REAL NUMBERS HAVING ULTIMATELY PERIODIC REPRESENTATIONS IN ABSTRACT NUMERATION SYSTEMS

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Abstract. Using a genealogically ordered infinite regular language, we know how to represent an interval of \( \mathbb{R} \). Numbers having an ultimately periodic representation play a special role in classical numeration systems. The aim of this paper is to characterize the numbers having an ultimately periodic representation in generalized systems built on a regular language. The syntactical properties of these words are also investigated. Finally, we show the equivalence of the classical \( \theta \)-expansions with our generalized representations in some special case related to a Pisot number \( \theta \).

1. Introduction

Enumerating the words of an infinite regular language \( L \) over a totally ordered alphabet \( (\Sigma, <) \) by genealogical ordering gives a one-to-one correspondence between \( \mathbb{N} \) and \( L \). This observation was the starting point of the study of the so-called abstract numeration systems which are a natural generalization of classical positional numeration systems like the Fibonacci system or the \( k \)-ary system. More generally, abstract systems generalize positional numeration systems where representations of integers are computed by the greedy algorithm and where the set of all the representations is a regular language \( \{L, \mathbb{L}, \mathbb{B}\} \). We were first interested in the representation of non-negative integers and in the syntactical properties of sets of representations \( \{L, \mathbb{L}, \mathbb{B}\} \).

In \cite{11} we extended these systems to the representation of real numbers. Mimicking the case of positional systems, a real number \( x \) is represented by an infinite word \( w \) which is the limit of a sequence \( (w_n)_{n \in \mathbb{N}} \) of words in \( L \). Each finite word \( w_n \) of the sequence corresponding to a numerical approximation of \( x \), the longer the common prefix of \( w \) and \( w_n \) is, the more accurate the approximation of \( x \) is. The ability of representing not only integers but also real numbers in abstract systems lead to several applications and generalizations like the study of the asymptotic properties of summatory functions of additive functions like the “sum-of-digits” function \( \mathbb{S} \) or the description of properties of generalized adding machines, i.e., “odometers” \( \mathbb{O} \).

Real numbers having an ultimately periodic representations are of particular interest. First, from the point of view of computational aspects, the amount of data needed to store completely such a number is finite (the information is given exactly by the aperiodic part and one period). Next, we shall see that the set of ultimately periodic representations is dense in the set of all the representations, so studying this subset of representations is relevant when dealing with approximations of real numbers. As an example, for the \( k \)-ary system, it is well-known that the numbers having an ultimately periodic representation is \( \mathbb{Q} \) which is dense in \( \mathbb{R} \) and therefore various number-theoretic problems concerning rational approximations of real numbers can arise. Finally, for classical systems (more precisely, for \( \beta \)-expansions...
when $\beta$ is a Pisot number) the set of real numbers having an ultimately periodic representation is exactly the field-extension $\mathbb{Q}((\beta))$. To be able to represent real numbers in a generalized numeration system, we consider some assumptions about the counting function of the language, namely $u(n) := \#(L \cap \Sigma^n) \sim P(n)\theta^n$ for some polynomial $P$ and $\theta > 1$. Therefore the problem of relating this number $\theta$ to the set of numbers having an ultimately periodic representation clearly appears in the case of abstract systems.

This paper has the following organization. First we recall definitions and notation about abstract numeration systems and the representation of real numbers. Next we recall the general assumptions we consider when dealing with the representation of real numbers. As stated before, these assumptions are related to the asymptotic behavior of the counting functions of the languages accepted from the different states of the minimal automaton of $L$. The reader could already note that we have slightly simplified the presentation given in [11]. The aim of Sections 2 and 3 is to give a summary of the relevant facts given in [10, 11, 15].

In Section 4 we study the syntactical properties of the ultimately periodic representations. We show that the corresponding language of infinite words is $\omega$-rational. This section has an automata theory flavor and can be read separately from the rest of the paper.

In Section 5 we obtain formulas for computing effectively the numerical value of an ultimately periodic representation. Moreover we show that the language made up of the ultimately periodic representations is dense in the set of all the representations. In [1], it is explained that for an abstract system built upon an arbitrary regular language $L$, a real number can have one, a finite number or even an infinite number of representations and the situation can be completely determined from the language $L$ (actually, from the asymptotic behavior of the counting functions associated to the different states). In Section 5, we show how to modify the language $L$ to obtain a new numeration system having exactly the same representations except that in this new system a number has at most two representations. Roughly speaking, we remove from the minimal automaton of $L$ the useless states which are giving redundant representations.

In Section 6, we use some intervals $I_w$ (a real number $x$ belongs to $I_w$ if $x$ has a representation having $w$ as prefix) to obtain a characterization of the real numbers having an ultimately periodic representation. From the ideas given in this result and its proof, we derive two algorithms for computing the representation of an arbitrary real number. These algorithms can be viewed as a generalization of the greedy algorithm used to compute $\beta$-expansions [14] and rely on the use of some affine functions completely defined by the minimal automaton of the language. We also present a dynamical system built upon those affine functions, the points having an ultimately periodic orbit in this dynamical system being exactly the real numbers having an ultimately periodic representation (this system is a generalization of the intervals exchange transformation [4, 12]). In Section 6, thanks to our algorithm of representation, we obtain another characterization of the real numbers having an ultimately periodic representation, these numbers are the fixed points of composition of some affine functions. Moreover, this composition can actually be viewed as a word belonging to a regular language over a finite alphabet of functions.

In the last section, we consider a Pisot number $\theta$. To this number, corresponds a unique linear Bertrand numeration system [6]. If $L$ is the language of representations of the integers in this latter Bertrand system then the representations of the real numbers in the abstract system built upon $L$ and the classical $\theta$-developments are the same. So thanks to a famous result of Klaus Schmidt, in this particular
case, we know precisely the structure of the set of real numbers having an ultimately periodic representation. This set is \( \mathbb{Q}(\theta) \).

2. Preliminaries

Let us precise notation and definitions. Let \( \Sigma \) be a finite alphabet. We denote by \( \Sigma^* \) the free monoid generated by \( \Sigma \) with identity \( \varepsilon \). Let \( L \) be an infinite regular language and \( \mathcal{M}_L = (Q, q_0, \Sigma, \delta, F) \) be its minimal automaton having \( Q \) as set of states, \( q_0 \) as initial state, \( F \) as set of final states. The transition function \( \delta : Q \times \Sigma \to Q \) of this automaton is naturally extended to \( Q \times \Sigma^* \) and we often write \( q.w \) as a shorthand for \( \delta(q, w) \), \( q \in Q \), \( w \in \Sigma^* \). (For more about automata theory see for instance [3].) If \( q \in Q \), we denote by \( L_q \) the language accepted in \( \mathcal{M}_L \) from the state \( q \), i.e.,

\[
L_q = \{ w \in \Sigma^* \mid q.w \in F \}.
\]

In particular, \( L_{q_0} = L \). In this paper, we shall extensively use the following linear recurrent sequences defined for each \( q \in Q \) by

\[
u_q(n) = \#(L_q \cap \Sigma^n), \quad v_q(n) = \#((L_q \cap \Sigma^n)^1).
\]

Since the initial state \( q_0 \) plays a special role, if \( q = q_0 \) then we simply write \( u(n) \) and \( v(n) \) (in the literature, \( u(n) \) is often called the growth function, the counting function or even the complexity of the language \( L \)).

Let \( (\Sigma, \prec) \) be a totally ordered alphabet. The genealogical ordering (or radix ordering) is defined as follows. Let \( u, v \) be two words over \( \Sigma \), \( u \prec v \) if \( |u| < |v| \) or if the words have the same length and \( u \) is lexicographically less than \( v \) (the lexicographic ordering is the usual order of the dictionary). If the context is clear, we write \( u \prec v \) instead of \( u \prec v \).

In [11] we introduced numeration systems generalizing classical numeration systems in which the set of representations of all the integers is a regular language. An abstract numeration system is a triple \( S = (L, \Sigma, \prec) \) where \( L \) is infinite regular language over the totally ordered alphabet \( (\Sigma, \prec) \). The genealogical ordering of \( L \) induced by the ordering of \( \Sigma \) gives a one-to-one correspondence between \( \mathbb{N} \) and \( L \). If \( w \in L \), we denote by \( \text{val}_S(w) \) the position of \( w \) in the genealogically ordered language \( L \) (positions are counted from zero). The number \( \text{val}_S(w) \) is said to be the numerical value of \( w \). Conversely, let \( n \in \mathbb{N} \), if \( w \) is the \((n + 1)\)th word in the genealogically ordered language \( L \), then \( w \) is the \( S \)-representation of \( n \) and is denoted by \( \text{rep}_S(n) \) (so \( \text{rep}_S = \text{val}_S^{-1} \)). In particular, these abstract systems generalize the well known class of positional linear numeration systems built upon a Pisot number [3] [12]. These latter systems are constructed on a strictly increasing sequence of integers satisfying a linear recurrence relation whose characteristic polynomial is the minimal polynomial of a Pisot number (a Pisot number is an algebraic integer \( \theta > 1 \) whose Galois conjugates have modulus less than one).

