Endomorphisms of the shift dynamical system, discrete derivatives, and applications

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Abstract

All continuous endomorphisms f_∞ of the shift dynamical system S on the 2-adic integers $\mathbb{Z}_2$ are induced by some $f : \mathcal{B}_n \to \{0,1\}$, where n is a positive integer, $\mathcal{B}_n$ is the set of n-blocks over $\{0,1\}$, and $f_\infty(x) = y_0y_1y_2\ldots$ where for all $i \in \mathbb{N}$, $y_i = f(x_ix_{i+1}\ldots x_{i+n-1})$. Define $D : \mathbb{Z}_2 \to \mathbb{Z}_2$ to be the endomorphism of S induced by the map $\{(00,0),(01,1),(10,1),(11,0)\}$ and $V : \mathbb{Z}_2 \to \mathbb{Z}_2$ by $V(x) = -1-x$. We prove that D, $V \circ D$, S, and $V \circ S$ are conjugate to S and are the only continuous endomorphisms of S whose parity vector function is solenoidal. We investigate the properties of D as a dynamical system, and use D to construct a conjugacy from the $3x+1$ function $T : \mathbb{Z}_2 \to \mathbb{Z}_2$ to a parity-neutral dynamical system. We also construct a conjugacy R from D to T. We apply these results to establish that, in order to prove the $3x+1$ conjecture, it suffices to show that for any $m \in \mathbb{Z}^+$, there exists some $n \in \mathbb{N}$ such that $R^{-1}(m)$ has binary representation of the form $\overline{x_0x_1\ldots x_{2^n-1}}$ or $x_0\overline{x_1x_2\ldots x_{2^n}}$.

1 Introduction

A discrete dynamical system is a function from a set or metric space to itself [4]. Given two dynamical systems $f : X \to X$ and $g : Y \to Y$, a function $h : X \to Y$ is a **morphism** from f to g if $h \circ f = g \circ h$. A morphism from a dynamical system to itself is called an **endomorphism**. A bijective morphism is called a **conjugacy**, and a bijective endomorphism is called an **autoconjugacy**. Note that conjugacies on metric spaces are not assumed to be continuous.

Let $\mathbb{Z}_2$ be the ring of 2-adic integers. Each element of $\mathbb{Z}_2$ is a formal sum $\sum_{i=0}^{\infty} 2^i x_i$ where $x_i \in \{0,1\}$ for all $i \in \mathbb{N}$. The binary representation of $x = \sum_{i=0}^{\infty} 2^i x_i$ is the infinite sequence of zeroes and ones $x_0x_1x_2\ldots$. (Throughout this paper x_{i-1} will denote the ith digit of the binary representation of a 2-adic integer x.) Note that $\mathbb{Z} \subseteq \mathbb{Z}_2$. For example, $13 = 1 \cdot 2^0 + 0 \cdot 2^1 + 1 \cdot 2^2 + 1 \cdot 2^3$, so the 2-adic binary representation of 13 is $1011\overline{0}$, where the overbar represents repeating digits as in decimal notation. The binary representation of -1 is $\overline{1}$, since $\overline{1} + 1 = 1\overline{1} + 1\overline{0} = \overline{0} = 0$.

By interpreting $\mathbb{Z}_2$ as the set of all binary sequences, there is a natural topology on $\mathbb{Z}_2$, namely the product topology induced by the discrete topology on $\{0, 1\}$. This topology is also induced by the metric δ on $\mathbb{Z}_2$ defined by $\delta(x, y) = 2^{-k}$ where k is the smallest natural number such that $x_k \neq y_k$.

The shift dynamical system, $S : \mathbb{Z}_2 \to \mathbb{Z}_2$, is a well-known map, continuous with respect to the 2-adic topology, defined by $S(x_0 x_1 x_2 \ldots) = x_1 x_2 x_3 \ldots$. This map can be extended to the shift map σ on binary bi-infinite sequences $\ldots x_{-2} x_{-1} x_0 x_1 x_2 \ldots$ by defining $\sigma(x) = y$ where $y_i = x_{i+1}$ for all integers i.

In [5], Hedlund classified all continuous endomorphisms of the shift dynamical system σ on bi-infinite sequence space ($\{0, 1\}^{\mathbb{Z}}$ with the product topology). Lind and Marcus [4] also stated this result, referring to the continuous endomorphisms of σ as *sliding block codes*.

In section 2, we will show that the continuous endomorphisms of S on $\mathbb{Z}_2$ can be classified as follows. For each $n \in \mathbb{Z}^+$, let $\mathcal{B}_n$ be the set of all binary sequences (or *blocks*) of length n. Then every continuous endomorphism of S is induced by a function $f : \mathcal{B}_n \to \{0, 1\}$ for some n. The endomorphism induced by such an f is the map $f_\infty : \mathbb{Z}_2 \to \mathbb{Z}_2$ defined by $f_\infty(x) = y_0 y_1 y_2 \ldots$ where $y_i = f(x_i x_{i+1} \ldots x_{i+n-1})$ for all $i \in \mathbb{N}$. These results are analogous to those already obtained for σ on $\{0, 1\}^{\mathbb{Z}}$.

These endomorphisms have applications to the famous $3x + 1$ conjecture. This conjecture states that the T-orbit $\{T^i(x)\}_{i=0}^{\infty}$ of any positive integer x contains 1, where $T : \mathbb{Z}_2 \to \mathbb{Z}_2$ is defined by

$$T(x) = \begin{cases} x/2 & \text{if } x \text{ is even} \\ (3x+1)/2 & \text{if } x \text{ is odd} \end{cases}.$$

In [3], Lagarias proved that there exists a continuous conjugacy Φ from S to T, whose inverse is also continuous. Since conjugacies preserve dynamics (fixed points, cycles, divergent orbits, etc.), the dynamics of S are the same as those of T. Furthermore, we can combine these results to classify all continuous endomorphisms of T. A map H is a continuous endomorphism of T if and only if $H = \Phi \circ f_\infty \circ \Phi^{-1}$ for some continuous endomorphism f_∞ of S.

Hedlund also showed that exactly two of the continuous endomorphisms of σ are autoconjugacies. It can be shown that this is true for $\mathbb{Z}_2$ as well (cf. [5], [6]). The two continuous autoconjugacies of S are the bit complement map $V = f_\infty$ where f is the map sending the block 0 to 1 and the block 1 to 0, and the identity map $\mathcal{I} = \mathbf{1}_{\mathbb{Z}_2}$ (induced by the map sending 0 to 0 and 1 to 1). Monks and Yazinski [6] investigated the corresponding autoconjugacies of T, namely $\Omega = \Phi \circ V \circ \Phi^{-1}$ and the identity map, respectively.

Continuing the line of research of Monks and Yazinski, it is natural to investigate the continuous endomorphisms of S which are not autoconjugacies. Note that each of these maps, in addition to being an endomorphism of S, is a dynamical system in its own right.

As such, it is natural to ask which of these dynamical systems are conjugate to S (and hence to T).

Let $f : B_2 \to \{0, 1\}$ be defined by $f(00) = f(11) = 0$ and $f(01) = f(10) = 1$, and define the discrete derivative $D : \mathbb{Z}_2 \to \mathbb{Z}_2$ by $D = f_\infty$. In section 5, we find that D is in fact conjugate to T. Furthermore, the dynamical systems D, S, and their "duals" (formed by interchanging the symbols 0 and 1) are the only endomorphisms of the shift dynamical system having a certain property (see section 3, Theorem 3.3). In section 4, we thoroughly investigate the dynamics of $D : \mathbb{Z}_2 \to \mathbb{Z}_2$, and apply these results to the $3x + 1$ conjecture in section 5.

2 Continuous endomorphisms of the shift map

We begin by classifying all continuous endomorphisms of the shift dynamical system $S : \mathbb{Z}_2 \to \mathbb{Z}_2$. As in the classification of the continuous endomorphisms of the shift map on bi-infinite sequence space, each such endomorphism is characterized by a "block code" as follows.

