SOME NEW EXAMPLES OF UNIVERSAL HYPERCYCLIC OPERATORS IN THE SENSE OF GLASNER AND WEISS

by

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Abstract. — A bounded operator $A$ on a real or complex separable infinite-dimensional Banach space $Z$ is universal in the sense of Glasner and Weiss if for every invertible ergodic measure-preserving transformation $T$ of a standard Lebesgue probability space $(X, \mathcal{B}, \mu)$, there exists an $A$-invariant probability measure $\nu$ on $Z$ with full support such that the two dynamical systems $(X, \mathcal{B}, \mu; T)$ and $(Z, \mathcal{B}_Z, \nu; A)$ are isomorphic. We present a general and simple criterion for an operator to be universal, which allows us to characterize universal operators among unilateral or bilateral weighted shifts on $\ell^p$ or $c_0$, to show the existence of universal operators on a large class of Banach spaces, and to give a criterion for universality in terms of unimodular eigenvectors. We also obtain similar results for operators which are universal for all ergodic systems (not only for invertible ones), and study necessary conditions for an operator on a Hilbert space to be universal.

1. Introduction and main results

Let $G$ be a topological group, and $Z$ a real or complex separable infinite-dimensional Banach space. We denote by $\mathcal{B}(Z)$ the set of bounded linear operators on $Z$. Let $S: G \to Z$, $g \mapsto S_g$ be a representation of the group $G$ by bounded operators on $Z$. If $\mathcal{B}_Z$ denotes the Borel $\sigma$-field of $Z$, and $\nu$ is a Borel probability measure on $Z$ which is $S$-invariant (i.e. $\nu$ is $S_g$-invariant for every $g$ in $G$), then $S$ naturally defines a probability-preserving action of the group $G$ on the probability space $(Z, \mathcal{B}_Z, \nu)$. Recall that the measure $\nu$ is said to have full support if $\nu(U) > 0$ for any non-empty open subset $U$ of $Z$.

Glasner and Weiss introduced in the paper [10] the following notion of a universal representation:

Definition 1.1. — [10] The representation $S = (S_g)_{g \in G}$ of the group $G$ on the Banach space $Z$ is said to be universal if for every ergodic probability-preserving free action $T = (T_g)_{g \in G}$ of $G$ on a standard Lebesgue probability space $(X, \mathcal{B}, \mu)$, there exists a Borel probability measure $\nu$ on $Z$ with full support which is $S$-invariant and such that the two actions of $T$ and $S$ of $G$ on $(X, \mathcal{B}, \nu)$ and $(Z, \mathcal{B}_Z, \nu)$ respectively are isomorphic.

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Recall that \((T_g)_{g \in G}\) is free if for any element \(g \in G\) different from the identity, \(\mu(\{x \in X; T_gx = x\}) = 0\), and ergodic if the following holds true: if \(A \in \mathcal{B}\) is such that \(T_g^{-1}(A) = A\) for every \(g \in G\), then \(\mu(A)(1 - \mu(A)) = 0\).

A universal representation of \(G\) thus simultaneously models every possible free ergodic action of \(G\) on a probability space. The existence of a universal representation is shown in [10] for a large class of groups \(G\), including all countable discrete groups and all locally compact, second countable, compactly generated groups.

When \(G = Z\), the main result of [10] states thus that there exists a bounded invertible operator \(S\) on \(H\) which is universal in the following sense: for every invertible ergodic probability-preserving transformation \(T\) of a standard Lebesgue probability space \((X, \mathcal{B}, \mu)\), there exists an \(S\)-invariant probability measure \(\nu\) on \(H\) with full support such that the two dynamical systems \((X, \mathcal{B}, \mu; T)\) and \((H, B_H, \nu; S)\) are isomorphic. Observe that any invertible probability-preserving transformation \(T\) of \((X, \mathcal{B}, \mu)\) acts freely on \((X, \mathcal{B}, \mu)\): for any \(n \in Z\), the set \(\{x \in X; T^n x = x\}\) is \(T\)-invariant, and the ergodicity of \(T\) implies that it is of \(\mu\)-measure zero. This definition of a universal operator is thus coherent with Definition 1.1.

Any of the systems \((H, B_H, \nu; S)\) is what is called a linear dynamical system, i.e. a system given by the action of a bounded linear operator \(A\) on an infinite-dimensional separable Banach space \(Z\). These systems can be studied from both the topological point of view and the ergodic point of view (when one endows the Banach space \(Z\) with an \(A\)-invariant probability measure), and we refer the reader to the two books [4] and [11] for more on this particular class of dynamical systems.

The result of [10], when specialized to the case where \(G = Z\), thus says that any invertible ergodic probability-preserving dynamical system can be represented as a linear dynamical system where the underlying space is a Hilbert space, and, moreover, the same operator \(S\) on \(H\) can serve as a model for any such dynamical system. Given the apparent rigidity entailed by linearity, the universality result of [10] in the case where \(G = Z\) may seem rather surprising. It is worth pointing out here that a topological version of this result had been obtained previously by Feldman in [8]: there exists a bounded operator \(A\) on the Hilbert space \(\ell_2(N)\) which has the following property: whenever \(\varphi\) is a continuous self-map of a compact metrizable space \(K\), there exists a compact subset \(L\) of \(\ell_2(N)\) which is \(A\)-invariant and an homeomorphism \(\Phi : K \to L\) such that \(\varphi = \Phi^{-1} \circ A \circ \Phi\). The proof of this topological result is rather straightforward, but it already gives a hint at the richness of the class of linear dynamical systems.

A bounded operator \(A\) acting on the Banach space \(Z\) is said to be hypercyclic if it admits a vector \(z \in Z\) whose orbit \(\{A^n z; n \geq 0\}\) is dense in \(Z\), and frequently hypercyclic if there exists a vector \(z \in Z\) such that for every non-empty open subset \(V\) of \(Z\), the set \(\{n \geq 0; A^n z \in V\}\) has positive lower density. If \(A\) admits an invariant probability measure with full support with respect to which it is ergodic, then Birkhoff’s ergodic theorem is easily seen to imply that almost all vectors of \(Z\) are frequently hypercyclic for \(A\). Thus any universal operator is frequently hypercyclic. Let us now say a few words about the construction of universal operators of [10].