A numeration system has to be able to represent not only integers but also real numbers. So in [11] we described how to obtain the representations of the elements belonging to an interval of real numbers of the form \( [1/\theta, 1] \) in an abstract numeration system (and therefore using some conventions we can represent \([0,1]\)). Let \( k \in \mathbb{N} \setminus \{0,1\} \). In the \( k \)-ary numeration system, a real number \( x \in (0,1) \) is represented by an infinite word \( w = w_0 w_1 w_2 \cdots \). On the one hand, we have finite prefixes \( w_0 \cdots w_{n-1} \) of \( w \) converging to the infinite word \( w \). On the other hand, each prefix \( w_0 \cdots w_{n-1} \) gives rise to a numerical approximation

\[
\sum_{i=0}^{n-1} w_i k^{n-i-1} \quad \text{with} \quad k^n \quad \text{(1)}
\]

and the sequence of these numerical approximations is converging to the real number \( x \). Actually, the numerator in (1) is the numerical value in base \( k \) of \( w_0 \cdots w_{n-1} \).
and the denominator is the number of words of length at most \( n \) in the language \( \{ \varepsilon \} \cup \{1, \ldots, k-1\}\{0, \ldots, k-1\}^* \) associated to the \( k \)-ary system. Having in mind these two kinds of convergence, we proceed in the same way for an abstract system built upon a regular language \( L \) and consider sequences of words in \( L \) converging to an infinite word. Mimicking the formula (1), the numerical approximation given by a word \( w \in L \cap \Sigma^n \) is

\[
\frac{\text{val}_S(w)}{v(n)}.
\]

Under suitable assumptions, a sequence of numerical approximations is convergent whenever the corresponding sequence of words is convergent [11].

3. Framework for the representation of real numbers

To represent real numbers in an abstract numeration system, we consider converging sequences of words in \( L \). So we introduce the following notation

\[
L_\infty = \{w \in \Sigma^\omega \mid \exists (w_n)_{n \in \mathbb{N}} \in L^\mathbb{N} : \lim_{n \to \infty} w_n = w\}.
\]

This set dedicated to be the set of the representations of the considered real numbers (the interval of real numbers that we are able to represent will be made explicit soon). Therefore \( L_\infty \) has to be uncountable (because we want to represent an interval of real numbers which is uncountable). In [11], to be able to prove the convergence of the numerical approximations, we considered the following work hypothesis concerning the asymptotic behavior of the sequences \( u_q(n) \)'s.

**Hypothesis.** The set \( L_\infty \) is uncountable and for all states \( q \) of \( M_L \), either

(i) \( \exists N_q \in \mathbb{N} : \forall n > N_q, u_q(n) = 0 \) or

(ii) there exist \( \theta_q \geq 1, P_q(x) \in \mathbb{R}[x] \) and \( b_q > 0 \) such that

\[
\lim_{n \to \infty} \frac{u_q(n)}{P_q(n)\theta_q^n} = b_q.
\]

Since \( L_\infty \) is uncountable, it can be shown that the language \( L \) has an exponential growth and therefore \( \theta = \theta_q > 1 \).

By choosing the coefficient of the dominant term in \( P_{q_0} \) (or in the same way by replacing \( P_{q_0} \) with \( P_{q_0}/b_{q_0} \)), we may assume in what follows that

\[
\lim_{n \to \infty} \frac{u_{q_0}(n)}{P_{q_0}(n)\theta_{q_0}^n} = 1.
\]

For all states \( q \) of \( M_L \), the following limit exists

\[
\lim_{n \to \infty} \frac{u_q(n)}{P_{q_0}(n)\theta_{q_0}^n}
\]

and we denote by \( a_q \geq 0 \) its value (\( a_{q_0} = 1 \)). For details, see [11].

**Remark 1.** If a state \( q \) is such that \( d(P_q) < d(P_{q_0}) \) or \( \theta_q < \theta \) then \( a_q = 0 \).

**Proposition 2.** [11, Corollary 7] If \( (w_n)_{n \in \mathbb{N}} \in L^\mathbb{N} \) is converging to an infinite word \( w \in L_\infty \) then

\[
\lim_{n \to \infty} \frac{\text{val}_S(w_n)}{v(|w_n|)} = \frac{\theta - 1}{\theta^2} \sum_{q \in Q} a_q \sum_{j=0}^\infty \beta_{q,j} \theta^{-j} = x
\]

where the coefficients \( \beta_{q,j} \) depends only on \( w \).

In this latter proposition, the infinite word \( w \) is said to be a *representation* of the real number \( x \). In the same way, \( x \) is said to be the *numerical value* of \( w \). Each real number in \([1/\theta, 1]\) has at least one representation in \( L_\infty \). Conversely, each infinite word in \( L_\infty \) is the representation of a unique number in \([1/\theta, 1]\).
Remark 3. We know precisely what are the coefficients $\beta_{q,j}$'s introduced in Proposition 2. If the infinite word $w$ is written $w_0w_1\cdots$ then for all states $q$

$$\beta_{q,j} = \#\{\sigma < w_j \mid q_0.w_0\cdots w_{j-1}\sigma = q\} + \delta_{q,0}$$

where $\delta$ is the Kronecker's symbol. As noticed in [8], those coefficients can be computed by a transducer $T$ built upon $M_L$. If $Q = \{q_0, q_1, \ldots, q_r\}$ and if in $M_L$, $p.\sigma = p'$ then in $T$, the directed edge between $p$ and $p'$ is labeled by $(\sigma, n_0, n_1, \ldots, n_r)$ where

$$n_i = \#\{\tau < \sigma \mid p.\tau = q_i\} + \delta_{i,0}.$$ 

The reading in $T$ of the $n$th letter of a word $w = w_0w_1\cdots$ gives the $(r+1)$-uple $(\beta_{q_0,n}, \ldots, \beta_{q_r,n})$ corresponding to $w$, $n \geq 0$.

Example 4. Consider the language made up of the words containing an even number of $a$'s (we assume that $a < b$). The transducer computing simultaneously the coefficients $\beta_{q_0,n}$ and $\beta_{q_1,n}$ is given in Figure 1.

![Figure 1](image)

Figure 1. An automaton and the corresponding transducer computing $(\beta_{q_0,j}, \beta_{q_1,j})_{j \in \mathbb{N}}$.

4. Syntactical properties of the periods in $L_\infty$

In this section, we are interested in the syntactical properties of the ultimately periodic representations of real numbers. Namely, if $uv^\omega$ is an element in $L_\infty$ then what can be said about the syntax of $u$ or $v$? Are the words $u$ and $v$ related in some way to $L$?

Definition 5. Let $X$ be a set of infinite words. The set of the periods of the ultimately periodic words in $X$ is denoted $\text{per}(X)$ and is defined by

$$v \in \text{per}(X) \iff \exists u \in \Sigma^* : uv^\omega \in X.$$ 

In the same way, we can also define the set $\text{aper}(X)$ of the aperiodic parts of the ultimately periodic words in $X$,

$$u \in \text{aper}(X) \iff \exists v \in \Sigma^+ : uv^\omega \in X.$$ 

Example 6. The periodic and aperiodic parts of a word are not necessarily unique. Consider the word

$$w = aba(ab)^\omega,$$

we have $\text{per}\{\{w\}\} = \{(ab)^i \mid i > 0\}$ and $\text{aper}\{\{w\}\}$ contains any prefix of $w$ of length at least 3. Nevertheless, the minimal aperiodic prefix is $aba$ and to this prefix is corresponding the period $ab$ of minimal length.

The first aim of this section is to show that $\text{per}(L_\infty) \subseteq \Sigma^*$ is a regular language. Next we shall see that $\text{aper}(L_\infty) \subseteq \Sigma^*$ is also regular.

In the following lemma, we are interested in the states reached in $M_L$ when reading an ultimately periodic word.
Lemma 7. Let \((x_n)_{n \in \mathbb{N}} = uv^\omega\) be an ultimately periodic word of \(L_\infty\), the word 
\[\xi = (q_0, x_0)(q_0, x_0, x_1)(q_0, x_0, x_1, x_2) \cdots (q_0, x_0 \cdots x_n, x_{n+1}) \cdots \in (Q \times \Sigma)^\omega\]
is ultimately periodic of period \(|v|\) for some \(t \leq |Q|\).

Proof. We use the same kind of reasoning as in the proof of the classical pumping lemma ([19, Lemma 4.1]). If \(#Q = r\) then, for any \(q \in Q\), at least two states of the following list of \(r + 1\) states are the same 
\[q, q.v, \ldots, q.v^r.\]
So for \(q = q_0.u\), there exist \(i, j, 0 \leq i < j \leq r\), such that \(q' = q.v^i = q.v^j\). Thus in \(\mathcal{M}_L\) after reading \(v^{j-i}\) from this state \(q'\), we are back in \(q'\) and we have still to read \(v^\omega\). The deterministic behavior of \(\mathcal{M}_L\) leads to the conclusion. Notice that the period of \(\xi\) is bounded by \((j - i) |v| \leq |Q| |v|\).

We now present the construction of an automaton \(\mathfrak{M}\) that will be used to show that \(\text{per}(L_\infty)\) is regular.