Definition 1 *Let $\mathcal{B}_n$ denote the set of all length-n sequences $x_0x_1 \dots x_{n-1}$ where each $x_i \in \{0, 1\}$. For any function $f : \mathcal{B}_n \to \{0, 1\}$, we define $f_\infty : \mathbb{Z}_2 \to \mathbb{Z}_2$ by $f_\infty(x) = y$ where $y_i = f(x_ix_{i+1} \dots x_{i+n-1})$.*

Theorem 2.1 *A map $F : \mathbb{Z}_2 \to \mathbb{Z}_2$ is a continuous endomorphism of the shift map S if and only if there is a positive integer n such that $F = f_\infty$ for some $f : \mathcal{B}_n \to \{0, 1\}$.*

Proof. First note that $\mathbb{Z}_2$ is homeomorphic to the (middle thirds) Cantor set. (See [2].) The Cantor set is a closed and bounded subset of $\mathbb{R}$, so it is compact by the Heine-Borel theorem. Hence, $\mathbb{Z}_2$ is a compact metric space.

Let n be a positive integer, and let $f : \mathcal{B}_n \to \{0, 1\}$ be arbitrary. We show f_∞ is a continuous endomorphism of S.

To show f_∞ is continuous, we show that the inverse image of every open ball is open. Let $B(x, \epsilon)$ be an arbitrary open ball in the metric space $\mathbb{Z}_2$. Let k be the smallest nonnegative integer such that $2^{-k} < \epsilon$. Then $B(x, \epsilon)$ is the set of all 2-adic integers y such that the first k digits of y are the same as the first k digits of x.

Let $a \in f_\infty^{-1}(B(x, \epsilon))$ be arbitrary, and let $b \in B(a, 2^{-(k+n-2)})$. Note that the first $k + n - 1$ digits of b are $a_0 \dots a_{k+n-2}$. Then for any nonnegative integer $m \leq k - 1$, we have $(f_\infty(b))_m = f(b_mb_{m+1} \dots b_{m+n-1}) = f(a_ma_{m+1} \dots a_{m+n-1}) = x_m$. Hence the first k digits of $f_\infty(b)$ are the same as those of x, so it follows that $f_\infty(b) \in B(x, \epsilon)$. Since b was arbitrary, it follows that any member of $B(a, 2^{-(k+n-2)})$ maps to an element of $B(x, \epsilon)$ under f_∞. Hence, $B(a, 2^{-(k+n-2)}) \subset f_\infty^{-1}(B(x, \epsilon))$. Since a was arbitrary, it follows that $f_\infty^{-1}(B(x, \epsilon))$ is open, as desired.

To show f_∞ is an endomorphism of S, let $x \in \mathbb{Z}_2$ be arbitrary. Then for any positive integer i,

$$\begin{aligned}(f_\infty(S(x)))_i &= f(S(x)_i S(x)_{i+1} \ldots S(x)_{i+n-1}) \\ &= f(x_{i+1}x_{i+2}\ldots x_{i+n}) \\ &= (f_\infty(x))_{i+1} \\ &= (S(f_\infty(x)))_i\end{aligned}$$

Hence, f_∞ is a continuous endomorphism of S.

It now remains to show that such maps are the only continuous endomorphisms of S. Let $F : \mathbb{Z}_2 \to \mathbb{Z}_2$ be a continuous endomorphism of S. Since $\mathbb{Z}_2$ is a compact metric space and F is continuous, it follows by the Heine-Cantor theorem that F is uniformly continuous. Hence, choosing $\epsilon = 1$, there is a positive real number $\delta > 0$ such that any two elements x and y of $\mathbb{Z}_2$ which are separated by at most δ have the property that the distance between $F(x)$ and $F(y)$ is less than $\epsilon = 1$, i.e. they match in the first digit.

Let n be the smallest positive integer such that $2^{-n} < \delta$. Then any two elements x and y having $x_0 \ldots x_{n-1} = y_0 \ldots y_{n-1}$ satisfy $(F(x))_0 = (F(y))_0$. We can now define the map $f : \mathcal{B}_n \to \{0, 1\}$ by $f(a_0a_1 \ldots a_{n-1}) = (F(a_0a_1 \ldots a_{n-1}000 \ldots))_0$. We show that $F = f_\infty$.

Since F is an endomorphism of S, we have $F \circ S = S \circ F$. We have that $F(x)_0 = f(x_0x_1 \ldots x_{n-1}) = f_\infty(x)_0$ for any x. We use this as the base case to show by induction that $F(x)_i = f_\infty(x)_i$ for any nonnegative integer i and $x \in \mathbb{Z}_2$. Let i be a positive integer and assume $F(x)_{i-1} = f_\infty(x)_{i-1}$ for any $x \in \mathbb{Z}_2$. Then since f_∞ commutes with S by the above argument, we have

$$\begin{aligned}(F(x))_i &= (S(F(x)))_{i-1} \\ &= (F(S(x)))_{i-1} \\ &= (f_\infty(S(x)))_{i-1} \\ &= (S(f_\infty(x)))_{i-1} \\ &= (f_\infty(x))_i\end{aligned}$$

This completes the induction. ■

3 Conjugacies to the shift dynamical system

For any $x, y \in \mathbb{Z}_2$, we write $x \underset{n}{\equiv} y$ if x is congruent to y mod 2^n, i.e. if the binary representations of x and y match in the first n digits. We extend this notation to include finite sequences, for example, $1\overline{011} \underset{2}{\equiv} 100$. Lagarias defined Φ^{-1} by $\Phi^{-1}(x) = a_0a_1a_2\ldots$ where $a_i \underset{1}{\equiv} T^i(x)$. We call Φ^{-1} the T-*parity vector function* and generalize this definition as follows.

Definition 2 *Let $F : \mathbb{Z}_2 \to \mathbb{Z}_2$. The F-**parity vector function** is the map $P_F : \mathbb{Z}_2 \to \mathbb{Z}_2$ given by $P_F(x) = a_0a_1a_2\ldots$ where $a_i \in \{0, 1\}$ and $a_i \underset{1}{\equiv} F^i(x)$ for all $i \in \mathbb{N}$.*

It is easily shown that the parity vector function P_F of every dynamical system $F : \mathbb{Z}_2 \to \mathbb{Z}_2$ is a morphism from F to S. To see this, let $x \in \mathbb{Z}_2$ and let $a = P_F(x)$. Then $S(P_f(x)) = a_1a_2a_3\ldots$ by the definition of S. By the definition of P_F, $P_F(F(x)) = b_0b_1b_2\ldots$ where $b_i \underset{1}{\equiv} F^i(F(x))$. Thus $b_i \underset{1}{\equiv} F^{i+1}(x) \underset{1}{\equiv} a_{i+1}$ for all $i \in \mathbb{N}$, so $P_F(F(x)) = S(P_F(x))$. Therefore $P_F \circ F = S \circ P_F$.

Note that F is not assumed to be continuous in the definition above. In the case that F is continuous with respect to the 2-adic topology, the composition of continuous functions F^i is also continuous for each i. Thus, if F is continuous then its parity vector function P_F is continuous as well.

Since every parity vector function is a morphism, it is natural to ask which of these are bijections and therefore conjugacies. The following theorem classifies all functions that are conjugate to S by their parity vector functions.

Theorem 3.1 *Let $F : \mathbb{Z}_2 \to \mathbb{Z}_2$, not necessarily continuous. Then P_F is a conjugacy from F to S if and only if $F = P^{-1} \circ S \circ P$ for some parity-preserving bijection $P : \mathbb{Z}_2 \to \mathbb{Z}_2$ (and in this situation $P_F = P$).*

Proof. Assume P_F is a conjugacy from F to S. Then $F = P_F^{-1} \circ S \circ P_F$ by the definition of conjugacy. By definition, P_F is parity-preserving, since $P_F(x) \underset{1}{\equiv} x$.

Now assume that there exists a parity-preserving bijection $P : \mathbb{Z}_2 \to \mathbb{Z}_2$ such that $F = P^{-1} \circ S \circ P$. It follows by induction on n that $F^n = P^{-1} \circ S^n \circ P$ for all $n \in \mathbb{Z}^+$.