The universal operators constructed in [10] are shift operators on certain weighted \(\ell_p\)-spaces of sequences on \(Z\) for \(1 < p < +\infty\), or, equivalently, weighted shift operators on \(\ell_p(Z)\). The proof uses in a crucial way an ergodic theorem for certain random walks of Jones, Rosenblatt, and Tempelman [12]. This theorem states in particular that whenever \(\eta\) is a symmetric strictly aperiodic probability measure on \(Z\), the following holds true: for any
probability-preserving dynamical system \((X, \mathcal{B}, \mu; T)\) and any function \(f \in L^p(X, \mathcal{B}, \mu)\), \(1 < p < +\infty\), the powers \(A^nf\) of the random walk operator on \(Z\) defined by
\[
A^nf(x) = \sum_{k \in \mathbb{Z}} f(T^kx) \eta(k)
\]
converge for almost every \(x \in X\) to the projection \(P_J f\) of \(f\) onto the subspace \(J\) of \(L^p(X, \mathcal{B}, \mu)\) consisting of \(T\)-invariant functions. This ergodic theorem can be applied for instance starting from the measure \(\eta = (\delta_{-1} + \delta_0 + \delta_1)/3\) on \(Z\). If \((p_n)_{n \geq 1}\) is a sequence of positive real numbers such that \(\sum_{n \geq 1} p_n = 1\) and \(\sup (p_n/p_{n+1}) < +\infty\), the weights considered in [10] are defined by setting \(w_k := \sum_{n \geq 1} p_n \eta^n(k)\) for every \(k \in \mathbb{Z}\). If \(S\) is the shift operator defined on
\[
\ell_p(Z, w) := \{\xi = (\xi_k)_{k \in \mathbb{Z}}; \sum_{k \in \mathbb{Z}} |\xi_k|^p w_k < +\infty\}
\]
by setting \(S\xi = (\xi_{k+1})_{k \in \mathbb{Z}}\) for each \(\xi \in \ell_p(Z, w)\), then \(S\) is shown in [10] to be bounded, and the ergodic theorem of [12] is then used to prove that for any function \(f \in L^{2p}(X, \mathcal{B}, \mu)\) the sequence \((f(T^kx))_{k \in \mathbb{Z}}\) belongs to \(\ell_p(Z, w)\) for \(\mu\)-almost every \(x \in X\). Setting
\[
\Phi_f : (X, \mathcal{B}, \mu) \rightarrow (\ell_p(Z, w), B_{\ell_p(Z, w)}, \nu_f)
\]
\[
x \mapsto (f(T^kx))_{k \in \mathbb{Z}}
\]
where \(\nu_f\) is the measure on \(\ell_p(Z, w)\) defined by \(\nu_f(B) = \mu(\Phi_f^{-1}(B))\) for any Borel subset \(B\) of \(\ell_p(Z, w)\), it is easy to check that \(\Phi_f\) intertwines the actions of \(T\) on \((X, \mathcal{B}, \mu)\) and of \(S\) on \(\ell_p(Z, w)\). The last (and most difficult) step of the proof of [10] is then to construct a function \(f\) such that \(\Phi_f\) is an isomorphism of dynamical systems and \(\nu_f\) has full support.

Our aim in this paper is to present an alternative construction of universal operators, which is elementary in the sense that it avoids the use of an ergodic theorem such as the one of [12]. It is also more flexible than the construction of [10], yields some rather simple criteria for universality, and allows us to show the existence of universal operators on a large class of Banach spaces. Moreover, this construction makes it possible to exhibit operators which are universal for all ergodic dynamical systems, not only for invertible ones. As we will often need to make a distinction between these two notions, we introduce the following definition:

**Definition 1.2.** — Let \(A\) be a bounded operator on a real or complex Banach space \(Z\).

- We say that \(A\) is universal for invertible ergodic systems if for every invertible ergodic dynamical system \((X, \mathcal{B}, \mu; T)\) on a standard Lebesgue probability space there exists a probability measure \(\nu\) on \(Z\) with full support which is \(A\)-invariant and such that the dynamical systems \((X, \mathcal{B}, \mu; T)\) and \((Z, B_Z, \nu; A)\) are isomorphic.
- We say that \(A\) is universal for ergodic systems if the same property holds true for all ergodic dynamical systems \((X, \mathcal{B}, \mu; T)\) on a standard Lebesgue probability space.

Universal operators in the sense of Glasner and Weiss are universal for invertible ergodic systems. When we use simply the term “universal operator” in the rest of the paper, we will mean an operator which is universal either for all ergodic systems or just for invertible ones. Before stating our main results, we introduce the following intuitive notation: suppose that \(A\) is a bounded operator on a real or complex separable Banach space \(Z\), and suppose that \((z_n)_{n \in \mathbb{Z}}\) is a sequence of vectors of \(Z\) such that, for every \(n \in \mathbb{Z}\), \(Az_n = z_{n+1}\). We then write \(z_n = A^nz_0\) for every \(n \in \mathbb{Z}\).
Our first result consists of a general and simple criterion for an operator to be universal for invertible ergodic systems.

**Theorem 1.3.** — Let $A$ be a bounded operator on a real or complex separable Banach space $Z$. Suppose that there exists a sequence $(z_n)_{n \in \mathbb{Z}}$ of vectors of $Z$ such that, for every $n \in \mathbb{Z}$, $Az_n = z_{n+1}$, and such that the following three properties hold true:

(a) the vector $z_0$ is bicyclic, i.e. $\text{span} [A^{-n}z_0; n \in \mathbb{Z}] = Z$;
(b) there exists a finite subset $F$ of $\mathbb{Z}$ such that $\text{span} [A^{-n}z_0; n \in \mathbb{Z} \setminus F] \neq Z$;
(c) the series $\sum_{n \in \mathbb{Z}} A^{-n}z_0$ is unconditionally convergent in $Z$.

Then $A$ is universal for invertible ergodic systems.

There is a very similar criterion which implies that an operator is universal for all ergodic systems:

**Theorem 1.4.** — Let $A$ be a bounded operator on a real or complex separable Banach space $Z$. If $A$ satisfies the assumptions of Theorem 1.3, and if moreover the sequence $(z_n)_{n \in \mathbb{Z}}$ is such that $A^\prime z_0 = 0$ for some $r \in \mathbb{Z}$ (or, equivalently, such that $z_0 = 0$), $A$ is universal for ergodic systems.

We have already mentioned that a universal operator is necessarily frequently hypercyclic. An operator satisfying the assumptions of either Theorem 1.3 or Theorem 1.4 is easily seen to satisfy the Frequent Hypercyclicity Criterion of [7] (see also [4] or [11]), and so is in particular frequently hypercyclic and chaotic.

