滑らかな常微分方程式の計算量

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概要

The computational complexity of the solution h to the ordinary differential equation $h(0) = 0$, $h'(t) = g(t, h(t))$ under various assumptions on the function g has been investigated in hope of understanding the intrinsic hardness of solving the equation numerically. Kawamura showed in 2010 that the solution h can be PSPACE-hard even if g is assumed to be Lipschitz continuous. We place further requirements on the smoothness of g and obtain the following results: the solution h is still PSPACE-hard if g is assumed to be continuously differentiable; for each $k \geq 2$, the solution h is hard for the counting hierarchy if g is assumed to be k-times continuously differentiable.

1 序論

Let $g\colon [0,1] \times \mathbf{R} \to \mathbf{R}$ be continuous and consider the following differential equation:

$$h(0) = 0, \qquad Dh(t) = g(t, h(t)) \quad t \in [0,1], \tag{1.1}$$

where Dh denotes the derivative of h. How complex can the solution h be, assuming that g is polynomial-time computable? Here, the polynomial-time computability and other notions of complexity are from the field of *Computable Analysis* [14] and measures how hard it is to approximate real functions with specified precisions (Section 2).

If we put no assumption on g other than being polynomial-time computable, the solution h (which is not unique in general) can be non-computable. Table 1.1 summarizes known results about the complexity of h under various assumptions on g, with the assumptions getting stronger as we go down. In particular, if g is (globally) Lipschitz continuous, then the (unique) solution h is known to be polynomial-space computable but still can be PSPACE-hard [3]. In this paper, we study the complexity of h when we put stronger assumptions about the smoothness of g.

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表 1.1　g が多項式時間計算可能であるときの常微分方程式 (1.1) の解 h の計算量

制限	上界	下界
—	—	計算不可能になりうる [11]
h が g の唯一解	計算可能 [1]	任意の時間がかかりうる [6, 9]
g が Lipschitz 条件を満たす	多項式領域計算可能 [6]	PSPACE 困難になりうる [3]
g が $(\infty, 1)$ 回連続微分可能	多項式領域計算可能	PSPACE 困難になりうる (定理 1.1)
g が (∞, k) 回連続微分可能 (k は任意の定数)	多項式領域計算可能	CH 困難になりうる (定理 1.2)
g が解析的	多項式時間計算可能 [10, 8, 2]	—

一般に数値計算においてはしばしば, 或る種の算法を適用できるようにするため, 或いは解析しやすくするために, 与えられる関数に何らかの滑らかさ (十分な回数微分可能であるなど) を仮定すると都合のよいことがある. しかしこれは経験則にすぎず, 実際に滑らかさの仮定が解の複雑さを計算量の意味で抑える効果をもつのかについてはあまり論ぜられて来なかった.

本稿で扱う微分方程式についていえば, 極端なのは g が解析的である場合であり, このときにはテイラー級数による解法により, 表の最下列にあるように h は g と同じく多項式時間計算可能になる. 本稿では Lipschitz 条件より強いが解析的よりは弱い滑らかさの仮定を考える (表の第 4, 5 行). ここで (i, j) 回連続微分可能とは, 第一, 第二変数についてそれぞれ i 回, j 回微分でき, その導関数が連続であることである[*1].

Theorem 1.1. 多項式時間計算可能かつ $(\infty, 1)$ 回連続微分可能な実関数 $g\colon [0,1] \times [-1,1] \to \mathbf{R}$ であって, 方程式 (1.1) が PSPACE 困難な解 $h\colon [0,1] \to \mathbf{R}$ を持つものが存在する.

Theorem 1.2. 任意の自然数 k に対して, 多項式時間計算可能かつ (∞, k) 回連続微分可能な実関数 $g\colon [0,1] \times [-1,1] \to \mathbf{R}$ であって, 方程式 (1.1) が CH 困難な解 $h\colon [0,1] \to \mathbf{R}$ を持つものが存在する. 但し $\mathsf{CH} \subseteq \mathsf{PSPACE}$ は計数階層 (3.2 節) である.

ここで $g\colon [0,1] \times \mathbf{R} \to \mathbf{R}$ でなく $g\colon [0,1] \times [-1,1] \to \mathbf{R}$ と書いたのは, 本稿では実関数の多項式時間計算可能性を, 定義域が有界閉領域のときにのみ定義するからである. このため h が区間 $[-1,1]$ の外に値を取ることがあると方程式 (1.1) が意味をなさなくなるが, 定理 1.1 において h が解であるというのは, 任意の $t \in [0,1]$ について $h(t) \in [-1,1]$ が満たされることも含めて述べて

[*1] 二変数関数 g が $i + j \leq k$ を満たす任意の自然数 i, j について (i, j) 回連続微分可能であることを k 回連続微分可能と言うこともあるが, 本稿では各変数について微分できる回数をこのように分けて書く.

いる. なお両定理とも Lipschitz 条件よりも強い仮定を置いているため, そのような h は g に対して, 存在すれば唯一である.

本稿のように対象を滑らかな関数に制限することによる計算量の変化について, 常微分方程式以外の問題では次のような否定的な結果がある. 多項式時間計算可能な関数から積分により得られる関数は, もとの関数を無限回微分可能なものに限ってもなお一般の場合と同じく #P 困難である. [7, 定理 5.33]. 最大化でも同様に, 無限回微分可能な関数に限っても一般の場合と同じく NP 困難である [7, 定理 3.7][*2] (なお対象を解析的な関数に限ると, やはり級数を用いた議論により, これらは多項式時間計算可能になる). 一方常微分方程式については, 定理 1.2 は各 k についてそれぞれ成立つが, g が (∞,∞) 回微分可能であると仮定したときの h の計算量については依然不明である.

