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Decidability and Universality in Symbolic Dynamical Systems

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Abstract. Many different definitions of computational universality for various types of dynamical systems have flourished since Turing's work. We propose a general definition of universality that applies to arbitrary discrete time symbolic dynamical systems. Universality of a system is defined as undecidability of a model-checking problem. For Turing machines, counter machines and tag systems, our definition coincides with the classical one. It yields, however, a new definition for cellular automata and subshifts. Our definition is robust with respect to initial condition, which is a desirable feature for physical realizability.

We derive necessary conditions for undecidability and universality. For instance, a universal system must have a sensitive point and a proper subsystem. We conjecture that universal systems have infinite number of subsystems. We also discuss the thesis according to which computation should occur at the 'edge of chaos' and we exhibit a universal chaotic system.

1. Introduction

Computability is usually defined via universal Turing machines. A Turing machine can be regarded as a dynamical system, i.e., a set of configurations together with a transformation acting on this set.

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A configuration consists of the state of the head and the content of the tape. Computation is done by observing the trajectory of an initial point under iterated transformation.

There is no reason why Turing machines should be the only dynamical systems capable of universal computation. Indeed, such capabilities have been also claimed for artificial neural networks [34, 18], piecewise linear maps [19], analytic maps [20], cellular automata [40], piecewise constant vector fields [2], billiard balls on particular pool tables [13], or a ray of light between a set of mirrors [28]. For all these systems, many particular definitions of universality have been proposed. Most of them mimic the definition of computation for Turing machines: an initial point is chosen, then we observe the trajectory of this point and see whether it reaches some 'halting' set; see for instance [35] and [5]. However, many variants of these definitions are possible and lead to different classes of universal dynamical systems. In particular, there is no consensus for what it means for a cellular automaton to be universal. Moreover, in the presence of noise many of these systems loose their computational properties [1, 25, 14]; see [32, 31, 30] for definitions of analog computation and issues relative to noise and physical realizability.

Another field of investigation is to make a link between the computational properties of a system and its dynamical properties. For instance, attempts have been made to relate 'universal' cellular automata to Wolfram's classification. It has also been suggested that a 'complex' system must be on the 'edge of chaos': this means that the dynamical behavior of such a system is neither simple (i.e., a globally attracting fixed point) nor chaotic; see [40, 27, 7, 24]. Other authors nevertheless argue that a universal system may be chaotic; see [34].

The basic questions we would like to address are the following:

- How to define computationally universality for dynamical systems?
- What are the dynamical properties of a universal system?

A long-term motivation is to answer these questions from the point of view of physics. What physical systems are universal? Is the gravitational N-body problem universal [28]? Is the Navier-Stokes equation universal [29]? However in this paper we focus on *symbolic effective* dynamical systems, i.e., systems defined on the Cantor set $\{0,1\}^{\mathbb{N}}$ or a subset of it, whose transformations are computable. Some motivating examples of such systems are Turing machines, cellular automata and subshifts.

Turing's machine was originally meant as a model of a computation performed by a human operator using paper and pencil [38]. We adapt Turing's reasoning to the case where the human operator does not compute by himself, but relies on a dynamical system to make the computation. The system is said to be computationally universal if the observations made by the human operator allow him to solve any problem that could also be solved by a universal Turing machine. We conclude that a system is universal if some property of its trajectories, such as reachability of a halting set, is r.e.-complete.

In this contribution, rather than considering point-to-point or point-to-set properties, we consider set-to-set properties. Typically, given an initial set and a halting set, we want to know whether there is at least one configuration in the initial set whose trajectory eventually reaches the halting set. We require the initial and halting sets to be clopen (closed and open) sets of the Cantor state space. Clopen sets can be described in a natural way with a finite number of bits. Finally, we do not restrict ourselves to the property 'Is there a trajectory going from U to V?' alone. In a previous paper [10] we have considered properties expressible by temporal logic. In the present paper we consider the wider class of all properties that can be observed by some finite automaton.

This definition addresses the two issues raised above. Firstly, it is a general definition directly applicable to any (effective) symbolic system. Secondly, dealing with clopen sets rather than points takes into account some constraints of physical realizability, such as robustness to noise.

With this definition in mind, we prove necessary conditions for a symbolic system to be universal. In particular, we show that a universal symbolic system is not minimal, not equicontinuous and does not satisfy the shadowing property. We conjecture that a universal system must have infinitely many subsystems, and we show that there is a chaotic system that is universal, contradicting the idea that computation can only happen at the 'edge of chaos'.

Preliminaries are given in Sections 2, 3 and 4. Decidable and universal systems are defined in Sections 5 and 6. In Section 7, necessary conditions for a system to be universal are given, related to minimality, equicontinuity and shadowing property; chaos and edge of chaos are considered in Section 8. The definition of universality is discussed in Section 9.

2. Effective symbolic spaces

A *symbolic space* is a compact metric space whose clopen (closed and open) sets form a countable basis: every open set is a union of clopen sets. The elements of a symbolic space are called *points* or *configurations*. A typical example is the Cantor set $\{0,1\}^{\mathbb{N}}$ endowed with the product topology. The topology is given by the metric $d(x,y) = 2^{-n}$, where n is the index of the first bit on which x and y differ. Note that this metric satisfies the *ultrametric inequality*: $d(x,z) \leq \max(d(x,y), d(y,z))$ for any x, y and z.

If $w \in \{0,1\}^*$ is a finite binary word, then $[w]$ denotes the set of all infinite configurations with prefix w. Sets of this form, usually called *cylinders*, are exactly the balls of the metric space. They are clopen sets and any clopen set of $\{0,1\}^{\mathbb{N}}$ is a finite union of cylinders. Similar distances are defined on the spaces $\{0,1\}^* \cup \{0,1\}^{\mathbb{N}}$, $A^{\mathbb{N}}$, $Q \times A^{\mathbb{Z}}$, $A^{\mathbb{Z}^d}$ where Q and A are finite and d is a positive integer. Closed subsets of the Cantor space are symbolic spaces themselves. The converse is well known to hold as well: Every symbolic space is homeomorphic to a closed subset of the Cantor space and every perfect symbolic space is homeomorphic to the Cantor space. For instance, $\{0,1\}^{\mathbb{Z}}$ is homeomorphic to $\{0,1\}^{\mathbb{N}}$.

To define computational universality, we need effective symbolic spaces, in which we can perform boolean combinations on clopen sets effectively.

Definition 1. An *effective symbolic space* is a pair (X,P), where X is a symbolic space and $P : \mathbb{N} \to 2^X$ is an injective function whose range is the set of all clopen sets of X, such that the intersection and complementation of clopen sets are computable operations. This means that there exist computable functions $f : \mathbb{N} \to \mathbb{N}$ and $g : \mathbb{N} \times \mathbb{N} \to \mathbb{N}$ such that $X \setminus P_n = P_{f(n)}$ and $P_n \cap P_m = P_{g(n,m)}$.

Of course, union of clopen sets is then also computable. Often we denote an effective symbolic space by X rather than (X,P) when no confusion is to be feared. In Cantor space $\{0,1\}^{\mathbb{N}}$, the lexicographic ordering yields a standard enumeration

$$[\lambda], [0], [1], [00], [01], [10], [11], [00] \cup [11], [01] \cup [10], [00] \cup [01] \cup [10], [00] \cup [01] \cup [11], \ldots$$

Other widely used symbolic spaces like $\{0,1\}^* \cup \{0,1\}^{\mathbb{N}}$, $A^{\mathbb{N}^d}$, $A^{\mathbb{Z}^d}$, $Q \times A^{\mathbb{Z}}$, have also their standard enumerations. Note that we could require intersections and complements to be primitive recursive rather than computable, without altering the examples and results of the paper.

Definition 2. Let (X, P) and (Y, Q) be two effective symbolic spaces. An *effective continuous map* is a continuous map $h : X \to Y$ such that $h^{-1}(Q_n) = P_{k(n)}$, for some computable map $k : \mathbb{N} \to \mathbb{N}$. If h is bijective then it is an *effective homeomorphism*, and (X, P) is said to be *effectively homeomorphic* to (Y, Q).

Note that the composition of effective continuous maps is an effective continuous map, the identity is an effective continuous map and the inverse map of an effective homeomorphism is also an effective homeomorphism. In particular, being effectively homeomorphic is an equivalence relation for effective symbolic spaces.

Given an effective symbolic space (X, P), a closed subset Y is said to be *effective*, if the family of clopen sets intersecting Y is decidable. In particular any clopen set is effective. An effective set Y can be endowed with the relative topology, whose clopen sets are all intersections of clopen sets of X with Y. Thus, the enumeration $P_0, P_1, P_2, \dots$ of clopen sets of X yields an enumeration of clopen sets of Y: $Y \cap P_0, Y \cap P_1, Y \cap P_2, \dots$. This enumeration may contain empty sets and repetitions, but we can detect them in an effective way and renumber the sequence accordingly. Hence we get an effective topology for the effective closed set Y. Equivalently, the inclusion $i : Y \hookrightarrow X$ is an effective continuous map.

Proposition 1. Every effective symbolic space is effectively homeomorphic to an effective subset of the Cantor space. Every perfect effective symbolic space is effectively homeomorphic to the Cantor space.

Proof:
Let (X, P) be an effective symbolic space. For every point $x \in X$, construct the infinite configuration $g(x) \in \{0, 1\}^{\mathbb{N}}$, where $g(x)_n = 1$ if and only if $x \in P_n$. Then the map $g : X \to \{0, 1\}^{\mathbb{N}}$ is injective and continuous. Since X is compact, $g(X)$ is closed. Moreover, every step of the construction is effective, and so $g(X)$ is an effective closed set and the map g is effective.