Definition 8. Let us define a set \(C \subseteq 2^Q \setminus \emptyset\). A set \(C = \{p_1, \ldots, p_k\}\) of states belongs to \(C\) if and only if the following two conditions are satisfied 
\begin{enumerate}
\item \(C\) is a cycle in \(\mathcal{M}_L\) : there exists a word \(w = w_1 \cdots w_t \in \Sigma^t, \ell \geq k\), such that 
\[\begin{align*}
&\forall i \leq \ell, p_1.w_1 \cdots w_i \in C, \\
&\forall i \leq k, \exists j \leq \ell: p_1.w_1 \cdots w_j = p_i.
\end{align*}\]
\item \(C\) is coaccessible : there exist \(p_i \in C\) and \(w \in \Sigma^*\) such that \(p_i.w \in F\).
\end{enumerate}

Remark 9. Let \(C \in C\). The set \(C\) is also accessible. Indeed, since \(\mathcal{M}_L\) is minimal, it is accessible. So for each state \(p \in C\), there exists a word \(w\) such that \(q_0.w = p\).

Another observation is the following. In Definition 8 the cycle given by the word \(w = w_1 \cdots w_t\) is not necessarily an Hamiltonian circuit.

It is clear that \(C\) is ordered by inclusion. We denote by \(C_1, \ldots, C_t\) the maximal elements of \((C, \subseteq)\). (As a consequence of the maximality, for \(i \neq j\), \(C_i \cap C_j = \emptyset\). Indeed, if a state belongs to \(C_i \cap C_j\) then \(C_i \cup C_j\) belongs to \(C\) because we can find a longer cycle in \(\mathcal{M}_L\) and therefore neither \(C_i\) nor \(C_j\) is maximal.)

Let \(i \in \{1, \ldots, t\}, C_i = \{p_{i_1}^{(i)}, \ldots, p_{i_r}^{(i)}\}\) \((r_i \geq 1)\) and \(j \in \{1, \ldots, r_i\}\). For each such indices \(i\) and \(j\), we define a NFA \(\mathcal{M}_{i,j}\) in the following way, 
\[\mathcal{M}_{i,j} = (C_i, p_j^{(i)}, \Sigma, \delta|_{C_i \times \Sigma \times C_i}, \{p_j^{(i)}\}),\]
the set of states is \(C_i\), the initial state is \(p_j^{(i)}\) and the transition relation is the restriction of the transition function \(\delta\) of \(\mathcal{M}_L\) to the states belonging to \(C_i : \delta(p, \sigma) = q\) with \(p, q \in C_i\) if \(p, \sigma, q\) belongs to \(\delta|_{C_i \times \Sigma \times C_i}\). The state \(p_j^{(i)}\) is the unique final state of \(\mathcal{M}_{i,j}\). (Observe that the automaton \(\mathcal{M}_{i,j}\) is non-deterministic only because the function \(\delta\) is not necessarily complete.)

Let \(\mathfrak{M}\) be the NFA obtained as the union of the different \(\mathcal{M}_{i,j}\)'s. In this construction we assume that the sets of states of two distinct automata \(\mathcal{M}_{i,j}\)'s are disjoint. To obtain the union, we only have to consider a set of initial states instead of a single one.

Example 10. Let us consider the trim minimal automaton depicted in Figure 2 (the sink has not been represented, this state is never coaccessible so it never belong to a set in \(C\)). Here \(C = \{(3, 4), (2, 3, 4)\}\) and we have a single maximal element \(C_1 = (2, 3, 4)\) in \((C, \subseteq)\). The corresponding NFA \(\mathfrak{M}\) is given in Figure 3. (We have three initial states.) With our notation, this automaton is built (from left to right in Figure 3) upon the automata \(\mathcal{M}_{1,2}, \mathcal{M}_{1,4}\) and \(\mathcal{M}_{1,3}\).
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Let $k > 0$. Recall that a word $u$ belongs to the $k$th-root $\sqrt[k]{L}$ of a language $L$ if and only if $u^k$ belongs to $L$. If $\mathcal{M}$ is an automaton (deterministic or not), the language accepted by $\mathcal{M}$ is denoted $L(\mathcal{M})$.

**Proposition 11.** We have

$$ \text{per}(L_\infty) = \bigcup_{k=1}^{\#Q} \sqrt[k]{L(\mathfrak{M})}. $$

In particular $\text{per}(L_\infty)$ is regular.

**Proof.** Let $w^k \in L(\mathfrak{M})$ for some $k \leq \#Q$. This means that $w^k$ is accepted by some $\mathcal{M}_{i,j}$ and $p^{(i)}_j.w^k = p^{(i)}_j$. By definition of $\mathcal{L}$ and $\mathcal{M}_{i,j}$, it is clear that in $\mathcal{M}_L$, there exist $x$ and $y$ in $\Sigma^*$ such that $q_0.x = p^{(i)}_j$ and $p^{(i)}_j.y \in F$. Therefore, we have

$$ \forall n \in \mathbb{N}, \ xw^k y \in L $$

and $xw^\omega \in L_\infty$ since $xw^k y \rightarrow xw^\omega$ if $n$ tends to infinity. So $w$ is a period of an ultimately periodic word in $L_\infty$.

Let $w$ be an element of $\text{per}(L_\infty)$. There exists an ultimately periodic word $u = vw^\omega = u_0 u_1 u_2 \cdots \in L_\infty$ having $w$ as period. By Lemma [7]

$$ \xi = (q_0, u_0)(q_0, u_0, u_1)(q_0, u_0 u_1, u_2) \cdots (q_0, u_0 \cdots u_n, u_{n+1}) \cdots $$

is ultimately periodic of period $t|w|$ for some $t \leq \#Q$. We can write $\xi = \alpha/\beta^\omega$. After

an initial mess $\alpha$, the periodic part $\beta^\omega$ of $\xi$ begins. In this latter part, there is a position $(q, \sigma)$ corresponding to the first reading of the beginning of $w$. (Imagine
that the words $u$ and $\xi$ are written on two tapes which are read simultaneously by a single head one element at a time, so to the $n$th letter of $u$ corresponds exactly the $n$th element of $\xi$. This situation is depicted schematically in Figure 4.)

By periodicity of $\xi$, after reading $t|w|$ letters, we are again in the same position $(q, \sigma)$ and by periodicity of $(u_n)_{n \in \mathbb{N}}$, we are ready to read the beginning of a new occurrence of $w$. This means that we have in $\mathcal{M}_L$ a cycle containing $q$ and such that $q.w^t = q$. So clearly $w^t$ is accepted by some previously defined automaton $\mathcal{M}_{i,j}$ having $q$ as initial state. In other words, since $t \leq \#Q$, 

$$w \in \sqrt[k]{L(\mathcal{M})} \subseteq \bigcup_{k=1}^{\#Q} \sqrt[k]{L(\mathcal{M})}.$$ 

We can conclude, applying Lemma 12 below. □

**Lemma 12.** If $L$ is a regular language then for $k \geq 1$, $\sqrt[k]{L}$ is also regular.

For the sake of completeness, we recall the proof of Lemma 12.

**Proof.** If $q = q_0.w$ is a state of $\mathcal{M}_L$ then 

$$q = w^{-1}.L = \{v \in \Sigma^* \mid vw \in L\}$$

is a regular language. For the properties of the minimal automaton of a language, we refer to [3, III.5]. We define the language

$$S(q) = \{m \in \Sigma^* \mid q = m^{-1}.L\}.$$

This language is also regular. If $Q$ is the finite set of states of $\mathcal{M}_L$, then for $k > 0$ the following formula holds

$$\sqrt[k+1]{L} = \bigcup_{q \in Q} (S(q) \cap \sqrt[k]{q}).$$

Hence we obtain the conclusion by using an easy induction argument. □

We can now show that $\text{aper}(\mathcal{L}_\infty)$ is regular.

If $q$ is a state belonging to a maximal element $C_i$ of $\mathcal{C}$ then we denote by $\mathcal{M}_q$ the DFA $\mathcal{M}_q = (Q, q_0, \Sigma, \delta, \{q\})$ built upon the minimal automaton of $L$ where the set of final states is replaced by $\{q\}$. The following proposition is obvious.

**Proposition 13.** If the maximal elements of $\mathcal{C}$ are $C_1, \ldots, C_t$ then

$$\text{aper}(\mathcal{L}_\infty) = \bigcup_{q \in C_1 \cup \cdots \cup C_t} L(\mathcal{M}_q)$$

and this language is therefore regular.

**Proposition 14.** The language $\text{uper}(\mathcal{L}_\infty) \subset \Sigma^\omega$ of the ultimately periodic words in $\mathcal{L}_\infty$ is $\omega$-rational.

**Proof.** If the maximal elements of $\mathcal{C}$ are $C_1, \ldots, C_t$ then, using the previous notation for the automata $\mathcal{M}_q$, we have

$$\text{uper}(\mathcal{L}_\infty) = \bigcup_{i=1}^{t} \left[ \bigcup_{q \in C_i} L(\mathcal{M}_q) \cdot \left( \bigcup_{k=1}^{\#C_i} \sqrt[k]{L(\mathcal{M}_i,q)} \right)^\omega \right]$$

where $\mathcal{M}_{i,q}$ is the NFA having $C_i$ as set of states and $q$ as initial and final state. In this formula, the dot “.” represents the concatenation. Hence the conclusion, using classical results on $\omega$-rational languages [13]. □
5. Computing the values of ultimately periodic representations

Thanks to Proposition 3, the numerical value of an ultimately periodic word in $L_\infty$ can be easily computed. As a consequence of Remark 3, if $w$ is an infinite ultimately periodic word with a period of length $\ell$ then the corresponding sequence $(\beta_{q,n})_{n \in \mathbb{N}}$ is ultimately periodic with a period of length bounded by $\#Q\ell$.

The following lemma is obvious.

