r$ for both $x$ and $y$ in (4.3) makes the definitions (6.1) appear arbitrary and “brittle.” The following theorem shows that this is not the case.

**Theorem 7.** Let $s : \mathbb{N} \to \mathbb{N}$. If $|s(r) - r| = o(r)$, then, for all $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$,

$$
\dim(x|y) = \liminf_{r \to \infty} \frac{K_{s(r)}(x|y)}{r},
$$

and

$$
\text{Dim}(x|y) = \limsup_{r \to \infty} \frac{K_{s(r)}(x|y)}{r}.
$$

The rest of this section is devoted to showing that our conditional dimensions have the correct information theoretic relationships with the previously developed dimensions and mutual dimensions.

Mutual dimensions were developed very recently, and Kolmogorov complexity was the starting point. The mutual (algorithmic) information between two strings $u, v \in \{0, 1\}^*$ is

$$
I(u : v) = K(v) - K(u|v).
$$

Again, routine coding extends $K(u|v)$ and $I(u : v)$ to other discrete domains. Discussions of $K(u|v)$, $I(u : v)$, and the correspondence of $K(u)$, $K(u|v)$, and $I(u : v)$ with Shannon entropy, Shannon conditional entropy, and Shannon mutual information appear in [19].

In parallel with (2.1) and (2.2), Case and J. H. Lutz [4] lifted the definition of $I(p : q)$ for rational points $p$ and $q$ in Euclidean spaces in two steps to define the mutual dimensions between two arbitrary points in (possibly distinct) Euclidean spaces. First, for $x \in \mathbb{R}^m$, $y \in \mathbb{R}^n$, and $r \in \mathbb{N}$, the mutual information between $x$ and $y$ at precision $r$ is

$$
I_r(x : y) = \min \left\{ I(p : q) : p \in B_{2^{-r}}(x) \cap \mathbb{Q}^m \text{ and } q \in B_{2^{-r}}(y) \cap \mathbb{Q}^n \right\},
$$

where $B_{2^{-r}}(x)$ and $B_{2^{-r}}(y)$ are the open balls of radius $2^{-r}$ about $x$ and $y$ in their respective Euclidean spaces. Second, for $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$, the lower and upper mutual dimensions between $x$ and $y$ are

$$
\text{mdim}(x : y) = \liminf_{r \to \infty} \frac{I_r(x : y)}{r} \quad \text{and} \quad \text{Mdim}(x : y) = \limsup_{r \to \infty} \frac{I_r(x : y)}{r},
$$

respectively. Useful properties of these mutual dimensions, especially including data processing inequalities, appear in [4].

**Lemma 8.** For all $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$,

$$
I_r(x : y) = K_r(x) - K_r(x|y) + o(r).
$$

The following bounds on mutual dimension follow from Lemma 8.
Theorem 9. For all $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$, the following hold.

1. $\text{mdim}(x : y) \geq \dim(x) - \text{Dim}(x|y)$.
2. $\text{Mdim}(x : y) \leq \dim(x) - \dim(x|y)$.

Our final theorem is easily derived from Theorem 3.

Theorem 10. (Chain rule for dimension) For all $x \in \mathbb{R}^m$ and $y \in \mathbb{R}^n$,

\[
\dim(x) + \dim(y|x) \leq \dim(x, y) \leq \dim(x) + \text{Dim}(y|x) \\
\leq \dim(x, y) \leq \dim(x) + \text{Dim}(y|x) .
\]

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References


A Appendix

A.1 Packing dimension

Let $E \subseteq \mathbb{R}^n$. For $\delta > 0$, define $\mathcal{V}_\delta(E)$ to be the collection of all countable packings of $E$ by disjoint open balls of diameter at most $\delta$. That is, for every packing $\{V_i\}_{i \in \mathbb{N}} \in \mathcal{V}_\delta(E)$ and every $i \in \mathbb{N}$, we have $V_i = B_{\varepsilon_i}(x_i) \subseteq E$ for some $x_i \in E$ and $\varepsilon_i \in [0, \delta/2]$.

For $s \geq 0$, define $P_s^\delta(E) = \lim_{\delta \to 0^+} P_s^\delta(E)$.

Then the $s$-dimensional packing measure of $E$ is

$$P_s(E) = \inf \left\{ \sum_{i \in \mathbb{N}} P_0^s(E_i) : E \subseteq \bigcup_{i \in \mathbb{N}} E_i \right\},$$

and the packing dimension of $E$ is

$$\dim_P(E) = \inf \{s : P_s(E) = 0\}.$$

Theorem 2. (Point-to-set principle for packing dimension) For every set $E \subseteq \mathbb{R}^n$,

$$\dim_P(E) = \min_{A \subseteq \mathbb{N}} \sup_{x \in E} \text{Dim}^A(x).$$

Proof. Let $E \subseteq \mathbb{R}^n$, and let $d = \dim_P(E)$. Fix $s > d$. Then $P_s(E) = 0$, so there is a cover $\{E_j^s\}_{j \in \mathbb{N}}$ for $E$ such that

$$\sum_{j \in \mathbb{N}} \lim_{\delta \to 0^+} P_s^\delta(E_j^s) < 1. \quad (A.1)$$

For every $r, j \in \mathbb{N}$, let

$$\{V_i^{r,s,j}\}_{i \in \mathbb{N}} \in \mathcal{V}_{2^{-r-2}}(E_j^s)$$

be a maximal packing of $E_j^s$ by open balls of radius exactly $2^{-r-2}$ (and higher-indexed balls of radius 0).