Let $x \in \mathbb{Z}_2$. Then for all $n \in \mathbb{Z}^+$, $F^n(x) \underset{1}{\equiv} P^{-1}(S^n(P(x))) \underset{1}{\equiv} S^n(P(x))$ since P is parity-preserving. Let $a = P(x)$. Then $S^n(P(x)) \underset{1}{\equiv} a_n$, so $F^n(x) \underset{1}{\equiv} a_n$ for all n, and thus $P(x) = P_F(x)$. Since x was arbitrary, $P = P_F$. Also, we know P is a conjugacy from F to S, so P_F is a conjugacy from F to S as well. ■

Lagarias [3] showed that $\Phi^{-1} = P_T$ is bijective by showing it has a property later named in [1]. Bernstein and Lagarias called a function $h : \mathbb{Z}_2 \to \mathbb{Z}_2$ **solenoidal** if for all $k \in \mathbb{Z}^+$, $x \underset{k}{\equiv} y \Leftrightarrow h(x) \underset{k}{\equiv} h(y)$. Such a map induces a permutation of $\mathbb{Z}_2/2^k\mathbb{Z}_2$ for all $k \in \mathbb{Z}^+$.

Bernstein and Lagarias [1] also showed that any solenoidal map $h : \mathbb{Z}_2 \to \mathbb{Z}_2$ is an isometry (bijective and continuous with continuous inverse). Since P_F is a morphism from F to S, we obtain the following corollary.

Corollary 3.2 *Let $F : \mathbb{Z}_2 \to \mathbb{Z}_2$. If P_F is solenoidal, then F is continuous and P_F is a conjugacy from F to S.*

Hence, we can prove that a function is conjugate to the shift map by showing that its parity vector function is solenoidal. In particular, it is of interest to determine which continuous endomorphisms of S have a solenoidal parity vector function. In order to classify these, we define a specific endomorphism D as follows.

Definition 3 *Let $f : B_2 \to \{0,1\}$ be the map $\{(00,0),(01,1),(10,1),(11,0)\}$. We define the **discrete derivative** $D : \mathbb{Z}_2 \to \mathbb{Z}_2$ by $D = f_\infty$.*

Note that $D(x)$ is obtained by replacing each subsequence $x_i x_{i+1}$ of the 2-adic binary representation of x with

$$x_i' = |x_i - x_{i+1}|,$$

so D resembles a discrete derivative, explaining our nomenclature. (The natural extension of this map to bi-infinite sequences has been discussed in [4], pp. 4, 16.)

Let $V : \mathbb{Z}_2 \to \mathbb{Z}_2$ be the map $V(x) = -1 - x$. Note that $V(x)$ is obtained by interchanging the symbols 0 and 1 in the binary representation of x. The "dual" $V \circ D$ of D is induced by $\{(00,1),(01,0),(10,0),(11,1)\}$ and is essentially the same as D if one were to interchange the symbols 0 and 1. For simplicity of notation we let $\mathcal{P} = P_D$.

Theorem 3.3 *The functions D, $V \circ D$, S, and $V \circ S$ are the only continuous endomorphisms of S with solenoidal parity vector functions.*

Combining this theorem with Corollary 3.2, we obtain the following result.

Corollary 3.4 *D is conjugate to S by its parity vector function $\mathcal{P}$.*

Before we present the proof of Theorem 3.3 we first prove two technical lemmas.

Definition 4 *For every positive integer $n \geq 2$, define $d : B_n \to B_{n-1}$ by $d(x_0 x_1 \ldots x_{n-1}) = y_0 y_1 \ldots y_{n-2}$ where $y_i = |x_i - x_{i+1}|$ for $0 \leq i \leq n-2$.*

Note that d is essentially D defined on finite sequences.

Lemma 3.5 *Let $x \in \mathbb{Z}_2$, $n \in \mathbb{Z}^+$, and $y = D^n(x)$. For all $i \in \mathbb{N}$, $y_i = d^n(x_i x_{i+1} \ldots x_{i+n})$.*

Proof. We proceed by induction on n. For the base case, $n = 1$, we see that for all i, $y_i = |x_i - x_{i+1}| = d(x_i x_{i+1})$ by the definition of D and d.

Assume the assertion is true for n, and let $i \in \mathbb{N}$. Then $d^{n+1}(x_i x_{i+1} \ldots x_{i+n+1}) = d^n(d(x_i x_{i+1} \ldots x_{i+n+1})) = d^n(z_i z_{i+1} \ldots z_{i+n})$ where $z_j = |x_j - x_{j+1}|$ for all j. Note that $D(x) = z_0 z_1 z_2 \ldots$ by the definition of D. Let $y = D^n(D(x))$. By the inductive hypothesis, we have $y_i = d^n(z_i z_{i+1} \ldots z_{i+n})$. Thus $D^{n+1}(x) = D^n(D(x)) = y$ and $d^{n+1}(x_i x_{i+1} \ldots x_{i+n+1}) = d^n(z_i z_{i+1} \ldots z_{i+n}) = y_i$, so our induction is complete. ■

Lemma 3.6 *Let $n \in \mathbb{Z}^+$, $x_0 x_1 \ldots x_{n-1} x_n \in B_{n+1}$, and $v = 1 - x_n$. Then $d^n(x_0 x_1 \ldots x_{n-1} x_n) \neq d^n(x_0 x_1 \ldots x_{n-1} v)$.*

Proof. Again, we show this by induction on n. The base case, $n = 1$, is clearly true since $d(01) \neq d(00)$ and $d(11) \neq d(10)$.

Let $n \in \mathbb{Z}^+$ and assume the assertion is true for n. Let $x_0 x_1 \ldots x_n x_{n+1} \in B_{n+2}$ and define $v = 1 - x_{n+1}$. Let $d(x_0 x_1 \ldots x_n x_{n+1}) = y_0 y_1 \ldots y_{n-1} y_n$. Then $d(x_0 x_1 \ldots x_n v) =$

$y_0y_1\ldots y_{n-1}w$ where $w = d(x_nv)$. We know $w = d(x_nv) \neq d(x_nx_{n+1}) = y_n$, and since $w, y_n \in \{0,1\}$, we conclude that $w = 1 - y_n$. By the inductive hypothesis, we have

$$\begin{aligned} d^{n+1}(x_0x_1\ldots x_nx_{n+1}) &= d^n(d(x_0x_1\ldots x_nx_{n+1})) \\ &= d^n(y_0y_1\ldots y_{n-1}y_n) \\ &\neq d^n(y_0y_1\ldots y_{n-1}w) \\ &= d^n(d(x_0x_1\ldots x_nv)) \\ &= d^{n+1}(x_0x_1\ldots x_nv) \end{aligned}$$

and the induction is complete. ∎

We are now ready to prove Theorem 3.3.

Proof. We first show that $\mathcal{P}$ is solenoidal. Let $k \in \mathbb{Z}^+$ and $x \in \mathbb{Z}_2$. For all $i \leq k-1$, we have by Lemma 3.5 that $D^i(x) \underset{1}{\equiv} d^i(x_0x_1\ldots x_i)$. Thus the finite sequence $a_0\ldots a_{k-1}$ where $a_i \underset{1}{\equiv} D^i(x)$ is entirely determined by the first k digits of x, i.e. $x \underset{k}{\equiv} y \Rightarrow \mathcal{P}(x) \underset{k}{\equiv} \mathcal{P}(y)$.

Let $x, y \in \mathbb{Z}_2$ be such that $\mathcal{P}(x) \underset{k}{\equiv} \mathcal{P}(y)$ and let $a_0\ldots a_{k-1}$ be the first k digits of $\mathcal{P}(x)$ and $\mathcal{P}(y)$. We will show that $x \underset{k}{\equiv} y$. Assume to the contrary that $x \underset{k}{\not\equiv} y$. Then $x_0x_1\ldots x_{k-1} \neq y_0y_1\ldots y_{k-1}$. Let j be the smallest nonnegative integer such that $x_j \neq y_j$ (note that $j < k$), so that $y_0y_1\ldots y_{j-1} = x_0x_1\ldots x_{j-1}$ and $y_j = 1 - x_j$. Then by Lemma 3.5, we have $a_j \underset{1}{\equiv} D^j(x) \underset{1}{\equiv} d^j(x_0x_1\ldots x_j)$ and $a_j \underset{1}{\equiv} D^j(x) \underset{1}{\equiv} d^j(y_0y_1\ldots y_j) = d^j(x_0x_1\ldots x_{j-1}y_j)$. But by Lemma 3.6, $d^j(x_0x_1\ldots x_j) \neq d^j(x_0x_1\ldots x_{j-1}y_j)$, so $a_j \neq a_j$, a contradiction. We conclude that $x \underset{k}{\equiv} y$, and hence $\mathcal{P}$ is solenoidal.