The proofs of Theorems 1.3 and 1.4 largely rely on the ideas of [10], but some extra work is needed, in particular in order to cope with the condition (b) in both theorems. The proofs would be simpler if we assumed that $F = \{0\}$ (which is what happens in some of the examples, in particular in those of [10]), but the generality of assumption (b) is needed in several of the examples given in Section 4.

The proofs of Theorems 1.3 and 1.4 are presented in Section 2, as well as two generalizations of these results (Theorems 2.5 and 2.6) in which assumption (a) is relaxed. The next two sections are devoted to applications and examples. In Section 3, we characterize universal operators (both for ergodic systems and for invertible ergodic systems) among unilateral or bilateral weighted backward shifts on the spaces $\ell_p(\mathbb{N})$, $1 \leq p < +\infty$ or $c_0(\mathbb{N})$. Recall that if $(e_n)_{n \geq 0}$ denotes the canonical basis of $\ell_p(\mathbb{N})$, or $c_0(\mathbb{N})$, and $(w_n)_{n \geq 1}$ is a bounded sequence of non-zero complex numbers, the weighted backward shift $B_w$ is defined on $\ell_p(\mathbb{N})$ or $c_0(\mathbb{N})$ by setting $B_we_0 = 0$ and $B_we_n = w_ne_{n-1}$ for every $n \geq 1$. In the same way, if $(f_n)_{n \in \mathbb{Z}}$ is the canonical basis of $\ell_p(\mathbb{Z})$ or $c_0(\mathbb{Z})$, and $(w_n)_{n \in \mathbb{Z}}$ is again a bounded sequence of non-zero complex numbers, the bilateral weighted shift $S_w$ on $\ell_p(\mathbb{Z})$ or $c_0(\mathbb{Z})$ is defined by setting $S_we_n = w_ne_{n-1}$ for every $n \in \mathbb{Z}$. Here is the characterization of universal weighted shifts which can be obtained thanks to Theorems 1.3 and 1.4:

**Theorem 1.5.** — With the notations above, the unilateral backward weighted shift $B_w$ is universal for (invertible) ergodic systems on $\ell_p(\mathbb{N})$, $1 \leq p < +\infty$, if and only if the series

$$\sum_{n \geq 1} \frac{1}{|w_1 \ldots w_n|^p}$$

is convergent. It is universal for (invertible) ergodic systems on $c_0(\mathbb{N})$ if and only if $|w_1 \ldots w_n| \to 0$ as $n \to +\infty$. 


In the same way, the bilateral backward weighted shift \( S_w \) is universal for (invertible) ergodic systems on \( \ell_p(\mathbb{Z}) \), \( 1 \leq p < +\infty \), if and only if the series

\[
\sum_{n \geq 1} |w_1 \ldots w_n|^p + \sum_{n \geq 1} |w_0 \ldots w_{-(n-1)}|^p
\]

is convergent. It is universal for (invertible) ergodic systems on \( c_0(\mathbb{Z}) \) if and only if \( |w_1 \ldots w_n| \rightarrow 0 \) and \( |w_0 \ldots w_{-(n-1)}| \rightarrow +\infty \) as \( n \rightarrow +\infty \).

This result shows in particular the existence of universal operators for ergodic systems living on any of the spaces \( \ell_p(\mathbb{N}) \), \( 1 \leq p < +\infty \), or \( c_0(\mathbb{N}) \). The existence of universal operators for invertible ergodic systems on \( \ell_p(\mathbb{N}) \), \( 1 < p < +\infty \), is already proved in [10]. A natural question, asked in [10], is to determine which Banach (or Fréchet) spaces support a universal operator. As a universal operator is necessarily frequently hypercyclic, and some Banach spaces (like the hereditarily indecomposable spaces, for instance), do not support frequently hypercyclic operators, it follows that not all Banach spaces support a universal operator. But, as a consequence of Theorem 1.3, we obtain the existence of such operators on Banach spaces with a sufficiently rich structure.

**Theorem 1.6.** — Let \( Z \) be a separable infinite dimensional Banach space containing a complemented copy of a space with a sub-symmetric basis. Then \( Z \) supports an operator which is universal for all ergodic systems.

This result implies for example that any separable Banach space containing a complemented copy of one of the spaces \( \ell_p(\mathbb{N}) \), \( 1 \leq p < +\infty \), or \( c_0(\mathbb{N}) \), supports a universal operator. This is the case for all spaces \( L^p(\Omega, \mu) \), where \( (\Omega, \mu) \) is a \( \sigma \)-finite measured space.

If \( A \) is a bounded operator on a complex infinite dimensional separable Hilbert space \( H \), it is known (see [2], or [4, Ch. 5]) that \( A \) admits an invariant measure with respect to which it is ergodic, and which additionally has full support and admits a second order moment, if and only if its unimodular eigenvectors are perfectly spanning: this means that there exists a continuous probability measure \( \sigma \) on the unit circle \( T = \{ \lambda \in \mathbb{C}, |\lambda| = 1 \} \) such that for any Borel subset \( B \) of \( T \) with \( \sigma(B) = 1 \),

\[
\overline{\text{span}} \left[ \ker(A - \lambda), \lambda \in B \right] = H.
\]

In this case, the unimodular eigenvectors of \( A \) are said to be \( \sigma \)-spanning. An eigenvector-field \( E \) of \( A \) is a map \( E : T \rightarrow Z \) such that \( A E(\lambda) = \lambda E(\lambda) \) for every \( \lambda \in T \). We will often be dealing in the rest of the paper with eigenvectorfields \( E \) belonging to \( L^2(T, \sigma; Z) \) where \( \sigma \) is a certain probability measure on \( T \): this means that \( E : T \rightarrow Z \) is \( \sigma \)-measurable, with

\[
\int_T ||E(\lambda)||^2d\sigma(\lambda) < +\infty
\]

and \( A E(\lambda) = \lambda E(\lambda) \) \( \sigma \)-almost everywhere. When we write simply that \( E \) belongs to \( L^2(T; Z) \), this means that \( \sigma \) is assumed to be the normalized Lebesgue measure \( d\lambda \) on \( T \).