If the space is perfect, then we construct another map $h : X \to \{0, 1\}^{\mathbb{N}}$. We may write X as a partition of two clopen sets $X = A_0 \cup A_1$, where A_0 is the clopen set of smallest index to be different from X and $\emptyset$; this is always possible thanks to perfectness. Suppose that we have already constructed A_w, where w is a binary word. Let n be the first index such that $A_w \cap P_n$ differs from both A_w and $\emptyset$, and set $A_{w0} = A_w \cap P_n$, $A_{w1} = A_w \setminus P_n$. For $x \in X$ let $h(x) \in \{0, 1\}^{\mathbb{N}}$ be the unique configuration such that $x \in A_w$ for all prefixes w of $h(x)$. Then $h : X \to \{0, 1\}^{\mathbb{N}}$ is an effective homeomorphism. □

We see that there is no loss of generality in supposing that in any effective symbolic space, for any rational ϵ there exists a finite number of balls of radius ϵ and that we can compute all of them. Indeed, this is the case for all effective subsets of the Cantor space.

3. Effective symbolic systems

Definition 3. An *effective symbolic dynamical system* is an effective continuous map from an effective symbolic space to itself.

In other words, an effective symbolic system is a symbolic space with a continuous self-map in which intersections, complements, and inverse images of clopen sets are computable. This definition of effective function in a Cantor space is equivalent to classical definitions in computable analysis; see for instance [39]. We denote an effective symbolic system by a map $f : X \to X$ or simply f, when the enumeration P of X is implicit. Extending Definition 2, we define a relation of equivalence between effective systems.

Definition 4. The effective symbolic systems $f : X \to X$ and $g : Y \to Y$ are *effectively conjugated* if there exists an effective homeomorphism $h : X \to Y$ such that $h \circ f = g \circ h$. If $h : X \to Y$ is an effective surjective map (and not bijective), then the system $g : Y \to Y$ is said to be an *effective factor* of $f : X \to X$. The factor g can be seen as a 'simplification' of f.

The identity on any symbolic space is the simplest example of an effective symbolic system. A cellular automaton is an effective symbolic system acting on the space $A^{\mathbb{Z}^d}$, where A is the finite alphabet and d is the dimension.

Turing machines are usually described as working on finite configurations. A finite configuration is an element of $\{0,1\}^* \times Q \times \{0,1\}^*$, where Q denotes the set of states of the head, the first binary word is the content of the tape to the left of the head and the second binary word is the right part of the tape. However, $\{0,1\}^*$ cannot be naturally equipped with a compact topology, so we consider its compactification $W = \{0,1\}^* \cup \{0,1\}^{\mathbb{N}}$, i.e., the set of finite and infinite binary words. Then the Turing machine function is also defined on $W \times Q \times W$, which is a compact space, whose isolated points are $\{0,1\}^* \times Q \times \{0,1\}^*$. An isolated point is clopen in $W \times Q \times W$. Hence a Turing machine with a blank symbol is an effective symbolic system on the space $W \times Q \times W$.

A Turing machine without blank symbol is an effective symbolic system as well. As we do not suppose that almost all cells are filled with a blank symbol, a configuration is given by an arbitrary element of $\{0,1\}^{\mathbb{N}} \times Q \times \{0,1\}^{\mathbb{N}}$ or, equivalently, $Q \times A^{\mathbb{Z}}$. This is a Turing machine with moving tape, as considered in [21]: the head is always in position zero, and the tape moves to the left or to the right.

3.1. Shifts and subshifts

A one-sided or two-sided *shift* is a dynamical system on $A^{\mathbb{N}}$ or $A^{\mathbb{Z}}$ (where A is a finite alphabet) with the map $\sigma : A^{\mathbb{N}} \to A^{\mathbb{N}}$ or $\sigma : A^{\mathbb{Z}} \to A^{\mathbb{Z}}$ defined by $\sigma(x)_i = x_{i+1}$. A shift is an effective system. A *subshift* is a subsystem of the shift, i.e., a closed subset that is invariant under the shift map. Most subshifts we consider in this article are one-sided subshifts. An *effective subsystem* of an effective symbolic system is an effective closed subset that is invariant under the map. With the relative topology, it is itself an effective symbolic system. In particular, a subshift that is an effective closed subset of $A^{\mathbb{N}}$ is again an effective symbolic system.

The set $\mathcal{L}(X)$ of all finite words appearing at least once in at least one point of the subshift X is called the *language* of the subshift. It is easy to see that a subshift is effective iff its language is recursive. In particular every *sofic* subshift (a subshift whose language is regular) is effective. A subshift of finite type is the set of sequences avoiding a finite set of forbidden subwords. Subshifts of finite type are sofic subshfits, hence are effective. Another widely studied class of subshifts are *substitutive* subshifts defined by substitutions $\vartheta : A \to A^+$. Since a substitution is a finitary object, every substitutive subshift is effective. A Sturmian subshift Σ_α associated to an irrational number α is a symbolic model of rotation of the circle $x \mapsto x + \alpha$; see e.g. [23]. A Sturmian subshift Σ_α is is effective iff α is a computable real number.

From any symbolic dynamical system (effective or not), we can generate one-sided subshifts in a natural way. A *clopen partition* of a symbolic space is a partition of the space into a finite number of disjoint clopen sets. A partition $\mathcal{A}$ is *finer* than $\mathcal{B}$, or $\mathcal{B}$ is *coarser* than $\mathcal{A}$, if every clopen set of $\mathcal{A}$

is included in some clopen set of $\mathcal{B}$. Given a clopen partition $\mathcal{A} = \{A_1, \ldots, A_N\}$ of X, the subshift *induced* by this partition is the set of infinite words $a_0a_1a_2a_3 \ldots \in \mathcal{A}^{\mathbb{N}}$, such that there is a point in a_0 whose trajectory goes successively through $a_1, a_2, \ldots$. Note that here A_1, say, is both a subset of X and a symbol from a finite alphabet. Thus $A_1A_3A_1$ denotes a word of three symbols and not for instance a cartesian product. The language of the subshift is also said to be *induced* by the partition. An induced subshift is a factor of the system and conversely any factor subshift is induced by a clopen partition. Following this observation, we can characterize effective symbolic systems in terms of their induced subshifts.

Proposition 2. A symbolic system is effective if and only if there is an algorithm deciding from any given clopen partition and any given finite word whether this word belongs to the language of the subshift induced by the partition.

Proof:
Let $\mathcal{A} = \{A_1, \ldots, A_N\}$ be a clopen partition. Then a word $a_0a_1 \ldots a_{l-1} \in \mathcal{A}^*$ is in the language of the subshift induced by the partition if and only if $a_0 \cap f^{-1}(a_1) \cap \cdots \cap f^{-(l-1)}(a_{l-1})$ is not empty. But this can be checked algorithmically.

Conversely, suppose that all induced subshifts have decidable languages, and that given the partition we can effectively find a decision algorithm for the corresponding language. Let P_n be a clopen set of X. There exists a clopen partition $\mathcal{A} = \{A_1, \ldots, A_N\}$ such that

- for every i, either $A_i \subseteq P_n$ or $A_i \subseteq X \setminus P_n$;
- if A_iA_j and A_iA_k belong to the language of the induced subshift, then A_j and A_k are either both parts of P_n or both parts of $X \setminus P_n$.

The first condition says that the partition is finer then P_n, the second condition says that the partition is finer than $f^{-1}(P_n)$. It can be checked algorithmically whether a clopen partition has these two properties. Thus a partition with these properties can be found algorithmically. Then we can compute $f^{-1}(P_n)$ as the union of all A_i such that there exists a word A_iA_j in the language of the induced subshift and that $A_j \subseteq P_n$. □

If the subshifts have decidable languages, but decision algorithms are not computable with respect to the clopen partition, then the system may fail to be effective. This happens in the following example.

Example 1. Assume $k : \mathbb{N} \to \mathbb{N}$ is an non-computable strictly increasing total function. We define a function f on the Cantor space $\{0,1\}^{\mathbb{N}}$ by $f(x) = f_0(x)f_1(x)f_2(x)\ldots$, where the ith bit $f_i(x_0x_1x_2\ldots)$ is given by $\max\{x_0, x_1, x_2, \ldots, x_{k(i)}\}$. There are two fixed points, 0^ω and 1^ω, and the image of a point is of the form 0^*1^ω or 0^ω (where 0^ω is a shortcut for $000\ldots$). Then it is easy to see that for any point x either $f(x) = 0^\omega$ or $f^n(x) = 1^\omega$ for some $n \geq 0$. For any partition $\mathcal{A} = \{A_1, \ldots, A_N\}$, if $0^\omega \in A_1$ and $1^\omega \in A_2$ (say), then every point in $A_3 \cup \ldots \cup A_N$ reaches A_2 in bounded time, say t. Then every finite word of the language of the subshift induced by the partition is of the form A_1^* or SA_2^*, where S is some subset of $\{A_1, \ldots, A_N\}^t$. This is certainly a decidable language. However f is not effective, for otherwise we could compute k.

In the rest of the paper, we use the terms 'symbolic system' or even 'system' to denote an effective symbolic dynamical system.

3.2. Products

Let $(f_n : X_n \to X_n)_{n\in\mathbb{N}}$ be a family of *uniformly effective* systems on the effective symbolic spaces (X_n, P_n) ; we mean that there exists an algorithm that, given n and two clopen sets of X_n, can compute their intersection, complements and inverse images. Then the *effective product* of $(f_n)_{n\in\mathbb{N}}$ is the system $f : X \to X$ on the effective symbolic space (X, P) such that

- the set X is the product of all sets X_n;
- the clopen sets of X are all products of clopen sets $\prod_{n\in\mathbb{N}} A_n$ such that only finitely many $A_n \subseteq X_n$ are different from X_n (this is the usual product topology);
- the clopen sets are indexed by finite sets of integers in a straightforward manner, and f is defined componentwise.

We see that this is indeed an effective symbolic dynamical system. The projections $\pi_n : X \to X_n$ are effective maps as well. Products are useful to build examples of systems with particular properties, as illustrated in Propositions 13 and 17.