記法

Let $\mathbf{N}$ denote the set of natural numbers, $\mathbf{Q}$ denote the set of rational numbers and $\mathbf{R}$ denote the set of real numbers.

Let A and B be bounded closed interval in $\mathbf{R}$. We denote $|f|$ as $\sup_{x\in A} f(x)$ where $f\colon A \to \mathbf{R}$.

A function $f\colon A \to \mathbf{R}$ is *i-times continuously differentiable* if there exist the derivatives $Df, D^2f, \ldots, D^if$ and all of them are continuous. A function $g\colon A \times B \to \mathbf{R}$ is *(i,j)-times continuously differentiable* if for each $n \in \{0,\ldots,i\}$ and $m \in \{0,\ldots j\}$, there exists the derivative $D_1^nD_2^mg$ and it is continuous. When a function g is (i,j)-times continuously differentiable, we write $D^{(i,j)}g$ for the derivatives $D_1^iD_2^jg$. A function g is *(∞,j)-times continuously differentiable* if g is (i,j)-times continuously differentiable for all $i \in \mathbf{N}$,

2 Computational Complexity of Real Functions

2.1 Computation of Real Function

Real numbers are represented by functions from string to string.

Definition 2.1. A function $\phi\colon \{0\}^* \to \{0,1\}^*$ is a *name* of a real number x if for all $n \in \mathbf{N}$, $\phi(0^n)$ is the binary representation of $\lfloor x\cdot 2^n\rfloor$ or $\lceil x\cdot 2^n\rceil$, where $\lfloor\cdot\rfloor$ and $\lceil\cdot\rceil$ are rounding down and up functions.

In effect, a name of a real number x receive n and return approximation of x with precision 2^{-n}.

[*2] ただし葛 [7, 定理 3.7] の証明において関数 f を

$$f(x) = \begin{cases} u_s & \text{if not } R(s,t) \\ u_s + 2^{-(p(n)+2n+1)\cdot n}\cdot h_1(2^{p(n)+2n+1}(x-y_{s,t})) & \text{if } R(s,t) \end{cases}$$

に修正する必要がある.

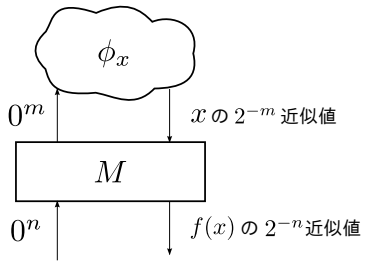

図 2.1　A machine M computing a real function f

We use *oracle Turing machines*(henceforth just machines) to work on names of real numbers(Figure 2.1).

Let M be a machine and ϕ be a function from string to string, We write $M^{\phi}(0^n)$ as the output string by computation of M given ϕ as oracle and string 0^n as input. So we also regard M^{ϕ} as a function from string to string.

Definition 2.2. Let A be a bounded closed interval of $\mathbf{R}$. A machine M *computes* a real function $f\colon A \to \mathbf{R}$ if for any $x \in A$ and any name ϕ_x of it, M^{ϕ_x} is a name of $f(x)$.

When A is a bounded closed interval of $\mathbf{R}^2$, we define a machine computing $f\colon A \to \mathbf{R}$ in a similar way using machines with two oracles. A real function is (*polynomial-time*) *computable* if there exists some machine that computes it (in polynomial time).

When a machine M computes a real function f, for each demanded precision 2^{-n}, precision 2^{-m}. Computable real functions are continuous. Giving all approximations of functions at rational points an relation between n and m, we can characterize (polynomial-time) computability of real function without oracle Turing machines

Lemma 2.3. A real function is (polynomial-time) computable if and only if there exist a (polynomial-time) computable function $\phi\colon (\mathbf{Q} \cap [0,1]) \times \{0\}^* \to \mathbf{Q}$ and polynomial $p\colon \mathbf{N} \to \mathbf{N}$ such that for all $d \in \mathbf{Q} \cap [0,1]$ and $n \in \mathbf{N}$,

$$|\phi(d, 0^n) - f(d)| \leq 2^{-n}, \tag{2.1}$$

and for all $x, y \in [0,1]$, $m \in \mathbf{N}$,

$$|x - y| \leq 2^{-p(m)} \Rightarrow |f(x) - f(y)| \leq 2^{-m}. \tag{2.2}$$

where each rational number in $\mathbf{Q}$ is represented by a pair of integers in binary representation.

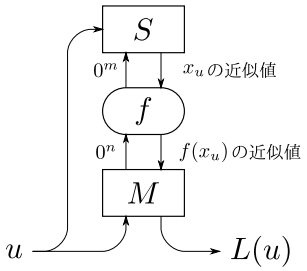

図 2.2 Reduction from a language L to a function $f\colon [0,1] \to \mathbf{R}$

2.2 Reduction and Hardness

A language $L \subseteq \{0,1\}^*$ is identified with the function $L\colon \{0,1\}^* \to \{0,1\}$ such that $L(u) = 1$ if and only if $u \in L$.

Definition 2.4 (Reduction)**.** A Language L reduces to a real function $f\colon [0,1] \to \mathbf{R}$ if there exists a polynomial-time function S and a polynomial-time oracle Turing machine M (Figure 2.2) such that for any string u:

(i) $S(u,\cdot)$ is a name of x_u;
(ii) $M^\phi(u)$ accepts if and only if $u \in L$ for any name ϕ of $f(x_u)$.

As a matter of form this definition is different from that by Kawamura but they have same power as reduction. Let C be a complexity class, a function f is *C-hard* if for all language in C is reducible to f.