Let $D = \mathbb{N}^3 \times (\mathbb{Q} \cap (d, \infty))$. Our oracle $A$ encodes a function $f_A : D \to \mathbb{Q}^n$ such that for every $(i, j, r, s) \in D$ we have

$$f_A(i, j, r, s) \in V_i^{r,s,j}.$$

We will show for every $x \in E$ that $\text{Dim}^A(x) \leq s$. 

A1
Let $M$ be a self-delimiting Turing machine with oracle access to $A$ such that, whenever $U(i) = i \in \mathbb{N}$, $U(j) = j \in \mathbb{N}$, $U(r) = r \in \mathbb{N}$, and $U(q) = q \in \mathbb{Q} \cap (d, \infty)$,

$$M(i, j, r, s) = f_A(i, j, r, s).$$

Fix $x \in E$, and let $k \in \mathbb{N}$ be such that $x \in E_k^s$. Notice that by our choice of packing, for every $r \in \mathbb{N}$ there must be some $i_r \in \mathbb{N}$ such that

$$V_{i_r}^{r, s, k} \subseteq B_{2^{-r}}(x).$$

Thus, for every $r \in \mathbb{N}$, letting $i, \kappa, \rho, \sigma$ testify to $K(i_r), K(k), K(r)$, and $K(s)$, respectively,

$$M(i, \kappa, \rho, \sigma) = f_A(i_r, k, r, s) \in V_{i_r}^{r, s, k} \subseteq B_{2^{-r}}(x),$$

hence $K^A_r(x) \leq K(i_r) + K(k) + K(r) + K(s) + c$, where $c$ is a machine constant for $M$. Because $k$ and $s$ are constant in $r$, $K(r) = o(r)$, and $K(i_r) \leq \log i_r + o(r)$, we have

$$K^A_r(x) \leq \log i_r + o(r).$$

By (A.1), $\lim_{\delta \to 0^+} P_s^r(E_k^s) < 1$, so there is some $R \in \mathbb{N}$ such that, for every $r > R, P_s^r(E_k^s) < 1$. Then for every $r > R$,

$$\sum_{i \in \mathbb{N}} |V_{i_r}^{r, s, k}|^s < 1,$$

hence there are fewer than $2^{(r+2)s}$ balls of radius $2^{-r-2}$ in the packing, and $\log i_r < (r + 2)s$. We conclude that $K^A_r(x) \leq rs + o(r)$ for every $r > R$, and thus

$$\dim^A(x) = \limsup_{r \to \infty} \frac{K^A_r(x)}{r} \leq s.$$

Since this holds for every $s > d$, we have shown $\dim^A(x) \leq d$ and thus

$$\min_{A \in \mathbb{N}} \sup_{x \in E} \dim^A(x) \leq d.$$

For the other direction, assume for contradiction that there is some oracle $A$ and $d' < d$ such that

$$\sup_{x \in E} \dim^A(x) = d'.$$

Then for every $x \in E$, $\dim^A(x) \leq d'$. Let $s \in (d', d)$. For every $k \in \mathbb{N}$, define the set

$$C_k = \bigcup \{B_{2^{-k}}(q) : q \in \mathbb{Q} \text{ and } K^A(q) \leq ks\},$$

and for every $i \in \mathbb{N}$, define

$$E_i = \bigcap_{k=1}^{\infty} C_k.$$
For \( r \geq i \), consider any packing in \( V_{2-r}(E_i) \). Let \( B_\varepsilon(x) \) be an element of the packing, and let \( k = \lceil -\log \varepsilon \rceil \). Then \( k \geq r + 1 > i \), so \( B_\varepsilon(x) \subseteq E_i \subseteq C_k \).

In particular \( x \in C_k \), meaning that there is some \( q \in \mathbb{Q} \) such that \( K^A(q) \leq k \varepsilon \) and \( x \in B_{2^{-k}}(q) \). As \( 2^{-k} \leq \varepsilon \), we also have \( q \in B_{\varepsilon}(x) \). Thus, every packing element of radius at least \( 2^{-k} \) contains a (distinct) member of the set \( \{ q \in \mathbb{Q} : K^A(q) \leq k \varepsilon \} \). It follows that for every \( k \geq r + 1 \), the packing includes at most \( 2^{ks} + 1 \) elements with diameters in the range \([2^{1-k}, 2^{2-k})\).

