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ON SOME BASIC PROPERTIES OF THE KOLMOGOROV COMPLEXITY

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Abstract. A. N. Kolmogorov in 1964 defined the notion of complexity of a finite word (see [**1,2**]). Some authors defined later some other kinds of complexity (see [**2, 5–13**]). Some basic properties of the Kolmogorov complexity are considered in this paper. Notations, definitions and statements used in this paper are mostly from [**2**].

0. Let us consider the set S of all finite words over $\{0,1\}$. By definition $\Lambda \in S$, Λ-empty word. The lenght of word $x = a_1a_2\dots a_n$, $a_i \in \{0,1\}$ will be denoted by $l(x) = n$, $l(\Lambda) = 0$. In the sequel the following one-to-one correspondence of the set S onto the set $\{0,1,2,\dots\}$ will be made use of:

word	Λ	0	1	00	01	10	11	000	001	010	011 ...
number	0	1	2	3	4	5	6	7	8	9	10 ...

or $x = a_1a_2\dots a_n \leftrightarrow 2^n - 1 + \sum_{i=1}^{n} a_i 2^{n-i}$. For example $x = 00\cdots 0 \leftrightarrow 2^n - 1$, $y = 11\cdots 1 \leftrightarrow 2(2^n - 1)$, $l(x) = l(y) = n$. The symbol x will denote both the word and its corresponding number. For two functions F, G on S we write $F \preceq G$ when $(\exists c)(\forall x \in S)(F(x) \le G(x) + c)$ and $F \asymp G$ when $F \preceq G$ and $G \preceq F$. The concatenation of words x and y we denote by xy. One-to-one function $\Phi : S^2 \to S$ is called the numeration of S^2. Denote by $x \circ y = \Phi(x,y)$. For $x = a_1a_2\dots a_n$ let $\bar{x} = a_1a_1a_2a_2\dots a_na_n01$ and $\overline{\Lambda} = 01$. Then $x \circ y = \bar{x}y$ is one numeration of S^2. We have

$$l(\bar{x}y) = 2l(x) + 2 + l(y) \asymp 2l(x) + l(y),$$
$$l(x) \asymp \log_2 x.$$

LEMMA: *There is no numeration such that $l(x \circ y) \preceq l(x) + l(y)$.*

Proof: Let the function Φ be a numeration and $(\exists)(\forall(x,y))(l(x \circ y) \le l(x) + l(y) + c)$. Let

$$S_k = \{(x,y) : l(x) + l(y) + c = k\},\ S'_k = \{x \circ y : l(x \circ y) \le k\}$$

Denote by $|A|$ the number of elements in A. Then

$$|S_k| = 2^{k-c}(k-c+1),\ |S'_k| \leq 2^{k+1}-1.$$

For k sufficiently large $|S_k| > |S'_k|$. On the other hand $((x,y) \in S_k) \Rightarrow (x \circ y \in S'_k)$ implying $|S_k| \leq |S'_k|$, which is contradiction. ▲

Notice that if $x \circ y = \overline{l(x)}xy$ and $\varepsilon > 0$, then

$$l(x \circ y) \preceq l(x) + l(y) + 2\log l(x) \preceq (1+\varepsilon)l(x) + l(y).$$

1. In what follows all considered functions F, G, H, Φ, ... are partial recursive functions. Following Kolmogorov, we define the complexity of word x with respect to $F^1, F^1 : S \to S$ by

$$K_{F^1}(x) = \min\{l(p) : F^1(p) = x\},$$

where by definition $\min \varnothing = \infty$.

The conditional complexity of x, given y, with respect to F^2, $F^2 : S^2 \to S$ is

$$K_{F^2}(x/y) = \min\{l(p) : F^2(p,y) = x\}.$$

Kolmogorov and Solomonoff proved (see [**2**]) that there exist optimal functions F_0^1, F_0^2 (but not unique) such that for any functions F^1, F^2

$$K_{F_0^1}(x) \preceq K_{F^1}(x),\ K_{F_0^2}(x/y) \preceq K_{F^2}(x/y).$$

The complexity of x with respect to a fixed optimal function $F_0^1(F_0^2)$ we shall call simply the complexity of x and denote by $K(x)(K(x.y))$. We denote by $p_x(p_x^y)$ any program for which $F_0^1(p_x) = x,\ l(p_x) = K(x)(F_0^2(p_x^y, y) = x,\ l(p_x^y) = K(x/y))$. We can define programs p_x and p_x^y uniquele, but those functions of x and y are not recursive in general. On the other hand there is an effective procedure for computing p_x given x, $K(x)$: Use the algorithm for computing F_0^1 and let it to t operations on words p, $l(p) = b$, $t = 1, 2, \ldots$ (for details see Remark 0.1. [**2**]). Then we define the recursive function $J(a,b)$ which equals to the first p for which $F_0^1(p) = a$, and then $p_x = J(x, K(x))$. In the same manner we can define p_x^y. In the following we assume $p_x = J(x, K(x))$.