As a universal operator on \( H \) is necessarily ergodic with respect to a certain invariant measure with full support (although this measure is not required to have a second-order moment), it is natural to look for conditions involving the unimodular eigenvectors of the operator \( A \) which imply its universality. This is done in Section 4, where we prove the two following general results:
Theorem 1.7. — Let $A$ be a bounded operator on a complex Banach space $Z$. Suppose that there exists an eigenvectorfield $E \in L^2(T; Z)$ for $A$ such that

(i) whenever $B$ is a Borel subset of $T$ of full Lebesgue measure, $\overline{\text{span}} \{E(\lambda), \lambda \in B\} = Z$;
(ii) there exists a non-zero functional $z^*_0 \in Z^*$ and a trigonometric polynomial $p$ such that $\langle z^*_0, E(\lambda) \rangle = p(\lambda)$ almost everywhere on $T$;
(iii) if we set for every $n \in \mathbb{Z}$

$$\hat{E}(n) = \int_T \lambda^{-n} E(\lambda) d\lambda,$$

then the series $\sum_{n \in \mathbb{Z}} \hat{E}(n)$ is unconditionally convergent.

Then the operator $A$ is universal for invertible ergodic systems. If moreover $\hat{E}(-r) = 0$ for some integer $r \in \mathbb{Z}$ (so that $\hat{E}(-n) = 0$ for every $n \geq r$), then $A$ is universal for ergodic systems.

Remark that if $E$ is sufficiently smooth (of class $C^2$ for instance), then the sequence of Fourier coefficients $(\hat{E}(n))_{n \in \mathbb{Z}}$ goes to zero sufficiently rapidly for the series $\sum_{n \in \mathbb{Z}} ||\hat{E}(n)||$ to be convergent. Hence the assumption (iii) is automatically satisfied in this case. If $E$ is analytic in a neighborhood of $T$, it can be renormalized in such a way that assumption (ii) is also satisfied, and this yields

Theorem 1.8. — Suppose that $A \in \mathcal{B}(Z)$ admits an eigenvectorfield $E$ which is analytic in a neighborhood of $T$, and that $\overline{\text{span}} \{E(\lambda); \lambda \in T\} = Z$. Then $A$ is universal for invertible ergodic systems. If $E$ is analytic in a neighborhood of the closed unit disk $\overline{D}$ and $\overline{\text{span}} \{E(\lambda); \lambda \in T\} = Z$, then $A$ is universal for ergodic systems.

Several applications of these two theorems are given in Section 4, in particular to adjoints of multipliers on $H^2(D)$ (Example 4.2) and to the rather unexpected case of a Kalish-type operator on $L^2(T)$ (Example 4.4).

In Section 5 we try to exhibit some necessary conditions for an operator to be universal. In this generality, and with the present definition of universality, this seems to be delicate. But if we restrict ourselves to operators acting on a Hilbert space, and if we additionally require in the definition of universality that the measure $\nu$ admits a moment of order 2 (see Definition 5.1), then we obtain:

Theorem 1.9. — Suppose that $A \in \mathcal{B}(H)$ is universal for ergodic systems in the modified sense presented above. Then the unimodular eigenvalues of $A$ form a subset of $T$ of Lebesgue measure 1.

It is a rather puzzling fact that we do not know whether Theorem 1.9 can be extended to operators which are universal for invertible ergodic systems only. This point is discussed in Section 5, as well as some open questions.

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2. A criterion for universality: proofs of Theorems 1.3 and 1.4

The proofs of Theorems 1.3 and 1.4 being very similar, we concentrate on the proof of Theorem 1.3, and will indicate briefly afterwards the modifications needed for proving Theorem 1.4.

2.1. General pattern of the proof of Theorem 1.3. — Let \( A \) be a bounded operator on the infinite-dimensional separable Banach space \( Z \) satisfying the assumptions of Theorem 1.3. We will suppose in the rest of the proof that \( Z \) is a complex Banach space, but the proof obviously holds true for real spaces as well. Let \((X, \mathcal{B}, \mu; T)\) be an invertible ergodic dynamical system on a standard probability space. For any complex-valued function \( f \in L^\infty(X, \mathcal{B}, \mu) \) let \( \Phi \) be the map from \((X, \mathcal{B}, \mu)\) into \( Z \) defined by setting

\[
\Phi_f(x) = \sum_{k \in \mathbb{Z}} f(T^k x) A^{-k} z_0.
\]

Since \( f \) is essentially bounded and the series \( \sum_{k \in \mathbb{Z}} A^{-k} z_0 \) is unconditionally convergent, \( \Phi_f(x) \) is well-defined for \( \mu \)-almost every \( x \in X \). Also we have

\[
\Phi_f(T x) = \sum_{k \in \mathbb{Z}} f(T^{k+1} x) A^{-k} z_0 = \sum_{k \in \mathbb{Z}} f(T^k x) A^{-k+1} z_0 = A \Phi_f(x)
\]

since \( A^{-k+1} z_0 = z_{-k+1} = A z_{-k} = A^{-k} z_0 \).

If we denote by \( \mathcal{B}_Z \) the Borel \( \sigma \)-field of \( Z \), and by \( \nu_f \) the Borel probability measure on \( Z \) which is the image of \( \mu \) under the map \( \Phi_f \) (i.e. \( \nu_f(B) = \mu(\Phi_f^{-1}(B)) \) for every Borel subset \( B \) of \( Z \)), it then follows that \( \Phi_f : (X, \mathcal{B}, \mu; T) \to (Z, \mathcal{B}_Z, \nu_f; A) \) is a factor map. This first argument is rather similar to the one employed in \( [10] \), but the map \( \Phi_f \) is defined differently in \( [12] \). The goal in \( [10] \) is then to construct a function \( f \in L^1(X, \mathcal{B}, \mu) \) as a limit of certain finitely-valued functions \( f_n \in L^\infty(X, \mathcal{B}, \mu) \), in such a way that \( \Phi_f \) becomes an isomorphism of dynamical systems and the measure \( \nu_f \) has full support. As \( \Phi_f \) is not necessarily well-defined here when \( f \in L^1(X, \mathcal{B}, \mu) \) (or \( f \in L^p(X, \mathcal{B}, \mu), 1 < p < +\infty \)), we will construct, in the same spirit as in \( [10] \), a sequence of finitely-valued functions \( f_n \in L^\infty(X, \mathcal{B}, \mu) \) such that \( \Phi_{f_n} \) converges in \( L^1(X, \mathcal{B}, \mu; Z) \) to a certain function \( \Phi \in L^1(X, \mathcal{B}, \mu; Z) \) which will be an isomorphism between the two systems \((X, \mathcal{B}, \mu; T)\) and \((Z, \mathcal{B}_Z, \nu; A)\), where \( \nu \) is the image of \( \mu \) under the map \( \Phi \).