Now let \( s' \in (s, d) \). For every \( i \in \mathbb{N} \) and \( r \geq i \), we have

\[
P^{s'}_{2-r}(E_i) = \sup \left\{ \sum_{j \in \mathbb{N}} |V_j|^{s'} : \{V_j\}_{j \in \mathbb{N}} \in V_{2-r}(E_i) \right\}
\]

\[
\leq \sum_{k=r+1}^{\infty} 2^{ks+1}(2^{2-k})^{s'}
\]

\[
= 2^{1+2s'} \cdot \sum_{k=r+1}^{\infty} 2^{(s-s')k}.
\]

This approaches 0 as \( r \to \infty \), so \( P^{s'}_0(E_i) = 0 \). Observe now that

\[
E \subseteq \bigcup_{i \in \mathbb{N}} E_i
\]

Thus,

\[
P^{s'}(E) \leq \sum_{i \in \mathbb{N}} P^{s'}_0(E_i) = 0,
\]

meaning that \( \dim \rho(E) \leq s' < d \), a contradiction. We conclude that for every oracle \( A \),

\[
\sup_{x \in E} \dim^A(x) \geq d.
\]

\[ \square \]

A.2 Chain rule for \( K_r \)

Theorem 3. For all \( x \in \mathbb{R}^m \), \( y \in \mathbb{R}^n \), and \( r \in \mathbb{N} \),

\[
K_r(x, y) = K_r(x|y) + K_r(y) + o(r).
\]

Proof. Theorem 4.10 of [4] tells us that

\[
I_r(x : y) = K_r(x) + K_r(y) - K_r(x,y) + o(r).
\]

Combining this with Lemma 8, we have

\[
K_r(x) + K_r(y) - K_r(x,y) + o(r) = K_r(x) - K_r(x|y) + o(r).
\]

The theorem follows immediately. \[ \square \]
A.3 Proof of Lemma 4

Lemma 4. For each \( m,n \in \mathbb{N} \) there is a constant \( c \in \mathbb{N} \) such that, for all \( x \in \mathbb{R}^m, y \in \mathbb{R}^n \), and \( r,s \in \mathbb{N} \),

\[
K_r^y(x) \leq K_{r,s}(x|y) + K(s) + c.
\]

In particular, \( K_r^y(x) \leq K_r(x|y) + K(r) + c \).

Proof. Let \( m,n \in \mathbb{N} \), and let \( U \) be the optimal Turing machine fixed for the definition of conditional Kolmogorov complexity. Let \( M \) be an oracle Turing machine that, on input \( \pi \in \{0,1\}^* \) with oracle \( g : \mathbb{N} \to \mathbb{Q}^n \), does the following. If \( \pi \) is of the form \( \pi = \pi_1 \pi_2 \), where \( U(\pi_1, \lambda) = t \in \mathbb{N} \), then \( M \) simulates \( U(\pi_2, g(t)) \). Let \( c \) be an optimality constant for the oracle Turing machine \( M \).

To see that \( c \) affirms the lemma, let \( x \in \mathbb{R}^m, y \in \mathbb{R}^n \), and \( r,s \in \mathbb{N} \). Let \( g_y : \mathbb{N} \to \mathbb{Q}^n \) be an oracle for \( y \), let \( \pi_s \in \{0,1\}^* \) testify to the value of \( K(s) \), and let \( \pi_x \) testify to the value of \( K_r(x|g_y(s)) \). Then

\[
g_y(s) \in \mathbb{Q}^n \cap B_{2^{-r}}(y)
\]

and

\[
M^{g_y}(\pi_s \pi_x) = U(\pi_x, g_y(s)) \in \mathbb{Q}^m \cap B_{2^{-r}}(x),
\]

so

\[
K_r^y(x) \leq K_{M,r}^y(x) + c
\]

\[
\leq |\pi_x \pi_s| + c
\]

\[
= K_r(x|g_y(s)) + K(s) + c
\]

\[
\leq K_{r,s}(x|y) + K(s) + c.
\]

\[\square\]

A.4 Claims in proof of Lemma 6

Claim 1. For every \( r \in \mathbb{N} \), \( K_r(b|m) = K_r(b|m_r) + o(r) \), where \( m_r = 2^{-r}[m \cdot 2^r] \).

Proof. \( K_r(b|m) \geq K_r(b|m_r) \) by definition, since \( m_r \in B_{2^{-r}}(m) \).

Let \( \hat{b} \in B_{2^{-r}}(b) \) be such that \( K(\hat{b}|m_r) = \hat{K}_r(b|m_r) \). Then

\[
|\hat{b}, m_r) - (b, m)| \leq \sqrt{2} \cdot 2^{-r} < 2^{1-r},
\]

so

\[
K(\hat{b}, m_r) \geq K_{r-1}(b, m) = K_r(b, m) + o(r),
\]

by Corollary 3.9 of [4].

Let \( \mu \) testify to the value of \( K_r(m) \), and let \( \hat{m} = U(\mu) \). Then \( |\hat{m} - m| < 2^{-r} \), so \( |\hat{m} - m_r| < 2^{1-r} \). Thus once \( \hat{m} \) and \( r \) have been specified, there are at most four possible values for \( m_r \). Therefore there is a self-delimiting Turing machine
that takes as input \( \mu \), an encoding of \( r \) of length \( o(r) \), and \( O(1) \) additional bits and outputs \( m_r \). We conclude that \( K(m_r) \leq K_r(m) + o(r) \). Therefore we have

\[
K_r(b|m_r) = K(b|m_r) \\
= K(b, m_r) - K(m_r) + o(r) \\
\geq K_r(b, m) + o(r) - (K_r(m) + o(r)) + o(r) \\
= K_r(b|m) + o(r),
\]

by Theorem 3.

\[\square\]

**Claim 2.** For each \( x \in [0, 1] \) and \( r \in \mathbb{N} \), there exists an \( h \in \mathbb{N} \) such that \( M \) halts on input \((\rho x, \sigma_r, \eta)\) with \( M(\rho x, \sigma_r, \eta) \in B_{2^{-r}}(m, b, x) \), where \( U(\rho) = r \) and \( U(\eta) = h \).