The complexity satisfies some basic properties [**2**]):

(1) $\quad K(x/\Lambda) \asymp K(x),\ K(x/y) \preceq K(x) \preceq l(x),$

(2) $\quad K(F(x)) \preceq K(x),$

(3) $\quad \lim\limits_{x\to\infty} K(x) = \infty,$

(4) $\quad |K(x+h/y) - K(x/y)| \preceq 2K(h) \preceq 2l(h),$

(5) $\quad n \leq \max\{K(x) : l(x) = n\} \preceq n,$

$\quad \max\{K(x/l(x)) : l(x) = n \asymp n\},$

and in general, for arbitrary set N, and arbitrary y

$\max\{K(x/y) : x \in N\} \geq l(|N|) - 1 \asymp \log|N|$.

We give some other properties of the complexity in the following.

(*a*) $K(p_x^y) \asymp l(p_x^y) = K(x/y)$,

$K(p_x^y) \preceq K(p)$, p such that $F_0^2(p,y) = x$. ▲

(b) If $F(x) \asymp G(x)$, then $K(F(x)/y) \asymp K(G(x)/y)$, $K(y/F(x)) \asymp K(y/G(x))$.

Proof: We can prove (b) using (e) in the following. F and G are not necessarily recursive. ▲

(*c*) $K(F(x)/y) \preceq K(x/G(y))$,

$K(F(x,y)/y) \preceq K(x/y)$. ▲

If, for fixed y, F is one-to-one function of x, then $K(F(x,y)/y) \preceq K(x/y)$. For example $K(xy/y) \asymp K(x/y)$.

(*d*) $K(x/y) \asymp K(|x-y|/y) \preceq K(|x-y|)$,

$K(x/p_x^y) \preceq K(y)$. ▲

(*e*) $|K(x+h/y+l) - K(x/y) \preceq 2K(\bar{h}l)$,

$I(y:x) = K(x) - K(x/y) \preceq 2K(y)$. ▲

(f) For any numeration and any F

$K(F(x,y) \preceq K(x \circ y)$. ▲

For example $K(x \circ y) \asymp K(\bar{x}y)$, and $\max\{K(x), K(y)\} \asymp K(x \circ y)$.

Remark 1.1. $K(\bar{x}y \preceq K(x) + K(y)$ is not valid but $K(\bar{x}y) \preceq K(x) + K(y) + 2\log\min\{K(x), K(y)\}$. We see that the function $x \circ y = P\bar{x}y$ is a numeration of S^2 and $l(x \circ y) = K(\bar{x}y)$, which implies (in view of Lemma in 0.) that $K(\bar{x}y) \preceq l(x) + l(y)$ is not true, and then $K(\bar{x}y) \preceq K(x) + K(y)$ does not hold neather. On the other hand $K(x) + K(y) \preceq K(\bar{x}y)$ is not valid because in the opposite case for $x = y$ we have $2K(x) \preceq K(\bar{x}x) \preceq K(x)$, or $K(x) \preceq 0$. For the proof of the second inequality it is sufficient to consider programs $\overline{l(p_x)}p_xp_y$ and $\overline{l(p_y)}p_yp_x$ with respect to specified function G. It is interesting that $K(xy) \preceq l(x) + l(y)$ but $K(xy) \preceq K(x) + K(y)$ does not hold(consider previous remark and $K(\bar{x}) \asymp K(x)$). ▲

(*g*) $\Pi(n) = \min\{K(x) : l(x) = n\} \asymp K(n) \preceq \log n$.

Proof: Let $K(l(x)) \leq K(x) + c_1$, $K(2^x - 1) \leq K(x) + c_2$, folowing (2). Then $K(n) \leq \Pi(n) + c_1 \leq K(2^n - 1) + c_1 \leq K(n) + c_1 + c_2$. ▲

(h) Let $A_m = \{x : K(x) \leq m\}$, $B_m = \{x : K(x/m) \leq m\}$. Then: (i) $m - 2\log m \preceq \log|A_m| \preceq m$, (ii) $\log|B_m| \asymp m$.