4. Finite automata

Consider an effective system $f : X \to X$ and two clopen sets $U, V \subseteq X$. We would like to know if there is a point of U that eventually reaches V, that is, if there exists an x such that

$$x \in U \text{ and } \exists n \in \mathbb{N} : f^n(x) \in V. \tag{1}$$

We call *halting problem of f*, the problem of answering this question given U and V. We will see later that this is indeed a generalization of the halting problem traditionally defined for Turing machines or counter machines. Note the relation of the halting problem with the (topological) *transitivity*: a dynamical system is transitive if from any two non-empty open sets U and V there is a trajectory from U to V. In such a system, the halting problem is trivial.

We consider now another formulation of the halting problem. Suppose that the system f is only partially observable. All we can know about f is whether the system is currently in U, in V or in $W = X \setminus (U \cup V)$ (we suppose for simplicity that U and V are disjoint). The system is observed by a finite automaton (formally defined below) as illustrated in Figure 1. At every time step, the automaton jumps to a new state, according to which set U, V or W the system is currently in. The halting problem amounts to deciding whether it is possible, for some initial point of the space X, that the automaton eventually reaches the final state from the initial state.

We would like also consider variants of the halting problem. For instance, given three disjoint clopen sets U, V and W, we want to check whether the following formula is satisfied for some x:

$$x \in U \text{ and } \exists n : f^n(x) \in V \text{ and } \forall m < n : f^m(x) \notin W, \tag{2}$$

where n and m are non-negative integers. A finite automaton which accepts exactly points with this property is constructed in Figure 2.

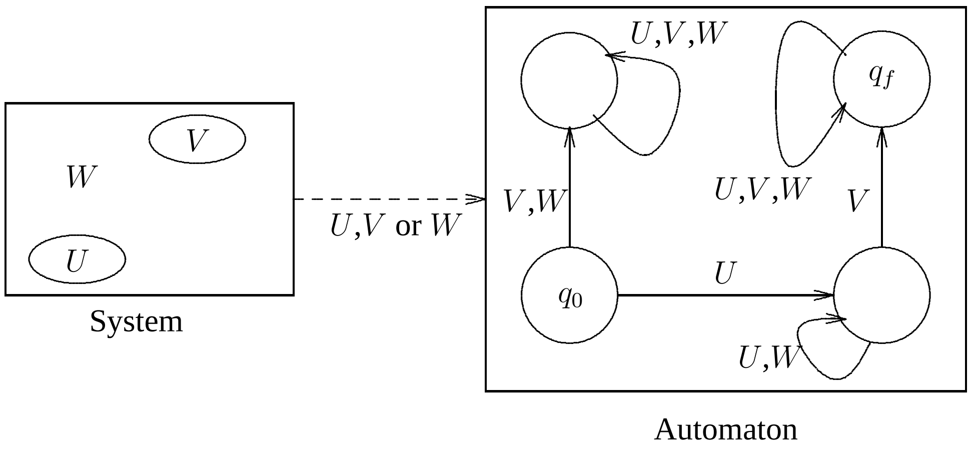

Figure 1. The symbolic system is partitioned into U, V and $W = X \setminus (U \cup V)$. At every time step, the finite automaton is fed with the symbol U, V or W and jumps to a new state. It is possible to reach the final state q_f from the initial state q_0 iff it is possible that q_f (and only q_f) is reached infinitely often from the initial state q_0 iff there is a point of U that eventually reaches V. Checking whether this is true given U and V, is the *halting problem* of f. The automaton can be considered as a finite automaton (the final state is q_f) or as a Muller automaton (for the family $\{\{q_f\}\}$).

We can also ask whether the formula

$$\forall n : f^n(x) \in U \tag{3}$$

is satisfied for some $x \in X$. This is the case if and only if the automaton in Figure 3, starting from the initial state and observing the system f, reaches infinitely often the final state from the initial state. This leads us to the theory of ω-regular languages which can be recognized by Muller or Büchi automata.

In general we are interested in all properties that can be observed by automata. A (deterministic) *finite automaton* is given by a finite *set of states* Q, an *initial state* $q_0 \in Q$, a set of *final* states $Q_1 \subseteq Q$, a finite *input alphabet* A and a transition function $\Delta : Q \times A \to Q$. The transition function is extended to $\Delta : Q \times A^* \to Q$ by $\Delta(q, ua) = \Delta(\Delta(q, u), a)$. A language $L \subseteq A^*$ is *regular* if there exists a finite automaton which accepts L, i.e., $u \in L$ iff $\Delta(q_0, u) \in Q_1$.

A *Muller automaton* consists of a finite set of states Q, a transition function $\Delta : Q \times A \to Q$, an initial state $q_0 \in Q$ and a family $\mathcal{F}$ of subsets of Q. A given infinite word $u \in A^{\mathbb{N}}$ is accepted by a Muller automaton if the set of states that are visited infinitely often by the path generated by the given word is a member of $\mathcal{F}$. A language $L \subseteq A^{\mathbb{N}}$ is *ω-regular*, if it is accepted by a Muller automaton, i.e.,

$$u \in L \text{ iff } \{q \in Q : \ \forall n, \exists m > n : \Delta(q_0, u_0 \ldots, u_{m-1}) = q\} \in \mathcal{F}.$$

Alternatively, ω-regular languages can be defined by nondeterministic Büchi finite automata. An infinite word is accepted, if there is a trajectory passing infinitely often through a given set of final states. Although Büchi automata are simpler to define, Muller automata are deterministic, which is sometimes an advantage. In this paper we make little use of Büchi automata. Coming back to Figure 1, the halting problem for a symbolic system asks whether there is a finite word induced by the partition U,V, W that

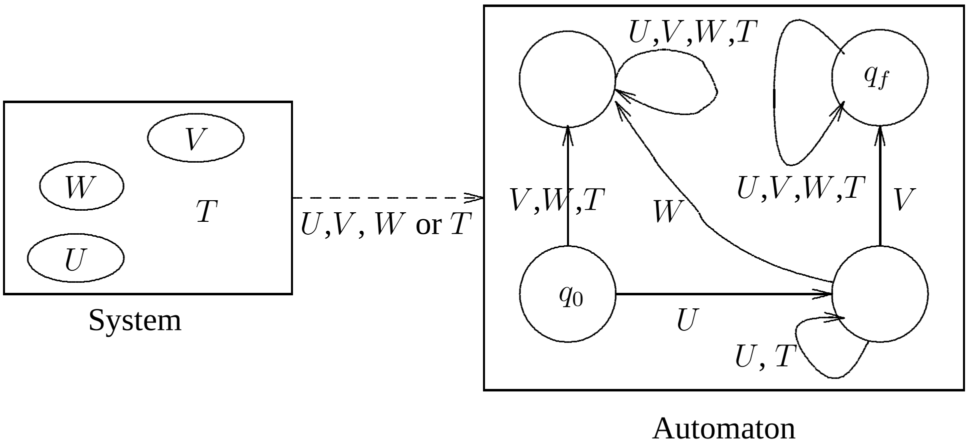

Figure 2. The symbolic system is partitioned into U, V, W and $T = X \setminus (U \cup V \cup W)$. There is a point of U that stays in $X \setminus W$ until it eventually reaches V, iff it is possible that q_f (and only q_f) is reached infinitely often from the initial state q_0.

is accepted by the finite automaton. It is equivalent to ask whether there is an infinite word induced by the partition that is accepted by the automaton interpreted as a Muller automaton.

In general, given a clopen partition $\mathcal{A} = \{A_1, \ldots, A_N\}$ and a finite automaton over $\mathcal{A}$, we would like to know whether there is a non-empty intersection between the language associated to the partition and the regular language accepted by the automaton. In other words, the problem is to know whether there exists a point of the symbolic system whose trajectory, when observed through the partition, is accepted by the automaton. The same question can be asked for a Muller automaton instead of a finite automaton.

The automaton may be interpreted as *observing* the system with a finite memory (where the 'memory' is the number of states of the automaton). This formalism includes all three properties described above, including the halting problem. These are examples of *model-checking* problems, although we prefer to call them *observation* problems. Model-checking aims at finding decision algorithms to check whether the trajectories of a dynamical system satisfy a given property. But systems considered in the literature of model-checking are often non-deterministic and finite or countable, whereas we deal with deterministic systems with a possibly uncountable configuration space.

Note that Muller (or Büchi) automata are rather powerful to express properties on infinite words. They are equivalent to several logical formalisms, including the so-called μ-calculus and monadic second-order formulae. First-order formulae, including (1), (2), (3), are equivalent to linear temporal logic and strictly weaker than Muller automata. For precise definitions of all these formalisms, see for instance [33, 17, 15].

5. Decidable systems

Definition 5. An effective symbolic system is *decidable* if there exists an algorithm that decides the *infinite-time observation problem*, i.e., that decides whether the subshift induced by a given clopen partition has a nonempty intersection with a given ω-regular language (described by a Muller automaton).

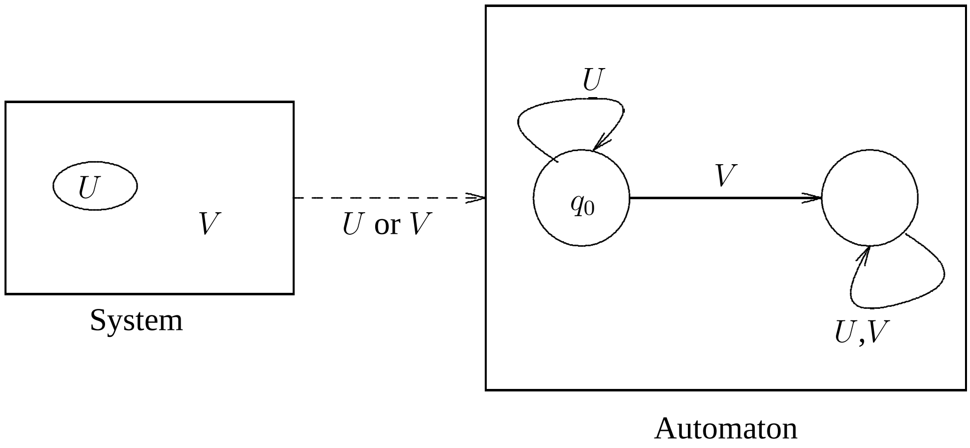

Figure 3. The system is partitioned into U and V. There is a point that never leaves U iff it is possible that q_0 (and only q_0) is reached infinitely often from the initial state q_0.

