Journal of Universal Computer Science, vol. 3, no. 11 (1997), 1162-1166
submitted: 8/8/97, accepted: 21/10/97, appeared: 28/11/97 © Springer Pub. Co.

Chaitin Ω Numbers and Strong Reducibilities[1]

Cristian S. Calude[2]
(Department of Computer Science, University of Auckland,
Private Bag 92019, Auckland, New Zealand
Email: cristian@cs.auckland.ac.nz)

André Nies[3]
(Department of Mathematics, University of Chicago, Chicago IL., USA
Email: nies@math.uchicago.edu)

Abstract: We prove that any Chaitin Ω number (i.e., the halting probability of a universal self-delimiting Turing machine) is wtt-complete, but not tt-complete. In this way *we obtain a whole class of natural examples of wtt-complete but not tt-complete r.e. sets.* The proof is direct and elementary.

Key Words: Chaitin Ω number, wtt-complete r.e. set, tt-complete r.e. set
Category: F.1

1 Introduction

Kučera [8] has used Arslanov's completeness criterion[4] to show that all random sets of r.e. T-degree are in fact T-complete. Hence, *every Chaitin Ω number is T-complete.* In this paper we will strengthen this result by proving that *every Chaitin Ω number is weak truth-table complete.* However, no Chaitin Ω number can be tt-complete as, because of a result stated by Bennett [1] (see Juedes, Lathrop, and Lutz [9] for a proof), there is no random sequence $\mathbf{x}$ such that $K \leq_{tt} \mathbf{x}$.[5] Notice that in this way *we obtain a whole class of natural examples of wtt-complete but not tt-complete r.e. sets* (a fairly complicated construction of such a set was given by Lachlan [10]).

We continue with a piece of notation. Let $\mathbf{N}, \mathbf{Q}$ be the sets of non-negative integers and rationals. Let $\Sigma = \{0, 1\}$ denote the binary alphabet, Σ^* is the set of (finite) binary strings, Σ^n is the set of binary strings of length n; the length of a string x is denoted by $|x|$. By $x|r$ we denote the prefix of length r of the string x. Let $p(x)$ be the place of x in Σ^* ordered quasi-lexicographically. Let Σ^ω the set of infinite binary sequences. The prefix of length n of the sequence $\mathbf{x} \in \Sigma^\omega$ is denoted by $\mathbf{x}|n$. For every $X \subset \Sigma^*$, $X\Sigma^\omega$ stands for the cylinder generated by X, i.e., set of all sequences having a prefix in X.

---

1 Proceedings of the *First Japan-New Zealand Workshop on Logic in Computer Science*, special issue editors D.S. Bridges, C.S. Calude, M.J. Dinneen and B. Khoussainov.
2 Partially supported by AURC A18/XXXXX/62090/F3414056, 1997.
3 Partially supported by NSF Grant DMS-9500983.
4 *An r.e. X is Turing equivalent to the halting problem iff there is a Turing computable in X function f without fixed-points, i.e. $W_x \neq W_{f(x)}$, for all x*; see Soare [12], p. 88.
5 To keep the paper self-contained, a direct simple proof for Bennett result will be included.

Fix an acceptable gödelization $(\varphi_x)_{x\in\Sigma^*}$ of all partial recursive (p.r.) functions from Σ^* to Σ^*, and let $W_x = \mathrm{dom}(\varphi_x)$ be the domain of (φ_x). Denote by K the set $\{x \in \Sigma^* \mid x \in W_x\}$. A Chaitin computer (self-delimiting Turing machine) is a p.r. function $C : \Sigma^* \xrightarrow{o} \Sigma^*$ with a prefix-free domain dom(C). The program-size (Chaitin) complexity induced by Chaitin's computer C is defined by $H_C(x) = \min\{|y| \mid y \in \Sigma^*, C(y) = x\}$ (with the convention $\min\emptyset = \infty$).

A Chaitin computer U is *universal* if for every Chaitin computer C, there is a constant $c > 0$ (depending upon U and C) such that for every x there is x' such that $U(x') = C(x)$ and $|x'| \leq |x| + c$;[6] c is the "simulation" constant of C on U.

A Martin-Löf test is an r.e. sequence $(V_i)_{i\geq 0}$ of subsets of Σ^* satisfying the following measure-theoretical condition:

$$\mu(V_i\Sigma^\omega) \leq 2^{-i},$$

for all $i \in \mathbf{N}$. Here μ denotes the usual product measure on Σ^ω, given by $\mu(\{w\}\Sigma^\omega) = 2^{-|w|}$, for $w \in \Sigma^*$.