**Lemma 15.** If $(\alpha_n)_{n \in \mathbb{N}}$ is an ultimately periodic sequence of real numbers of the form $\alpha_0, \ldots, \alpha_{r-1}, (\alpha_r, \ldots, \alpha_{r+p-1})^\omega$ then

$$\sum_{j=0}^\infty \alpha_j \theta^{-j} = \sum_{j=0}^{r-1} \alpha_j \theta^{-j} + \frac{\theta^p}{\theta^p - 1} \sum_{j=r}^{r+p-1} \alpha_j \theta^{-j}.$$ 

If $(\beta_{q,n})_{n \in \mathbb{N}}$ is ultimately periodic, we denote by $r_q$ the minimal length of its aperiodic part and by $p_q$ the length of the corresponding minimal period of the sequence. As a consequence of Proposition 3 and Lemma 15, if $(w_n)_{n \in \mathbb{N}} \in L^\infty$ is converging to an ultimately periodic word $w$ corresponding to ultimately periodic sequences $(\beta_{q,n})_{n \in \mathbb{N}}$, then we have

$$\lim_{n \to \infty} \frac{\text{val}_S(w_n)}{\text{val}(w_n)} = \frac{\theta - 1}{\theta^2} \sum_{q \in Q} a_q \left( \sum_{j=0}^{r_q-1} \beta_{q,j} \theta^{-j} + \frac{\theta^{p_q}}{\theta^{p_q} - 1} \sum_{j=r_q}^{r_q+p_q-1} \beta_{q,j} \theta^{-j} \right).$$

If $r = \max_{q \in Q} r_q$ and $p = \text{lcm}_{q \in Q} p_q$ then

$$\lim_{n \to \infty} \frac{\text{val}_S(w_n)}{\text{val}(w_n)} = \frac{\theta - 1}{\theta^2} \left( \sum_{j=0}^{r-1} \left( \sum_{q \in Q} a_q \beta_{q,j} \right) \theta^{-j} + \frac{\theta^p}{\theta^p - 1} \sum_{j=r}^{r+p-1} \left( \sum_{q \in Q} a_q \beta_{q,j} \right) \theta^{-j} \right).$$

**Remark 16.** The coefficients $\sum_{q \in Q} a_q \beta_{q,j}$ could also be computed by a transducer built in a similar way as $T$.

With formulas (3) or (4), we can compute easily the real number represented by an ultimately periodic word.

Moreover, $\theta$ is an eigenvalue of the adjacency matrix $A$ of $M_L$ and $\overrightarrow{a} = (a_{q_0}, a_{q_1}, \ldots, a_{q_n})$ is one of its eigenvectors (recall that if $p, q \in Q$ then the adjacency matrix is defined by $A_{p,q} = \#\{\sigma \in \Sigma \mid p.\sigma = q\}$). For $n \geq 1$ and $p \in Q$, it is obvious that

$$u_p(n) = \sum_{q \in Q} A_{p,q} u_q(n-1).$$

Dividing both sides by $P_{q_0}(n) \theta^n$ and letting $n$ tend to infinity, we obtain

$$a_p = \frac{1}{\theta} \sum_{q \in Q} A_{p,q} a_q.$$

So $A \overrightarrow{a} = \theta \overrightarrow{a}$. This latter observation could be useful to determine in a practical way the value of $\overrightarrow{a}$ (remember that we have chosen $a_{q_0}$ to be equal to 1).

To conclude this section, we show that the set of ultimately periodic words in $L_\infty$ is dense in $L_\infty$. This can be related to the classical fact that for the base 10 system, $\mathbb{Q}$ is exactly the set of numbers having an ultimately periodic representation and $\mathbb{Q}$ is dense in $\mathbb{R}$.

**Proposition 17.** The set $\text{uper}(L_\infty) \subset \Sigma^\omega$ of the ultimately periodic words in $L_\infty$ is dense in $L_\infty$.
Proof. Let $w \in \mathcal{L}_\infty$. By definition of the set, there exists a sequence $(w_n)_{n \in \mathbb{N}}$ of words in $L$ such that $w_n \to w$. For any $\ell > 0$ there exist $N$ such that $w$ and $w_N$ have a common prefix of length $\ell$ and $|w_N| \geq \ell + \#Q$. When reading the suffix of length $\#Q$ of $w_N$ in $\mathcal{M}_L$ we go at least twice through the same state $q$ and let $a$ be the corresponding factor of $w_N$ such that $q.a = q$. Therefore, $w_N$ can be written $xuz$ with $|x| \geq \ell$ and it is clear that $xu^nz \in L$ for all $n \geq 1$. So $xu^n \in \mathcal{L}_\infty$ and has a prefix of length $\ell$ in common with $w$. We can therefore build a sequence of ultimately periodic words converging to $w$. \hfill \square

6. Simplifying the language

In the first part of this section, we explain how a real number can have more than one representation and even an infinite number of representations. Next, we explain how we can slightly change the language to avoid this situation of having an infinite number of representations but without altering the other representations.

In [11], we gave a partition of the interval $[1/\theta, 1]$ into intervals $I_w$. These intervals will play a central role in what follows so let us recall their definition. First consider the $k$-ary system. In this system, the representation of a real number $x \in [1/10, 1]$ has a prefix $w = w_0 \cdots w_n$ ($w_0 \neq 0$) if $x$ belongs to the interval

$$I_w = \left[ \frac{\sum_{i=0}^{n-1} w_i k^{n-i-1}}{k^n}, \frac{1 + \sum_{i=0}^{n-1} w_i k^{n-i-1}}{k^n} \right].$$

Observe that the endpoints of the intervals $I_w$ are the only numbers having two representations. For instance, if $k = 10$ then $2/10$ can be written $0, 1999\cdots$ and $2/10$ is the upper bound of $I_1$ but it can also be written $0, 2000\cdots$ and is the lower bound of $I_2$. For an abstract numeration system, we have the following definition.

Definition 18. A real number $x \in [1/\theta, 1]$ belongs to $I_w$ if there exist a representation of $x$ having $w$ as prefix.

For an arbitrary regular language $L$, the set $\mathcal{L}_\infty$ can contains an infinite number of words having $w$ as prefix even if the length of the interval $I_w$ is zero. In this situation, all the elements of $\mathcal{L}_\infty$ having $w$ as prefix are representing the same real number $x$ and $I_w = [x, x]$. Therefore $x$ has an infinite number of representations. To avoid this situation, we proceed as follows.

We can only consider the states $q$ such that $a_q > 0$. We have the following rules

- If $a_q \neq 0$ and there exists $w$ such that $p.w = q$, then $a_p \neq 0$.
- If $a_q = 0$ and there exists $w$ such that $q.w = p$, then $a_p = 0$.

Indeed, in the first case, if $p.w = q$ then $u_n(p) \geq u_{n-|w|}(q)$. In the second case, if $q.w = p$ then $u_n(q) \geq u_{n-|w|}(p)$. Hence we obtain the conclusion by dividing both sides by $P_{\theta^n}(n)\theta^n$.

We can split the set of states of $\mathcal{M}_L$ into two subsets $Q_0 = \{q \mid a_q = 0\}$ and $Q_{>0} = \{q \mid a_q > 0\}$. If we consider only the states of $Q_{>0}$ and the corresponding edges connecting those states, we obtain a new automaton accepting a new language $L'$. Representations of real numbers for the numeration system built upon $L$ or $L'$ are the same except that for the system built on $L'$ a real number has at most two representations (only when it is the endpoint of some interval $I_w$).

Example 19. We consider the language $L$ accepted by the automaton depicted in Figure 3. This language is such that the number of words beginning with $b$ (resp. $a$ or $c$) has a polynomial (resp. exponential) behavior. This means that the length of the interval $I_b$ is zero (computations are given in [11, Example 6]). Therefore the greatest word in the lexicographical ordering of $\mathcal{L}_\infty$ beginning with $a$ represents the same real number $x$ as any word in $\mathcal{L}_\infty$ beginning with $b$ or the smallest word
beginning with $c$. Removing the states of $Q_0$, gives a new language $L'$. In the numeration system built upon $L'$, the number $x$ has exactly two representations: the greatest word beginning with $a$ and the smallest one beginning with $c$. In this latter system, if $w$ is prefix of an infinite number of words in $L$ then the length of the interval $I_w$ is strictly positive.

In the following of this paper, we shall assume that $a_q > 0$ for all states $q$ in $M_L$ except possibly for the sink state.

7. Determining the Numbers Having an Ultimately Periodic Representation

Let us have a closer look at those intervals $I_w$ (for the details, the reader is referred to [11]). If $w \in \Sigma^\ell$ is prefix of an infinite number of words in $L$ then the interval $I_w$ is given by

\[
\lim_{n \to \infty} \left( \frac{v(n-1)}{v(n)} + \sum_{m \in \Sigma^\ell, m < w} u_{q_0,m}(n-\ell) \right) \frac{v(n)}{v(n)} + \sum_{m \in \Sigma^\ell, m \leq w} u_{q_0,m}(n-\ell) \frac{v(n)}{v(n)} \right)
\]

Using the fact that (see [11, Proposition 5])

\[
\left\{ \begin{array}{l}
\lim_{n \to \infty} v_q(n)/v(n) = a_q \\
\lim_{n \to \infty} u_q(n)/v_q(n) = (\theta - 1)/\theta
\end{array} \right.
\]

the interval $I_w$ be rewritten as

\[
\left[ \frac{1}{\theta} + \frac{\theta - 1}{\theta^{\ell+1}} \sum_{m \in \Sigma^\ell, m < w} a_{q_0,m} \frac{1}{\theta} + \frac{\theta - 1}{\theta^{\ell+1}} \sum_{m \in \Sigma^\ell, m \leq w} a_{q_0,m} \right].
\]

Notice that this formulation differs slightly from [11] because we have here $a_{q_0} = 1$ and the others $a_q$’s are strictly positive (except for the sink). Observe also that the length of $I_w$ is $\frac{\theta - 1}{\theta^{\ell+1}} a_{q_0,w} > 0$.