Observe that $V \circ D$ is induced by $\{(00,1),(01,0),(10,0),(11,1)\}$, which is exactly the same map as that which induces D except with 0 and 1 interchanged. With this in mind, we see that since $\mathcal{P}$ is solenoidal, $P_{V\circ D}$ must be solenoidal as well.

For P_S, let $x \in \mathbb{Z}_2$. By the definition of S, for all $k \in \mathbb{N}$, $S^k(x) \underset{1}{\equiv} x_k$. Thus $P_S(x) = x_0x_1x_2\ldots = x$ and therefore $P_S = \mathcal{I}$. Since $\mathcal{I}$ is clearly solenoidal, P_S is as well.

Let $v_i = 1 - x_i$ for all $i \in \mathbb{N}$. Note that the "dual" shift map $V \circ S$ is induced by the function $\{(00,1),(01,0),(10,1),(11,0)\}$, so $V \circ S\,(x) = v_1v_2v_3\ldots$. Similarly, $(V \circ S)^2\,(x) = x_2x_3x_4\ldots$. Continuing this pattern, it follows by induction that

$$(V \circ S)^n\,(x) = \begin{cases} x_nx_{n+1}x_{n+2}\ldots & \text{if } n \text{ is even} \\ v_nv_{n+1}v_{n+2}\ldots & \text{if } n \text{ is odd} \end{cases}$$

Taking the $V \circ S$-orbit of x mod 2, we obtain $P_{V\circ S}(x) = x_0v_1x_2v_3x_4v_5\ldots$. This implies that the first k digits of $P_{V\circ S}(x)$ are entirely determined by the first k digits of x and vice versa, and thus $P_{V\circ S}$ is solenoidal.

We now know that the parity vector functions of D, $V \circ D$, S, and $V \circ S$ are solenoidal. To show that these are the only ones, we first eliminate all endomorphisms induced by a map $f : B_1 \to \{0,1\}$. Clearly P_V and $P_{\mathcal{I}}$ are not solenoidal, since $P_V(x)$ is either $\overline{10}$ or $\overline{01}$ for all x by the definition of V, and $P_{\mathcal{I}}(x)$ is either $\overline{1}$ or $\overline{0}$ for all x by the definition of $\mathcal{I}$. The trivial maps induced by $\{(0,0),(1,0)\}$ and $\{(0,1),(1,1)\}$ map everything to $\overline{0}$ and $\overline{1}$ respectively, and thus their parity vector functions are not solenoidal.

We now examine endomorphisms induced by $f : B_2 \to \{0,1\}$. There are sixteen such maps, four of which are equivalent to the endomorphisms induced by a map $f : B_1 \to \{0,1\}$. For example, if $s = \{(00,0),(01,0),(10,1),(11,1)\}$, then $f_\infty = \mathcal{I}$ since the second digit is irrelevant. Another four are D, $V \circ D$, S, and $V \circ S$. The remaining eight maps are induced by a function which sends three of $00, 01, 10, 11$ to 0 and the other to 1 or vice versa. Consider as an illustrative case $s = \{(00,1),(01,1),(10,1),(11,0)\}$. In this case, f_∞ never maps an even 2-adic integer to an even 2-adic integer, since whether x_0x_1 is 00 or 01, $f_\infty(x)$ begins with 1. Thus $P_{f_\infty}(x)$ cannot have 00 as its first two digits, and it is not solenoidal. The other seven cases are similar.

Finally, we show by induction that for any $n \geq 1$ and any $f : B_n \to \{0,1\}$, either $f_\infty \in \{D, V \circ D, S, V \circ S\}$ or P_{f_∞} is not solenoidal. The base cases $n = 1$ and $n = 2$ are done above.

Let $n \geq 2$, assume the assertion is true for n, and let $f : B_{n+1} \to \{0,1\}$. We consider two cases.

Case 1: Suppose that for all $b = b_0b_1 \dots b_n$ and $c = c_0c_1 \dots c_n \in B_{n+1}$, $s(b) = s(c)$ whenever $b \underset{n}{\equiv} c$. Then $f_\infty = t_\infty$ where $t : B_n \to \{0,1\}$ is defined by $t(b_0b_1 \dots b_{n-1}) = s(b_0b_1 \dots b_{n-1}0) = s(b_0b_1 \dots b_{n-1}1)$. By the inductive hypothesis, either t_∞ is a member of $\{D, V \circ D, S, V \circ S\}$ or P_{t_∞} is not solenoidal, and we are done.

Case 2: Suppose that for some $b_0b_1 \dots b_{n-1} \in B_n$, the digits $s(b_0b_1 \dots b_{n-1}0)$ and $s(b_0b_1 \dots b_{n-1}1)$ are distinct. Let $x, y \in \mathbb{Z}_2$ be such that $x \underset{n+1}{\equiv} b_0b_1 \dots b_{n-1}0$ and $y \underset{n+1}{\equiv} b_0b_1 \dots b_{n-1}1$. Then $f_\infty(x) \underset{1}{\not\equiv} f_\infty(y)$, and thus $P_{f_\infty}(x) \underset{2}{\not\equiv} P_{f_\infty}(y)$. Also, since $n \geq 2$, we have $x \underset{2}{\equiv} y$. Hence, P_{f_∞} does not induce a permutation on $\mathbb{Z}_2/2^2\mathbb{Z}_2$, so P_{f_∞} is not solenoidal.

This completes the induction, and we conclude that D, $V \circ D$, S, and $V \circ S$ are the only endomorphisms of S with solenoidal parity vector functions. ■

4 Dynamics of D

Let us consider the implications of Theorem 3.3 and Corollary 3.4. The map D, although defined as a specific endomorphism of S, is actually conjugate to S when viewed as a dynamical system on its own. In addition, D is special in that only D, S itself, and their duals $V \circ D$ and $V \circ S$ have solenoidal parity vector functions. This provides incentive to further investigate the dynamical system $D : \mathbb{Z}_2 \to \mathbb{Z}_2$.

To begin our investigation of the dynamics of D, we observe some properties of the function itself.

Lemma 4.1 *Let $x \in \mathbb{Z}_2$ and $y = D(x)$. Then for any $i \in \mathbb{N}$, $y_i = |x_i - x_{i+1}|$, $x_{i+1} = |x_i - y_i|$, and $x_i = |x_{i+1} - y_i|$.*

Proof. Let $i \in \mathbb{N}$. There are four cases to consider: $x_ix_{i+1} = 00$, 01, 10, or 11.

Case 1: Suppose $x_ix_{i+1} = 01$. By the definition of D, $y_i = |x_i - x_{i+1}| = 1$. Also, $x_{i+1} = 1 = |0 - 1| = |x_i - y_i|$ and $x_i = 0 = |1 - 1| = |x_{i+1} - y_i|$.

The remaining three cases are similar. ■

The symmetry of D revealed by Lemma 4.1 implies a surprising and beautiful symmetry of the function $\mathcal{P}$, the D-parity vector function.

Theorem 4.2 *$\mathcal{P}^2 = \mathcal{I}$. Equivalently, $\mathcal{P} = \mathcal{P}^{-1}$.*

Proof. Let $x \in \mathbb{Z}_2$, and let A be the infinite matrix defined as follows. For all $i, j \in \mathbb{N}$, $A[i, j]$ is a_j where $a = D^i(x)$, i.e. the $i+1$st row of A consists of the digits of $D^i(x)$. Note that the leftmost column of A (with $j = 0$) consists of the digits of $\mathcal{P}(x)$.

By Lemma 4.1, we see that for all $i, j \in \mathbb{N}$, $A[i, j+1] = |A[i, j] - A[i+1, j]|$. Let $j \in \mathbb{N}$. Define $d_i = A[i, j]$ and $e_i = A[i, j+1]$for all i. Then for all $i \in \mathbb{N}$, $e_i = |d_i - d_{i+1}|$, so by the definition of D, $D(d_0 d_1 d_2 \ldots) = e_0 e_1 e_2 \ldots$. Thus the 2-adic integer formed by the entries of the $j+1$st column in A is D of the 2-adic integer formed by the jth column for any j. This implies that for all $j \in \mathbb{N}$, the digits of $D^j(\mathcal{P}(x))$ are the entries of the $j+1$st column of A, so $D^j(\mathcal{P}(x)) \underset{1}{\equiv} A[0, j] = x_j$. By the definition of $\mathcal{P}$, $\mathcal{P}(\mathcal{P}(x)) = x_0 x_1 x_2 \ldots = x$. We conclude that $\mathcal{P}^2 = \mathcal{I}$. ■

Theorem 4.2 shows, remarkably, that the D-parity vector of the D-parity vector of a 2-adic integer is itself. In other words, $\mathcal{P}$ is an involution.