3 Proof of The Theorems

We give a proof sketch of Theorem 1.1 and Theorem 1.2. First we define a discrete version of differential equations in Section 3.1, and show PSPACE-hardness or CH-hardness of the problem with restrictions similar to once differentiable or k-times differentiable in Section 3.2. In Section 3.3, we show that these discrete problems is simulatable by certain families of smooth differential equations. We construct the smooth differential equations stated in theorems putting one family into one real function in Section 3.4. Henceforth we call the discrete version of differential equations as difference equations.

The idea to simulate difference equations with differential equations is essentially from the proof of Lipschitz version [3]. In this paper we focus on the structure of difference equations to analyze precisely the effect of the smoothness restriction. Consequently we show with the restriction differentiable more than once differential equations can simulate difference

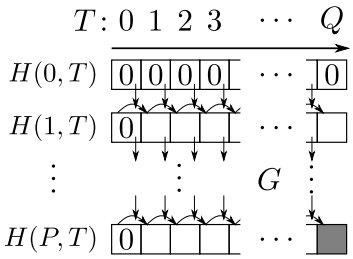

図 3.1　差分方程式 G とその解 H

equations whose height is enough small, and it gives the CH-hardness of smooth differential equations.

3.1 Difference Equations

This section we define difference equations, which is a discrete version of differential, and show that PSPACE-hardness or CH-hardness depending on restrictions on height.

Let $[n]$ denote $\{0, \ldots, n-1\}$. Let $G\colon [P] \times [Q] \times [R] \to \{-1, 0, 1\}$ and $H\colon [P+1] \times [Q+1] \to [R]$, H is the solution of the *difference equation* given by G if for all $i \in [P]$ and $T \in [Q]$(Figure 3.1),

$$H(i, 0) = H(0, T) = 0 \tag{3.1}$$

$$H(i+1, T+1) - H(i+1, T) = G(i, T, H(i, T)). \tag{3.2}$$

We call P, Q and R as *height*, *width*, *cell size* of the difference equation. The equation (3.1) is similar to the initial condition $h(0) = 0$, and (3.2) is similar to $Dh(t) = g(t, h(t))$ in (1.1). In Section 3.3, we simulate difference equations by differential equations using this similarity.

We regard a family of difference equations $(G_u)_u$ computing L, by regarding the value of the bottom right cell as $L(u)$ for each u. A family $(G_u)_u$ of functions $G_u\colon [P_u] \times [Q_u] \times [R_u] \to \{-1, 0, 1\}$ *recognizes* a language L if let $(H_u)_u$ be as the solution of the difference equation given by G_u $H_u(P_u, Q_u) = L(u)$. A family $(G_u)_u$ is *uniform* if the height and width and cell size of G_u are polynomial-time computable from u and $G_u(i, T, Y)$ is polynomial-time computable from (u, i, T, Y). Note that height, width and cell size of a uniform G_u is bounded by $2^{p(|u|)}$ where p is some polynomial. A family $(G_u)_u$ has *polynomial height* if the height P_u is bounded by some polynomial $p(|u|)$. A family $(G_u)_u$ has *logarithmic height* if the height P_u is bounded by $c \log |u| + d$ where some constants c and d. In terms of these definition, [3, 補題 4.7], which proved by Kawamura to show that PSPACE-hardness of Lipschitz version, can be written in following form:

Lemma 3.1. There exists a PSPACE-hard language such that it is recognized by some uniform

family of functions with polynomial height. [*3].

By simulating this difference equation using certain Lipschitz differential equation, Kawamura obtained the result at the third row in Table 1.1. Also Theorem 1.1 follows from Lemma 3.1, by arranging the construction of g and h so that g is $(\infty, 1)$-times differential(Section 3.3 and Section 3.4).

In this paper, we show real functions differentiable more than once in x can simulate difference equations restricted to have logarithmic height (Section 3.3 and Section 3.4). Theorem 1.2 follows from the above argument with the following lemma.

Lemma 3.2. There exists a CH-hard language such that it is recognized by some uniform family of functions with logarithmic height.

In the next section we provide the definition of the counting hierarchy(CH), its connection with difference equations and the proof of this lemma.

3.2 The Counting Hierarchy and Difference Equations of Logarithmic Height

The polynomial hierarchy PH is defined using non-deterministic polynomial-time oracle Turing machines:

$$\Sigma_0^p = \mathsf{P}, \qquad \Sigma_{n+1}^p = \mathsf{NP}^{\Sigma_n^p}, \qquad \mathsf{PH} = \bigcup_n \Sigma_n^p. \tag{3.3}$$

In the same way, the counting hierarchy CH [13] is defined using probabilistic polynomial-time oracle Turing machines[*4]:

$$\mathsf{C}_0\mathsf{P} = \mathsf{P}, \qquad \mathsf{C}_{n+1}\mathsf{P} = \mathsf{PP}^{\mathsf{C}_n\mathsf{P}}, \qquad \mathsf{CH} = \bigcup_n \mathsf{C}_n\mathsf{P}. \tag{3.4}$$

It is known that $\mathsf{PH} \subseteq \mathsf{CH} \subseteq \mathsf{PSPACE}$, but we do not know whether $\mathsf{PH} = \mathsf{PSPACE}$.

Each level of the counting hierarchy has a complete problem defined as follows. For every formula $\phi(X)$ with the list X of l free propositional variables, we write

$$\mathsf{C}^m X \phi(X) \longleftrightarrow \sum_{X \in \{0,1\}^l} \phi(X) \geq m, \tag{3.5}$$

where $\phi(X)$ is identified with the function $\phi\colon \{0,1\}^l \to \{0,1\}$ such that $\phi(X) = 1$ if and only if $\phi(X)$ is true. This "counting quantifier" C^m generalizes the usual quantifiers $\exists$ and $\forall$, because $\mathsf{C}^1 = \exists$ and $\mathsf{C}^{2^l} = \forall$. For lists $X_1, \ldots, X_n$ of variables and a formula $\phi(X_1, \ldots, X_n)$

[*3] The language class recognized by difference equations is closed under Karp reduction and the language class recognized by uniform families with polynomial height coincides PSPACE.