**Remark 20.** Notice that if $w \in \Sigma^*$ is prefix of an infinite number of words in $L$ then $q_{q_0,w}$ is a coaccessible state (so it cannot be the sink) and with our assumptions, $a_{q_0,w} > 0$.

**Example 21.** Consider the numeration system associated to the language accepted by the automaton depicted in Figure 6. Here, easy computations show that $\theta = 2$, $a_{q_0} = a_{q_2} = 1$ and $a_{q_1} = 2$ (to obtain the $a_q$’s, one has only to compute the eigenvectors of the eigenvalue $\theta$ of the adjacency matrix). Any word in $L_\infty$ begins with $a$, so $I_a = [1/2, 1]$ (instead of this reasoning, formula [4] could also be used to compute the values of the endpoints of $I_a$). This interval is partitioned into three parts,

$I_{aa} = [1/2, 5/8], \ I_{ab} = [5/8, 3/4], \ I_{ac} = [3/4, 1]$. 
Thus if a real number \( x \) belongs to \( I_{a\sigma} \) then we have an infinite word representing \( x \) beginning with \( a\sigma \), \( \sigma \in \Sigma \). For the next step, we have
\[
I_{aac} = I_{aa} = [1/2, 5/8], \quad I_{aba} = I_{ab} = [5/8, 3/4]
\]
and \( I_{ac} \) is split into three parts
\[
I_{aca} = [3/4, 5/6], \quad I_{acb} = [5/6, 7/8], \quad I_{aca} = [7/8, 1].
\]

Actually the form of the partition of an interval \( I_w \) into intervals \( I_{w\sigma} \) depends only on the state \( q_0 \cdot w \) and not on the word \( w \) itself.

**Definition 22.** If \( 0 \leq \lambda < \mu \leq 1 \), the strictly increasing function
\[
f_{[\lambda, \mu]} : [\lambda, \mu] \to [0, 1], \quad x \mapsto \frac{x - \lambda}{\mu - \lambda}
\]
maps the interval \([\lambda, \mu]\) onto \([0, 1]\). If \( z \) belongs to \([\lambda, \mu]\) then we say that \( f_{[\lambda, \mu]}(z) \) is the relative position of \( z \) inside \([\lambda, \mu]\). We denote by \( L_w \) (resp. \( U_w \)) the lower (resp. upper) bound of the interval \( I_w \).

Roughly speaking, the next proposition states that two intervals corresponding to the same state are homothetic. But first, we need a technical lemma.

**Lemma 23.** We have, for all states \( q \),
\[
\sum_{\sigma \in \Sigma} a_{q, \sigma} = \theta a_q
\]
in particular, \( \sum_{\sigma \in \Sigma} a_{q_0, \sigma} = \theta \).

**Proof.** Clearly, \( I_w = \bigcup_{\sigma \in \Sigma} I_{w\sigma} \) and the length of \( I_w \) is equal to \( \sum_{\sigma \in \Sigma} |I_{w\sigma}| \). The conclusion follows directly from (8). \(\square\)

**Proposition 24.** Let \( m \) and \( w \) be two words such that \( q_0 \cdot m = q_0 \cdot w \). For all \( \sigma \in \Sigma \), the interval \( I_{m\sigma} \) exists\(^1\) iff \( I_{w\sigma} \) exists and the relative position of \( L_{m\sigma} \) (resp. \( U_{m\sigma} \)) inside \( I_m \) is equal to the relative position of \( L_{w\sigma} \) (resp. \( U_{w\sigma} \)) inside \( I_w \).

**Proof.** The interval \( I_{m\sigma} \) exists if \( a_{q_0, m\sigma} > 0 \). Since \( q_0 \cdot m = q_0 \cdot w \) then for all \( \sigma \in \Sigma \), \( a_{q_0, m\sigma} > 0 \) iff \( a_{q_0, w\sigma} > 0 \). Using (8), the relative position of \( L_{m\sigma} \) inside \( I_m \) is given by
\[
\left( L_{m\sigma} - \frac{1}{\theta} \right) - \frac{\theta - 1}{\theta |m| + 1} \sum_{u \in \Sigma^{|m|}, u < m} a_{q_0, u} \left( \frac{\theta - 1}{\theta |m| + 1} a_{q_0, m} \right)
\]
this can be rewritten as
\[
\frac{\theta |m|}{(\theta - 1) a_{q_0, m}} (\theta L_{m\sigma} - 1) - \sum_{u \in \Sigma^{|m|}, u < m} a_{q_0, u} a_{q_0, m}
\]

\(^1\)An interval \( I_w \) exists if there exists a word in \( L_\infty \) having \( w \) as prefix. This means that \( w \) is prefix of an infinite number of words in \( L \).
and using the definition of $L_{m\sigma}$, we get

$$(7) \quad \frac{1}{a_{q_0,m}} \left( \frac{1}{\theta} \left( \sum_{u \in \Sigma_1^{\mid\mid m\mid + 1}} a_{q_0,u} - \sum_{u < m, u \in \Sigma} a_{q_0,u} \right) \right).$$

First notice that the sum over the words $u$ of length $\mid m \mid + 1$ and lexicographically less than $m\sigma$ can be split into two subsets: the words $m\tau$ with $\tau < \sigma$ and the words having a prefix of length $\mid m \mid$ lexicographically less than $m$. So (7) can be written

$$\frac{1}{a_{q_0,m}} \left[ \frac{1}{\theta} \left( \sum_{\tau \in \Sigma, \tau < \sigma} a_{q_0,m\tau} + \sum_{u \in \Sigma_1^{\mid\mid m\mid + 1}, \text{pref}_{m}(u) < m} a_{q_0,u} \right) - \sum_{u \leq m, u \in \Sigma} a_{q_0,u} \right]$$

where $\text{pref}_{m}(u) < m$ means that the prefix of length $\mid m \mid$ of $u$ is lexicographically less than $m$. To conclude the proof, notice that

$$\sum_{u \in \Sigma_1^{\mid m \mid + 1}, \text{pref}_{m}(u) < m} a_{q_0,u} = \sum_{u' \in \Sigma_1^{\mid m \mid}, \sigma \in \Sigma} \sum_{u'' < m} a_{q_0,u''}$$

and using Lemma 23, we have

$$\frac{1}{\theta} \sum_{u \in \Sigma_1^{\mid m \mid + 1}, \text{pref}_{m}(u) < m} a_{q_0,u} - \sum_{u \in \Sigma_1^{\mid m \mid}, u < m} a_{q_0,u} = \frac{1}{\theta} \sum_{u' \in \Sigma_1^{\mid m \mid}} \sum_{u'' < m} \theta a_{q_0,u''} - \sum_{u \in \Sigma_1^{\mid m \mid}, u < m} a_{q_0,u} = 0.$$

So the relative position of $L_{m\sigma}$ inside $I_m$ is

$$(8) \quad \frac{1}{\theta a_{q_0,m}} \sum_{\tau \in \Sigma, \tau < \sigma} a_{q_0,m\tau}$$

and depends only on the state $q_0,m$.

Example 25. Continuing Example 21. We have $q_0.a = q_0.ac = q_1$. Observe that $I_a$ is split into three parts ($I_{aa}$, $I_{ab}$ and $I_{ac}$) and the relative positions of $5/8$ and $3/4$ inside $I_a$ are respectively $1/4$ and $1/2$. In the same way, $I_{ac}$ is split into three parts ($I_{aca}$, $I_{acb}$ and $I_{acc}$) the relative positions of $5/6$ and $7/8$ inside $I_{ac}$ are also respectively $1/4$ and $1/2$.

Theorem 26. A real number $x$ has an ultimately periodic representation if and only if there exist two words $m$ and $w$ such that

1. $m$ is a prefix of $w$,
2. $x$ belongs to $I_w \subset I_m$,
3. $q_0,m = q_0,w$,
4. the relative position of $x$ inside $I_m$ is equal to the relative position of $x$ inside $I_w$.

Proof. The condition is sufficient. If $x$ belongs to $I_m$ then a representation of $x$ has $m$ has prefix. The following letter of the representation depends only on the relative position of $x$ inside $I_m$. Assume that this letter is $\sigma$ (i.e., $x \in I_{m\sigma}$). Thanks to Proposition 24, since $q_0,m = q_0,w$ and the relative position of $x$ inside $I_m$ is equal to the relative position of $x$ inside $I_w$, it is clear that $x$ belongs to $I_{w\sigma}$. The same arguments can be used with $I_{m\sigma}$ and $I_{w\sigma}$ and so on. Actually, if $w = mw$ then the representation of $x$ is $mw^\omega$.