Proof: (i) We have immediately $|A_m| \leq 2^{m+1} - 1$. Let for given $p = \bar{a}b$, $x = G(p)$ be such that: We choose the set A of exactly b words y such that $K(y) \leq a$ (see Theorem 1.6) in [**2**]), and $x = G(p)$ is the first y such that $y \notin A$. Then, if $a = m$. $b = |A_m|$, we have $x = G(p) \notin A_m$, and

$m < K(x) \preceq K_G(x) \leq l(p) \preceq \log |A_m| + 2 \log m.$ ▲

(j) $\lim_{y\to\infty} K(x/y) \preceq 0$ is not true (compare (3)), but

$\lim_{y\to\infty} \inf K(x/y) \preceq 0.$

Proof: Let $(\exists c)(\forall x)(\exists y_0)(\forall y \geq y_o)(K(x/y) \leq c)$. Then $l(p_x^y) \leq c$ and the number of such programs is at most $N = 2^{c+1} - 1$. Let $M > N$ and consider $0 < x_1 < x_2 < \cdots < x_M$. Let y_i is chosen such that for $y \geq y_i$, $K(x/y) \leq c$. Let $y_0 = \max\{y_1, y_2, \cdots, y_M\}$, then for arbitrary $y \geq y_0$, $F_0^2(p_{x_i}^y, y) = x_i$, $i = 1, 2, \cdots, M$. and programs $p_{x_i}^y$ are all different, which is a contradiction. It means that $(\forall c)(\exists x)(\forall y_0)(\exists y \geq y_0)(K(x/y) \geq c)$. It is easy to see that $K(x/\bar{x}i) \preceq 0$ for all i, or $\lim_{y\to\infty} \inf K(x/y) \preceq 0$. ▲

2. The complexity of a sequence of words $x_1, x_2, \ldots, x_m$, given a sequence $y_1, y_2, \ldots, y_k$, with respect to a sequence of functions $F = (F_1, F_2, \ldots, F_m)$, $F_i : S^{k+1} \to S$, can be defined as

$$K_F(x_1, \ldots, x_m/y_1, \ldots, y_k) = \min\{l(p) : F_i(p, y_1, \ldots, y_k) = x_i,\ i = 1, 2, \ldots, m\}.$$

It can be shown that there exists an optimal sequence $F_0 = (F_{01}, \ldots, F_{0m})$ such that $K_{F_0} \preceq K_F$, and we define $K(x_1, \ldots, x_m/y_1, \ldots, y_k)$ as the complexity with respect to F_0. In the similar way we can define $K(x_1, \ldots, x_m)$. It can be proved that

$$(*) \qquad K(x_1, \ldots, x_m/y_1, \ldots, y_k) \asymp K(x_1 \circ \cdots \circ x_m/y_1, \ldots, y_k),$$

$$(**) \qquad K(x/y_1, \ldots, y_k) \asymp K(x/y_1 \circ \cdots \circ y_k),$$

where $z_1 \circ \cdots \circ z_j$ is notation for a numeration of S^j. Considering $(*)$ and $(**)$ we have $K(x, y) \asymp K(\bar{x}y)$, $K(x/y, z) \asymp K(x/\bar{y}z)$. Some authors define directly $K(x, y) = K(\bar{x}y)$ (see [**5**] p. 332, for example). It is easy to show some properties of the complexity, for example

$$\begin{aligned}
&K(x, F(x)) \asymp K(x),\ K(x/y, x) \preceq K(x/F(y, z)),\\
&K(F(x, y)) \preceq K(x, y),\ K(F(x), G(y)) \preceq K(x, y),\\
&K(x/y), z) \preceq K(x/F(y),\ G(z)),\\
&|K(x + h,\ y + l) - K(x, y)| \preceq 2K(h, l),\\
&K(x, y/l(x),\ l(y)) \preceq K(x, y/l(x)) \preceq l(x) + K(y/x) \preceq l(x) + l(y),\\
&\max\{K(x, y/l(x),\ l(y)) : l(x) = n,\ l(y) = m\} \asymp n + m,\\
&\max\{K(x/l(x),\ s(x)) : l(x) = n,\ s(x) = s\} \asymp \log \binom{n}{s},
\end{aligned}$$

where for $x = a_1 a_2 \ldots a_n$, $s(x) = \sum_{i=1}^{n} a_i$ (it is an immediate consequence of 1.(5), but see [**1, 3, 4**]).