[*4] This characterization, introduced by Torán in [12], is different from Wagner's original one.

with all free variables listed, we define

$$\langle \phi(X_1, \ldots, X_n), m_1, \ldots, m_n \rangle \in \mathsf{C}_n B_{be} \longleftrightarrow \mathsf{C}^{m_1} X_1 \cdots \mathsf{C}^{m_n} X_n \phi(X_1, \ldots, X_n). \tag{3.6}$$

Lemma 3.3 ([13, Theorem 7])**.** For every $n \geq 1$, the problem $\mathsf{C}_n B_{be}$ is $\mathsf{C}_n\mathsf{P}$-complete.

We define a problem $\mathsf{C}_{\log} B_{be}$ by

$$\langle 0^{2^n}, u \rangle \in \mathsf{C}_{\log} B_{be} \longleftrightarrow u \in \mathsf{C}_n B_{be}. \tag{3.7}$$

We show that $\mathsf{C}_{\log} B_{be}$ is CH-hard and recognized by a logarithmic-height uniform function family, as required in Lemma 3.2.

Proof of Lemma 3.2. First we prove that $\mathsf{C}_{\log} B_{be}$ is CH-hard. For each problem A in CH, there is a constant n such that $A \in \mathsf{C}_n\mathsf{P}$. From Lemma 3.3, for each $u \in \{0,1\}^*$ there is a polynomial-time function f_n such that $u \in A \leftrightarrow f_n(u) \in \mathsf{C}_n B_{be}$. So

$$u \in A \longleftrightarrow \langle 0^{2^n}, f_n(u) \rangle \in \mathsf{C}_{\log} B_{be}. \tag{3.8}$$

Since $\langle 0^{2^n}, f_n(\cdot) \rangle$ is polynomial time computable, A is reducible to $\mathsf{C}_{\log} B_{be}$.

Next we construct a logarithmic-height uniform function family $(G_u)_u$ recognizing $\mathsf{C}_{\log} B_{be}$. Let $u = \langle 0^{2^n}, \langle \phi(X_1, \ldots, X_n), m_1, \ldots, m_n \rangle \rangle$, where n, $m_1, \ldots, m_n$ are nonnegative integers and ϕ is a formula. (If u is not of this form, then $u \notin \mathsf{C}_{\log} B_{be}$.)

We write $l_i = |X_i|$ and $s_i = i + \sum_{j=1}^{i} l_j$. For each $i \in \{0, \ldots, n\}$ and $Y_{i+1} \in \{0,1\}^{l_{i+1}}, \ldots, Y_n \in \{0,1\}^{l_n}$, we write $\phi_i(Y_{i+1}, \ldots, Y_n)$ for the truth value of the subformula $\mathsf{C}^{m_i} X_i \cdots \mathsf{C}^{m_1} X_1 \phi(X_1, \ldots, X_i, Y_{i+1}, \ldots, Y_n)$, so that $\phi_0 = \phi$ and $\phi_n() = \mathsf{C}_{\log} B_{be}(u)$. We regard the quantifier C^m as a function from $\mathbf{N}$ to $\{0,1\}$:

$$C^m(x) = \begin{cases} 1 & \text{if } x \geq m, \\ 0 & \text{if } x < m. \end{cases} \tag{3.9}$$

Thus,

$$\phi_{i+1}(Y_{i+2}, \ldots, Y_n) = C^{m_{i+1}} \left(\sum_{X_{i+1} \in \{0,1\}^{l_i}} \phi_i(X_{i+1}, Y_{i+2}, \ldots, Y_n) \right). \tag{3.10}$$

For $T \in \mathbf{N}$, we write T_i for the ith digit of T written in binary, and $T_{[i,j]}$ for the string $T_{j-1} T_{j-2} \cdots T_{i+1} T_i$.

For each $(i, T, Y) \in [n+1] \times [2^{s_n} + 1] \times [2^{|u|}]$, we define $G_u(i, T, Y)$ as follows. The first row is given by

$$G_u(0, T, Y) = (-1)^{T_{s_1}} \phi(T_{[1,s_1]}, T_{[s_1+1,s_2]}, \ldots, T_{[s_{n-1}+1,s_n]}), \tag{3.11}$$

and for $i \neq 0$, we define

$$G_u(i, T, Y) = \begin{cases} (-1)^{T_{s_{i+1}}} C^{m_i}(Y) & \text{if } T_{[1,s_i+1]} = 10 \cdots 0, \\ 0 & \text{otherwise.} \end{cases} \tag{3.12}$$

Define H_u from G_u by (3.1) and (3.2).

We prove by induction on i that $H_u(i,T) \in [2^{l_u}]$ for all T, and that

$$G_u(i,T,H_u(i,V)) = (-1)^{V_{s_{i+1}}}\phi_i(V_{[s_i+1,s_{i+1}]},\ldots,V_{[s_{n-1}+1,s_n]}) \tag{3.13}$$

for all $i \in [n+1]$ and $V \in [2^{s_n}+1]$ such that $V_{[1,s_i+1]} = 10\cdots 0$.