Clearly, decidability is preserved by effective conjugacies and the factor of a decidable system is decidable. The identity map on any effective symbolic space is decidable. Indeed, for a partition $A_1, A_2, \dots, A_N$, the only words induced by the partition are A_1^ω, A_2^ω, $\dots$ and A_N^ω. Given a Muller automaton, it is enough to check whether one of these paths starting from an initial state of the automaton passes infinitely often through a final state. Alternatively it is a consequence of the forthcoming Proposition 20. The map $x \mapsto 0x$ on $\{0,1\}^{\mathbb{N}}$ with a unique attracting fixed point 0^ω is decidable. This follows from Proposition 7. The full shift on any finite alphabet is a decidable system by a corollary to Proposition 15.

If a system is not decidable, how undecidable can it be? We show that the infinite-time observation problem is at most Σ_1^1-complete, which is rather high. A Σ_1^1 *set* is the set of integers m satisfying a formula of the kind

$$\exists k,\, Q_1 n_1,\, \dots\, , Q_i n_i : R(k, m, n_1, \dots, n_i),$$

where k runs over all total functions from $\mathbb{N}$ to $\mathbb{N}$, $Q_1, \dots, Q_i$ are quantifiers, $n_1, \dots, n_i$ run over $\mathbb{N}$, and R is a recursive relation. By recursive we mean that there is a Turing machine with k as oracle and $m, n_1, \dots, n_i$ as data that decides in finite time whether $R(k, m, n_1, \dots, n_i)$ holds or not. A Σ_1^1 set is Σ_1^1-*complete* if every Σ_1^1 is many-one reducible to it. The class of Σ_1^1 problems belongs to the so-called analytical hierarchy; see [16] for more details.

Proposition 3. The infinite-time observation problem on an effective symbolic system is Σ_1^1 for every effective symbolic system and Σ_1^1-complete for at least one effective symbolic system.

Proof:
Let $f : X \to X$ be an effective symbolic system. First we show that the infinite-time observation problem is in Σ_1^1. Then we construct a system simulating a universal Turing machine with oracle for which the infinite-time observation problem is Σ_1^1-complete. The proof, although rigorous, is not completely formalized.

We can suppose that the space X of the system is an effective closed subset of the Cantor space $\{0,1\}^{\mathbb{N}}$. Let x be a sequence taking values in $\mathbb{N}$. Then the assertion '$x \in X$' is equivalent to the recursive relation '$\forall t \in \mathbb{N} : x_0, x_1, \ldots, x_t \in \{0,1\}$ and $[x_0 x_1 \ldots x_t] \cap X \neq \emptyset$'. Let m be a natural integer encoding a Büchi automaton whose alphabet is a partition of X. Here Büchi automata are of easier use than Muller automata. A Büchi automaton is given by a finite set of states, an alphabet and a transition relation, a set of initial states and a set of final states. For any $x \in X$, call $R_f(x, m, t)$ the relation 'for the initial condition x, the Büchi automaton m observing the system can be in a final state at time t'. It is a recursive relation; the configuration x can be seen as a function from $\mathbb{N}$ to $\mathbb{N}$. Then the infinite-time observation problem can be expressed by the logical formula

$$\exists x : x \in X \text{ and } \forall t, \exists t' \geq t : R_f(x, m, t'),$$

with m as free variable; hence the infinite-time observation problem is in Σ_1^1.

The set of natural integers n such that there exists a sequence of integers $k : \mathbb{N} \to \mathbb{N}$ for which the universal Turing machine with initial data n and oracle k does not halt is well known to be Σ_1^1-complete; see [16]. An oracle universal Turing machine can be built in the following way. We take a one-tape universal Turing machine in the usual sense, to which we adjoin a tape that contains on its right part the oracle encoded in form $10^{k(0)}10^{k(1)}10^{k(2)}1\ldots$. The head has access to both tapes. Not every possible content of the second tape is a valid oracle; indeed the word 0^ω cannot appear on the tape. We can suppose without loss of generality that when the head wants to query $k(i)$, it first checks that $k(i)$ is properly encoded by scanning the tape in some state q_{search} until it discovers a 1 and then jumps to the state q_{found}. This two-tape Turing machine is an effective dynamical system, similar to the one-tape Turing machine discussed just above Section 3.1. Call Q the states of the head, q_0 the initial state and q_h the halting state. It can be supposed that it is impossible to leave q_h once we reach it. We want to know whether there is an initial configuration of this system, composed of a state of Q and the contents of both tapes, that is in the clopen set $\{q_0\} \times [n] \times [1]$ (i.e., the head is in state q_0, the initial data n is encoded at the right of the head on the first tape and a symbol 1 is currently read by the head on the second tape) and such that the head reaches infinitely often $Q \setminus \{q_{\text{search}}, q_h\}$. For if an initial configuration is such that the head does not reach infinitely often $Q \setminus \{q_{\text{search}}, q_h\}$, then it either reaches the halting state or gets stuck in a query on an invalid oracle. This property can be observed by a Muller automaton in a straightforward manner. Putting all together, we have constructed a reduction from a Σ_1^1-complete problem to an infinite-time observation problem of some fixed symbolic system; the latter is therefore Σ_1^1-complete as well. □

6. Universal systems

We are now ready to state the main definition of computational universality. We define a universal symbolic system as a special kind of undecidable system, where Muller automata are replaced by finite automata. The universality of Turing machines is a particular example of this definition.

Definition 6. An effective dynamical system is *universal* if the *finite-time observation problem* of this system, i.e., the problem whether the language induced by a given clopen partition has a nonempty intersection with a given regular language, is recursively-enumerable complete.

An *r.e.-complete* problem, or Σ_1-*complete* problem, is a recursively enumerable problem, to which any recursively enumerable problem is many-one reducible. Note that the finite-time observation problem (described in Definition 6) is always recursively enumerable, because the language induced by a clopen partition is recursively enumerable and the language accepted by a finite automaton is recursive; the intersection can be recursively enumerated and if it is nonempty then we can know it after a finite time. Universality is obviously preserved by effective conjugacies, and a system with a universal factor is also universal.

Proposition 4. A universal system is not decidable.

Proof:
If the infinite-time observation problem is decidable then so is the finite-time observation problem. Indeed, the latter is reducible to the former in the following way. Given a deterministic finite automaton, modify it in a such a way that the final states are fixed points of the transition function, whatever the input is; the resulting automaton is interpreted as a Muller automaton, for the family of all sets whose unique elements is a final state. □

Note that a non-deterministic scheme of computation underlies the definition of universality. The computation succeeds if and only if at least one trajectory exhibits a given behavior. For example, recall from Section 4 that the halting problem consists in determining, given the clopen sets U and V, whether there is a configuration in U that eventually reaches V. We may think of V as the halting set and of U as an initial configuration of which we know only the first digits. The unspecified digits of the initial configuration may be seen as encoding the non-deterministic choices occurring during the computation.

6.1. Examples

Turing machines with blank symbol.

A Turing machine with blank symbol that is universal in the sense of Turing, is also universal according to Definition 6, because the halting problem 'Can we go from a clopen set U to a clopen set V?' is r.e.-complete. Indeed the halting problem restricted to clopen sets that are isolated points is already r.e.-complete. Recall that isolated points are exactly finite configurations. Incidentally, we have shown that what we have called 'halting problem' for a general symbolic system is indeed a generalization of the usual halting problem for Turing machines.

Turing machines without blank symbol.

It is only slightly more complicated to build a universal Turing machine without blank symbol. In such a Turing machine, there is no obvious notion of 'finite configuration'. The trick is basically to encode the initial data in a self-delimiting way. Take a Turing machine that is universal in the sense given by Turing. Then add two new symbols L and R to the tape alphabet. On an initial configuration, put an L on the left end and an R on the right end of the encoded data. When the head encounters an L, it pushes it one cell to the left, leaving some more space available for computation. It acts similarly for an R symbol. The working space is always delimited by an L and an R; the symbols situated outside this zone are considered as noise, and do not influence the computation. For this modified universal Turing machine, the (clopen-set-to-clopen-set) halting problem is again undecidable.

Cellular automata.

Let us take a universal Turing machine with a blank symbol. We suppose that when the halting state is reached, then the head comes back to the cell of index 0. We can simulate it in a classic way with a one-dimensional cellular automaton. The alphabet of the automaton is $A \cup (A \times Q) \cup \{L, R, Error\}$, where A is the tape alphabet (including the blank symbol) and Q the set of states. Let us take a point in the cylinder $[L, \text{initial data of the Turing machine}, R]$, and observe its trajectory. The symbol L moves to the left at the speed of one cell per time step, leaving behind blank symbols. The symbol R moves to the right in a similar way. Meanwhile, the space between L and R is used to simulate the Turing machine and is composed of symbols from A and exactly one symbol from $A \times Q$, which denotes the position of the head. When L or R symbols meet each other, then a spreading $Error$ symbol is produced, that erases everything.

This cellular automaton is again universal, because the (clopen-set-to-clopen-set) halting problem is r.e.-complete. Indeed, there is an orbit from the cylinder $[L, \text{initial data of the Turing machine}, R]$ to the cylinder $[A \times \{\text{halting state}]\}$ (both cylinders centered at cell of index zero) if and only if the universal Turing machine halts on the initial data.

Tag systems.