Let \((Q_j)_{j \geq 0}\) be a sequence of Borel subsets of \( X \) which is dense in \((\mathcal{B}, \mu)\) (i.e. for every \( \varepsilon > 0 \) and every \( B \in \mathcal{B} \), there exists a \( j \geq 0 \) such that \( \mu(Q_j \Delta B) < \varepsilon \) with \( Q_0 = X \)). Moreover, we suppose that for any \( i \geq 0 \), the set \( J_i = \{ j \geq i \mid Q_j = Q_i \} \) is infinite. Since the span of the vectors \( A^k z_0, k \in \mathbb{Z} \), is dense in \( Z \), there exists a sequence \((u_n)_{n \geq 1}\) of vectors of \( Z \) of the form

\[
u_n = \sum_{|k| \leq d_n} a_k^{(n)} A^{-k} z_0, \quad a_k^{(n)} \in \mathbb{C}, \quad \max_{|k| \leq d_n} |a_k^{(n)}| > 0
\]

which is dense in \( Z \). Let, for each \( n \geq 1 \), \( r_n \) be a positive number such that the open balls \( U_n = B(u_n, r_n) \) centered at \( u_n \) and of radius \( r_n \) form a basis of the topology of \( Z \). We set \( U_0 = Z \). Lastly, by assumption (b) of Theorem 1.3 there exists a finite subset \( F \) of \( Z \) and a non-zero functional \( z^*_0 \in Z^* \) such that \( \langle z^*_0, A^{-n} z_0 \rangle = 0 \) for all \( n \in \mathbb{Z} \setminus F \) and \( \langle z^*_0, A^{-n} z_0 \rangle \neq 0 \) for all \( n \in F \) (we may have to modify the initial set \( F \) to obtain this property). If we replace the vector \( z_0 \) by the vector \( z'_0 = A^{-p} z_0 \), then \( \langle z^*_0, A^{-n} z'_0 \rangle \neq 0 \) if and only if \( n \in F' = F - p \). If we choose \( p \in F, \langle z^*_0, z'_0 \rangle \neq 0 \). So, replacing \( z_0 \) by \( z'_0 \) and
$F$ by $F'$, we can suppose that $0 \in F$ and that $z_0$ and $z_0'$ are such that $c_n = \langle z_0^*, A^{-n}z_0 \rangle$ is non-zero if and only if $n \in F$. We let $d = \max |F|$.

2.2. Construction of the functions $f_n$, $n \geq 0$. --- We are now ready to start the construction of the functions $f_n$. This construction is very much inspired from that of [10], but many technical details need to be adjusted to the present situation. For any $z \in \mathbb{C}$ and $r > 0$, $D(z, r)$ denotes the open disk centered at $z$ of radius $r$.

We construct by induction

- a sequence $(f_n)_{n \geq 0}$ of functions of $L^\infty(\mathbb{R}, \mathcal{B}, \mu; \mathbb{C})$;
- sequences $(\alpha_n)_{n \geq 0}$, $(\beta_n)_{n \geq 0}$, $(\gamma_n)_{n \geq 0}$, $(\delta_n)_{n \geq 0}$, and $(\eta_n)_{n \geq 0}$ of positive real numbers, decreasing to zero extremely fast;
- for each $n \geq 0$, families $(D^{(n)}_{i,0})_{0 \leq i \leq n}$ and $(D^{(n)}_{i,1})_{0 \leq i \leq n}$, $(E^{(n)}_{i,0})_{0 \leq i \leq n}$ and $(E^{(n)}_{i,1})_{0 \leq i \leq n}$, $(F^{(n)}_{i,0})_{0 \leq i \leq n}$ and $(F^{(n)}_{i,1})_{0 \leq i \leq n}$ of Borel subsets of $\mathbb{C}$;
- for each $n \geq 0$, families $(G^{(n)}_{i,0})_{0 \leq i \leq n}$ and $(H^{(n)}_{i,0})_{0 \leq i \leq n}$ of $\mu$-measurable subsets of $X$,

and two measurable subsets $B_n$ and $C_n$ of $X$ such that

1. the sets $E^{(n)}_{i,0}$ and $E^{(n)}_{i,1}$, $0 \leq i \leq n$, are finite, and the range of $f_n$ is equal to
$$\left( \bigcup_{i=0}^{n} E^{(n)}_{i,0} \right) \cup \left( \bigcup_{i=0}^{n} E^{(n)}_{i,1} \right);$$

moreover, for every $i \in \{0, \ldots, n\}$, $E^{(n)}_{i,0} \cap E^{(n)}_{i,1} = \emptyset$;

2. we have
   (2a) $\mu(C_n) > 1 - \eta_n$;
   (2b) if we set, for every $i \in \{0, \ldots, n\}$
   $$D^{(n)}_{i,0} = \left\{ \sum_{p \in F} c_p f_n(T^p x) ; x \in C_n \text{ and } f_n(x) \in E^{(n)}_{i,0} \right\},$$

and
   $$D^{(n)}_{i,1} = \left\{ \sum_{p \in F} c_p f_n(T^p x) ; x \in C_n \text{ and } f_n(x) \in E^{(n)}_{i,1} \right\},$$

then $D^{(n)}_{i,0} \cap D^{(n)}_{i,1} = \emptyset$;

(2c) if we set, for every $i \in \{0, \ldots, n\}$
$$F^{(n)}_{i,0} = D^{(n)}_{i,0} + D(0, \beta_n) \quad \text{and} \quad F^{(n)}_{i,1} = D^{(n)}_{i,1} + D(0, \beta_n),$$

then $F^{(n)}_{i,0} \cap F^{(n)}_{i,1} = \emptyset$;

3. for every $i \in \{0, \ldots, n\}$,
   (3a) $\mu(H^{(n)}_{i,0}) < \alpha_i(1 - 2^{-n})$;
   (3b) $H^{(n-1)}_{i} \subseteq H^{(n)}_{i}$ for every $i \in \{0, \ldots, n-1\}$;
   (3c) for every $x \in Q_i \setminus H^{(n)}_{i,0}$, $f_n(x) \in E^{(n)}_{i,0}$, and for every $x \in (X \setminus Q_i) \setminus H^{(n)}_{i,1}$, $f_n(x) \in E^{(n)}_{i,1}$;
We write this finite set as $\{g\}$.

The function $\mu$ which has $\mu$-measure larger than $1 - \eta_n$.

We suppose that $\mu$-measure larger than $1 - \eta_n$.

We start the construction by setting (recall that $Q_0 = X$ and $U_0 = Z$): $E^{(0)}_{0,0} = \{0\}$, $E^{(0)}_{0,1} = \emptyset$, $B_0 = C_0 = X$, $c_0 = \beta_0 = \gamma_0 = \delta_0 = \eta_0 = 1/8$, $G^{(0)}_0 = X$, $H^{(0)}_0 = \emptyset$ and $f_0 = 0$.