For $i = 0$, the claims follows from (3.11). For the induction step, assume (3.13). We have

$$H_u(i+1,T) = \sum_{V=0}^{T-1} G_u(i,V,H_u(i,V)) = \sum_V (-1)^{V_{s_{i+1}}}\phi_i(V_{[s_i+1,s_{i+1}]},\ldots,V_{[s_{n-1}+1,s_n]}), \tag{3.14}$$

where we write $\overline{U}$ for the number represented by string U as binary expression. For each $V < \overline{T_{[s_{i+1}+1,s_n]}0\cdots 0}$ in (3.14), the terms $\phi_i(V_{[s_i+1,s_{i+1}]},\ldots,V_{[s_{n-1}+1,s_n]})$ and $-\phi_i(V_{[s_i+1,s_{i+1}]},\ldots,V_{[s_{n-1}+1,s_n]}) = 0$ cancel each other out. Then

$$H_u(i+1,T) = \sum_{X\in\{0,1\}^{l_i}} \phi_i(X,T_{[s_{i+1}+1,s_{i+2}]},\ldots,T_{[s_{n-1}+1,s_n]}). \tag{3.15}$$

From this equation and (3.10), it follows that

$$\begin{aligned} G_u(i+1,T,H_u(i+1,T)) &= (-1)^{T_{s_{i+2}}}C^{m_{i+1}}(H_u(i+1,T)) \\ &= (-1)^{T_{s_{i+2}}}\phi_{i+1}(T_{[s_{i+1}+1,s_{i+2}]},\ldots,T_{[s_{n-1}+1,s_n]}). \end{aligned} \tag{3.16}$$

By substituting n for i and 2^{s_n} for T in (3.13), we get $G_u(n,2^{s_n},H_u(n,2^{s_n})) = \phi_n() = \mathsf{C}_{\log}B_{be}(u)$. Hence $H_u(n+1,2^{s_n}+1) = \mathsf{C}_{\log}B_{be}(u)$.

The height $n+1$, the width $2^{s_n}+1$, and the cell size $2^{|u|}$ of G_u are polynomial-time computable from u, and $n+1 \le \log(|0^{2^n}|)+1 \le \log|u|+1$. Hence $(G_u)_u$ is uniform and has logarithmic height. □

The language class recognized by uniform function families with i rows contains $\mathsf{C}_i\mathsf{P}$ (the ith level of the counting hierarchy) and is contained in $\mathsf{C}_{i+1}\mathsf{P}$. While the class $\mathsf{C}_i\mathsf{P}$ is defined by (3.4) using oracle Turing machines, it is also characterized as those languages Karp-reducible to C_iB_{be}, or as those accepted by a polynomial-time alternating Turing machine extended with "threshold states" and having at most i alternations. Likewise, the language class accepted by uniform function families of logarithmic height coincided with languages Karp-reducible to $\mathsf{C}_{\log}B_{be}$ and with those accepted by an extended alternating Turing machine with logarithmic alternations. Since this class contains CH, we only state CH-hard in Lemma 3.4 and Theorem 1.2, but it is not known such class how hard the class is between CH and PSPACE.

3.3 Families of Real Functions Simulating Difference Equations

We show that families of smooth differential equations can simulate PSPACE-hard or CH-hard difference equations stated in previous section.

Before stating Lemma 3.4 and Lemma 3.5, we extend the definition of polynomial-time computability of real function to families of real functions. A machine M *computes* a family $(f_u)_u$ of functions $f_u\colon A \to \mathbf{R}$ indexed by strings u if for any $x \in A$ and any name ϕ_x of x, the function taking v to $M^{\phi_x}(u, v)$ is a name of $f_u(x)$. We say a family of real functions $(f_u)_u$ is polynomial-time if there is a polynomial-time machine computing $(f_u)_u$.

Lemma 3.4. There exist a CH-hard language L and a polynomial μ such that for all $k \geq 1$ and polynomials γ, there are a polynomial ρ and families $(g_u)_u$, $(h_u)_u$ of real functions having following properties that $(g_u)_u$ is polynomial-time computable and for any string u:

(i) $g_u\colon [0,1] \times [-1,1] \to \mathbf{R}$, $h_u\colon [0,1] \to [-1,1]$;
(ii) $h_u(0) = 0$ and $Dh_u(t) = g_u(t, h_u(t))$ for all $t \in [0,1]$;
(iii) g_u is (∞, k)-times continuously differentiable;
(iv) $D^{(i,0)}g_u(0,y) = D^{(i,0)}g_u(1,y) = 0$ for all $i \in \mathbf{N}$ and $y \in [-1,1]$;
(v) $\left|D^{(i,j)}g_u(t,y)\right| \leq 2^{\mu(i,|u|)-\gamma(|u|)}$ for all $i \in \mathbf{N}$ and $j \in \{0,\ldots,k\}$;
(vi) $h_u(1) = 2^{-\rho(|u|)}L(u)$.

Lemma 3.5. There exist a PSPACE-hard language L and a polynomial μ, such that for all polynomials γ, there are a polynomial ρ and families $(g_u)_u$, $(h_u)_u$ of real functions such that $(g_u)_u$ is polynomial-time computable and for any string u satisfying (i)–(vi) of Lemma 3.4 with $k = 1$.

We will prove Lemma 3.4 using Lemma 3.2 as follows. Let a function family $(G_u)_u$ be as in Lemma 3.2, and let $(H_u)_u$ be the solution of the difference equation given by $(G_u)_u$. We construct h_u and g_u from H_u and G_u such that $h_u(T/2^{q(|u|)}) = \sum_{i=0}^{p(|u|)} H_u(i,T)/B^{d_u(i)}$ for each $T = 0, \ldots, 2^{q(|u|)}$ and $Dh_u(t) = g_u(t, h_u(t))$. The polynomial-time computability of $(g_u)_u$ follows from that of $(G_u)_u$. We can prove Lemma 3.5 from Lemma 3.1 in the same way.