We give some other properties.

(a) $K(x,y) \preceq K(p_x,y) \asymp K(x,y,K(x)) \preceq$
$\preceq K(p_x,p_y) \asymp K(x,y,K(x),\ K(y))$. ▲

(b) $K(y/x,\ K(x)) \asymp K(y/p_x) \preceq K(y/x)$. ▲

(c) $K(x/z) \preceq K(x/y,\ K(y/z)) + 2K(y/z)$,
$(K(x/z) \preceq 2K(x/y,\ K(y/z)) + K(y/z)$, ▲

(d) $K(x,y) \preceq K(x) + 2K(y/x),\ K(x))$,
$K(x,y/K(x)) \preceq K(x) + K(y/x,\ K(x))$. ▲

If we put $z = \Lambda$ in (c) we have

$$-2K(y/x) \preceq -2K(y/p_x) \preceq K(x) - K(y) \preceq 2K(x/py) \preceq 2K(x/y).$$

Remark 2.1. Theorem 1. (Levin) in [**12**] states that $KP(x,y) \asymp KP(x) + KP(y/x, KP(x))$ (also see Th. 5.1. (b) in [**5**]), where $KP(x)$ is some variant of complexity (see [**5, 10-13**]). But for the Kolmogorov complexity $K(x,y) \preceq K(x) + K(y/x,\ K(x))$ is not valid. We shall prove $(\forall c)(\exists (x,y))(K(x)+K(y/p_x) \geq K(\bar{x}y) + c)$. Following 1. (5) $(\forall l_0)(\exists x)(l(x) = l_0,\ \ K(x/l_0) \geq l_0 - 1)$. In view of 1. (1) and 1. (2), $(\exists c_1)(\forall x)(l(x) \geq K(x) - c_1)$, $(\exists c_2)(\forall x)$ $(K(x) \geq K\overline{l(x)}x) - c_2)$ and following 2. (a) $(\exists c_3)(\forall (x,y))(K(\bar{p}_x y) \geq K(\bar{x}y) - c_3)$.

Let x be chosen such that for fixed $c, l(p_x) = K(x) \geq c + c_1 + c_2 + c_3 + 1$. Let y be chosen such that $l(y) = l_0 = p_x$, and $K(y/l_0) \geq l_0 - 1 = l(y) - 1$. Then $K(y/p_x) \geq l(y) - 1 \geq K(y) - c_1 - 1 \geq K(\overline{l(y)}y) - c_2 - c_1 - 1 = K(\bar{p}_x y) - c_2 - c_1 - 1 \geq K(\bar{x}y) - c_3 - c_2 - c_1 - 1$ and $K(x) + K(y/p_x) \geq K(\bar{x}y) + c$. ▲

(e)

(i) $\min\{K(p_x/x) : l(x) = n\} \preceq 0$,

(ii) $\log n - \log\log n \preceq \max\{K(p_x/x) : l(x) = n\} \preceq \log n$,

(see Theorem 2. in [**12**] and Theorem 5.1. (f) in [**5**].)

Proof: Basic ideas for proving follow the proof of Theorem 2. in [**12**]. We have

$$K(p_x/x) \asymp K(K(x)/x) \preceq l(K(x)) \preceq l[l(x)].$$

(i) Let $K(x) \leq l(x) + c$, and $A = \{x : |K(x) - l(x)| \leq c\}$.

Following 1.(5), we have $(\forall n)(\exists x)(l(x) = n,\ x = A)$. Then by 1. (c) and 1. (d), for $x \in A$, $K(K(x)/x) \preceq K(K(x)/l(x)) \preceq l(|K(x) - l(x)|) \preceq l(c)$, or $\min\{K(p_x/x) : l(x) = n\} \preceq 0$.

(ii) Let $r = r(n) = \max\{K(p_x/x) : l(x) = n\}$. Then $r \preceq \log n$, and $(\forall x, l(x) = n)(\exists p)(l(p) \leq r,\ F_0^2(p,x) = p_x)$. Let $M_i = \{x : l(x) = n$ and for at least i programs $p, l(p) \leq r,\ F_0^1(F_0^2(p,x)) = x\}$, $i = 1, 2, \ldots$. Then $|M_1| = 2^n$, $M_1 \supset M_2 \supset \cdots \supset M_j \supset M_{j+1}$, $M_j \neq \varnothing$, $M_{j+1} = \varnothing$, and $2^{r+1} - 1 \geq j$ or $r \preceq \log j$.