Suppose now that the construction has been carried out until step $n$. At step $n + 1$, we start by introducing

- an integer $N \geq 1$, which will be chosen very large at the end of the construction;
- two positive numbers $\eta$ and $\gamma$, independent of each other, which will be chosen very small at the end of the construction.

As $T$ is invertible and ergodic, there exists a measurable subset $E$ of $X$ such that $\mu(E) > 0$, $\mu\left(\bigcup_{|k| \leq N} T^k E\right) < \eta$ and the sets $T^k E$, $|k| \leq N$, are pairwise disjoint.

Recall that $u_{n+1} = \sum_{|k| \leq d_{n+1}} a_k^{(n+1)} A^{-k} z_0$ and $U_{n+1} = B(u_{n+1}, r_{n+1})$.

We suppose that $N \geq d_{n+1}$.

**Step 1:** We first define an auxiliary function $g_{n+1}$ on $X$ in the following way:

$$g_{n+1}(x) = \begin{cases} a_k^{(n+1)} & \text{if } x \in T^k E, \quad |k| \leq d_{n+1} \\ 0 & \text{if } x \in T^k E, \quad d_{n+1} < |k| \leq N \\ f_n(x) & \text{if } x \notin \bigcup_{|k| \leq N} T^k E. \end{cases}$$

The function $g_{n+1}$ thus defined is finite-valued and it coincides with $f_n$ on the set $B = X \setminus \bigcup_{|k| \leq N} T^k E$, which has $\mu$-measure larger than $1 - \eta$. The range of $g_{n+1}$ is equal to

$$\text{Ran}(f_n |_B) \cup \{0\} \cup \{a_k^{(n+1)}; \quad |k| \leq d_{n+1}\},$$

and we write this finite set as $\{c_l^{(n+1)}; \quad 0 \leq l \leq l_{n+1}\}$, with all numbers $c_l^{(n+1)}$ distinct.
By the Rokhlin Lemma, we can choose a subset $E' \in \mathcal{B}$ of $X$ and an integer $M \geq d$ such that the sets $T^k E'$, $|k| \leq M$, are pairwise disjoint, and

$$\mu\left(\bigcup_{|k| \leq M-d} T^k E'\right) > 1 - \eta.$$

**Step 2:** We state and prove in this step a simple abstract lemma, which will be used in the forthcoming Steps 3 and 4 in order to approximate certain finite families of scalars (like the family $(c_{l}^{(n+1)})_{0 \leq l \leq l_{n+1}}$) by other families of scalars with further additional properties.

**Lemma 2.1.** — Let $r \geq 1$ and let $d = (d_1, \ldots, d_r)$ be an $r$-tuple of positive integers. We denote by $E_d$ the subset of $\mathbb{Z}^r$ defined by

$$E_d = \{ u = (u_1, \ldots, u_r) ; 0 \leq u_i \leq d_i \text{ for every } i = 1, \ldots, r \}.$$

For every $i = 1, \ldots, r$, let $\lambda_i$ be a map from $F$ into $\{0, \ldots, d_i\}$. We denote by $\lambda$ the $r$-tuple of maps $\lambda = (\lambda_1, \ldots, \lambda_r)$ from $F$ into $\{0, \ldots, d_1\} \times \ldots \times \{0, \ldots, d_r\}$. For any such $\lambda$, let $\sigma_{\lambda}$ be the functional on $\mathbb{C}^{d_1 \ldots d_r}$ defined by

$$\sigma_{\lambda} : \mathbb{C}^{d_1 \ldots d_r} \rightarrow \mathbb{C}$$

$$(\gamma_u)_{u \in E_d} \mapsto \sum_{p \in F} c_p \gamma_{\lambda(p)}.$$

There exists a dense subset of $\mathbb{C}^{d_1 \ldots d_r}$ consisting of elements $(\gamma_u)_{u \in E_d}$ with the following property:

$$\sigma_{\lambda}((\gamma_u)_{u \in E_d}) \neq \sigma_{\lambda'}((\gamma_u)_{u \in E_d})$$

for every maps $\lambda$ and $\lambda'$ such that $\lambda(F) \neq \lambda'(F)$.

**Proof.** — Let us first observe that if $\lambda(F) \neq \lambda'(F)$, $\sigma_{\lambda} \neq \sigma_{\lambda'}$. This follows from the fact that all coefficients $c_p$, $p \in F$, are distinct. Let then

$$\Sigma = \{ (\lambda, \lambda') ; \lambda(F) \neq \lambda'(F) \}.$$

For each $(\lambda, \lambda') \in \Sigma$, the kernel $\ker(\sigma_{\lambda} - \sigma_{\lambda'})$ is different from the whole space $\mathbb{C}^{d_1 \ldots d_r}$. The set $\Sigma$ being finite, the Baire Category Theorem yields that

$$\bigcup_{(\lambda, \lambda') \in \Sigma} (\sigma_{\lambda} - \sigma_{\lambda'})^{-1}(\mathbb{C}^*)$$

is dense in $\mathbb{C}^{d_1 \ldots d_r}$, which proves our claim. \qed

**Step 3:** We define a second auxiliary function $h_{n+1}$ on $X$ by setting

$$h_{n+1}(x) = \begin{cases} c_{l}^{(n+1)} & \text{if } g_{n+1}(x) = c_{l}^{(n+1)} \text{ and } x \in T^k E' \text{ for some } |k| \leq M, \\ c_{l}^{(n+1)} & \text{if } g_{n+1}(x) = c_{l}^{(n+1)} \text{ and } x \not\in \bigcup_{|k| \leq M} T^k E', \end{cases}$$

where for every $l \in \{0, \ldots, l_{n+1}\}$, $c_{l,k}^{(n)}$ is so close to $c_{l,k}^{(n+1)}$ for each $|k| \leq M$ that

$$||h_{n+1} - g_{n+1}||_{\infty} \leq \frac{\gamma}{2},$$

all the numbers $c_{l,k}^{(n+1)}$, $l \in \{0, \ldots, l_{n+1}\}$, $|k| \leq M$, and $c_{l,k}^{(n+1)}$, $l \in \{0, \ldots, l_{n+1}\}$, are distinct, and, moreover, the numbers $c_{l,k}^{(n+1)}$, $l \in \{0, \ldots, l_{n+1}\}$, $|k| \leq M$, have the following property:
whenever \( \tau, \tau' \) are two maps from \( F \) into \( \{0, \ldots, l_{n+1}\} \), and \( k, k' \) are two integers with \( |k|, |k'| \leq M - d \), we have

\[
\sum_{p \in F} c_p c_{\tau(p), k+p}^{(n+1)} \neq \sum_{p \in F} c_p c_{\tau'(p), k'+p}^{(n+1)}
\]
as soon as there exists a \( p \in F \) such that \( (\tau(p), k+p) \neq (\tau'(p), k'+p) \).