Assume now that $x$ has an ultimately periodic representation $w = w_0w_1\cdots = wv^\omega$. It is well known that $I_{w_0\cdots w_i} \subset I_{w_0\cdots w_j}$ for $i < j$. Since the automaton $M_L$ is finite, there exist infinitely many indices $i_1 < i_2 < \ldots$ and a constant $C$ such that

$$q_0.w_0\cdots w_{i_1} = q_0.w_0\cdots w_{i_2} = \ldots, \quad i_1 \geq \mid u \mid \quad \text{and} \quad \forall k \geq 1, i_{k+1} - i_k = C\mid v \mid.$$
Assume that for any pair $i_j < i_k$ of such indices the relative position of $x$ inside $I_{w_0 \cdots w_{i_j}}$ is different from its relative position inside $I_{w_0 \cdots w_{i_k}}$. To conclude the proof, we have to show that the representation of $x$ is not ultimately periodic. If $x$ belongs to some $I_W (W = w_0 \cdots w_i)$, then $x$ has a representation beginning with $W$ and to determine the following letter of this representation, the interval $I_W$ is divided into intervals $I_{W,W \cdots W}$. This process of dividing intervals into smaller intervals is repeated continuously and we already know that the length of $I_W$ is $\frac{q_{n-1}}{q_n} - a_{q_n} W \in \mathcal{O}(\theta^{-|W|})$. Since relative positions of $x$ inside $I_{w_0 \cdots w_{i_j}}$ and $I_{w_0 \cdots w_{i_k}}$ are different, by Proposition 24 there exist $n$ and $\sigma \neq \tau$ such that

$$x \in I_{w_0 \cdots w_{i_j} w_{i_j+1} \cdots w_{i_j+n\sigma}} \quad \text{and} \quad x \in I_{w_0 \cdots w_{i_k} w_{i_k+1} \cdots w_{i_k+n\tau}}.$$

Therefore $w$ is not ultimately periodic.

Since the form of the intervals $I_w$ depends only on the states of $M_L$, we can define some dynamical system.

**Definition 27.** For each $q \in Q$, we define a partition of $A_q = [0, 1]$ into intervals $A_{q_1} \cdots A_{q_n}$ in the following way. Since $M_L$ is accessible, there exists $w$ such that $q = q_0 \cdot w$. For each $\sigma \in \Sigma$ such that $I_{w_\sigma}$ exists consider the relative position $\ell_{q,\sigma}$ (resp. $u_{q,\sigma}$) of $I_{w_\sigma}$ (resp. $U_{w_\sigma}$) inside $I_w$. We denote

$$A_{q,\sigma} = [\ell_{q,\sigma}, u_{q,\sigma}].$$

(If $\sigma$ is the largest letter such that $I_{w_\sigma}$ exists then $A_{q,\sigma} = [\ell_{q,\sigma}, u_{q,\sigma}] = [\ell_{q,\sigma}, 1]$.)

Let us define a function $h : Q \times [0, 1] \to Q \times [0, 1] : (q, x) \mapsto (q', x')$ in the following manner. Since we have a partition of $A_q$, there exists a unique letter $\sigma$ such that $x \in A_{q,\sigma}$ and therefore

$$\begin{cases} q' = q \cdot \sigma \\ x' = f_{A_{q,\sigma}}(x) \end{cases}$$

where $f_{A_{q,\sigma}}(x)$ denotes the relative position of $x$ inside $A_{q,\sigma}$. (For the interested reader, this dynamical system looks like up to some extend to interval exchange transformations.)

**Example 28.** Continuing Example 21. The interval $A_{q_0} = [0, 1]$ is partitioned into a single interval $A'_{q_0} = [0, 1]$. The interval $A_{q_1} = [0, 1]$ is partitioned into $A'_{q_1} = [0, 1/4)$, $A'_{q_1, b} = [1/4, 1/2]$ and $A'_{q_1, c} = [1/2, 1]$. Finally $A_{q_2} = [0, 1]$ is partitioned into a single interval $A'_{q_2, c} = [0, 1]$. 

Let us now present two equivalent algorithms for computing the representation of a real number. We recall that $I_\varepsilon = [1/\theta, 1]$. We denote by $f_I(x)$ the relative position of $x$ inside the interval $I$.

**Algorithm 29.** Let $x \in [1/\theta, 1]$

**Initialization**

$q \leftarrow q_0$

$w \leftarrow \varepsilon$

$y \leftarrow f_{I_\varepsilon}(x)$

**repeat**

Determine the letter $\sigma \in \Sigma$ such that $y \in A'_{q,\sigma}$.

$q \leftarrow q \cdot \sigma$

$w \leftarrow \text{concat}(w, \sigma)$

$y \leftarrow f_{I_w}(x)$

**until** a stop condition.
The stop condition of the algorithm can be a fixed number of \( k \) iterations to determine the first \( k \) letters of a representation. One could check if a representation is ultimately periodic. Indeed, if we denote by \( q_n \) and \( y_n \) the values of the variables \( q \) and \( y \) during the \( n \)th iteration of the algorithm then thanks to Theorem 26, a representation is ultimately periodic if there exist \( i \neq j \) such that \( q_i = q_j \) and \( y_i = y_j \). A variant of this algorithm is the following one.

**Algorithm 30.** Let \( x \in [1/\theta, 1] \)

**Initialization**
- \( q \leftarrow q_0 \)
- \( w \leftarrow \varepsilon \)
- \( I \leftarrow [1/\theta, 1] \)
- \( x \leftarrow f_I(x) \)

**repeat**
- Determine the letter \( \sigma \in \Sigma \) such that \( x \in A'_{q,\sigma} \).
- \( q \leftarrow q.\sigma \)
- \( w \leftarrow \text{concat}(w, \sigma) \)
- \( I \leftarrow A'_{q,\sigma} \)
- \( x \leftarrow f_I(x) \)

**until a stop condition.**

In this latter algorithm, a periodicity in the representation is found when \( q_i = q_j \) and \( x_i = x_j \).

**Example 31.** Continuing Example 21. We can try to obtain the representation of \( x = 4/7 \) using Algorithm 29. The computations are given in Table 1. At each step of the procedure, the intervals \( I_w \) are given below their corresponding \( A'_{q,\sigma} \).

| \( q \) | \( w \) | \( f_I(x) \) | \( A'_{q,a} \) | \( A'_{q,b} \) | \( A'_{q,c} \) |
|---|---|---|---|---|---|
| 0 | \( \varepsilon \) | 1/7 | [0, 1] | --- | --- |
| 1 | \( a \) | 1/7 | [0, 1/4] | [1/4, 1/2] | [1/2, 1] | 1/7 < 1/4 |
| 2 | \( aa \) | 4/7 | --- | --- | [0, 1] | 1/2 < 4/7 |
| 1 | \( aac \) | 4/7 | [0, 1/4] | [1/4, 1/2] | [1/2, 1] | 1/2 < 4/7 |
| 1 | \( aacc \) | 1/7 | [1/2, 17/32] | [17/32, 9/16] | [9/16, 5/8] | 9/16 < 4/7 |

**Table 1.** Representation of \( x = 4/7 \).

to Theorem 26, \( 4/7 \) is represented by \( a(acc)^\omega \). The iteration of the function \( h \) introduced in Definition 23 can also be used to find the real numbers having an ultimately periodic representation, indeed here we have

\[
(q_0, 1/7) \overset{h}{\rightarrow} (q_1, 1/7) \overset{h}{\rightarrow} (q_2, 4/7) \overset{h}{\rightarrow} (q_1, 4/7) \overset{h}{\rightarrow} (q_1, 1/7).
\]

8. A characterization

With the abstraction of the previous section, we can summarize the informations needed to compute representations of real numbers: a finite number of partitions
\( A_q = \cup A'_{q, \sigma} \) of the interval \([0, 1]\) and the transition function of \( M_L \). The aim of this section is to give a characterization of the real numbers having an ultimately periodic representation in terms of composition of some affine functions.

**Definition 32.** Let us consider the automaton \( F_L \) defined as follows

- The set of states is \( \{ A_q \mid q \in Q \} \).
- If \( A_q \) is partitioned into \( A'_{q, \sigma_1} \cup \ldots \cup A'_{q, \sigma_t} \) then we have an edge labeled by \( f_{A'_{q, \sigma_i}} \) from \( A_q \) to \( A_{q, \sigma_i} \) (where the dot in \( q, \sigma_i \) denotes the transition function of \( M_L \)) for \( i = 1, \ldots, t \).
- All the states are final.

Except that the initial state is not important in what follows and that the labels of the edges have changed, \( F_L \) is more or less a copy of \( M_L \).

**Example 33.** Continuing Example 21. Here, \( f_{A'_{q_0, \sigma}} = f_{A'_{q_2, \sigma}} = id \) and

\[
\begin{align*}
&f_{A'_{q_1, \sigma}} : [0, 1/4) \rightarrow [0, 1): x \mapsto 4x, \\
&f_{A'_{q_1, \beta}} : [1/4, 1/2) \rightarrow [0, 1): x \mapsto 4x - 1, \\
&f_{A'_{q_1, \gamma}} : [1/2, 1] \rightarrow [0, 1): x \mapsto 2x - 1.
\end{align*}
\]

The automaton \( F_L \) is depicted in Figure 7. For the sake of simplicity, \( f_{A'_{q, \sigma}} \) is denoted by \( f_{\sigma} \), for \( \sigma = a, b, c \) (since it does not lead to any confusion). We also put an index \( a \) or \( c \) to id to remember the corresponding letter. A path \( f_1 \cdots f_t \) in \( F_L \) corresponds to the composition of affine functions \( f_t \circ \cdots \circ f_1 \) in reversed order. Through \( F_L \), we can determine the real numbers having ultimately periodic representations.