An infinite sequence $\mathbf{x}$ is *random* if for every Martin-Löf test $(V_i)_{i\geq 0}$, $\mathbf{x} \notin \bigcap_{i\geq 0} A_i\Sigma^\omega$. A real $\alpha \in (0,1)$ is *random* in case its binary expansion is a random sequence.[7]

The halting probability of Chaitin's computer C is

$$\Omega_C = \mu(\mathrm{dom}(U)\Sigma^\omega) = \sum_{x\in\mathrm{dom}(C)} 2^{-|x|}.$$

Any real Ω_C is recursively enumerable (r.e.) in the sense that the set $\{q \in (0,1) \cap \mathbf{Q} \mid q < \Omega_C\}$ is r.e. (see more about r.e. reals in [3]). Reals of the form Ω_U, for some universal Chaitin computer U, are called *Chaitin* (Ω) *numbers* (see [4, 6, 2]). Chaitin [4] has proved that *every Chaitin number is random.* See Calude [2] for more details.

For a set $A \subset \Sigma^*$ we denote by χ_A the characteristic function of A. We say that A is Turing reducible to B, and we write $A \leq_T B$, if there is an oracle Turing machine φ_w^B such that $\varphi_w^B(x) = \chi_A(x)$. We say that A is weak truth-table reducible to B, and we write $A \leq_{wtt} B$, if $A \leq_T B$ via a Turing reduction which on input x only queries strings of length less than $g(x)$, where $g : \Sigma^* \to \mathbf{N}$ is a fixed recursive function. We say that A is truth-table reducible to B, and we write $A \leq_{tt} B$, if there is a recursive sequence of Boolean functions $\{F_x\}_{x\in\Sigma^*}$, $F_x : \Sigma^{r_x+1} \to \Sigma$, such that for all x, we have $\chi_A(x) = F_x(\chi_B(0)\chi_B(1)\cdots\chi_B(r_x))$.[8] An r.e. set A is tt(wtt)-complete if $K \leq_{tt} A$ ($K \leq_{wtt} A$). See Odifreddi [11] for more details.

2 Main Results

In what follows we will fix a universal Chaitin computer U and write $H = H_U$, $\Omega = \Omega_U$.

[6] In fact, c can be effectively obtained from U and C.

[7] Actually, the choice of base is irrelevant, cf. Theorem 6.111 in Calude [2].

[8] Note that in contrast with tt-reductions, a wtt-reduction may diverge.

Theorem 2.1 *The set* $\mathcal{H} = \{(x,n) \mid x \in \Sigma^*, n \in \mathbf{N},\ H(x) \leq n\}$[9] *is wtt-complete.*

Proof. We will refine the proof by Arslanov and Calude in [7]. To this aim we will use Arslanov's Completeness Criterion (see Theorem III.8.17 in Odifreddi [11], p. 338) for wtt-reducibility

> *an r.e. set A is wtt-complete iff there is a function $f \leq_{wtt} A$ without fixed-points*

and the estimation due to Chaitin [4, 5] (see Theorem 5.4 in Calude [2], pp. 77):

$$\max_{x \in \Sigma^n} H(x) = n + \mathrm{O}(\log n). \tag{1}$$

First we construct a positive integer $c > 0$ and a p.r. function $\psi : \Sigma^* \stackrel{o}{\to} \Sigma^*$ such that for every $x \in \Sigma^*$ with $W_x \neq \emptyset$,

$$U(\psi(x)) \in W_x, \tag{2}$$

and

$$|\psi(x)| \leq p(x) + c. \tag{3}$$

Consider now a Chaitin computer C such that $C(0^{p(x)}1) \in W_x$ whenever $W_x \neq \emptyset$. Let c' be the simulation constant of C on U, and let θ be a p.r. function satisfying the following condition: if $C(u)$ is defined, then $U(\theta)(u) = C(u)$ and $|\theta(u)| \leq |u| + c'$. Put $c = c' + 1$ and notice that in case $W_x \neq \emptyset$, $C(0^{p(x)}1) \in W_x$, so $\theta(0^{p(x)}1)$ is defined and and belongs to W_x. Finally, put $\psi(x) = \theta(0^{p(x)}1)$ and notice that