Tag systems were introduced by Post in 1920. A *tag system* is a transformation rule acting on finite binary words. At every step, a fixed number of bits is removed from the beginning of the word and, depending on the values of these bits, a finite word is appended at the end of the word. Minsky [26] proved that there is a so-called universal tag system, for which checking whether a given word will eventually produce the empty word when repeating the transformation is an r.e.-complete problem.

We can extend the rule of tag systems to infinite words, by just removing from them a fixed number of bits. Thus we have a dynamical system on the compact space $\{0,1\}^* \cup \{0,1\}^{\mathbb{N}}$ of finite and infinite words, in which finite words are clopen sets. Again, if the tag system is universal for the word-to-word definition, then it is universal for Definition 6 with the halting problem on clopen sets of $\{0,1\}^* \cup \{0,1\}^{\mathbb{N}}$.

Collatz functions.

We can also apply our definition to functions on integers. Let $\mathbb{N} \cup \{\infty\}$ be the topological space with the metric $d(n,m) = |2^{-n} - 2^{-m}|$. This is effectively homeomorphic to the set $\{1^n 0^\omega | n \in \mathbb{N}\} \cup \{1^\omega\}$. Then some functions on integers may be extended to infinity. For instance, the famous $3n+1$ function sends even n's to $n/2$, odd n's to $3n+1$ and ∞ to ∞. Whether this map is decidable is unsettled. But Conway [6] proved that similar functions, called Collatz functions, can be universal.

Counter machines.

A k-counter machine is composed of k counters, each containing a non-negative integer, and a head that can test which counters are at zero and can increment or decrement every counter (with the convention $0 - 1 = 0$). Thus a counter machine is a map $f : Q \times \mathbb{N}^k \to Q \times \mathbb{N}^k$, where Q is the finite set of states of the head. There exists such a machine f for which given two configurations $x, y \in Q \times \mathbb{N}^k$, the problem to check whether the trajectory of x reaches y is r.e.-complete; see Minsky [26].

The map f is easily extended to the compact space $Q \times (\mathbb{N} \cup \{\infty\})^k$, with the convention $\infty \pm 1 = \infty$. Here again, the points of $Q \times \mathbb{N}^k$ are clopen sets of $Q \times (\mathbb{N} \cup \{\infty\})^k$, hence f is universal for the halting problem.

More examples.

In Section 8 we give an example of a universal system that is chaotic, and for which the halting problem is decidable, but not the variant expressed by logical formula (2). In Section 7.3 we build a system which is neither decidable nor universal. In the setting of point-to-point properties, it was proved by Sutner [36] that there exist cellular automata with a halting problem of an intermediate degree between decidability and r.e.-completeness. The same kind of examples for Turing machines are known for long time (Friedberg-Muchnik theorem, see for instance [16]). However we have not been able to build a system for which finite-automata properties of trajectories are undecidable, but not r.e.-complete.

7. Sufficient conditions for decidability

The purpose of this section is to link computational capabilities of a system to its dynamical properties: minimality, equicontinuity, etc. Most results proved in this section are in fact sufficient conditions of decidability and can thus be interpreted as necessary conditions for universality. For instance, we prove that minimal systems are decidable, thus universal systems are not minimal. We have chosen these sufficient conditions because they are natural and often used in the analysis of a system, and because we can derive clear-cut results from them.

The following constructions and propositions are useful in several proofs. Given an effective system $f : X \to X$, a clopen partition $\mathcal{A} = \{A_1, \ldots, A_N\}$ of X and the transition function $\Delta : Q \times \mathcal{A} \to Q$ of a deterministic finite automaton, we construct the *observation system* $f_\Delta : X \times Q \to X \times Q$ by

$$f_\Delta(x, q) = (f(x), \Delta(q, A_i)), \text{ where } x \in A_i$$

Clearly f_Δ is an effective system, and the projection $\pi_X : X \times Q \to X$ is an effective factor map of f_Δ to f.

Definition 7. We say that a dynamical system $f : X \to X$ has *clopen basins*, if for every clopen set $V \subseteq X$, its basin $\mathcal{B}(V) = \bigcup_{n \geq 0} f^{-n}(V)$ is a clopen set.

Proposition 5. If $f : X \to X$ is an effective system with clopen basins, then the operation $V \mapsto \mathcal{B}(V)$ is computable.

Proof:
If V and $\mathcal{B}(V)$ are clopen sets, then by compactness there exists $m > 0$ such that

$$\mathcal{B}(V) = \bigcup_{n<m} f^{-n}(V) = \bigcup_{n<m+1} f^{-n}(V).$$

Given V we can determine m effectively so the operation $\mathcal{B}(V)$ is effective too. Hence there exists a computable function $k : \mathbb{N} \to \mathbb{N}$ such that $\mathcal{B}(P_n) = P_{k(n)}$, where P_n is the clopen set of index N. □

Proposition 6. If an effective system is such that for any transition function, the resulting observation system has clopen basins, then the system is decidable.

Proof:
For every clopen partition $\mathcal{A}$, for every finite set Q and for every transition function $\Delta : Q \times \mathcal{A} \to Q$, the system $f_\Delta : X \times Q \to X \times Q$ has clopen basins.

Assume now that $V \subseteq X \times Q$ is clopen, so that $\mathcal{B}(V)$ is clopen and the index of $\mathcal{B}(V)$ can be computed from the index of V. Moreover $I(V)$, defined as $\mathcal{B}(\mathcal{B}(V)^c)^c$, where ^{c} denotes the complement, is a clopen set too and its index can be again computed from that of V. A point (x, q) belongs to $I(V)$ iff the trajectory of (x, q) passes through V infinitely often. Given $q_0, q_1 \in Q$, then $(X\times\{q_0\})\cap I(X\times\{q_1\})$ is again a computable clopen set, so the set $\{x \in X : \forall n, \exists m > n, f_\Delta^m(x, q_0) = q_1\}$ is computable as well. It follows that for a family $\mathcal{F}$ of subsets of Q, the set

$$\{x \in X : \{q \in Q : \forall n, \exists m > n, f_\Delta^m(x, q_0) = q\} \in \mathcal{F}\}$$

is computable too. In particular, whether this set is empty can be decided algorithmically. Hence the infinite-time observation problem is decidable. □

7.1. Minimality

A *minimal* dynamical system is a system with no subsystem (except the empty set and itself). In a minimal system, all orbits are dense and the basin of any clopen set is the full set.

Any dynamical system has a minimal subsystem, thanks to Zorn's lemma and compactness. In particular, any point comes arbitrarily close to a minimal system, since the closed orbit of the point is itself a dynamical system. Suppose that the symbolic system is not minimal but consists of one minimal subsystem attracting the whole space of configurations. In other words, the limit set is minimal. The limit set of a dynamical system $f : X \to X$ is the set $\bigcap_{n\geq 0} f^n(X)$. Then such a system is decidable. This results from the more general following proposition.

Proposition 7. A symbolic system whose limit set is the union of finitely many minimal systems is decidable.

Proof:
Given a symbolic system $f : X \to X$ and a Muller automaton whose set of states is Q, we build the observation system $f_\Delta : X \times Q \to X \times Q$.

First we prove that the observation system f_Δ contains finitely many minimal sets. Let $X_1, \ldots, X_k$ be the minimal subsystems of $f : X \to X$. For every $i = 1, \ldots, k$ choose an arbitrary point $x_i \in X_i$. A minimal subsystem of f_Δ, when projected on X, is exactly a minimal subsystem of f, as easily seen. Thus any minimal subsystem of f_Δ must contain at least one point of the form (x_i, q), for some $q \in Q$. Since any two different minimal subsystems are disjoint, this means that there are at most $k|Q|$ minimal subsystems in f_Δ.

Then we show that the limit set of f_Δ is exactly the union of all minimal subsystems.

It is clear that the minimal subsystems are in the limit set of f_Δ. Now we prove that each minimal subsystem Z of f_Δ has a nonempty interior in the limit set of f_Δ (for the relative topology). The projection of the limit set of f_Δ on X is the limit set of f. The projection of Z on X is a minimal subsystem of f, which has a nonempty interior in the limit set of f, and the projection of Z is $\bigcup_{q\in Q} Z_q$, where $Z = \bigcup_q Z_q \times \{q\}$. From Baire's theorem, one of these Z_q has a nonempty interior in the limit set of f, and Z itself has a nonempty interior in the limit set of $f_\triangle$.

Let Y_i be a set included in Z_i that is open in the limit set of $f_\triangle$, where $Z_1, \ldots, Z_m$ are the minimal subsystems of $f_\triangle$. All sets $\bigcup_{n\in\mathbb{N}}(f_\triangle^{-n}(Y_i))$ are disjoint sets, are open in the limit set and cover the limit set, since the closed orbit of every point in the limit set of $f_\triangle$ must include a minimal subsystem. From compactness, all points of the limit set of $f_\triangle$ fall in a minimal subsystem in bounded time. We conclude that the union of all minimal subsystems is the exactly the limit set of $f_\triangle$.

So the limit set of the observation system $f_\triangle$ is a finite union of minimal subsystems. We get from the lemma below that $f_\triangle$ has clopen basins. From Proposition 6 we deduce that f is decidable. □

For instance, the system $f : \{0,1\}^{\mathbb{N}} \to \{0,1\}^{\mathbb{N}} : x \mapsto 0x$ is decidable. The following lemma finishes the proof.

Lemma 8. A symbolic system whose limit set is the finite union of minimal systems has clopen basins.

Proof:
Suppose that the limit set is $Y_1 \cup \cdots \cup Y_k$, where Y_i are minimal subsystems, so that $Y_i \cap Y_j = \emptyset$ for $i \neq j$. Let $V \subseteq X$ be a clopen set. If $V \cap Y_i = \emptyset$, then $\mathcal{B}(V) \cap Y_i = \emptyset$. If $V \cap Y_i \neq \emptyset$, then for some $m > 0$, $Y_i \subseteq V_m = \bigcup_{n<m} f^{-n}(V)$. Thus there exists $m > 0$ such that for all i either $Y_i \subseteq V_m$ or $Y_i \cap V_m = \emptyset$. Then $W_m = f^{-m}(V) \setminus V_m$ is a clopen set disjoint from the limit set. From compactness there exists $k > 0$ such that $f^{-k}(W_m) = \emptyset$, so $\mathcal{B}(W_m)$ is a clopen set. It follows that $\mathcal{B}(V) = V_m \cup \mathcal{B}(W_m)$ is a clopen set too. □

We immediately have the following corollary.