It is well-known that any function $h : X \to Y$ induces an equivalence relation $\approx$ on X defined by $x \approx y$ if and only if $h(x) = h(y)$. This equivalence relation in turn induces a quotient set Q_h of equivalence classes mod $\approx$. Consider the quotient set Q_D induced by D. Due to the symmetry of D shown in Lemma 4.1, we have the following:

Theorem 4.3 $Q_D = \{\{x, V(x)\} \mid x \in \mathbb{Z}_2\}$.

Proof. Let $x, y \in \mathbb{Z}_2$ and $v = V(x)$. Assume $y = D(x)$. By Lemma 4.1,

$$x_{i+1} = |x_i - y_i| \tag{4.1}$$

for all $i \geq 0$. If $x_0 = 0$, equation (4.1) is a recursion for the sequence $x_0, x_1, x_2, \ldots$ and thus there is exactly one even x such that $D(x) = y$. Similarly, there is exactly one odd x such that $D(x) = y$. Therefore, each class in the quotient set induced by D has two elements, one even and one odd. By the definition of V, $v_i = 1 - x_i$ for all i. Thus for all i, $|v_i - v_{i+1}| = |(1 - x_i) - (1 - x_{i+1})| = |x_i - x_{i+1}| = y_i$ and so $D(V(x)) = y = D(x)$. We conclude that each equivalence class mod $\approx$ consists of two elements, x and $V(x)$. ■

4.1 Periodic Points

It is desirable to classify the fixed points and periodic points of any dynamical system. There are exactly two fixed points of S, namely $\overline{0}$ and $\overline{1}$. Since D is conjugate to S there are exactly two fixed points of D, namely $\overline{0}$ and $1\overline{0}$. To classify the remaining periodic points of D, we introduce some new notation.

Definition 5 *Let x be a 2-adic integer with an eventually repeating binary representation $x_0x_1\ldots x_{t-1}\overline{x_tx_{t+1}\ldots x_{t+m-1}}$. Then x is in **reduced form** if and only if $x_{t-1}\neq x_{t+m-1}$ and m is the least integer such that x can be expressed in this form. For any x having reduced form $x_0x_1\ldots x_{t-1}\overline{x_tx_{t+1}\ldots x_{t+m-1}}$, we define the S**-period length** $\|x\|=m$ and the S**-preperiod length** $\underline{x}=t$.*

Note that x is cyclic for S if and only if $\underline{x}=0$.

Definition 6 *An eventually repeating 2-adic integer that has reduced form*

$$x_0x_1\ldots x_{t-1}\overline{x_tx_{t+1}\ldots x_{t+m-1}}$$

*is **half-flipped** if and only if m is even and for all $i\geq t$, $x_i=1-x_{i+m/2}$.*

For instance, the 2-adic integers $\overline{1100}$ and $010\overline{110100}$ are half-flipped.

In order to avoid confusion between 2-adic integers which are periodic (or eventually periodic) points of D and those having repeating (or eventually repeating) binary representation, we will refer to the former as **D-periodic** (or **eventually D-periodic**) and the latter as **repeating** or **eventually repeating**. Note that x has an eventually periodic S-orbit if and only if x is eventually repeating. It is much less obvious which 2-adic integers have an eventually periodic D-orbit, so we prove several lemmas about D-orbits to answer this question.

Lemma 4.4 *Let x be an eventually repeating 2-adic integer. Then*

$$\|D(x)\|=\begin{cases}\|x\| & \text{if } x \text{ is not half-flipped}\\ \frac{1}{2}\|x\| & \text{if } x \text{ is half-flipped}\end{cases}$$

Proof. Let $m=\|x\|$ and $t=\underline{x}$, with $x=x_0x_1\ldots x_{t-1}\overline{x_tx_{t+1}\ldots x_{t+m-1}}$ in reduced form. Let $x'=S^t(x)=\overline{x_tx_{t+1}\ldots x_{t+m-1}}$, so that for all $i\in\mathbb{N}$, $x'_i=x'_{m+i}$, i.e. $\|x'\|=\|x\|=m$. Note that since D is an endomorphism of S, $S^t(D(x))=D(S^t(x))=D(x')$, so $\|D(x)\|=\|S^t(D(x))\|=\|D(x')\|$. We proceed to find $\|D(x')\|$.

Let $y=D(x')$ and $n=\|D(x')\|$. For all $i\in\mathbb{N}$, $y_{m+i}=|x'_{m+i}-x'_{i+m+1}|=|x'_i-x'_{i+1}|=y_i$. Thus n divides m.

If x' is half-flipped, then for all i, $x'_i=1-x_{i+m/2}$, and $y_{i+m/2}=|x'_{i+m/2}-x'_{i+m/2+1}|=|1-x'_i-(1-x'_{i+1})|=|x'_i-x'_{i+1}|=y_i$. Therefore

$$x' \text{ is half-flipped} \Rightarrow n\leq\frac{m}{2}. \tag{4.2}$$

Consider the case $x'_0=0$. We have two cases: either $x'_{n-1}=y_{n-1}$ or $x'_{n-1}\neq y_{n-1}$.

Case 1: Suppose $x'_{n-1}=y_{n-1}$. Then by Lemma 4.1, $x'_n=\left|x'_{n-1}-y_{n-1}\right|=0=x'_0$. This being our base case, we show by induction that for all $i\in\mathbb{N}$, $x'_{n+i}=x'_i$. Let $j\in\mathbb{N}$ and assume $x'_{n+j}=x'_j$. Then $x'_{n+j+1}=\left|x'_{n+j}-y_{n+j}\right|=\left|x'_j-y_j\right|=x'_{j+1}$, completing the induction. We now have $m\mid n$ and $n\mid m$, so $n=m$. Thus $\|D(x)\|=\|x\|$. It follows from (4.2) that x is not half-flipped, and the theorem holds in this case.

Case 2: Suppose $x'_{n-1} \neq y_{n-1}$. Then by Lemma 4.1, $x'_n = \left|x'_{n-1} - y_{n-1}\right| = 1 = 1 - x'_0$. This being our base case, we show by induction that for all $i \in \mathbb{N}$, $x'_{n+i} = 1 - x'_i$. Let $j \in \mathbb{N}$ and assume $x'_{n+j} = 1 - x'_j$. Then $x'_{n+j+1} = \left|x'_{n+j} - y_{n+j}\right| = \left|1 - x'_j - y_j\right| \neq |x_j - y_j| = x'_{j+1}$, and therefore $x'_{n+j+1} = 1 - x'_{j+1}$, completing the induction. This implies that $m \neq n$, and since $n \mid m$, we conclude that $n \leq \frac{1}{2}m$. Also, for all $i \in \mathbb{N}$, $x'_{2n+i} = 1 - x'_{n+i} = 1 - (1 - x'_i) = x'_i$. Therefore $m \leq 2n$. Since $n \leq \frac{1}{2}m$ and $\frac{1}{2}m \leq n$, we have $n = \frac{1}{2}m$. Thus $\|D(x')\| = \frac{1}{2}\|x\|$. Finally, making the substitution $n = \frac{1}{2}m$ we have that for all $i \in \mathbb{N}$, $x'_{m/2+i} = 1 - x'_i$, so x is half-flipped as well.

Hence the theorem holds for $x'_0 = 0$. The proof for the case $x'_0 = 1$ is analogous. ■

Lemma 4.5 *Let x be an eventually repeating 2-adic integer. Then for all $k \in \mathbb{N}$, $\underline{D^k(x)} = \underline{x}$.*

Proof. Let $y = D(x)$, $m = \|x\|$, and $t = \underline{x}$, so that

$$x = x_0 x_1 \dots x_{t-1} \overline{x_t x_{t+1} \dots x_{t+m-1}}$$

in reduced form. Then $D(x) = y_0 y_1 \dots y_{t-1} \overline{y_t y_{t+1} \dots y_{t+m-1}}$, but not necessarily in reduced form. We consider two cases: either x is half-flipped or x is not half-flipped.