**Proof.** Fix \( x \in [0, 1] \) and \( r \in \mathbb{N} \). It is clear that for some \( j \in \{0, 1, \ldots, 2^r\} \), \( |u_j - m| < 2^{-r} \). By the definition of \( K_r(b|m) \), \( u_j \in \mathbb{Q} \cap B_{2^{-r}}(m) \) implies that \( U(\pi_r, u_j) \) halts and outputs \( v_j \in \mathbb{Q} \cap B_{2^{-r}}(b) \). \( U(\sigma_r) \in B_{2^{-r}}(m x + b) \) by the definition of \( \sigma_r \), so \( |p - x| < 2^{-r} \). It follows that

\[
|(u_j, v_j, p) - (m, x, b)| < \sqrt{3(2^{-r})^2} < 2^{1-r}.\]

It remains to show that \( |u_i p + v_j - q| < 2^{2-r} \). To do so, we repeatedly apply the triangle inequality and use the fact that \( x, m \in [0, 1] \):

\[
|u_i p + v_j - q| \leq |u_i p + v_j - (mx + b)| + |mx + b - q| \\
< |u_i p - mx + v_j - b| + 2^{-r} \\
\leq |u_i p - mx| + |v_j - b| + 2^{-r} \\
< |u_i p - u_j x| + |u_j x - mx| + 2^{1-r} \\
\leq |p - x| + |u_j - m| + 2^{1-r} \\
< 2^{2-r}.\]

\[\square\]

**Claim 3.** For almost every \( x \in [0, 1] \), \( \log(h(x, r)) = o(r) \).

**Proof.** By the countable additivity of Lebesgue measure, it suffices to show for every \( k \in \mathbb{N} \) that the set

\[
D_k = \{ x \in [0, 1] : \exists \text{ infinitely many } r \in \mathbb{N} \text{ such that } \log(h(x, r)) > r/k \}
\]

has Lebesgue measure 0. For each \( r \in \mathbb{N} \), let \( D_{k, r} = \{ x : h(x, r) > 2^{r/k} \} \). We now estimate \( \lambda(D_{k, r}) \), the Lebesgue measure of \( D_{k, r} \).

For fixed \( x \) and \( r \), the algorithm run by the Turing machine \( M \) entails

\[
h(x, r) \leq \left| \{ i : |u_i p + v_i - q| < 2^{2-r} \} \right| .
\]

A5
For fixed $i$,
\[
\begin{align*}
|u_ip + v_i - q| &> |u_i x - u_ip| + |u_ip + v_i - q| - 2^{-r} \\
&\geq |u_i x + v_i - q| - 2^{-r} \\
&> |u_i x + v_i - q| + |q - (mx + b)| - 2^{1-r} \\
&\geq |u_i x + v_i - (mx + b)| - 2^{1-r}.
\end{align*}
\]
That is,
\[
\{ i : |u_i p + v_i - q| < 2^{2-r} \} \subseteq \{ i : |u_i x + v_i - (mx + b)| - 2^{1-r} < 2^{2-r} \},
\]
so
\[
h(x, r) \leq \left| \left\{ i : |u_i x + v_i - (mx + b)| < 2^{3-r} \right\} \right|.
\]
For fixed $r$ and $i = 0, 1, \ldots, 2^r$, define
\[
C^r_i = \{ x \in [0, 1] : |u_i x + v_i - (mx + b)| < 2^{3-r} \},
\]
For each $i$, if $m = u_i$, then $C^r_i$ is either $[0, 1]$ or empty; otherwise, $C^r_i$ is an interval of length
\[
\lambda(C^r_i) \leq \min \left\{ \frac{2^{3-r}}{|u_i - m|}, 1 \right\}.
\]
Notice that for each $k = 0, \ldots, 2^r$, there are at most 2 values of $i$ for which $2^{-r} k \leq |u_i - m| < 2^{-r} (k + 1)$, so we have
\[
\int_0^1 h(x, r) dx \leq \sum_{i=0}^{2^r} \lambda(C^r_i) \\
\leq 2 + \sum_{k=1}^{2^r} \frac{2^{3-r}}{2^{r-k}} \\
= 2 + 2^4 \sum_{k=1}^{2^r} \frac{1}{k} \\
< r 2^6.
\]
Thus, as $h(x, r) > 2^{r/k}$ for all $x \in D_{k,r}$,
\[
\lambda(D_{k,r}) < \frac{r 2^6}{2^{r/k}} = r 2^{6-r/k}.
\]
This implies that
\[
\sum_{r=1}^{\infty} \lambda(D_{k,r}) < \infty,
\]
so the Borel-Cantelli Lemma tells us that $\lambda(D_k) = 0$. $\square$
Claim 4. For every \( x \in [0, 1] \), if \( \log(h(x,r)) = o(r) \), then

\[
\liminf_{r \to \infty} \frac{K_r(m,b,x) - K_r(b|m)}{r} \leq \dim(x, mx + b).
\]