In Lemma 3.4, we have the new conditions (iii)–(v) about the smoothness and the derivatives of g_u that were not present in [3, Lemma 4.1]. To satisfy these conditions, we construct g_u using the smooth function f in following lemma.

Lemma 3.6 ([7, Lemma 3.6])**.** There exist a polynomial-time infinitely differentiable function $f\colon [0,1] \to \mathbf{R}$ and a polynomial s such that

(i) $f(0) = 0$ and $f(1) = 1$;
(ii) $D^n f(0) = D^n f(1) = 0$ for all $n \geq 1$;
(iii) f is strictly increasing;
(iv) $D^n f$ is polynomial-time computable for all $n \geq 1$;
(v) $|D^n f| \leq s(n)$ for all $n \geq 1$.

Although the existence of the polynomial s satisfying the condition (v) is not stated in [7, Lemma 3.6], it can be shown easily.

We only prove Lemma 3.4 here and omit the analogous and easier proof of Lemma 3.5.

Proof of Lemma 3.4. Let L, $(G_u)_u$ and $(H_u)_u$ be as in Lemma 3.2, and let a function family $(H_u)_u$ be the solution of the difference equation given by $(G_u)_u$.

By a similar argument to the beginning of the proof of [3, Lemma 4.1], we may assume that there exist polynomial-time functions p, j_u and polynomials q, r satisfying the following properties:

$$G_u \colon [p(|u|)] \times [2^{q(|u|)}] \times [2^{r(|u|)}] \to \{-1, 0, 1\}, \tag{3.17}$$

$$H_u(i, 2^{q(|u|)}) = \begin{cases} L(u) & \text{if } i = p(|u|), \\ 0 & \text{if } i < p(|u|), \end{cases} \tag{3.18}$$

$$i \neq j_u(T) \to G_u(i, T, Y) = 0. \tag{3.19}$$

Since G_u has logarithmic height, there exists a polynomial σ such that $(k+1)^{p(x)} \leq \sigma(x)$

We construct the families of real functions $(g_u)_u$ and $(h_u)_u$ simulating G_u and H_u in the sense that $h_u(T/2^{q(|u|)}) = \sum_{i=0}^{p(|u|)} H_u(i, T)/B^{d_u(i)}$, where the constant B and the function $d_u \colon [p(|u|) + 1] \to \mathbf{N}$ are defined by

$$B = 2^{\gamma(|u|)+r(|u|)+s(k)+k+3}, \qquad d_u(i) = \begin{cases} \sigma(|u|) & (i = p(|u|)), \\ (k+1)^i & (i < p(|u|)). \end{cases} \tag{3.20}$$

For each $(t, y) \in [0, 1] \times [-1, 1]$, there exist unique $N \in \mathbf{N}$, $\theta \in [0, 1)$, $Y \in \mathbf{Z}$ and $\eta \in [-1/4, 3/4)$ such that $t = (T + \theta)2^{-q(|u|)}$ and $y = (Y + \eta)B^{-d_u(j_u(T))}$. Using f and a polynomial s of Lemma 3.6, we define $\delta_{u,Y} \colon [0, 1] \to \mathbf{R}$, $g_u \colon [0, 1] \times [-1, 1] \to \mathbf{R}$ and $h_u \colon [0, 1] \to [-1, 1]$ by

$$\delta_{u,Y}(t) = \frac{2^{q(|u|)} Df(\theta)}{B^{d_u(j_u(T)+1)}} G_u\big(j_u(T), T, Y \bmod 2^{r(|u|)}\big), \tag{3.21}$$

$$g_u(t, y) = \begin{cases} \delta_{u,Y}(t) & \text{if } \eta \leq \frac{1}{4}, \\ (1 - f(\frac{4\eta-1}{2}))\delta_{u,Y}(t) + f(\frac{4\eta-1}{2})\delta_{u,Y+1}(t) & \text{if } \eta > \frac{1}{4}, \end{cases} \tag{3.22}$$

$$h_u(t) = \sum_{i=0}^{p(|u|)} \frac{H_u(i, T)}{B^{d_u(i)}} + \frac{f(\theta)}{B^{d_u(j_u(T)+1)}} G_u\big(j_u(T), T, H_u(j_u(T), T)\big). \tag{3.23}$$

We will verify that $(g_u)_u$ and $(h_u)_u$ defined above satisfy all the conditions stated in Lemma 3.4. The condition (ii) are verified by the same argument as [3, Lemma 4.1].

We will show that the condition (iii) holds, that is, g_u is (∞, k)-times continuously differentiable. For each $i \in \mathbf{N}$,

$$D^i \delta_{u,Y}(t) = \frac{2^{(i+1)q(|u|)} D^{i+1} f(\theta)}{B^{d_u(j_u(T)+1)}} G_u\big(j_u(T),\ T,\ Y \bmod 2^{r(|u|)}\big), \tag{3.24}$$

$$D^{(i,0)} g_u(t, y) = \begin{cases} D^i \delta_{u,Y}(t) & \text{if } -\frac{1}{4} < \eta < \frac{1}{4}, \\ \big(1 - f\left(\frac{4\eta-1}{2}\right)\big) D^i \delta_{u,Y}(t) + f\left(\frac{4\eta-1}{2}\right) D^i \delta_{u,Y+1}(t) & \text{if } \frac{1}{4} < \eta < \frac{3}{4}, \end{cases} \tag{3.25}$$

and for each $j \in \{1, \dots, k\}$,

$$D^{(i,j)}g_u(t,y) = \begin{cases} 0 & \text{if } -\frac{1}{4} < \eta < \frac{1}{4}, \\ (2B^{d_u(j_u(T))})^j D^j f(\frac{4\eta-1}{2})(D^i\delta_{u,Y+1}(t) - D^i\delta_{u,Y}(t)) & \text{if } \frac{1}{4} < \eta < \frac{3}{4}. \end{cases} \tag{3.26}$$

It is easy to check that they are also continuous on the boundaries ($\theta = 0$ and $\eta = -1/4, 3/4$). Hence g_u is (∞, j)-times continuously differentiable. Substituting $t = 0, 1$ ($\theta = 0$) into (3.25), we get $D^{(i,0)}g_u(0,y) = D^{(i,0)}g_u(1,y) = 0$, so the condition (iv) holds.