Case 1: Suppose x is not half-flipped. By Lemma 4.4, $\|D(x)\| = m$. Also, by the definition of t, $x_{t-1} \neq x_{t+m-1}$. Thus

$$y_{t-1} = |x_{t-1} - x_t| \neq |x_{t+m-1} - x_{t+m}| = y_{t+m-1}$$

so $y_0 y_1 \dots y_{t-1} \overline{y_t y_{t+1} \dots y_{t+m-1}}$ is in reduced form. We conclude that $\underline{D(x)} = t = \underline{x}$.

Case 2: Suppose x is half-flipped. By Lemma 4.4, $\|D(x)\| = \frac{1}{2}m$. It follows that $D(x) = y_0 y_1 \dots y_{t-1} \overline{y_t y_{t+1} \dots y_{t+m/2-1}}$. By the definition of half-flipped and t, $x_{t+m/2-1} = 1 - x_{t+m-1} = x_{t-1}$ and $x_{t+m/2} = 1 - x_t$. Therefore

$$\begin{aligned} y_{t-1} &= \left|x_{t-1} - x_t\right| \\ &= \left|x_{t+m/2-1} - (1 - x_{t+m/2})\right| \\ &\neq \left|x_{t+m/2-1} - x_{t+m/2}\right| \\ &= y_{t+m/2-1} \end{aligned}$$

so $y_0 y_1 \dots y_{t-1} \overline{y_t y_{t+1} \dots y_{t+m/2-1}}$ is in reduced form. We conclude that $\underline{D(x)} = t = \underline{x}$.

Therefore, $\underline{D(x)} = \underline{x}$ for all $x \in \mathbb{Z}_2$. It follows by induction that for all $k \in \mathbb{N}$, $\underline{D^k(x)} = \underline{x}$. ■

We are now ready to classify all 2-adic integers which are eventually D-periodic.

Theorem 4.6 *Let $x \in \mathbb{Z}_2$. Then x is eventually D-periodic if and only if it is eventually S-periodic, i.e. its 2-adic binary representation is eventually repeating.*

Proof. Assume that the 2-adic binary representation of x is eventually repeating (so that x is eventually S-periodic), with $x = x_0 x_1 \dots x_{t-1} \overline{x_t x_{t+1} \dots x_{t+m-1}}$ where $t = \underline{x}$ and

$m = \|x\|$. Let a be the greatest odd divisor of m, with $m = a \cdot 2^b$. Lemma 4.4 implies that for any $k, n \in \mathbb{N}$ with $k < n$, $\left\|D^k(x)\right\| = a \cdot 2^{b'}$ and $\|D^n(x)\| = a \cdot 2^{b''}$ for some $b', b'' \in \mathbb{N}$ with $b \geq b' \geq b''$. Hence the sequence $\left\{\log_2\left(\frac{1}{a}\left\|D^k(x)\right\|\right)\right\}_{k=0}^{\infty}$ is a non-increasing sequence of nonnegative integers, and thus is eventually constant. Let β be the minimum value of $\log_2\left(\frac{1}{a}\left\|D^k(x)\right\|\right)$ over all k, so that there exists an $N \in \mathbb{N}$ such that for all $n \geq N$, $\|D^n(x)\| = a \cdot 2^\beta$. Define $c = a \cdot 2^\beta$. For all $n \geq N$, there are at most 2^c possibilities for the repeating digits of $D^n(x)$, and by Lemma 4.5, there are at most $2^{\underline{x}}$ possibilities for the first $\underline{x}$ digits of $D^n(x)$. Thus there are at most $2^c \cdot 2^{\underline{x}} = 2^{c+\underline{x}}$ possibilities for the values of $D^n(x)$ for all $n \geq N$. By the pigeonhole principle, two of $D^N(x), D^{N+1}(x), \ldots, D^{N+2^{c+\underline{x}}}(x)$ are equal, and thus the D-orbit of x is eventually periodic. So if x is eventually repeating then x is eventually D-periodic.

Now assume that the 2-adic representation of x is not eventually repeating, and assume to the contrary that x is eventually D-periodic. Then $\mathcal{P}(x)$ is eventually repeating. So the D-orbit of $\mathcal{P}(x)$ is eventually periodic, and thus $\mathcal{P}(\mathcal{P}(x))$ is eventually repeating as well. But Theorem 4.2 implies $\mathcal{P}(\mathcal{P}(x)) = x$, and x is not eventually repeating by assumption. This contradiction completes the proof. ■

Note that Theorem 4.6 is not a consequence of D being conjugate to S, for $D = \mathcal{P}S\mathcal{P}^{-1} = \mathcal{P}S\mathcal{P}$ implies that x is eventually periodic for D if and only if $\mathcal{P}(x)$ is eventually periodic for S.

In the proof of Theorem 4.6, we found that the S-period length of elements in the D-orbit of x is either divided by 2 or remains constant with each iteration, until the orbit becomes periodic and the S-period length $\|x\|$ stabilizes. However, the value of $\|x\|$ at which it stabilizes may be even. For example, $x = \overline{100111}$ has the periodic D-orbit $\overline{100111}, \overline{101000}, \overline{111001}, \overline{001010}, \overline{011110}, \overline{100010}, \ldots$.

4.2 Eventually Fixed Points

We now classify those 2-adic integers whose D-orbit contains a fixed point (0 or 1).

Lemma 4.7 *Let $n \in \mathbb{N}$ and $a = a_0a_1a_2\ldots a_{2^n-1} \in B_{2^n}$. Then*

$$d^{2^n-1}(a) = \left(\sum_{i=0}^{2^n-1} a_i\right) \bmod 2$$

i.e. $d^{2^n-1}(a) = \begin{cases} 0 & \text{if } a \text{ contains an even number of } 1\text{'s among its digits} \\ 1 & \text{otherwise} \end{cases}$.

Proof. We proceed by induction on n. The base case, $n = 0$, is trivial since $d^{2^0-1}(1) = d^0(1) = 1$ and $d^{2^0-1}(0) = d^0(0) = 0$.

Let $n \in \mathbb{N}$ and assume the assertion is true for n. Let $a_0a_1a_2\ldots a_{2^{n+1}-1} \in B_{2^{n+1}}$, and let $b = a_0a_1a_2\ldots a_{2^n-1}$ and $c = a_{2^n}a_{2^n+1}\ldots a_{2^{n+1}-1}$ be the first and second halves of a. We now consider two cases.

Case 1: Suppose $\sum_{i=0}^{2^{n+1}-1} a_i \underset{1}{\equiv} 0$, i.e. a has an even number of 1's among its digits. We have

$$\left(\sum_{i=0}^{2^n-1} a_i\right) + \left(\sum_{i=2^n}^{2^{n+1}-1} a_i\right) = \sum_{i=0}^{2^{n+1}-1} a_i \underset{1}{\equiv} 0$$

and therefore $\sum_{i=0}^{2^n-1} a_i \underset{1}{\equiv} \sum_{i=2^n}^{2^{n+1}-1} a_i$. By the inductive hypothesis, $d^{2^n-1}(b) = d^{2^n-1}(c)$. Let $z_0 z_1 \ldots z_{2^n}$ be the digits of $d^{2^n-1}(a)$. Note that $z_0 = d^{2^n-1}(b)$ and $z_{2^n} = d^{2^n-1}(c)$, so $z_0 = z_{2^n}$. Now, consider all subsequences of $z_0 z_1 \ldots z_{2^n}$ of length 2. Such a subsequence $z_i z_{i+1}$ is a **switch** if $z_i \neq z_{i+1}$. Clearly, the first and last digit will match if and only if there are an even number of switches, so in this case there are an even number of switches in $z_0 z_1 \ldots z_{2^n}$. Since each 1 in $d(z_0 z_1 \ldots z_{2^n})$ corresponds to a switch in $z_0 z_1 \ldots z_{2^n}$, there are an even number of 1's among the digits of $d(z_0 z_1 \ldots z_{2^n})$. By the definition of d, $d(z_0 z_1 \ldots z_{2^n}) \in B_{2^n}$. Using the inductive hypothesis a second time, we have

$$d^{2^{n+1}-1}(a) = d^{2^n-1}(d(d^{2^n-1}(a)) = d^{2^n-1}(d(z_0 z_1 \ldots z_{2^n})) = 0$$

and the induction is complete.