Proof. For fixed \( r \), Claim 2 gives

\[
K_{r-1}(m,b,x) \leq K(u_i, v_i, p) \leq K_M(u_i, v_i, p) + c_M,
\]

where \( c_M \) is an optimality constant for \( M \). Let \( \rho \) and \( \eta \) testify to the values of \( K_r(b|m) \) and \( K_r(x, mx + b) \), respectively. Then

\[
|\rho \pi_r \sigma_r \eta| = K(r) + K_r(b|m) + K_r(x, mx + b) + K(h(x,r))
\]

by Claim 1. By Corollary 3.9 of [4],

\[
\liminf_{r \to \infty} \frac{K_r(m,b,x) - K_r(b|m)}{r} = \liminf_{r \to \infty} \frac{K_{r-1}(m,b,x) - K_r(b|m) + o(r)}{r} \leq \liminf_{r \to \infty} \frac{K(r) + K_r(x, mx + b) + K(h(x,r)) + o(r)}{r} \leq \liminf_{r \to \infty} \frac{K_r(x, mx + b)}{r} + \limsup_{r \to \infty} \frac{K(h(x,r)) + o(r)}{r}
\]

Applying Observation A.2, for some constant \( c \),

\[
\limsup_{r \to \infty} \frac{K(h(x,r))}{r} \leq \limsup_{r \to \infty} \frac{\log(1 + h(x,r)) + 2 \log(2 + h(x,r)) + c}{r} = \limsup_{r \to \infty} \frac{\log(h(x,r)) + 2 \log(2 + h(x,r))}{r}.
\]

If \( \log(h(x,r)) = o(r) \), then this is

\[
\limsup_{r \to \infty} \frac{o(r) + 2 \log(o(r))}{r} = 0.
\]

A.5 Observations about Kolomogorov Complexity in Euclidean Space

Observation A.1. For every open ball \( B \subseteq \mathbb{R}^m \) of radius \( 2^{-r} \),

\[
B \cap 2^{-(r + \frac{1}{2} \log m) + 1} \mathbb{Z}^m \neq \emptyset.
\]
For $a \in \mathbb{Z}^m$, let $|a|$ denote the distance from the origin to $a$.

**Observation A.2.** There is a constant $c_0 \in \mathbb{N}$ such that, for all $j \in \mathbb{N}$,
\[
K(j) \leq \log(1 + j) + 2 \log \log(2 + j) + c_0.
\]

**Observation A.3.** There is a constant $c \in \mathbb{N}$ such that, for all $a \in \mathbb{Z}^m$,
\[
K(a) \leq m \log(1 + |a|) + \varepsilon(|a|),
\]
where $\varepsilon(t) = c + 2 \log \log(2 + t)$.

Observation A.2 holds by a routine technique [19]. The proof of Observation A.3 is also routine:

**Proof.** Fix a computable, nonrepeating enumeration $a_0, a_1, a_2, \ldots$ of $\mathbb{Z}^m$ in which tuples $a_j$ appear in nondecreasing order of $|a_j|$. Let $M$ be a Turing machine such that, for all $\pi \in \{0, 1\}^*$, if $U(\pi) \in \mathbb{N}$, then $M(\pi) = a_{U(\pi)}$. Let $c = c_0 + c_M + m + [2 \log m] + 2$, where $c_0$ is as in Observation A.2 and $c_M$ is an optimality constant for $M$.

To see that $c$ affirms Observation A.3, let $a \in \mathbb{Z}^m$. Let $j \in \mathbb{N}$ be the index for which $a_j = a$, and let $\pi \in \{0, 1\}^*$ testify to the value of $K(j)$. Then $M(\pi) = a_{U(\pi)} = a_j = a$, so
\[
K(a) \leq K_M(a) + c_M \leq |\pi| + c_M = K(j) + c_M.
\]
It follows by Observation A.2 that
\[
K(a) \leq \log(1 + j) + 2 \log \log(2 + j) + c + c_M. \tag{A.2}
\]
We thus estimate $j$.

Let $B$ be the closed ball of radius $|a|$ centered at the origin in $\mathbb{Z}^m$, and let $Q$ be the solid, axis-parallel $m$-cube circumscribed about $B$. Let $B' = B \cap \mathbb{Z}^m$ and $Q' = Q \cap \mathbb{Z}^m$. Then
\[
j \leq |B'| - 1 \leq |Q'| - 1 \leq (2|a| + 1)^m - 1,
\]
so (A.2) tells us that
\[
K(a) \leq m \log(2|a| + 1) + 2 \log \log(1 + (2|a| + 1)^m) + c + c_M
\leq m \log(2|a| + 2) + 2 \log(m \log(2|a| + 4)) + c + c_M.
\]
Since
\[
m \log(2|a| + 2) = m + m \log(1 + |a|)
\]
and
\[
\log(m \log(2|a| + 4)) = \log m + \log(1 + \log(2 + |a|))
\leq \log m + 1 + \log \log(2 + |a|),
\]
it follows that $K(a) \leq m \log(1 + |a|) + \varepsilon(|a|)$.
Observation A.4. For every \( r, n \in \mathbb{N} \), \( x \in \mathbb{R}^n \), and \( q \in \mathbb{Q}^n \),

\[
K_r(x + q) = K_r(x) + O(1).
\]