Corollary 9. A minimal symbolic system is decidable.

This is in a way not surprising since in some way all trajectories of a minimal system have the same behavior. The following proposition leads to another consequence of Proposition 7:

Proposition 10. A symbolic system such that all nonempty subsystems have a nonempty interior has a limit set composed of finitely many minimal subsystems.

Proof:
Let f be a system such that all nonempty subsystems have a nonempty interior. In the interior of every minimal subsystem choose a clopen set U_i. The basin of the open set $\bigcup_i U_i$ is the full space, because every point of the system must come arbitrarily close to some minimal subsystem, thus must fall in some U_i. By compactness, there is a finite set of is and a natural integer m such that $\bigcup_{i\in I}\bigcup_{n<m} f^{-n}(U_i)$ is the full space. So there are finitely many minimal subsystems, and every point falls in a finite time into a minimal subsystems. The union of the minimal subsystems is therefore the limit set. □

Corollary 11. A symbolic system such that all nonempty subsystems have a nonempty interior is decidable.

In another words, an undecidable system must have a 'thin' subsystem. A stronger statement than Proposition 7 is suggested by the intuition that an undecidable system (and especially a universal system) is likely to be able to 'simulate' many other systems.

Conjecture 1. A universal symbolic system has infinitely many minimal subsystems.

7.2. Regular Systems

A subshift is called sofic, if its language is regular. A symbolic system is called *regular*, if all its induced subshifts are sofic; see [22]. Can a regular system be universal? We first consider a closely related question. We say that an effective system is *effectively regular* if it is regular and there is an algorithm that builds from a given clopen partition the finite automaton recognizing the regular language induced by the partition.

Proposition 12. An effectively regular system is decidable.

Proof:
The intersection of two ω-regular languages is well known to be an ω-regular language, and a Muller automaton accepting the intersection can be computed; see [33] for instance. Moreover, whether the language accepted by a given Muller automaton is empty is a decidable problem too. And a sofic subshift is an ω-regular language: the finite automaton accepting the language, interpreted as a Büchi automaton with the same set of final states, accepts the sofic subshift.

Suppose that we are given an effectively regular system, a clopen partition $\mathcal{A}$ of the space and a Muller automaton over the alphabet $\mathcal{A}$. Then we construct another Muller automaton that accepts exactly the subshift induced by $\mathcal{A}$ and verify whether the languages accepted by these two Muller automata has a nonempty intersection. Hence the system is decidable. □

If the system is regular but not effectively regular, then the argument of the proof fails.

Proposition 13. There exists a symbolic system that is regular and universal.

Proof:
Let X_n be the subshift of $\{0,1\}^{\mathbb{N}}$ whose forbidden words are words of the form 10^t1, where t is less than the (possibly infinite) halting time of the universal Turing machine launched on data n. If the Turing machine does not halt, then X_n is the sofic subshift $\{0^*10^\omega, 0^\omega\}$. If the Turing machine halts in k steps, then X_n is the subshift of finite type with forbidden words 11, 101, 1001, $\dots$, $10^{k-1}1$. So all subshifts are sofic, but we cannot effectively build the automaton recognizing the language, for it would allow to solve the halting problem.

Now consider the product of all X_n. This product is again an effective symbolic system X, and all its induced subshifts are sofic, due to the fact that the finite product of sofic subshifts is a sofic subshift and the induced subshift of a sofic subshift is again sofic; see [23]. Thus the system is regular, but not effectively regular. Finally, it is r.e.-complete to check whether there is a trajectory starting from $\pi_n^{-1}([1])$ which eventually reaches $\pi_n^{-1}([01])$. Here $\pi_n : X \to X_n$ is the projection. □

7.3. Shadowing property

Definition 8. Let $f : X \to X$ be a symbolic dynamical system. A δ*-pseudo-orbit* is a (finite or infinite) sequence of points $(x_n)_{n\geq 0}$ such that $d(f(x_n), x_{n+1}) < \delta$ for all n. A point x ϵ*-shadows* a (finite or infinite) sequence $(x_n)_{n\geq 0}$ if $d(f^n(x), x_n) < \epsilon$ for all n. A dynamical system is said to have the *shadowing property* if for every $\epsilon > 0$ there is a $\delta > 0$ such that any δ-pseudo-orbit is ϵ-shadowed by some point. If moreover such a rational δ can be effectively computed from a rational ϵ then we say that the system has the *effective shadowing property*.

For example, the one-sided and two-sided shifts have the shadowing property for $\delta = \epsilon$. By a theorem of Walters, a subshift of finite type has the shadowing property, with a linear relation between ϵ and δ (see [23] for a proof), thus has the effective shadowing property. Clearly, the effective shadowing property is invariant under effective conjugacies. We can give the following interpretation to the effective shadowing property. Suppose that we want to compute numerically the trajectory of x such that at every step numerical errors are bounded by δ. The resulting sequence of points is a δ-pseudo-orbit, and the shadowing property ensures that this pseudo-orbit is ϵ-close to an actual trajectory of the system, ensuring that the result of the numerical computation is not meaningless.

Proposition 14. A symbolic system (effective or not) with the shadowing property is regular. An effective symbolic system with the effective shadowing property is effectively regular.

Proof:
The proof generalizes Proposition 5.69 of [23] about cellular automata. Consider a symbolic system $f : X \to X$ with the shadowing property and a clopen partition $\mathcal{A} = \{A_1, \ldots, A_N\}$. There exists an ϵ such that all clopen sets of the partition are finite unions of balls of radius ϵ. By the shadowing property, there exists δ such that every δ-pseudo-orbit is ϵ-shadowed. We may suppose without loss of generality that $\delta \leq \epsilon$. Let $\mathcal{B} = \{B_1, \ldots, B_M\}$ the clopen partition where each B_i is a ball of radius δ. Then the set of all infinite words induced by all δ-pseudo-orbits through $\mathcal{B}$ is a subshift of finite type: the word B_iB_j is forbidden iff $B_i \cap f^{-1}(B_j) = \emptyset$, i.e., we cannot go from B_i to B_j in one step. But the partition $\mathcal{A}$ is coarser than $\mathcal{B}$, so the subshift induced by $\mathcal{A}$ is a factor of a subshift of finite type, hence sofic. If the system has the effective shadowing property, then we can effectively find δ, effectively describe the subshift of finite type and effectively build the sofic subshift. □

Theorem 15. A symbolic system that has the effective shadowing property is decidable.

Proof:
By Propositions 14 and 12. □

In particular, the shift and any subshift of finite type is decidable. We also have the following result.

Proposition 16. A symbolic system that has the shadowing property is not universal.

Proof:
Let $f : X \to X$ be a symbolic system with the shadowing property. Given a deterministic finite automaton observing the system through a given clopen partition, the problem is to check whether there exists a finite word induced by the clopen partition that is accepted by the automaton. As we have noticed

after stating Definition 6, this problem is recursively enumerable. We show that it is also co-recursively enumerable. This will prove that the problem is decidable and that f is not universal.

Let $\mathcal{A} = \{A_1, \ldots, A_N\}$ be a clopen partition and $\Delta : Q \times \mathcal{A} \to Q$ the transition function of a deterministic finite automaton. We must essentially prove that the halting problem is decidable for the observation system $f_\Delta : X \times Q \to X \times Q$.

But f_Δ is an effective symbolic system with the shadowing property, as we now show. We can suppose that the distance between (x, q) and (x', q') is 1 if $q \neq q'$ and $d(x, x')$ otherwise. For an $\epsilon > 0$, choose an $\epsilon' \leq \epsilon$ such that any A_i can be written as a union of balls of radius ϵ'. Then the shadowing property for f yields a corresponding δ'. Choose a $\delta \leq \delta'$ such that δ is strictly smaller than the distance between any two sets $X \times \{q\}$ and $X \times \{q'\}$. Then it is easy to see that any δ-pseudo-orbit of f_δ is ϵ-shadowed by some point of $X \times Q$: such a pseudo-orbit is projected onto a δ-pseudo-orbit of f, which is ϵ-shadowed by some point, and this point can be lifted to a point that ϵ-shadows the pseudo-orbit of f_Δ.

Take two clopen sets $U, V \subseteq X \times Q$. There exists an orbit from U to V iff for every $\delta > 0$ there exists a δ-pseudo-orbit from U to V (see Proposition 2.15 of [23]). If there is no orbit starting in U that reaches V, then there exists a δ such that no δ-pseudo-orbit goes from U to V, and we can algorithmically check it by the following method. For a fixed δ, define V' as the union of balls of radius δ whose center is in $f_\Delta^{-1}(V)$. Then compute V'', V''', and so on. As there are only finitely many balls of radius δ, $V^{(t)} = V^{(t+1)}$ for some t. Then check whether $V^{(t)} \cap U$ is empty; it is the case if and only if there is no δ-pseudo-orbit from U to V. Start again with smaller and smaller δ.

Thus the halting problem for f_Δ is decidable. In particular if $U = X \times \{q_0\}$ (where q_0 is the initial state of the automaton) and $V = X \times F$ (where $F \subseteq Q$ is the set of final states of the automaton), then we can algorithmically check whether there exists a point of X which induces through the clopen partition a word that is accepted by the automaton. □

The following proposition shows that the effective shadowing property is stronger than the shadowing property.

Proposition 17. There exists an undecidable effective symbolic system that has the shadowing property, but not the effective shadowing property.