We show that the condition (v) holds with $\mu(x,y) = (x+1)q(y) + s(x+1)$. Note that μ is a polynomial independent of k and γ. Since $|D^i\delta_{u,Y}(t)| \le 2^{(i+1)q(|u|)+s(i+1)}B^{-d_u(j_u(|u|)+1)}$ by (3.21), for all $i \in \mathbf{N}$ and $j \in \{0, \dots, k\}$, we have

$$|D^{(i,j)}g_u| \le 2^k B^{k\cdot j_u(T)} 2^{s(k)} \cdot 2 \cdot \frac{2^{(i+1)q(|u|)+s(i+1)}}{B^{d_u(j_u(|u|)+1)}} \le \frac{2^{\mu(i,|u|)+s(k)+k+1}}{B} \le 2^{\mu(i,|u|)-\gamma(|u|)} \tag{3.27}$$

by our choice of B.

We have (vi) with $\rho(x) = \sigma(x)\cdot(\gamma(x) + r(x) + s(k) + k + 3)$, because

$$h_u(1) = \frac{H_u(p(|u|), 2^{q(|u|)})}{B^{d_u(p(|u|))}} = \frac{L(u)}{2^{\sigma(|u|)\cdot(\gamma(|u|)+r(|u|)+s(k)+k+3)}} = 2^{-\rho(|u|)}L(u). \tag{3.28}$$

□

To prove Lemma 3.5, let a function family $(G_u)_u$ be as Lemma 3.1 and let $(H_u)_u$ be the solution of the difference equation given by $(G_u)_u$, and define $(g_u)_u$ and $(h_u)_u$ as (3.22) and (3.23) with $d_u(i) = i$. It is shown in the same way as above that they meet all the conditions stated in Lemma 3.5.

3.4 Proof of the Main Theorems

We describe the sketch of proof. Let $(g_u)_u$ and $(h_u)_u$ be as Lemma 3.4 or Lemma 3.5. The real functions g and h in theorems are constructed from $(g_u)_u$ and $(h_u)_u$ as follows. Divide $[0,1)$ into infinity many subintervals $[l_u^-, l_u^+]$, with midpoints c_u. We construct h putting a scaled copy of h_u onto $[l_u^-, c_u]$ and putting a horizontally reversed scaled copy of $h_u(t)$ onto $[c_u, l_u^+]$ so that $h(l_u^-) = 0$, $h(c_u) = 2^{-\rho'(|u|)}L(u)$ and $h(l_u^+) = 0$ where ρ' is a polynomial. In the same way, g is constructed from $(g_u)_u$ so that g and h satisfy (1.1).

We omit the proof of Theorem 1.1 since we can get it applying the same argument as the proof of Theorem 1.2 and using Lemma 3.5.

Proof of Theorem 1.2. Let L and μ be as Lemma 3.5. Define

$$\lambda(x) = 2x + 2, \qquad \gamma(x) = x\mu(x,x) + x\lambda(x). \tag{3.29}$$

and for each u

$$\Lambda_u = 2^{\lambda(|u|)}, \qquad c_u = 1 - \frac{1}{2^{|u|}} + \frac{2\bar{u}+1}{\Lambda_u}, \qquad l_u^{\mp} = c_u \mp \frac{1}{\Lambda_u} \tag{3.30}$$

where $\bar{u} \in \{0, \dots, 2^{|u|}-1\}$ is the number represented by u as binary expression. Let ρ, $(g_u)_u$, $(h_u)_u$ be as Lemma 3.4 with γ.

We define

$$g\left(l_u^{\mp} \pm \frac{t}{\Lambda_u}, \frac{y}{\Lambda_u}\right) = \begin{cases} \pm \sum_{l=0}^{k} \frac{D^{(0,l)} g_u(t,1)}{l!}(y-1)^l & (1 < y) \\ \pm g_u(t,y) & (-1 \le y \le 1) \\ \pm \sum_{l=0}^{k} \frac{D^{(0,l)} g_u(t,-1)}{l!}(y+1)^l & (1 < y) \end{cases} \tag{3.31}$$

$$h\left(l_u^{\mp} \pm \frac{t}{\Lambda_u}\right) = \frac{h_u(t)}{\Lambda_u} \tag{3.32}$$

for each string u, $t \in [0,1)$, $y \in [-1,1]$. Let $g(1,y) = 0$ and $h(1) = 0$ for any $y \in [-1,1]$

It can be shown in a similar way as the Lipschitz version that g and h satisfy (1.1) and g is polynomial-time computable, so see the proof of [3, Theorem 3.2] for more details. We only show that g is (∞, k)-times continuously differentiable.