Proof. Let \( M \) be a self-delimiting Turing machine such that \( M(\pi \kappa) = U(\pi) + U(\kappa) \) whenever \( U(\pi), U(\kappa) \in \mathbb{Q}^n \). If \( \pi \) is a witness to \( K_r(x) \) and \( \kappa \) is a witness to \( q \), then \( M(\pi \kappa) = p + q \) for some \( p \in B_{2^{-r}}(x) \), so \( M(\pi \kappa) \in B_{2^{-r}}(x + q) \). Thus

\[
K_r(x + q) \leq K_r(x) + K(q) + c,
\]

where \( c \) is a machine constant for \( M \). Since \( K(q) \) is constant in \( r \), we have \( K_r(x + q) \leq K_r(x) + O(1) \). Applying the same argument with \(-q\) replacing \( q \) completes the proof. \( \square \)

A.6 Linear Sensitivity of \( \hat{K}_r(x|q) \) to \( r \)

Lemma A.5. There is a constant \( c_1 \in \mathbb{N} \) such that, for all \( x \in \mathbb{R}^m \), \( q \in \mathbb{Q}^n \), and \( r, \Delta r \in \mathbb{N} \),

\[
\hat{K}_r(x|q) \leq \hat{K}_{r+\Delta r}(x|q) \leq \hat{K}_r(x|q) + m\Delta r + \varepsilon_1(r, \Delta r),
\]

where \( \varepsilon_1(r, \Delta r) = 2 \log(1 + \Delta r) + K(r, \Delta r) + c_1 \).

Proof. Let \( M \) be a Turing machine such that, for all \( \pi_1, \pi_2, \pi_3 \in \{0,1\}^* \) and \( q \in \mathbb{Q}^n \), if \( U(\pi_1, q) = p \in \mathbb{Q}^m, U(\pi_2) = (r, \Delta r) \in \mathbb{N}^2, \) and \( U(\pi_3) = a \in \mathbb{Z}^m \), then \( M(\pi_1 \pi_2 \pi_3, q) = p + 2^{-r}a \), where \( r^* = r + \Delta r + \left\lfloor \frac{1}{2} \log m \right\rfloor + 1 \). Let \( c_1 = c + c_M + 3m + m \left\lfloor \frac{1}{2} \log m \right\rfloor + \left\lceil 2 \log(3 + \left\lfloor \frac{1}{2} \log m \right\rfloor) \right\rceil \), where \( c \) is the constant from Observation A.3 and \( c_M \) is an optimality constant for \( M \).

To see that \( c_1 \) affirms the lemma, let \( x, q, r, \) and \( \Delta r \) be as given. The first inequality holds trivially. To see that the second inequality holds, let \( \pi_1, \pi_2 \in \{0,1\}^* \) testify to the values of \( \hat{K}_r(x|q) \) and \( K(r, \Delta r) \), respectively. Let \( B = B_{2^{-r}}(x), B' = B_{2^{-(r+\Delta r)}}(x) \) and \( p = U(\pi_1, q) \), noting that \( p \in \mathbb{Q}^m \cap B \). Applying Observation A.1 to the ball \( B' - p \) tells us that

\[
(B' - p) \cap 2^{-r^*} \mathbb{Z}^m \neq \emptyset,
\]

i.e., that

\[
B' \cap (p + 2^{-r^*} \mathbb{Z}^m) \neq \emptyset.
\]

So fix a point \( p' \in B' \cap (p + 2^{-r^*} \mathbb{Z}^m) \), say, \( p' = p + 2^{-r^*}a \), where \( a \in \mathbb{Z}^m \), and let \( \pi_3 \in \{0,1\}^* \) testify to the value of \( K(a) \). Then

\[
M(\pi_1 \pi_2 \pi_3, q) = p' \in \mathbb{Q} \cap B',
\]

so

\[
\hat{K}_{r+\Delta r}(x|q) \leq K(p'|q)
\]

\[
\leq \hat{K}_M(p'|q) + c_M
\]

\[
\leq |\pi_1 \pi_2 \pi_3| + c_M.
\]
By our choice of \( \pi_1, \pi_2, \) and \( \pi_3 \), this implies that
\[
\hat{K}_{r+\Delta r}(x|q) \leq \hat{K}_r(x|q) + K(r, \Delta r) + K(a) + c_M. \tag{A.3}
\]
We thus estimate \( K(a) \).

Since
\[
|a| = 2^r |p' - p| \\
\leq 2^r (|p' - x| + |p - x|) \\
< 2^r \left( 2^{-(r+\Delta r)} + 2^{-r} \right) \\
= 2^{1+\left( \frac{1}{2} \log m \right)} (1 + 2^{\Delta r}) ,
\]
Observation A.3 tells us that
\[
K(a) \leq m \log \left( 1 + 2 \left( \frac{1}{2} \log m \right) (1 + 2^{\Delta r}) \right) + \varepsilon(|a|) \\
\leq m \log \left( 2^{\Delta r+\frac{1}{2} \log m} \right) + \varepsilon(|a|) ,
\]
i.e., that
\[
K(a) \leq m \Delta r + 3m + m \left( \frac{1}{2} \log m \right) + \varepsilon(|a|) , \tag{A.4}
\]
where
\[
\varepsilon(|a|) \leq c + 2 \log \log \left( 2 + 2^{1+\left( \frac{1}{2} \log m \right)} (1 + 2^{\Delta r}) \right) \\
\leq c + 2 \log \log \left( 2^{\Delta r+\frac{1}{2} \log m} \right) \\
= c + 2 \log (\Delta r + \left( \frac{1}{2} \log m \right) + 3) \\
\leq c + 2 \log \left( (1 + \Delta r) (3 + \left( \frac{1}{2} \log m \right) \right) \\
= c + 2 \log(1 + \Delta r) + 2 \log (3 + \left( \frac{1}{2} \log m \right) .
\]