Proof:
Let X_n be the subshift with forbidden words 0^t, where the universal Turing machine stops on data n in at most t steps. If the Turing machine does not halt on n, then X_n is the full shift; if it stops in k steps, then the forbidden word is 0^k. All these subshifts are effective, but we cannot compute their set of forbidden words.

The product X of all X_n is an effective system. Whether there is a point that remains for ever in $\pi_n^{-1}[0]$ is co-r.e.-complete (where $\pi_n : X \to X_n$ is the projection). This property has been shown in Figure 3 to be expressible in terms of Muller automata. Hence the system is undecidable.

Recall that a subshift of finite type has the shadowing property. We show that the countable product of subshifts that have the shadowing property also has the shadowing property. A ball of radius ϵ in the product system may be expressed as the finite union of products of balls of radius ϵ' in a finite number of constituent subshifts. We choose the smallest of the corresponding δ' given by shadowing property in the subshifts. The product of balls of radius δ' may be expressed as union of balls of radius δ; this is the δ corresponding to ϵ.

Hence the system X has the shadowing property but not the effective shadowing property, since it is undecidable. □

As the shadowing property implies non-universality, it also proves that universality is stronger than undecidability.

Corollary 18. There exists a symbolic system that is neither decidable nor universal.

Note also that Turing machines that satisfy the shadowing property have been given a combinatorial characterization in [21]; in particular, the proof shows that the link between ϵ and δ (see Definition 8) is linear. Hence the effective shadowing property is not stronger than the shadowing property in the case of Turing machines.

7.4. Equicontinuity

A system $f : X \to X$ is *equicontinuous* if for every $\epsilon > 0$ there exists a $\delta > 0$ such that $d(x, y) < \delta$ implies $d(f^t(x), f^t(y)) < \epsilon$, for any points x, y and $t \in \mathbb{N}$. Note that equicontinuity in symbolic systems is a topological property, not just a metric one. Instead of 'For every $\epsilon > 0$, there is a $\delta \ldots$' we could say 'For every clopen partition, there is a finer clopen partition such that if two points are in the same subset of the finer partition, then they generate the same infinite word in the coarser partition.'

Proposition 19. An equicontinuous effective symbolic system has the effective shadowing property.

Proof:
Let $f : X \to X$ be an equicontinuous system. Then for every $\epsilon > 0$, there is a δ such that any two points distant of less than δ have ϵ-close trajectories. We show that any δ-pseudo-orbit is ϵ-shadowed by some point.

Let $x_0, x_1, x_2, \ldots$ be a δ-pseudo-orbit. We show by induction on m that $d(f^n(x_m), f^{n+m}(x_0)) < \epsilon$ for every m and n. The case $m = 0$ is obvious. If it is true for m then $d(f^{n+1}(x_m), f^{n+m+1}(x_0)) < \epsilon$. But $d(x_{m+1}, f(x_m)) < \delta$ implies $d(f^n(x_{m+1}), f^{n+1}(x_m)) < \epsilon$. From the ultrametric inequality we have $d(f^n(x_{m+1}), f^{n+m+1}(x_0)) < \epsilon$.

It is now enough to prove that a suitable δ is computable from ϵ, i.e. an equicontinuous symbolic system is always 'effectively' equicontinous. Take the partition $\mathcal{B}_0$ of all balls of radius ϵ. For every $n = 0, 1, 2, \ldots$, let $\mathcal{B}_{n+1}$ be the coarsest partition finer than $\mathcal{B}_n$ and $f^{-1}(\mathcal{B}_n)$. From equicontinuity, this sequence of finer and finer partitions must stabilize to some $\mathcal{B}_n = \mathcal{B}_{n+1} = \mathcal{B}_{n+2} = \cdots$. To check that we have reached this point it is enough to check that $\mathcal{B}_n = \mathcal{B}_{n+1}$. We choose δ so that the clopen sets of $\mathcal{B}_n$ can be expressed as balls of radius δ. □

Corollary 20. An equicontinuous effective symbolic system is decidable.

Proof:
By the above proposition and Proposition 15. Alternatively, we can prove it from Proposition 6. □

We say that a point x of a dynamical system f is *sensitive* if there is an $\epsilon > 0$ such that for every $\delta > 0$ there is a point y with $d(x, y) < \delta$ and a non-negative time t such that $d(f^t(x), f^t(y)) > \epsilon$. It is easy to show with compactness that an equicontinuous dynamical system is exactly a system with no sensitive point. Hence, Proposition 20 implies that an undecidable symbolic system must have a sensitive point. Equicontinuity in the case of cellular automata are given a combinatorial characterization in [23], where it is also proved that equicontinuous cellular automata are eventually periodic, thus confirming in this particular case that equicontinuity is incompatible with computational universality.

7.5. Families of dynamical systems

Let us take for instance Proposition 7. The proof shows that a decision procedure for an individual system can be effectively found from programs of the computable functions that compute inverse image and the boolean connectors. So we can generalize Proposition 7:

Proposition 21. Let $(X_n, f_n)_{n\in\mathbb{N}}$ be a family of effective dynamical systems such that given n and two clopen sets U and V of X_n, we can compute $U \cap V$, $U \setminus V$ and $f_n^{-1}(U)$. Suppose in addition that any (X_n, f_n) has a limit set composed of finitely many minimal systems. Then, given n and an instance for (X_n, f_n) of the infinite-time observation problem, we can decide it.

For instance, the problem of infinite-time, finite-memory observation can be solved for the whole family of sturmian subshifts with algebraic slopes. Indeed, given an algebraic number (described by the polynomial it is the root of), we can effectively find a program witnessing that the corresponding sturmian subshift is effective; hence the above proposition applies.

Similar results can be proved with families of equicontinuous systems, for instance. For other results about decidable and undecidable properties in families of dynamical systems, see [9].

8. A universal chaotic system

According to Devaney [11], a system is *chaotic* if it is infinite, topologically transitive and has a dense set of periodic points. By *topologically transitive* we mean that for any two open sets U and V, there is a point of U that eventually reaches V. One can prove that every point of a chaotic system is sensitive [3]. For instance, the full shift is chaotic and sensitive in every point.

It is not difficult to construct a universal subshift. Indeed, in $\{0,1\}^{\mathbb{N}}$ consider all forbidden words of the form 01^n00^t1, where the universal Turing machine launched on data n does not halt in less than t steps. Then the subshift of all configurations avoiding this set of words is effective and universal: the halting problem is r.e.-complete. Note that it is not paradoxical or unreasonable to have a universal subshift while the shift itself is decidable: it is a common observation that a subshift can be much more complicated than the shift itself.

Modifying this construction, we get the following result:

Proposition 22. There exists an effective system on the Cantor space that is chaotic and universal.

Proof:
Consider a subshift $X \subset \{0,1,\S\}^{\mathbb{N}}$ whose forbidden words are all 01^n00^t1, where the universal Turing machine launched on data n does not halt in less than t steps. Denote by $L \subset \{0,1\}^*$ the language of binary words with no forbidden subword. Then the language of X consists of words $w_1\S w_2\S\ldots\S w_n$, where $w_i \in L$. We show that X is a universal chaotic system.

First note that X is a perfect subshift, so it is effectively conjugated to a system on the Cantor space. Then X has dense periodic points: if $w \in L$, then $(w\S)^\omega$ is in X. Finally X is topologically transitive: for any two finite words v, w of the language we can go from $[v]$ to $[w]$ with the point $v\S w\ldots$. Thus X is chaotic.

Moreover, given n it is r.e.-complete whether there is a point of $[01^n0]$ that eventually reaches $[001]$ without passing through $[\S]$. This property can be expressed by the finite automaton constructed in Figure 2. Thus X is universal. □

Note that the system built in the proof is a one-sided subshift, hence it is positively expansive: there is an ϵ such that any two points are eventually separated by at least ϵ. Note also that the halting problem for a chaotic symbolic system is trivially decidable, because of the topological transitivity.

The central idea of the 'edge of chaos' is that a system that has a complex behavior should be neither too simple nor chaotic. There are several ways to understand that. Here we interpret 'complex system' by 'universal symbolic system'. Then 'too simple' could refer to the situation treated in Proposition 7: one or several attracting minimal subsystems. This includes of course the case of a globally attracting fixed point. If we take 'chaotic' as meaning 'Devaney-chaotic', then computational universality need not be on the 'edge of chaos', since we have just constructed a chaotic system that is universal.

However, many examples of chaotic systems (whatever the exact meaning given to 'chaotic', and for symbolic systems as well as for analog ones), have the shadowing property. For instance the shift and Smale's horseshoe (present in some physical systems), as well as hyperbolic systems, satisfy the shadowing property.

Thus we suggest that the term 'edge of shadowing property' would be more appropriate (at least for symbolic systems), although not as thrilling.

Note nevertheless that the 'edge of chaos' has been much studied in cellular automata, and we don't know whether an example of a chaotic universal cellular automaton exists.

9. Discussion of universality

Turing [38] justified the form of his machine along the following lines. A human operator applying an algorithmic procedure can be supposed to be at every step of time in a unique mental state. He can be supposed to have finitely many possible mental states, and to have at his disposal a pencil and as much paper as needed, on which he may write out letters or digits. In a finite time he may read or write only finitely many symbols on the paper. Paper is modelled by the tape and the human by a kind of finite automaton that is able to read, write or shift the tape.

Now suppose that the human operator has no paper or pencil, but can observe a (physical realization of) a symbolic dynamical system, without being able to control it. The system can serve as a 'universal computer' if with its help, the human operator is able to solve all problems he could also solve with paper and pencil. As the human operator has finitely many possible mental states, at every step he can distinguish only finitely many configurations of the system. If we group together all points that are undistinguishable between them, we obtain a partition of the system state space. We suppose that this partition is clopen, because clopen partitions express in a natural way that finitely many symbols are observed from the system at every step of time, analogously to Turing's assumption.