$$|\psi(x)| = |\theta(0^{p(x)}1)| \leq |0^{p(x)}1| + c' = p(x) + c.$$

Next define the function

$$F(y) = \min\{x \in \Sigma^* \mid H(x) > p(y) + c\},$$

where the minimum is taken according to the quasi-lexicographical order and c comes from (3). In view of (1) it follows that

$$F(y) = \min\{x \in \Sigma^* \mid H(x) > p(y) + c, |x| \leq p(y) + c\}.$$

The function F is total, H-recursive and $U(\psi(y)) \neq F(y)$ whenever $W_y \neq \emptyset$. Indeed, if $W_y \neq \emptyset$ and $U(\psi(y)) = F(y)$, then $\psi(y)$ is defined, so $U(\psi(y)) \in W_y$ and $|\psi(y)| \leq p(y) + c$. But, in view of the construction of F, $H(F(y)) > p(y) + c$, an inequality which contradicts (3): $H(F(y)) \leq |\psi(y)| \leq p(y) + c$.

Let f be an H-recursive function satisfying $W_{f(y)} = \{F(y)\}$. To compute $f(y)$ in terms of $F(y)$ we need to perform the test $H(x) > p(y) + c$ only for those

[9] This set is essential in deriving Chaitin's information-theoretical version of incompleteness, Chaitin [4].

strings x satisfying the inequality $|x| \leq p(y)+c$, so the function f is wtt-reducible to $\mathcal{H}$.

We conclude by proving that for every $y \in \Sigma^*$, $W_{f(y)} \neq W_y$. If $W_{f(y)} = W_y$, then $W_y = \{F(y)\}$, so by (3), $U(\psi(y)) \in W_y$, that is $U(\psi(y)) = F(y)$. Consequently, by (2) $H(F(y)) \leq |\psi(y)| \leq p(y) + c$, which contradicts the construction of F. □

Theorem 2.2 *The set $\mathcal{H}$ is wtt-reducible to Ω.*

Proof. Let $g : \mathbf{N} \to \Sigma^*$ be a recursive, one-to-one function which enumerates the domain of U and put $\omega_m = \sum_{i=0}^{m} 2^{-|g(i)|}$. Given x and $n > 0$ we compute the smallest $t \geq 0$ such that

$$\omega_t \geq 0.\Omega_0\Omega_1 \cdots \Omega_n.$$

¿From the relations

$$0.\Omega_0\Omega_1 \cdots \Omega_n \leq \omega_t < \omega_t + \sum_{s=t+1}^{\infty} 2^{-|g(s)|} = \Omega < 0.\Omega_0\Omega_1 \cdots \Omega_n + 2^{-n}$$

we deduce that $|g(s)| > n$, for every $s \geq t+1$. Consequently, if x is not produced by an element in the set $\{g(0), g(1), \ldots, g(t)\}$, then $H(x) > n$ as $H(x) = |g(s)|$, for some $s \geq t+1$; conversely, if $H(x) \leq n$, then x must be produced via U by one of the elements of the set $\{g(0), g(1), \ldots, g(t)\}$. □

Since the result in Juedes, Lathrop, and Lutz [9] is obtained in a rather indirect way, we conclude the paper by proving directly that $K \not\leq_{tt} \mathbf{x}$, for every random sequence $\mathbf{x}$.

Theorem 2.3 *If $K \leq_{tt} \mathbf{x}$, then $\mathbf{x}$ is not random.*

Proof. Assume $\mathbf{x}$ is random and $K \leq_{tt} \mathbf{x}$, that is there exists a recursive sequence of Boolean functions $\{F_u\}_{u\in\Sigma^*}$, $F_u : \Sigma^{r_u+1} \to \Sigma$, such that for all $w \in \Sigma^*$, we have $\chi_A(w) = F_w(x_0x_1 \cdots x_{r_w})$. We will construct a Martin-Löf test V such that $\mathbf{x} \in \bigcap_{n\geq 0} V_n\Sigma^\omega$, which will contradict the randomness of $\mathbf{x}$.