It follows by (A.3) and (A.4) that
\[
\hat{K}_{r+\Delta r}(x|q) \leq \hat{K}_r(x|q) + m \Delta r + \varepsilon_1(r, \Delta r) .
\]

\[
A.7 \quad \text{Linear Sensitivity of } K_{r,s}(x|y) \text{ to } s
\]

Lemma A.6. There is a constant \( c_2 \in \mathbb{N} \) such that, for all \( x \in \mathbb{R}^m \), \( y \in \mathbb{R}^n \), and \( r, s, \Delta s \in \mathbb{N} \),
\[
K_{r,s}(x|y) \geq K_{r,s+\Delta s}(x|y) \geq K_{r,s}(x|y) - n \Delta s - \varepsilon_2(s, \Delta s) ,
\]
where \( \varepsilon_2(s, \Delta s) = 2 \log(1 + \Delta s) + K(s + \Delta s) + c_2. \)
Proof. Let \( M \) be a Turing machine such that, for all \( \pi_1, \pi_2, \pi_3 \in \{0,1\}^* \) and \( q \in \mathbb{Q}^n \), if \( U(\pi_1) = (s, \Delta s) \in \mathbb{N}^2 \) and \( U(\pi_2) = a \in \mathbb{Z}^m \), then \( M(\pi_1 \pi_2, q) = U(\pi_3, q + 2^{-s} a) \), where \( s^{-} = s + \Delta s + \lceil \frac{1}{2} \log n \rceil \). Let \( c_2 = c + c_M + 3n + n \lfloor \frac{1}{2} \log n \rfloor + 2 \cdot 2 \log(3 + \lfloor \frac{1}{2} \log n \rfloor) \), where \( c \) is the constant from Observation A.3 and \( c_M \) is an optimality constant for \( M \).

To see that \( c_2 \) affirms the lemma, let \( x, y, r, s, \) and \( \Delta s \) be as given. The first inequality holds trivially. To see that the second inequality holds, let \( B = B_{2^{-s}}(y), B' = B_{2^{-(s+\Delta s)}}(y), \) and \( q \in \mathbb{Q}^n \cap B \). It suffices to prove that

\[
\hat{K}_r(x|q) \leq K_{r,s+\Delta s}(x|y) + n\Delta s + \varepsilon_2(s, \Delta s) .
\]  

(A.5)

Let \( \pi_3 \in \{0,1\}^* \) testify to the value of \( K(s, \Delta s) \). Applying Observation A.1 to the ball \( B' - q \) tells us that

\[
(B' - q) \cap 2^{-s} \mathbb{Z}^n \neq \emptyset ,
\]

i.e., that

\[
B' \cap (q + 2^{-s} \mathbb{Z}^n) \neq \emptyset .
\]

So fix a point \( q' \in B' \cap (q + 2^{-s} \mathbb{Z}^n) \), say, \( q' = q + 2^{-s} a \), where \( a \in \mathbb{Z}^n \). Note that

\[
\hat{K}_r(x|q') \leq K_{r,s+\Delta s}(x|y) .
\]

(A.6)

Let \( \pi_2, \pi_3 \in \{0,1\}^* \) testify to the values of \( K(a) \) and \( \hat{K}_r(x|q') \), respectively, noting that \( U(\pi_3, q') = p \) for some \( p \in \mathbb{Q}^m \cap B_{2^{-r}}(x) \). Then

\[
M(\pi_1 \pi_2 \pi_3, q) = U(\pi_3, q') = p \in \mathbb{Q}^m \cap B_{2^{-r}}(x) ,
\]

so

\[
\hat{K}_r(x|q) \leq K(p|q) \leq K_M(p|q) + c_M \leq |\pi_1 \pi_2 \pi_3| + c_M .
\]

By our choice of \( \pi_1, \pi_2, \) and \( \pi_3 \), and by (A.6), this implies that

\[
\hat{K}_r(x|q) \leq K_{r,s+\Delta s}(x|y) + K(a) + K(s, \Delta s) + c_M .
\]

(A.7)

We thus estimate \( K(a) \).

Since

\[
|a| = 2^s|q' - q| \\
\leq 2^s(|q' - y| + |q - y|) \\
< 2^s(s^{-}(s+\Delta s) + 2^{-s}) \\
= 2^{1+\lfloor \frac{1}{2} \log n \rfloor}(1 + 2^{\Delta s}) ,
\]

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Observation A.3 tells us that
\[ K(a) \leq n \log(1 + 2^{1 + \lfloor \frac{1}{2} \log n \rfloor} (1 + 2^\Delta s)) + \varepsilon(|a|) \]
\[ \leq n \log(2^{\Delta s + 3 + \lfloor \frac{1}{2} \log n \rfloor}) + \varepsilon(|a|), \]
i.e., that
\[ K(a) \leq n \Delta s + 3n + n \lfloor \frac{1}{2} \log n \rfloor + \varepsilon(|a|), \quad (A.8) \]
where
\[ \varepsilon(|a|) \leq c + 2 \log \log(2 + 2^{1 + \lfloor \frac{1}{2} \log n \rfloor} (1 + 2^\Delta s)) \]
\[ \leq c + 2 \log(\Delta s + 3 + \lfloor \frac{1}{2} \log n \rfloor) \]
\[ \leq c + 2 \log ((1 + \Delta s)(3 + \lfloor \frac{1}{2} \log n \rfloor)) \]
\[ = c + 2 \log(1 + \Delta s + 2 \log(3 + \lfloor \frac{1}{2} \log n \rfloor)). \]