Observe that since \( |k|, |k'| \leq M - d \) and \( d = \max |F|, |k| + |k'| \leq M \) for every \( p \in F \), so that the quantities \( c_{\tau(p), k+p}^{(n+1)} \) and \( c_{\tau'(p), k'+p}^{(n+1)} \) in the expression above are well-defined.

That the scalars \( c_{l, k}^{(n+1)} \) can indeed be chosen so as to satisfy these properties is a consequence of Lemma 2.1. Denote by \( \Sigma \) the set of all 4-tuples \((\tau, \tau', k, k')\), where \( \tau, \tau' \) are maps from \( F \) into \( \{0, \ldots, l_{n+1}\} \) and \( k, k' \) are integers with \( |k|, |k'| \leq M - d \), such that there exists a \( p \in F \) with \( (\tau(p), k+p) \neq (\tau'(p), k'+p) \). For any map \( \tau : F \to \{0, \ldots, l_{n+1}\} \) and any integer \( k \) with \( |k| \leq M - d \), let

\[
\lambda_{\tau, k} : \quad F \to \{0, \ldots, l_{n+1}\} \times \{-M, \ldots, M\}
\]

\[
p \mapsto (\tau(p), p+k).
\]
Let us check that if \( (\tau, \tau', k, k') \) belongs to \( \Sigma \), \( \lambda_{\tau, k}(F) \neq \lambda_{\tau', k'}(F) \). If \( \lambda_{\tau, k}(F) = \lambda_{\tau', k'}(F) \), then

\[
\{ (\tau(p), k+p); p \in F \} = \{ (\tau'(p), k'+p); p \in F \},
\]
so that \( k + F = k' + F \). As the set \( F \) is finite, \( k = k' \), and thus for every \( p \in F \) there exists a \( p' \in F \) such that \( (\tau(p), k+p) = (\tau'(p'), k'+p') \). So \( p = p' \) and \( \tau(p) = \tau'(p) \). Thus \( (\tau(p), k+p) = (\tau'(p), k+p) \) for every \( p \in F \), which is contrary to our assumption. So \( \lambda_{\tau, k}(F) \neq \lambda_{\tau', k'}(F) \) as soon as \( (\tau, \tau', k, k') \) belongs to \( \Sigma \).

Applying Lemma 2.1, it follows from the observation above that we can choose a family of scalars \( (c_{l, k}^{(n+1)})_{0 \leq l \leq l_{n+1}, |k| \leq M} \) such that

\[
|c_{l, k}^{(n+1)} - c_l^{(n+1)}| < \frac{\gamma}{2}
\]
for every \( l \in \{0, \ldots, l_{n+1}\} \) and \( |k| \leq M \),

all the numbers \( c_{l, k}^{(n+1)} \) and \( c_l^{(n+1)} \) are distinct, and

\[
\big(\sigma_{\lambda_{\tau, k}} - \sigma_{\lambda_{\tau', k'}}\big)\big((c_{l, k}^{(n+1)})_{0 \leq l \leq l_{n+1}, |k| \leq M}\big) \neq 0
\]
for every \( (\tau, \tau', k, k') \in \Sigma \), i.e.

\[
\sum_{p \in F} c_p c_{\tau(p), k+p}^{(n+1)} \neq \sum_{p \in F} c_p c_{\tau'(p), k'+p}^{(n+1)}
\]
for every \( (\tau, \tau', k, k') \in \Sigma \).

Now the function \( h_{n+1} \) has been defined, we observe that it is finite-valued, and we write its range as

\[
\{b_{j}^{(n+1)}; \ 0 \leq j \leq j_{n+1}\}
\]
where all the numbers \( b_{j}^{(n+1)} \) are distinct. We also set

\[
C_{n+1} = \bigcup_{|k| \leq M-d} T^k E'.
\]
By our assumptions on \( M \) and \( E' \), \( \mu(C_{n+1}) > 1 - \eta \).
Step 4: We construct in this step complex numbers \(b_{j,0}^{(n+1)}\) and \(b_{j,1}^{(n+1)}\), \(0 \leq j \leq j_{n+1}\), which are such that all the numbers \(b_{j,0}^{(n+1)}\) and \(b_{j,1}^{(n+1)}\) are distinct, and both \(b_{j,0}^{(n+1)}\) and \(b_{j,1}^{(n+1)}\) are so close to \(b_j^{(n+1)}\) for each \(j \in \{0, \ldots, j_{n+1}\}\) that
\[
\sup_{j \in \{0, \ldots, j_{n+1}\}} \left( |b_{j,0}^{(n+1)} - b_j^{(n+1)}| + |b_{j,1}^{(n+1)} - b_j^{(n+1)}| \right) < \frac{\gamma}{2}.
\]
Moreover, if \(b_j^{(n+1)} = c_{l,k}^{(n+1)}\) for some \(l \in \{0, \ldots, l_{n+1}\}\) and \(|k| \leq M\), we write
\[
b_j^{(n+1)} = c_{l,k}^{(n+1)} \quad \text{and} \quad b_j^{(n+1)} = c_{l,k,1}^{(n+1)},
\]
and we require that the following holds true:

for any maps \(\theta, \theta' : F \to \{0, 1\}\), \(\tau, \tau' : F \to \{0, \ldots, l_{n+1}\}\) and any integers \(k, k'\) with \(|k|, |k'| \leq M - d\),
\[
\sum_{p \in F} c_{p}^{(n+1)}(\tau(p), k+p, \theta(p)) \neq \sum_{p \in F} c_{p}^{(n+1)}(\tau'(p), k'+p, \theta'(p))
\]
as soon as there exists a \(p \in F\) such that \((\tau(p), k+p, \theta(p)) \neq (\tau'(p), k'+p, \theta'(p))\).