We shall prove by induction that $\log|M_i| \geq n - (i-1)(3\log n + k)$, $i = 1.2, \ldots, j$, where k—constant. For $i = 1$, the proposition is valid.

Let the function G be defined for programs p of the form $p = \overline{l(a)l(b)l(c)l(d)}$ $abcde$, in the following way:

I Let the algorithm for computing $F_0^1(F_0^2(p,x))$ do t operations on words $x, l(x) = a$, and programs $p, l(p) \leq b$ (see Remark 0.1. in [**2**]), $t = 1, 2, \ldots$. We stop the computation when we get exactly e words x such that for at least $c+1$ programs p $F_0^1(F_0^2(p,x)) = x$.

II From the set of the remaing $2^a - e$ words x, we take the first word x such that for exactly c programs $p\,F_0^1(F_0^2(p,x)) = x$, and $\min\{l[F_0^2(p,x)]\} \geq \log[2^{a-(c-1)(3\log a+\varphi(d))} - e] - 2$, where $\varphi(d)d = d + \log d + 2\log\log d + B$, B an absolute constant.

Now, let $K(x) \leq K_G(x) + A$. Suppose that $\log|M_i| \geq n - (i-1)(3\log n + \varphi(A)) = m_i$. Then $|M_i - M_{i+1}| = |M_i| - |M_{i+1}| \geq 2^{m_i} - |M_{i+1}|$. If $2^{m_i} - |M_{i+1}| \leq 0$ is true, then $|M_{i+1}| \geq 2^{m_i+1}$. Supose that $2^{m_i} - |M_{i+1}| > 0$. Then in $M_i - M_{i+1}$ there exists x such that $K(x) \geq \log[2^{m_i} - |M_{i+1}|] - 2$, and we can get such x if we compute $G(p)$ for $a = n,\ b = r,\ c = i,\ d = A,\ e = |M_{i+1}|$. Then $\log[2^{m_i} - |M_{i+1}|] - 2 \leq K(x) \leq K_G(x) + A \leq l(p) + A \leq \log|M_{i+1}| + 3\log n + A + \log A + 2\log\log A + D$, and $\log|M_{i+1}| \geq n - i(3\log n + \varphi(A))$, $B = D + 3$.

In the same manner we have $2^{m_{j+1}} \preceq 0$ or $j \succeq \frac{n}{3\log n + \varphi A}$ and $r \succeq \log j \succeq \log n - \log\log n$. ▲

For example, using (e), we have $(\forall c)(\exists(x,y))(K(y/x) \geq (K(y/p_x) + c)$ (put $y = p_x$).

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Corrections of some relevant printing errors in paper "Algorithmical definition of finite Markov sequence", D. Banjević and Z. Ivković, Publ. l'Inst. Math. **28(42)**, 1980. pp. 13–17.

Page	Printed:	Correction:
13^{11}	$H_i(x_0, t_{x1}; \dots ; x_1, t_{xi})$	$H_i(x_1, t_{x_1}; \dots ; x_i, t_{xi})$
14^{7}	t_{i_j-1}	t_{i_j-1}
14^{8}	$\frac{1}{v_i}\sum_{j-u}^{k}(1-t_{i_j-1})1-t_{i_j})$	$\frac{1}{v_i}\sum_{j-u}^{k}(1-t_{i_j-1})(1-t_{i_j})$
14_{6}	$R_3, \dots\}$	$R_2, \dots\}$
15^{10}	$V = V_0$	$v = v_0$
15^{16}	(n, δ, p)	(m, δ, p)
15_{2}	$\geq P(v_0 \geq n_0, \Delta_0 \geq \varepsilon_0)+$	$\leq P(v_0 \geq n_0, \Delta_0 \geq \varepsilon_0)+$
16^{2}	$i_1, i_3 \dots ,$	$i_1, i_2, \dots ,$
16^{12}	$v_+^0 = n_0$	$v_0^* = n_0$
16^{13}	$\sum_{i=0}^{j}$	$\sum_{i=1}^{j}$
16_{12}	$\frac{1}{V_0^*}$	$\frac{1}{v_0^*}$
16_{8}	$\leq P[$	$\leq \varrho[$
16_{6}	sequence is $1 - P(\mathcal{R}) < 0$	sequence is $1 - P(\mathcal{R}) > 0$
17^{1}	REFRENCEES	REFERENCES
17_{3}	$538 - 550$	$548 - 550$