For each $i \in \mathbf{N}$ and $j \in \{0, \dots, k\}$ differentiating (3.31) (i,j)-times,

$$D^{(i,j)} g\left(l_u^{\mp} \pm \frac{t}{\Lambda_u}, \frac{y}{\Lambda_u}\right) = \begin{cases} \pm \Lambda_u^{(i,j)} \sum_{l=j}^{k} \frac{D^{(i,l)} g_u(t,1)}{(l-j)!}(y-1)^l & (1 < y) \\ \pm \Lambda_u^{(i,j)} D^{(i,j)} g_u(t,y) & (-1 < y < 1) \\ \pm \Lambda_u^{(i,j)} \sum_{l=j}^{k} \frac{D^{(i,l)} g_u(t,-1)}{(l-j)!}(y+1)^l & (1 < y). \end{cases} \tag{3.33}$$

for $t \in (0,1)$ and $y \in [-\Lambda_u, \Lambda_u]$ where $y \neq -1, 1$. It is continuous where $t \in (0,1)$ and $y \neq -1, 1$ since each $D^{(i,j)} g_u$ is continuous. We can verify that it is continuous on the boundary($t = 0, 1$ or $y = -1, 1$) by the definition and Lemma 3.4 (iv). Finally we show that it is continuous at 1 for the first variable. By Lemma 3.4 (v),

$$\begin{aligned} \left| D^{(i,j)} g\left(l_u^{\mp} \pm \frac{t}{\Lambda_u}, \frac{y}{\Lambda_u}\right) \right| &\le \Lambda_u^{i+j} \sum_{l=j}^{k} |D^{(i,l)} g_u| (\Lambda_u + 1)^l \\ &\le \Lambda_u^{i+j+k} 2^{k+\mu(i,|u|)-\gamma(|u|)} = 2^{(i+j+k)\lambda(|u|)+k+\mu(i,|u|)-\gamma(|u|)}. \end{aligned} \tag{3.34}$$

While $|u| \to \infty$, (3.34) correspondingly approaches to 0 by our choice of γ. Hence $\lim_{t \to 1-0} D^{(i,j)} g(t,y) = g(1,y) = 0$. and we complete to show that g is (∞, k)-times continuously differentiable. □

4 演算子の計算量

定理 1.1, 1.2 はいづれも関数 g を多項式時間計算可能と仮定した上で解 h の計算量について述べている. しかし微分方程式を「解く」困難さ, すなわち与えられた g から h を求める演算子の計算量は如何であろうか. この問に答えるにはまず実関数を実関数へ写す演算子の計算量を定義することを要する.

実数を入出力する関数の計算量を論ずるには, 実数を文字列関数で表した. 即ち $\mathbf{R}$ の各元の名として文字列関数を使ったのであり, その対応を $\mathbf{R}$ の表現という. 同じように実関数を入出力する演算子の計算量を論ずるには, 実関数を文字列関数で表す. つまり連続な実関数 $h\colon [0,1] \to \mathbf{R}$ の空間 $\mathrm{C}[0,1]$ や, Lipschitz 連続な実関数 $g\colon [0,1]\times[-1,1] \to \mathbf{R}$ の空間 $\mathrm{C_L}[[0,1]\times[-1,1]]$ について, 表現を指定すればよい. 演算子の計算可能性や計算量はその表現に依ることになるが, ここでは [5] に従い, $\mathrm{C}[0,1]$ の表現として $\delta_\Box$ を, $\mathrm{C_L}[[0,1]\times[-1,1]]$ の表現として $\delta_{\Box\mathrm{L}}$ をそれぞれ用いる. $\delta_\Box$ は関数空間 $\mathrm{C}[0,1]$ の表現として或る意味で自然な唯一のものであることが判っており [4], また $\delta_{\Box\mathrm{L}}$ は $\delta_\Box$ に Lipschitz 定数の情報を附加した表現である.

これらの表現では使われる文字列関数の長さが有界でないため, 神託機械の時間・空間を測る方法を二階多項式を使って拡張し, これに基いて多項式空間 **FPSPACE** などの計算量クラスや, 多項式時間 Weihrauch 帰着 $\leq_{\mathrm{W}}$ などの帰着, その下での困難性を定義する [5]. この枠組を上述の実関数の表現と組合せることで, 本稿の結果も以下の如く構成的な形で述べることができる.

実関数 $g \in \mathrm{C_L}[[0,1]\times[-1,1]]$ を, (1.1) の解 $h \in \mathrm{C}[0,1]$ に対応させる演算子 ODE を考える. ODE は $\mathrm{C_L}[[0,1]\times[-1,1]]$ から $\mathrm{C}[0,1]$ への部分写像である. [5, 定理 4.9] では表 1.1 第三行の証明を構成的に書き直すことで, ODE が $(\delta_{\Box\mathrm{L}},\delta_\Box)$-**FPSPACE**-$\leq_{\mathrm{W}}$ 完全であることが示された. 本稿の定理 1.1 も同じように構成的に書き直すことができる. 即ち ODE を (∞,k) 回連続微分可能な入力に制限したものを ODE_k と書くと,

Theorem 4.1. *ODE_1 は $(\delta_{\Box\mathrm{L}},\delta_\Box)$-**FPSPACE**-$\leq_{\mathrm{W}}$ 完全.*

これを示すには, 定理 1.1 の証明において関数の構成に使われた情報が入力から容易に得られることを確かめればよく, 新たな技巧を要しないから詳細は省略する. この構成的な主張は非構成的な主張よりも強いものであり [5, 補題 3.7, 3.8], 定理 1.1 は定理 4.1 の系として従う.

なお定理 1.2 も同様に構成的な形で成立ち, 各 $k \in \mathbf{N}$ について ODE_k は $(\delta_{\Box\mathrm{L}},\delta_\Box)$-**CH**-$\leq_{\mathrm{W}}$ 困難であるが, この [5] の枠組における **CH** を定義するには相対化の扱いについて今少しの議論を要するので別稿で扱う.

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