Consequently, we model the situation as a symbolic system endowed with a clopen partition observed by a finite automaton. Now suppose that deciding whether the finite automaton can reach a final state from an initial state is at least as difficult as deciding the halting problem for a universal Turing machine. Then to get the answer to a recursively enumerable problem, it is enough to observe the system, provided we are 'lucky' and wait long enough. We say that such a system is computationally universal.

Our definition of universality perhaps differs in several ways from what we could expect at first glance from a generalization of Turing machine universality. We give now various arguments to support the present definition against seemingly more obvious attempts. In particular, we justify the use of *set-to-set* properties, observed by *finite automata*, on systems defined by a *computable* map.

9.1. Set-to-set properties

Many definitions of universality for particular systems (cellular automata, for instance) propose to observe point-to-point properties. Typically, a countable set of points $(x_n)_{n\in\mathbb{N}}$, and the system is said universal if the relation 'x_n is in the orbit of x_m' is r.e.-complete (this is a generalization of Davis' definition of universality for Turing machines [8]).

This definition has in our opinion three drawbacks.

- If the system is uncountable, there are infinitely many choices for the countable family of points (x_n). In the literature points with periodic or eventually periodic sequence of symbols are often considered, but there is apparently no *a priori* argument for this somewhat arbitrary choice (although Sutner's reflection principle [37] sheds some light into that direction).
- As remarked in [12], this definition leads to conclude that the shift is universal, for some choice of the $(x_n)_n$; a consequence that sounds unreasonable, because the shift does not compute anything but just reads the memory. Indeed, consider the set of all configurations with primitive recursive digits. This set is countable and dense, and every such configuration is computable. Then we take as an initial configuration the sequence of pairs (state of the head, currently read symbol) of a universal Turing machine during a computation. And we only have to shift it to know whether the halting state will ever appear.
- From a physical point of view, point-to-point properties are rather unsatisfactory. Indeed, if the system is uncountable, specifying an initial point for the computation means that we must give an infinite amount of information. Preparing a physical system to be in a very particular configuration is likely to be impossible, because of the noise or finite precision inherent to every measure.

The definition presented in Section 6 overcomes these three problems in a simple manner: the user needs only to specify a finite number of bits as an initial condition. Instead of initial *configurations* we should rather talk about initial *sets*, which may be seen as 'fuzzy points', points defined with finite accuracy. The system is said universal if some property about these sets is r.e.-complete.

9.2. Finite automata

What kind of property are we going to test on clopen sets (or, equivalently, on induced subshifts)? We choose properties that can be expressed by finite automata because they agree with Turing's idea of modelling a human operator as having finitely many possible mental states. Finite automata are also a simple and well-established framework, extensively studied in the literature.

Moreover, observing a larger class of properties may lead to absurdities. For instance, suppose that we look at identity on the Cantor space. We now choose to observe the following property: a clopen set satisfies the property if and only if its index (i.e., the integer describing the clopen set) satisfies some r.e.-complete property on $\mathbb{N}$. Then we find that the identity is computationally universal, which is a result not to be desired. The complexity of computation is artificially hidden in the decoding.

On the other hand, we see no reason to restrict ourselves to the sole halting property: ‘there is a trajectory from this clopen set to that clopen set’. For instance, the chaotic system built in Section 8 is universal but the halting property is decidable.

We do not use the powerful setting of Muller automata to define universality, because it may need an infinite time to check that a trajectory has the required property, which goes against the idea that a successful computation should end in a finite time. Whether a given observer Muller automaton accepts at least one trajectory of the system is actually a more general question, which is dealt with in our definition of ‘decidable system’. This question is interesting as well (independently of the debate over universality), since many properties of interest in dynamical systems, such as ‘Is there a trajectory that reaches the set A infinitely often’ for instance, can be expressed in this simple formalism. Informally, they observe all properties that can be observed with a finite memory of the past.

9.3. Effectiveness

Finally, the following example shows the usefulness to add an effectiveness structure on dynamical systems. Fix an r.e.-complete set $H \subset \mathbb{N}$ of integers and consider the symbolic dynamical system $f : \{0,1\}^{\mathbb{N}} \to \{0,1\}^{\mathbb{N}}$ such that $f(1^\omega) = 1^\omega$ and $f(1^n 0 x_0 x_1 x_2 \ldots) = 1^m 0 x_0 x_1 x_2 \ldots$, where m depends on n in the following way. If $n \in H$, then m is the largest integer strictly smaller than n such that $m \in H$ or 0 if no such number exists. If $n \notin H$, then $m = n$. Suppose now that $13 \in H$. Then the relation ‘the clopen set $[1^n 0]$ will eventually reach $[1^{13} 0]$’ is r.e.-complete, because H is.

On the other hand, if we were provided with an actual implementation of $f : \{0,1\}^{\mathbb{N}} \to \{0,1\}^{\mathbb{N}}$, we could decide an undecidable problem (namely, H) by observing the trajectories. So this system has ‘super-Turing’ capabilities, whereas the goal of this paper is to characterize those systems that have exactly the same power as universal Turing machines. To exclude such examples, we therefore restrict ourselves to systems such that the inverse image of a clopen set is computable. Note that for instance in [34] Siegelmann allows neural networks with non-recursive weights, leading to a non-computable maps and to super-Turing capabilities.

10. Conclusions and future work

We provided a definition of decidability and universality for a symbolic systems, and established some links between decidability and the dynamical properties of the system. We also constructed a chaotic system that is universal. These results are summed up in Figure 4. Let us list some open problems.

Is there a cellular automaton that is chaotic and universal (Section 8)? Do undecidable system have infinitely many disjoint subsystems (Conjecture 1)? Can we find sufficient conditions of universality? What can be said about distal systems, Furstenberg systems, topological entropy with respect to universality? Are the Game of Life and the automaton 110 universal for our definition? Can a linear cellular automaton be universal?

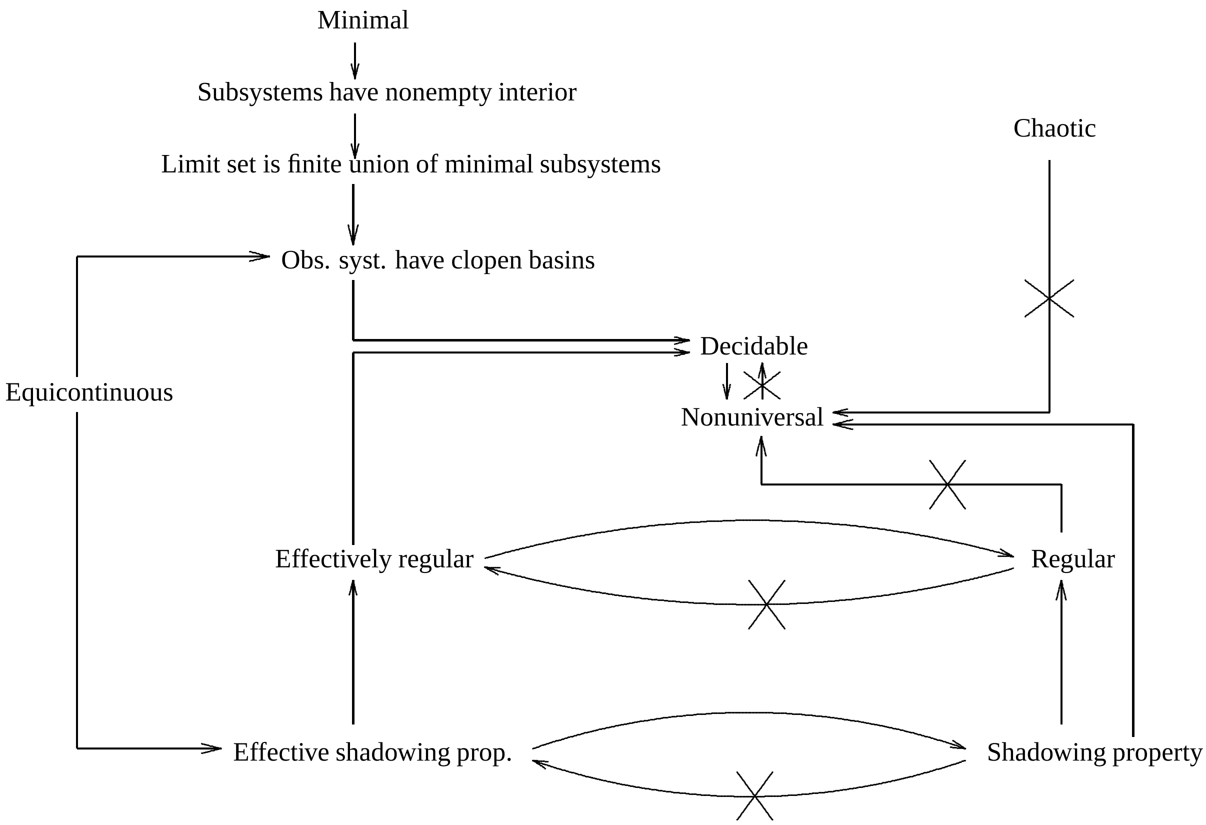

Figure 4. Summary of the results. Arrows read 'implies', crossed arrows read 'does not imply'.

The collection of Σ_1^1 problems can be stratified into a rich variety of intermediate levels. For instance, it contains the so-called arithmetic hierarchy. Which of these levels contain the infinite-time observation problem of some symbolic system?

It also remains to extend the definitions and results to systems in $\mathbb{R}^n$ in discrete time or even continuous time. The resulting definition of universality could then be compared to existing definitions, for instance [35, 5, 32, 30]. Then, results such as those of Section 7 could hopefully be adapted. For instance, are minimal systems capable of universal computation? Such results could then be applied to physical systems. What systems that can be found in Nature are able to compute? For instance, hyperbolic dynamical systems are known to have the effective shadowing property. This would suggest that hyperbolic systems are not universal.

A theory a computational complexity could also be investigated. What problems can be solved in polynomial time with a discrete-time dynamical system? Can we formulate a 'P$\neq$NP' conjecture? See [4, 35] for theories of complexity in analog computation.

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