Indeed, if we consider a cycle \( f_1 \cdots f_t \) in \( F_L \) starting in \( A_{q_0} \), then, in view of Algorithm 30, if the unique fixed point of the corresponding function \( F = f_t \circ \cdots \circ f_1 \) is \( x \) then \( f_t^{-1}(x) \), with \( f_t : x \mapsto \frac{\theta x - 1}{\theta - 1} \) and \( f_t^{-1}(y) = \frac{(\theta - 1)y + 1}{\theta} \), has an ultimately periodic representation (we are back in the initial state \( q_0 \) and since \( x = F(x) \), we have the same initial value; due to the initialization step in Algorithm 8, we have to apply \( f_t^{-1} \) once). As an example, the fixed points of \( f_b \circ id_a \), \( f_b \circ id_c \circ f_a \circ id_a \) and \( f_b \circ c \circ id_c \circ f_a \circ id_a \) are respectively \( 1/3 \), \( 1/5 \) and \( 5/31 \) and therefore \( 2/3 \), \( 8/15 \) and \( 18/31 \) have ultimately periodic representations. From the path in \( F_L \), we also know these representations: \((ab)^\omega\), \((aaccb)^\omega\) and \((aaccb)^\omega\).

We can also consider a cycle \( f_1 \cdots f_t \) in \( F_L \) starting in \( A_{q_1} \) instead of \( A_{q_0} \) and a path \( g_1 \cdots g_s \) from \( A_{q_0} \) to \( A_{q_1} \). Once again, let \( x \) be the fixed point of \( F = f_t \circ \cdots \circ f_1 \). From Algorithm 30, the number \( f_t^{-1} \circ g_1^{-1} \circ \cdots \circ g_s^{-1}(x) \) has an ultimately periodic representation. As an example, consider \( F = f_c \circ id_c \circ f_a \circ f_c \), having \( 3/5 \) has fixed point. A trivial path from \( A_{q_0} \) to \( A_{q_1} \) is given by \( id_a \), so \( f_t^{-1}(3/5) = 4/5 \) has an ultimately periodic representation: \((aacc)^\omega\). Another path in \( F_L \) from \( A_{q_0} \) to \( A_{q_1} \) is \((id_a, f_a, id_c)\), so \( f_t^{-1} \circ f_a^{-1}(3/5) = 23/40 \) is represented by \((aacc)^\omega\).

Let us introduce some notation. Let

\[ \phi_q = \{ w \mid \delta_F(A_q, w) = A_q \} \]
where $\delta_F$ is the transition function of $F_L$. If $w = f_1 \cdots f_t \in \phi_0$, we denote by $F_{q,w}$ the composed function (in reversed order) $f_t \circ \cdots \circ f_1$ corresponding to $w$. Let

$$ \nu_q = \{ w \mid \delta_F(A_{q_0}, w) = A_q \}, $$

If $w = f_1 \cdots f_s \in \nu_q$, we denote by $(F_{q,w})^{-1}$ the composition of the inverse functions $f_s^{-1} \circ \cdots \circ f_1^{-1}$ corresponding to $w$.

**Theorem 34.** Let $L$ be a regular language satisfying our basic assumptions. Set

$$ f_t^{-1} : y \mapsto \frac{(\theta - 1) y + 1}{\theta}. $$

The set of real numbers having an ultimately periodic representation is given by

$$ \{ f_t^{-1} \circ (F_{q,w})^{-1}(x) \mid \exists q \in Q, z \in \nu_q, w \in \nu_q : x = F_{q,z}(x) \}. $$

**Proof.** This is a direct consequence of Algorithm 31. \qed

**Remark 35.** For all states $q$, the languages $\phi_q$ and $\nu_q$ over a finite alphabet of functions are regular.

### 9. Equivalence with $\theta$-development

Let $\theta > 1$ be a Pisot number. To this number corresponds a unique positional and linear Bertrand number system $U_\theta = (U_n)_{n \in \mathbb{N}}$ having its characteristic polynomial equal to the minimal polynomial of $\theta$. We denote by $L$ the language $\rho_U(\mathbb{N})$ of all the normalized representations computed by the greedy algorithm (without leading zeroes). In this section we show that this latter language $L$ satisfies the hypotheses given in Section 3. We also prove that the representations of real numbers in the abstract numeration system built upon $L$ and the classical $\theta$-developments of the numbers in $[0,1]$ coincide. (For a presentation of the $\theta$-development, we refer the reader to Chapter 7 or 13.)

**Definition 36.** Recall that a positional numeration system $U = (U_n)_{n \in \mathbb{N}}$ is said to be a Bertrand numeration system if

$$ \forall n \in \mathbb{N}, w 0^n \in \rho_U(\mathbb{N}) \Leftrightarrow w \in \rho_U(\mathbb{N}). $$

As an example, the $k$-ary number system is a Bertrand system.

**Example 37.** The golden ration $\tau = \frac{1 + \sqrt{5}}{2}$ is a Pisot number, indeed its minimal polynomial is $P(X) = X^2 - X - 1$ and the other root of $P$ has modulus less than one. The polynomial $P$ is also the characteristic polynomial of the linear recurrence relation defined by

$$ U_{n+2} = U_{n+1} + U_n, \quad n \in \mathbb{N}. $$

If we consider the initial conditions $U_0 = 1$ and $U_1 = 2$, then as a consequence of the greedy algorithm, the set of representations of the integers is $\rho_U(\mathbb{N}) = \{\varepsilon\} \cup \{0,01\}^\ast$. Due to the particular form of the language $\rho_U(\mathbb{N})$, it is clear that this system (namely the Fibonacci system) is the linear Bertrand number system associated to $\tau$.

Consider an arbitrary Pisot number $\theta$. It is well known that the $\theta$-development of one is finite or ultimately periodic [13]. In the first case, $e_\theta(1) = t_1 \cdots t_m$ and we define, as usual,

$$ e_\theta(1) = (t_1 \cdots t_{m-1}(t_m - 1))^\omega. $$

It is clear that we still have

$$ 1 = \frac{t_1}{\theta} + \frac{t_2}{\theta^2} + \cdots + \frac{t_{m-1}}{\theta^m} + \frac{t_1}{\theta^{m+1}} + \cdots. $$

Let $\beta > 1$ be a real number. The set $D_\beta$ of $\beta$-developments of numbers in $[0,1)$ is characterized as follows.
Theorem 38. \cite{14} Let $\beta > 1$ be a real number. A sequence $(x_n)_{n \geq 1}$ belongs to $D_\beta$ if and only if for all $i \in \mathbb{N}$, the shifted sequence $(x_{n+i})_{n \geq 1}$ is lexicographically less than the sequence $e_\beta(1)$ or $e_\beta^*(1)$ whenever $e_\beta(1)$ is finite.

For any real number $\beta > 1$, we denote by $F(D_\beta)$, the set of finite factors of the sequences in $D_\beta$. Bertrand numeration systems are characterized by the theorem of Bertrand given below. Notice that $U$ is not necessarily linear.

Theorem 39. \cite{1} Let $U = (U_n)_{n \in \mathbb{N}}$ be a positional numeration system. Then $U$ is a Bertrand numeration system if and only if there exists a real number $\beta > 1$ such that $0^* \rho_U(\mathbb{N}) = F(D_\beta)$. In this case, if $e_\beta(1) = (d_n)_{n \geq 1}$ (or $e_\beta^*(1) = (d_n)_{n \geq 1}$ whenever $e_\beta(1)$ is finite) then $U_0 = 1$ and

$$U_n = d_1 U_{n-1} + d_2 U_{n-2} + \cdots + d_n U_0 + 1, \ n \geq 1.$$ 

Let $\theta > 1$ be a Pisot number. First we assume that $e_\theta(1)$ is ultimately periodic; there exist minimal integers $N \geq 0$, $p \geq 1$ such that

$$e_\theta(1) = t_1 \cdots t_N (t_{N+1} \cdots t_{N+p})^\omega.$$ 

The Bertrand numeration system $U_\theta = (U_n)_{n \in \mathbb{N}}$ belonging to the class of positional systems related to $\theta$ is a linear numeration system satisfying the recurrence relation

$$U_n = t_1 U_{n-1} + \cdots + t_{p-1} U_{n-p+1} + (t_p + 1) U_{n-p} + (t_{p+1} - t_1) U_{n-p-1} + \cdots + (t_{N+p} - t_N) U_{n-N-p}, \ n \geq N + p.$$ 

(In other words, $(U_n)_{n \in \mathbb{N}}$ satisfies the canonical beta polynomial of $\theta$.) In what follows, $\theta$ is given and we denote $U_\theta$ simply by $U$.

The main point is the following. Since $\theta$ is a Pisot number, the set $F(D_\theta) = 0^* \rho_U(\mathbb{N})$ is recognizable by a finite automaton $A$ (i.e., the $\theta$-shift is sofic). This automaton has $N + p$ states $q_1, \ldots, q_{N+p}$. For each $i \in \{1, \ldots, N + p\}$, there are edges labeled by $0, 1, \ldots, t_i - 1$ from $q_i$ to $q_1$, and an edge labeled $t_i$ from $q_i$ to $q_{i+1}$ if $i < N + p$. Finally, there is an edge labeled $t_{N+p}$ from $q_{N+p}$ to $q_{N+1}$. All states are final and $q_1$ is the initial state. The set $F(D_\theta)$ is recognized by the automaton depicted in Figure 8 (the sink is not represented).