It follows by (A.7) and (A.8) that (A.5) holds. \( \square \)

### A.8 Proof of Theorem 7

**Theorem 7.** Let \( s : \mathbb{N} \to \mathbb{N} \). If \( |s(r) - r| = o(r) \), then, for all \( x \in \mathbb{R}^m \) and \( y \in \mathbb{R}^n \),
\[ \dim(x|y) = \liminf_{r \to \infty} \frac{K_{r,s(r)}(x|y)}{r}, \]
and
\[ \Dim(x|y) = \limsup_{r \to \infty} \frac{K_{r,s(r)}(x|y)}{r}. \]

**Proof.** Assume the hypothesis. Define \( s^-, s^+ : \mathbb{N} \to \mathbb{N} \) by
\[ s^-(r) = \min\{r, s(r)\}, \quad s^+(r) = \max\{r, s(r)\}. \]

Lemma A.6 tells us that, for all \( x \in \mathbb{R}^m \) and \( y \in \mathbb{R}^n \),
\[ K_{r,s^-(r)}(x|y) \geq K_{r,s(r)}(x|y) \geq K_{r,s^+(r)}(x|y) \]
\[ \geq K_{r,s^-}(x|y) - O(s^+(r) - s^-(r)) - o(r) \]
\[ = K_{r,s^-}(x|y) - O(|s(r) - r|) - o(r) \]
\[ = K_{r,s^-}(x|y) - o(r). \]

Since
\[ K_{r,s^-}(x|y) \geq K_{r,s(r)}(x|y) \geq K_{r,s^+(r)}(x|y), \]
it follows that
\[ |K_{r,s(r)}(x|y) - K_{r,r}(x|y)| = o(r). \]
The theorem follows immediately. \( \square \)
A.9 Proof of Lemma 8

Lemma 8. For all $x \in \mathbb{R}^m$, $y \in \mathbb{R}^n$, and $r \in \mathbb{N}$,

$$I_r(x : y) = K_r(x) - K_r(x|y) + o(r).$$

Proof. Let $B_x = B_{2^{-r}}(x) \cap Q^m$ and $B_y = B_{2^{-r}}(y) \cap Q^n$. Let $p_0$ and $q_0$ be $K$-minimizers for $B_x$ and $B_y$, respectively, such that

$$I_r(x : y) = I(p_0 : q_0) + o(r). \quad \text{(A.9)}$$

These exist by Theorem 4.6 of [4]. Then

$$K_r(x) - K_r(x|y) = \min_{p \in B_x} K(p) - \max_{q \in B_y} \min_{p \in B_x} K(p|q)$$

$$\geq \min_{p \in B_x} K(p) - \min_{p \in B_x, q \in B_y} \max_{p \in B_x} K(p|q)$$

$$= \min_{p \in B_x} K(p) - \min_{p \in B_x} K(p|q_0) + o(r),$$

by Lemma 4.2 and Observation 3.7 of [4].

$$= K(p_0) - \min_{p \in B_x} K(p|q_0) + o(r)$$

$$\geq K(p_0) - K(p_0|q_0) + o(r)$$

$$= I(p_0 : q_0) + o(r)$$

$$= I_r(x : y) + o(r). \quad \text{(A.10)}$$

For the other direction, let $p_1 \in B_x$ be such that

$$K(p_1|q_0) = \min_{p \in B_x} K(p|q_0).$$

By Lemma 4.5 of [4],

$$I(p_0 : q_0) \geq K(p_1) - K(p_1|p_0, K(p_0)) - K(p_1|q_0, K(q_0)) + o(r)$$

$$\geq K(p_1) - K(p_1|p_0, K(p_0)) - K(p_1|q_0) + o(r). \quad \text{(A.10)}$$

Now

$$K(p_0) + K(p_1|p_0, K(p_0)) + o(r) = K(p_0, p_1)$$

$$= K(p_1) + K(p_0|p_1, K(p_1)) + o(r)$$

$$\leq K(p_1) + K(p_0|p_1) + o(r)$$

$$= K(p_1) + o(r),$$

by Corollary 4.4 of [4]. So

$$K(p_1) - K(p_1|p_0, K(p_0)) \geq K(p_0) + o(r),$$

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thus by (A.10),

\[ I(p_0 : q_0) \geq K(p_0) - K(p_1|q_0) + o(r) \]
\[ = K(p_0) - \min_{p \in B_x} K(p|q_0) + o(r) \]
\[ = K_r(x) - \min_{p \in B_x} K(p|q_0) + o(r) \]
\[ \geq K_r(x) - \max_{q \in B_y} \min_{p \in B_x} K(p|q) + o(r) \]
\[ = K_r(x) - K_r(x|y) + o(r). \]

Then by (A.9), \( I_r(x : y) \geq K_r(x) - K_r(x|y) + o(r) \), so equality holds. \( \square \)