For every string z let

$$M(z) = \{u \in \Sigma^{r_z+1} \mid F_z(u) = 0\}.$$

Consider the set

$$\{z \in \Sigma^* \mid \mu(M(z)\Sigma^\omega) \geq \frac{1}{2}\}$$

of inputs to the tt-reduction of K to $\mathbf{x}$ where at least half of the possible oracle strings give the output 0. This set is r.e., so let W_{z_0} be a name for it. From the construction it follows that

$$z_0 \in K \Leftrightarrow F_{z_0}(x_0x_1 \cdots x_{r_{z_0}}) = 1,$$

hence if we put $r = r_{z_0} + 1$ and

$$V_0 = \{u \in \Sigma^r \mid \mu(M(z_0)\Sigma^\omega) \geq \frac{1}{2} \Leftrightarrow F_{z_0}(u) = 1\}$$

we ensure that V is r.e. and $\mu(V_0\Sigma^\omega) \leq \frac{1}{2}$. Moreover $\mathbf{x} \in V_0\Sigma^\omega$, because if $u = \mathbf{x}|r$, then

$$\mu(M(z_0)\Sigma^\omega) \geq \frac{1}{2} \Leftrightarrow z_0 \in K \Leftrightarrow F_{z_0}(u) = 1.$$

Assume now that z_n, V_n have been constructed such that $\mathbf{x} \in V_n\Sigma^\omega$ and $\mu(V_n\Sigma^\omega) \leq 2^{-n-1}$. Let $z_{n+1} \notin \{z_0, z_1, \ldots, z_n\}$ be such that

$$W_{z_{n+1}} = \{u \in \Sigma^* \mid \mu(M(u)\Sigma^\omega \cap V_n\Sigma^\omega) \geq \frac{1}{2} \cdot \mu(V_n\Sigma^\omega)\}.$$

Then

$$z_{n+1} \in K \Leftrightarrow \mu(M(u)\Sigma^\omega \cap V_n\Sigma^\omega) \geq \frac{1}{2} \cdot \mu(V_n\Sigma^\omega).$$

Finally put $r = r_{z_{n+1}+1}$ and

$$V_{n+1} = \{u \in \Sigma^r \mid u|r_{z_n} \in V_n \wedge (\mu(M(z_{n+1})\Sigma^\omega \cap V_n\Sigma^\omega) \geq \frac{1}{2} \cdot \mu(V_n\Sigma^\omega) \\ \Leftrightarrow F_{z_{n+1}}(u) = 1)\}$$

and note that V_{n+1} is r.e., $\mathbf{x} \in V_{n+1}$ and

$$\mu(V_{n+1}\Sigma^\omega) \leq \frac{1}{2} \cdot \mu(V_n\Sigma^\omega) \leq 2^{-n-2}.$$

Consequently, $(V_n)_n$ is a Martin-Löf test with $\mathbf{x} \in \bigcap_{n\geq 0} V_n\Sigma^\omega$. □

References

1. C. H. Bennett. Logical depth and physical complexity, in R. Herken (ed.). *The Universal Turing Machine. A Half-Century Survey*, Oxford University Press, Oxford, 1988, 227–258.
2. C. Calude. *Information and Randomness. An Algorithmic Perspective.* Springer-Verlag, Berlin, 1994.
3. C. S. Calude, P. H. Hertling, B. Khoussainov, Y. Wang. Recursively enumerable reals and Chaitin Ω numbers, *CDMTCS Research Report* 055, 1997, 22 pp.
4. G. J. Chaitin. *Information, Randomness and Incompleteness, Papers on Algorithmic Information Theory*, World Scientific, Singapore, 1987. (2nd ed., 1990)
5. G. J. Chaitin. On the number of N-bit strings with maximum complexity, *Applied Mathematics and Computation* 59(1993), 97-100.
6. G. J. Chaitin. *The Limits of Mathematics*, Springer-Verlag, Singapore, 1997.
7. G. J. Chaitin, A. Arslanov, C. Calude. Program-size complexity computes the halting problem, *EATCS Bull.* 57 (1995), 198-200.
8. A. Kučera. Measure, Π^0_1-classes and complete extensions of PA, In: H. D. Ebbinghaus and G. H. Müller (eds.) *Recursion Theory Week* (Oberwolfach, 1984), Lecture Notes in Math., 1141, Springer-Verlag, Berlin, 1985, 245-259.
9. D. Juedes, J. Lathrop, and J. Lutz. Computational depth and reducibility, *Theoret. Comput. Sci.* 132 (1994), 37-70.
10. A. H. Lachlan. wtt-complete sets are not necessarily tt-complete, *Proc. Amer. Math. Soc.* 48 (1975), 429-434.
11. P. Odifreddi. *Classical Recursion Theory*, North-Holland, Amsterdam, Vol.1, 1989.
12. R. I. Soare. *Recursively Enumerable Sets and Degrees*, Springer-Verlag, Berlin, 1987.