![Figure 8. Automaton recognizing $F(D_\theta) = 0^* \rho_U(\mathbb{N})$.](image)

In an abstract numeration system, allowing leading zeroes changes the representations (indeed, $0w$ is genealogically greater than $w$ then $\text{val}_S(0w) > \text{val}_S(w)$, see for instance \cite{14} Example 1). Therefore, we modify slightly the automaton $A$ to
obtain an automaton $A'$ recognizing exactly $\rho_V(\mathbb{N})$ (i.e., without leading zeroes). To that end, we add a new state $q_0$. There are edges labeled by $1, \ldots, t_1 - 1$ from $q_0$ to $q_1$ and an edge labeled $t_1$ from $q_0$ to $q_2$. This state $q_0$ is the initial state of $A'$ and is also final. The automaton $A'$ is sketched in Figure 9.

![Figure 9. The automaton $A'$ recognizing $\rho_V(\mathbb{N})$.](image)

Since $q_0$ is the initial state of $A'$, as usual we write $u(n)$ and $v(n)$ instead of $u_{q_0}(n)$ and $v_{q_0}(n)$.

Since $\theta$ is a Pisot number and the characteristic polynomial of $U$ is the minimal polynomial of $\theta$, there exists a real number $\gamma$ such that

$$U_n \sim \gamma \theta^n.$$ 

For $n \geq 1$, from the form of $A'$ we deduce that

$$u(n) = (t_1 - 1) u_{q_1}(n - 1) + u_{q_3}(n - 1)$$

and

$$u_{q_1}(n) = t_1 u_{q_1}(n - 1) + u_{q_2}(n - 1) = u(n) + u_{q_1}(n - 1).$$

As a consequence of (10), since all the states are final $u_{q_1}(0) = u(0) = 1$, we find

$$u_{q_1}(n) = \sum_{i=1}^{n} u(i) + u_{q_1}(0) = v(n).$$

From (10) we also have $u_{q_1}(n - 1) = u_{q_1}(n) - t_1 u_{q_2}(n - 1)$ and thus $u_{q_1}(n) = v(n + 1) - t_1 v(n)$. But considering the path in $A'$, we get $u_{q_1}(n) = t_2 u_{q_1}(n - 1) + u_{q_3}(n - 1)$. So we find $u_{q_1}(n) = v(n + 2) - t_1 v(n + 1) - t_2 v(n)$. Continuing this way, for $i \leq N + p$

$$u_{q_1}(n) = v(n + i - 1) - t_1 v(n + i - 2) - t_2 v(n + i - 3) - \cdots - t_{i-1} v(n).$$

We are now able to determine the endpoints of the intervals $I_n$. It is clear from (9) that $v(n) = U_n \sim \gamma \theta^n$. Since $v(n - 1) = v(n) - u(n)$ using (9), it is clear that

\[\sum_{i=1}^{n} u(i) + u_{q_1}(0) = v(n).\]
\[ v(n-1)/v(n) \to 1/\theta \] if \( n \to \infty \) and therefore, for \( i \in \mathbb{N} \)

\[
\lim_{n \to \infty} \frac{u_{q_i}(n-i)}{v(n)} = \lim_{n \to \infty} \frac{v(n-i)}{v(n-i+1)} \cdot \frac{v(n-i+1)}{v(n-i+2)} \cdots \frac{v(n-1)}{v(n)} = \theta^{-i}.
\]

In the same manner,

\[
\lim_{n \to \infty} \frac{u_{q_k}(n-i)}{v(n)} = \theta^{1-i} - t_1 \theta^{-i}.
\]

Continuing this way, for \( j \leq N + p \) and \( i \in \mathbb{N} \)

\[
\lim_{n \to \infty} \frac{u_{q_j}(n-i)}{v(n)} = \theta^{j-i-1} - t_1 \theta^{j-i-2} - \cdots - t_{j-1} \theta^{-i}.
\]

We can now compute the different intervals \( I_w \). The first words in \( \rho_L(\mathbb{N}) \) are

\[ 1, \ldots, (t_1-1), t_1, 10, \ldots, t_1, 20, \ldots, (t_1-1) t_1, t_1 0, \ldots, t_1 t_2, 100 \ldots \]

Using (4) we have the intervals corresponding to words of length one

\[ I_j = \left[ \frac{j}{\theta}, \frac{j+1}{\theta} \right], \quad 1 \leq j < t_1 \]

and

\[ I_{t_1} = \left[ \frac{t_1}{\theta}, t_1 \right). \]

For the words of length two, if \( 1 \leq j < t_1 \) and \( 0 \leq k < t_1 \) then

\[ I_{jk} = \left[ \frac{j}{\theta} + \frac{k}{\theta^2}, \frac{j+k}{\theta^2} + \frac{1}{\theta^2} \right]. \]

and

\[ I_{jt_1} = \left[ \frac{j}{\theta} + \frac{t_1}{\theta^2}, \frac{j+t_1}{\theta^2} + \frac{1}{\theta^2} \right]. \]

For the words of length two beginning with \( t_1 \), we have

\[ I_{t_1 j} = \left[ \frac{t_1}{\theta} + \frac{j}{\theta^2}, \frac{j+1}{\theta^2} \right], \quad 0 \leq j < t_2 \]

and

\[ I_{t_1 t_2} = \left[ \frac{t_1}{\theta} + \frac{t_2}{\theta^2}, \frac{t_1+t_2}{\theta^2} + \frac{1}{\theta^2} \right]. \]

Continuing this way, it is straightforward computation to see that we have three situations:

1. if \( w = w_0 \cdots w_r \) with \( q_i = q_0, w_0 \cdots w_{r-1} \) and \( w_r < t_1 \) then

\[ I_w = \left( \sum_{i=0}^{r} w_i \theta^{-i-1}, \sum_{i=0}^{r} w_i \theta^{-i-1} + \theta^{-r-1} \right). \]

2. if \( w = w_0 \cdots w_r w_{r+1} \cdots w_{r+s} \) is such that \( q_i = q_0, w_0 \cdots w_{r-1}, w_r < t_1 \) and \( w_{r+1} \cdots w_{r+s} \) is the maximal word read from \( q_0, w_0 \cdots w_r \) in \( A' \) (in other words, \( q_0, w_0 \cdots w_r = q_1 \) and \( w_{r+1} \cdots w_{r+s} \) is the prefix of length \( s \) of \( e_\theta(1) \)) then

\[ I_w = \left( \sum_{i=0}^{r+s} w_i \theta^{-i-1}, \sum_{i=0}^{r+s} w_i \theta^{-i-1} + \theta^{-r-1} \right). \]

3. finally, if \( w = w_0 \cdots w_r \) is a prefix of \( e_\theta(1) \) then

\[ I_w = \left( \sum_{i=0}^{r} w_i \theta^{-i-1}, 1 \right). \]
Now instead of considering the abstract numeration system built upon $L = \rho_U([N])$, we can consider the classical $\theta$-development of a real number $x \in [1/\theta, 1]$. The first digit of $e_\theta(x)$ is an integer $j$ belonging to \{1, 2, \ldots, t\}. Since $\theta$-developments are computed through the greedy algorithm, it is clear that the first digit is $j < t$ if and only if $x \in I'_j = [j/\theta, (j+1)/\theta)$ and it is $t$ if and only if $x \in I'_t = [t/\theta, 1]$. So the interval $I_j$ for the abstract numeration systems considered above and the intervals $I'_j$ corresponding to the greedy algorithm are the same for the first step (except that in the abstract system, a real number can have two representations but we can avoid this ambiguity by considering intervals of the form $[a, b)$ and therefore the two intervals $I_j$ and $I'_j$ will coincide exactly). By application of the greedy algorithm, we can compute intervals $I'_w$ such that $x \in I'_w$ if $e_\theta(x)$ has $w$ as prefix. Clearly those intervals $I'_w$ coincide with the intervals $I_w$ and therefore, the classical $\theta$-developments are the same as the representation obtained in the framework of the abstract numeration systems (naturally, under the extra assumptions of this section corresponding to regular languages associated to Pisot number).

Now we can use a result of Klaus Schmidt concerning ultimately periodic $\theta$-developments \cite{17} and state the following result.

**Theorem 40.** If $L$ is the language of all the representations of the integers in a linear Bertrand numeration system associated to a Pisot number $\theta$ then the set of real numbers having an ultimately periodic representation in the abstract system built upon $L$ is exactly

\[ \mathbb{Q}(\theta) \cap [1/\theta, 1] . \]

**Remark 41.** In this section, we have only considered the case $e_\theta(1)$ ultimately periodic. If $e_\theta(1) = t_1 \cdots t_m$ is finite ($t_m \neq 0$) then the same situation holds. The construction of the automaton $\mathcal{A}$ is the same as before but with $N = m$ and $p = 0$. All the edges from $q_m$ lead to $q_1$ and are labeled by $0, \ldots, t_m - 1$. The automaton $\mathcal{A}$ is depicted in Figure 10.

![Figure 10. The automaton $\mathcal{A}$ in the case $e_\theta(1)$ finite.](image)

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