Case 2: Suppose $\sum_{i=0}^{2^{n+1}-1} a_i \underset{1}{\equiv} 1$. By an argument similar to that of Case 1, we have $d^{2^{n+1}-1}(a) = 1$ and the induction is complete. ■

Theorem 4.8 *Let $n \in \mathbb{N}$ and $a = a_0 a_1 a_2 \ldots a_{2^n} \in B_{2^n+1}$. Then $d^{2^n}(a) = d(a_0 a_{2^n})$.*

Proof. Suppose $d(a)$ has an even number of 1's among its digits. As in the proof of Lemma 4.7, we know there are an even number of switches in a, so $a_0 = a_{2^n}$. But by Lemma 4.7, $d^{2^n-1}(d(a)) = 0 = d(a_0 a_{2^n})$. Similarly, if $d(a)$ has an odd number of 1's among its digits then $a_0 \neq a_{2^n}$, and $d^{2^n-1}(d(a)) = 1 = d(a_0 a_{2^n})$. Thus in all cases $d^{2^n}(a) = d(a_0 a_{2^n})$. ■

Theorem 4.8 gives us an easy method for computing large iterations of D without computing each individual iteration. For example, if we wish to compute $D^8(x_0 x_1 x_2 \ldots)$, we merely compute $d(x_0 x_8)$, $d(x_1 x_9)$, etc., which yields the digits of $D^8(x_0 x_1 x_2 \ldots)$ in one step rather than eight. This technique is also of use in the proof of the following theorem, which classifies the 2-adic integers whose D-orbit is eventually fixed.

Theorem 4.9 *The D-orbit of x is eventually fixed if and only if the reduced form of x is either $\overline{x_0 x_1 \ldots x_{2^n-1}}$ (in which case it eventually maps to 0) or $x_0\overline{x_1 x_2 \ldots x_{2^n}}$ (which eventually maps to 1) for some $n \in \mathbb{N}$.*

Proof. We first show that the D-orbit of x contains 0 if and only if the reduced form of x is $\overline{x_0 x_1 \ldots x_{2^n-1}}$ for some $n \in \mathbb{N}$. Assume the D-orbit of x eventually contains 0. Since $\|0\| = 1$, we know by Lemma 4.4 that $\|x\| = 1 \cdot 2^n$ for some $n \in \mathbb{N}$.

Now, assume to the contrary that $\underline{x} \neq 0$. Then by Lemma 4.5, for all $k \in \mathbb{N}$, $\underline{D^k(x)} = \underline{x} > 0$. However, $\underline{0} = 0$, so the D-orbit of x cannot eventually contain 0. We conclude that our assumption was false and $\underline{x} = 0$. Thus the reduced form of x is $\overline{x_0 x_1 \ldots x_{2^n-1}}$ for some $n \in \mathbb{N}$.

Assume $x = \overline{x_0 x_1 \dots x_{2^n - 1}}$ in reduced form. Let $y = D^{2^n}(x)$. By Theorem 4.8 and Lemma 3.5, we have for all $i \in \mathbb{N}$, $y_i = d(x_i x_{i+2^n})$. Since $x_i = x_{i+2^n}$, $y_i = 0$ for all i and thus $D^{2^n}(x) = \overline{0} = 0$.

We now show that the D-orbit of x contains 1 if and only if the reduced form of x is $x_0\overline{x_1 x_2 \dots x_{2^n}}$ for some $n \in \mathbb{N}$. Since D is an endomorphism of S, we have $S(D^j(x)) = D^j(S(x))$ for all $j \in \mathbb{N}$. Assume $D^k(x) = 1$ for some $k \in \mathbb{N}$. Then $D^k(S(x)) = S(D^k(x)) = S(1) = 0$. By the above argument, $S(x) = \overline{x_1 x_2 \dots x_{2^n}}$ in reduced form for some $n \in \mathbb{N}$. By the definition of S, x either has reduced form $\overline{x_0 x_1 x_2 \dots x_{2^n - 1}}$ or $x_0\overline{x_1 x_2 \dots x_{2^n}}$. By Lemma 4.5, $\underline{x} = \underline{D^k(x)} = \underline{1} = 1$, so $x = x_0\overline{x_1 x_2 \dots x_{2^n}}$ in reduced form.

Assume $x = x_0\overline{x_1 x_2 \dots x_{2^n}}$ in reduced form. By the above argument, $D^{2^n}(S(x)) = D^{2^n}(\overline{x_1 x_2 \dots x_{2^n}}) = 0$. Therefore $S(D^{2^n}(x)) = 0$ as well, so $D^{2^n}(x)$ is either 0 or 1 by the definition of S. By Lemma 4.5, $\underline{D^{2^n}(x)} = \underline{x} = 1$, so $D^{2^n}(x) = 1$. ■

4.3 The D-Orbit of an Integer

Any nonnegative integer is eventually repeating (ending in $\overline{0}$), so all nonnegative integers are eventually D-periodic by Theorem 4.6. Surprisingly, they all are purely periodic points of D with minimum period 2^n for some $n \in \mathbb{N}$, as we now show.

Theorem 4.10 *Let x be a nonnegative integer. Then x is a purely periodic point of D with minimum period 2^n being the smallest power of 2 that is at least as large as the S-preperiod length of x, i.e. $2^n \geq \underline{x}$.*

Proof. Let $t = \underline{x}$. By Lemma 4.5, for any $i \in \mathbb{N}$, $\underline{D^i(x)} = t$ as well. Thus for all $i \in \mathbb{N}$, $2^{t-1} \leq D^i(x) < 2^t$ by the definition of 2-adic integer.

Let $x_0 x_1 x_2 \dots x_{t-1}\overline{0}$ be the 2-adic expansion of x, and $y_0 y_1 \dots y_{t-1}\overline{0}$ the 2-adic expansion of $D^{2^n}(x)$. Then by Theorem 4.8, we have that for all $i \in \mathbb{N}$, $y_i = d^{2^n}(x_i x_{i+1} \dots x_{i+2^n}) = d(x_i x_{i+2^n}) = d(x_i 0) = x_i$. Thus $D^{2^n}(x) = x$, and x is D-periodic with minimum period dividing 2^n. Note that if x is 0 or 1, $2^n = 1$, so 2^n must be the minimum period of x in both of these cases.

Assume that $x > 1$ and the minimum D-period of x is less than 2^n. Since it divides 2^n it must be 2^k for some $k \leq n-1$. Also, since n is the smallest natural number such that $2^n \geq t$, we have $2^{n-1} < t$, and thus $2^k < t$ as well. Let $z_0 z_1 \dots z_{t-1}\overline{0}$ be the 2-adic expansion of $D^{2^k}(x)$. Since $t - 2^k - 1 \geq 0$, we have $z_{t-2^k-1} = d^{2^k}(x_{t-2^k-1} x_{t-2^k} \dots x_{t-1}) = d(x_{t-2^k-1} x_{t-1}) = d(x_{t-2^k-1} 1) \neq x_{t-2^k-1}$. Therefore $D^{2^k}(x) \neq x$, and x is not D-periodic with minimum period 2^k. We conclude that the assumption was incorrect and thus 2^n is the minimum period of x. ■

Negative integers have a 2-adic expansion ending in $\overline{1}$. This is because for any $x \in \mathbb{Z}_2$, $-1 - x = V(x)$ by binary arithmetic, so $-x = V(x) + 1$. Therefore, if x is a positive integer, $-x$ is one more than $V(x)$, which ends in $\overline{1}$. Notice that D of a negative integer is a positive integer, so by Theorem 4.10, the D-orbit of a negative integer enters a cycle of positive integers after one iteration.

These facts are consistent with the duality of $\mathcal{P}$ seen in Theorem 4.2. Given a 2-adic integer x whose reduced form is $\overline{x_0 x_1 \dots x_{2^n-1}}$ or $x_0\overline{x_1 x_2 \dots x_{2^n}}$, we have by Theorem 4.9

that $\mathcal{P}(x)$ is an integer. Also, given a 2-adic integer x which is also an integer, we have by Theorem 4.10 that $\mathcal{P}(x)$ has reduced form $\overline{x_0 x_1 \dots x_{2^n-1}}$ or $x_0\overline{x_1 x_2 \dots x_{2^n}}$.

5 Applications to the $3x+1$ Conjecture

Recall that the $3x+1$ conjecture states that the T-orbit of any positive integer contains 1, or equivalently, eventually enters the $\overline{1,2}$ cycle.

Corollary 3.4 states that $\mathcal{P}$ is a conjugacy from D to S. Also, as stated in the introduction, Φ is a conjugacy from S to T. Since the composition of conjugacies is a conjugacy, this implies that D, the endomorphism of S resembling a discrete derivative, is conjugate to T, the famous $3x+1$ function.

Theorem 5.1 *The map $R = \Phi \circ \mathcal{P}$ is a conjugacy from D to T.*

Thus T and D have the same dynamics, and hence to solve the $3x+1$ conjecture it suffices to have an understanding of the dynamics of D and the correspondence R between the orbits of D and those of T.

Having studied the dynamics of D in Section 4, we turn our attention to understanding the correspondence R. Since $\overline{1,2}$ and $\overline{2,1}$ are the unique 2-cycles of the dynamical system $T : \mathbb{Z}_2 \to \mathbb{Z}_2$ and $\overline{3,2}$ and $\overline{2,3}$ are 2-cycles of $D : \mathbb{Z}_2 \to \mathbb{Z}_2$, these 2-cycles of D must be unique. Thus, since R preserves parity, $R(3) = 1$ and $R(2) = 2$. Similarly, $R(0) = 0$ and $R(1) = -1$ since they are fixed points of corresponding parity of the two dynamical systems.

By an argument similar to the proof of Theorem 4.9, the D-orbit of a 2-adic integer x eventually enters the $\overline{3,2}$ cycle (or, equivalently, the $\overline{2,3}$ cycle) if and only if x has reduced form $x_0 x_1 \overline{x_2 x_3 \dots x_{2^n+1}}$ for some $n \in \mathbb{N}$. However, since an element x in the dynamical system $T : \mathbb{Z}_2 \to \mathbb{Z}_2$ eventually enters the $\overline{1,2}$ cycle if and only if the D-orbit of $R^{-1}(x)$ eventually enters the $\overline{3,2}$ cycle, we have the following equivalence theorem.

Theorem 5.2 *The following statements are equivalent:*

1) The $3x+1$ conjecture is true.

2) For all positive integers m, $R^{-1}(m)$ has reduced form $x_0 x_1 \overline{x_2 x_3 \dots x_{2^n+1}}$ for some $n \in \mathbb{N}$.

Thus it suffices to determine R^{-1} on positive integers in order to solve the $3x+1$ conjecture. In particular, it would suffice to find a tractable formula for $R^{-1}(m)$ for positive integers m.

There is yet another way that D can be of use in solving the $3x+1$ conjecture, and that is in its role as an endomorphism of the shift map.

Recall that Monks and Yazinski [6] defined $\Omega = \Phi \circ V \circ \Phi^{-1}$, and showed that Ω is the unique nontrivial continuous autoconjugacy of T and that $\Omega^2 = \mathcal{I}$. They also defined an equivalence relation $\sim$ on $\mathbb{Z}_2$ by $x \sim y \Leftrightarrow (x = y \text{ or } x = \Omega(y))$. This induces a set of equivalence classes $\mathbb{Z}_2/\!\sim\, = \{\{x, \Omega(x)\} \mid x \in \mathbb{Z}_2\}$, and note that each equivalence class in $\mathbb{Z}_2/\!\sim$ consists of two elements of opposite parity. This enables one to define a parity-neutral map Ψ as follows.

Definition 7 *The* ***parity-neutral*** $3x+1$ ***map*** $\Psi : \mathbb{Z}_2/\!\sim\, \to \mathbb{Z}_2/\!\sim$ *is the map given by* $\Psi(\{x, \Omega(x)\}) = \{T(x), \Omega(T(x))\}$.

Monks and Yazinski also showed that the $3x+1$ conjecture is equivalent to the claim that the Ψ-orbit of any $X \in \mathbb{Z}_2/\!\sim$ contains $\{1, 2\}$.

Making use of the endomorphism D, the following theorem improves upon this result.

Theorem 5.3 *The dynamical system* $T : \mathbb{Z}_2 \to \mathbb{Z}_2$ *is conjugate to* $\Psi : \mathbb{Z}_2/\!\sim\, \to \mathbb{Z}_2/\!\sim$.

Proof. Define $H = \Phi \circ D \circ \Phi^{-1}$. Since D is an endomorphism of S and Φ is a conjugacy from S to T, H is an endomorphism of T. Recall that H induces the quotient set Q_H discussed in Section 4. We now show that $Q_H = \mathbb{Z}_2/\!\sim$. By Theorem 4.3, $D \circ V = D$, so

$$\begin{aligned} H \circ \Omega &= (\Phi \circ D \circ \Phi^{-1}) \circ (\Phi \circ V \circ \Phi^{-1}) \\ &= \Phi \circ D \circ V \circ \Phi^{-1} \\ &= \Phi \circ D \circ \Phi^{-1} \\ &= H \end{aligned}$$

Thus for all $x \in \mathbb{Z}_2$, $H(x) = H(\Omega(x))$, so $\{x, \Omega(x)\}$ is a subset of the equivalence class of x in Q_H.

To see that these are the only elements in the equivalence class of x, let $y \in \mathbb{Z}_2$ and assume $y \neq x$ and $H(y) = H(x)$. Then $\Phi\left(D\left(\Phi^{-1}(x)\right)\right) = \Phi(D(\Phi^{-1}(y)))$, and since Φ and Φ^{-1} are bijections, $\Phi^{-1}(x) \neq \Phi^{-1}(y)$ and $D(\Phi^{-1}(x)) = D(\Phi^{-1}(y))$. Therefore $\Phi^{-1}(x) = V(\Phi^{-1}(y))$ by Theorem 4.3. Thus $x = \Phi \circ V \circ \Phi^{-1}(y) = \Omega(y)$. Therefore, $Q_H = \mathbb{Z}_2/\!\sim$.

Now define $G : \mathbb{Z}_2/\!\sim\, \to \mathbb{Z}_2$ by $G(\{x, \Omega(x)\}) = H(x) = H(\Omega(x))$. By the definition of Q_H, G is injective. Also, since D is surjective and Φ and Φ^{-1} are bijective, H is surjective as well, and therefore G is surjective. Thus G is a bijection. Finally, for any $x \in \mathbb{Z}_2$,

$$\begin{aligned} G(\Psi(\{x, \Omega(x)\})) &= G(\{T(x), T(\Omega(x))\}) \\ &= G(\{T(x), \Omega(T(x))\}) \\ &= H(T(x)) \\ &= T(H(x)) \\ &= T(G(\{x, \Omega(x)\})) \end{aligned}$$

and therefore $G \circ \Psi = T \circ G$.O So G is a conjugacy from Ψ to T. ■

This theorem is fascinating, for it proves that the parity-neutral function Ψ is conjugate to, and thus has the same dynamical structure as, the function T defined piecewise on even and odd 2-adic integers.

6 Conclusion

We have discovered an interesting finite subset of the set of all continuous endomorphisms of S in that D, $V \circ D$, S, and $V \circ S$ are the only such maps whose parity vector functions are solenoidal. In addition, each of these four maps are conjugate to S when viewed as dynamical systems on $\mathbb{Z}_2$, and we have seen that the "discrete derivative" D has fascinating dynamics. In particular, we have proven that x is eventually D-periodic if and only if it is eventually repeating, and have classified all eventually fixed points (Theorem 4.9) and the D-orbits of integers (Theorem 4.10) as well. We have observed that D exhibits remarkable symmetry in that $Q_D = \{\{x, V(x)\} \mid x \in \mathbb{Z}_2\}$ and that $\mathcal{P}$ is an involution. Given that D has such rich structure, it would be of interest to study the dynamics of other continuous endomorphisms of S and their applications as an area of future research.

We have also seen that the map D has applications to other branches of mathematics. Using Lagarias's result that S is conjugate to T, we have demonstrated that D is conjugate to T via R, and thus that to prove the $3x+1$ conjecture, it suffices to show that for all positive integers m, $R^{-1}(m)$ has reduced form $x_0x_1\overline{x_2x_3\dots x_{2^n+1}}$ for some $n \in \mathbb{N}$. Using D, we have also constructed a conjugacy G between T and the parity-neutral function Ψ. Hence, our results open the door to future research on the conjugacies R and G, motivated by the possibility of making progress on the $3x+1$ conjecture.

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