The proof of the existence of such numbers again relies on Lemma 2.1. Denote by \(\mathcal{F}\) the set of all 6-tuples \((\tau, \tau', k, k', \theta, \theta')\), where \(\theta, \theta'\) are maps from \(F\) into \(\{0, 1\}\), \(\tau, \tau'\) maps from \(F\) into \(\{0, \ldots, l_{n+1}\}\) and \(k, k'\) integers with \(|k|, |k'| \leq M - d\), such that there exists a \(p \in F\) with \((\tau(p), k+p, \theta(p)) \neq (\tau'(p), k'+p, \theta'(p))\). For any maps \(\theta : F \to \{0, 1\}\), \(\tau : F \to \{0, \ldots, l_{n+1}\}\) and any integer \(k\) with \(|k| \leq M - d\), let
\[
\lambda_{\tau, k, \theta} : F \to \{0, \ldots, l_{n+1}\} \times \{-M, \ldots, M\} \times \{0, 1\},
\]
\[
p \mapsto (\tau(p), k+p, \theta(p)).
\]
We claim that if \((\lambda, \lambda', k, k', \theta, \theta')\) belongs to \(\mathcal{F}\), then \(\lambda_{\tau, k, \theta}(F) \neq \lambda_{\tau', k', \theta'}(F)\). Indeed, if these two sets were were equal, we would have
\[
\left\{ (\tau(p), k+p, \theta(p)) : p \in F \right\} = \left\{ (\tau'(p), k'+p, \theta'(p)) : p \in F \right\}.
\]
Hence \(k + F = k' + F\), so that \(k = k'\). Thus for every \(p \in F\) there exists \(p' \in F\) such that \((\tau(p), k+p, \theta(p)) = (\tau'(p'), k' + p, \theta'(p'))\). Necessarily, \(p = p'\), so that \((\tau(p) = \tau'(p)\) and \(\theta(p) = \theta'(p)\). Hence \((\tau(p), k+p, \theta(p)) = (\tau'(p), k+p, \theta'(p))\) for every \(p \in F\), and this contradicts our initial assumption. So \(\lambda_{\tau, k, \theta}(F) \neq \lambda_{\tau', k', \theta'}(F)\). It thus follows from Lemma 2.1 that numbers \(c_{l,k,0}^{(n+1)}\) and \(c_{l,k,1}^{(n+1)}\) can be chosen as close to \(c_{l,k}^{(n+1)}\) as we wish, all distinct, and such that
\[
\sum_{p \in F} c_{p}^{(n+1)}(\tau(p), k+p, \theta(p)) \neq \sum_{p \in F} c_{p}^{(n+1)}(\tau'(p), k'+p, \theta'(p)) \quad \text{for every} \ (\tau, \tau', k, k', \theta, \theta') \in \mathcal{F}.
\]

This defines \(b_{j,0}^{(n+1)}\) and \(b_{j,1}^{(n+1)}\) when \(b_{j}^{(n+1)} = c_{l,k}^{(n+1)}\) for some \(l \in \{0, \ldots, l_{n+1}\}\) and \(|k| \leq M\). It is then easy to define the numbers \(b_{j,0}^{(n+1)}\) and \(b_{j,1}^{(n+1)}\) for the remaining indices in such a way that they are sufficiently close to \(b_{j}^{(n+1)}\), distinct, and distinct from all the numbers \(c_{l,k,0}^{(n+1)}\) and \(c_{l,k,1}^{(n+1)}\).

Step 5: We can now define the function \(f_{n+1}\) on \(X\) by setting
\[
f_{n+1}(x) = \begin{cases} b_{j,0}^{(n+1)} & \text{if } h_{n+1}(x) = b_{j}^{(n+1)} \text{ and } x \in Q_{n+1} \\ b_{j,1}^{(n+1)} & \text{if } h_{n+1}(x) = b_{j}^{(n+1)} \text{ and } x \in X \setminus Q_{n+1}. \end{cases}
\]
Obviously
\[ ||h_{n+1} - f_{n+1}||_\infty < \frac{\gamma}{2}. \]

If \( x \) belongs to \( C_{n+1} \), then there exists an integer \( k \) with \( |k| \leq M - d \) such that \( x \in T^k E' \).
Hence \( T^p x \in T^{p+k} E' \) for every \( p \in F \), and \( |k + p| \leq M \). It follows that there exists a map \( \tau : F \to \{0, \ldots, l_{n+1}\} \) such that
\[ h_{n+1}(T^p x) = c_{\tau(p), k + p}^{(n+1)} \quad \text{for every } p \in F. \]

By the definition of the function \( f_{n+1} \), there exists a map \( \theta : F \to \{0, 1\} \) such that
\[ f_{n+1}(T^p x) = c_{\tau(p), k + p, \theta(p)}^{(n+1)} \quad \text{for every } p \in F. \]

This map \( \theta \) satisfies \( \theta(0) = 0 \) if \( x \in Q_{n+1} \) and \( \theta(0) = 1 \) if \( x \in X \setminus Q_{n+1} \). We have
\[ \sum_{p \in F} c_p f_{n+1}(T^p x) = \sum_{p \in F} c_p c_{\tau(p), k + p, \theta(p)}^{(n+1)}. \]

**Step 6:** For every \( i \in \{0, \ldots, n\} \), let
\[ J_{i,0}^{(n+1)} = \{ j \in \{0, \ldots, j_{n+1}\} : \text{there exists } l \in \{0, \ldots, l_{n+1}\} \text{ such that } c_l^{(n+1)} \in E_{i,0}^{(n+1)} \]
with either
\[ b_j^{(n+1)} = c_l^{(n+1)} \text{ or } b_j^{(n+1)} = c_{l,k}^{(n+1)} \text{ for some } |k| \leq M \}

\[ J_{i,1}^{(n+1)} = \{ j \in \{0, \ldots, j_{n+1}\} : \text{there exists } l \in \{0, \ldots, l_{n+1}\} \text{ such that } c_l^{(n+1)} \in E_{i,1}^{(n+1)} \]
with either
\[ b_j^{(n+1)} = c_l^{(n+1)} \text{ or } b_j^{(n+1)} = c_{l,k}^{(n+1)} \text{ for some } |k| \leq M \}.

Set for \( i \in \{0, \ldots, n\} \)
\[ E_{i,0}^{(n+1)} = \{ b_j^{(n+1)} : j \in J_{i,0}^{(n+1)} \} \cup \{ b_j^{(n+1)} : j \in J_{i,1}^{(n+1)} \}, \]
\[ E_{i,1}^{(n+1)} = \{ b_j^{(n+1)} : j \in J_{i,0}^{(n+1)} \} \cup \{ b_j^{(n+1)} : j \in J_{i,1}^{(n+1)} \}, \]
\[ E_{n+1,0}^{(n+1)} = \{ b_j^{(n+1)} : j \in \{0, \ldots, j_{n+1}\}\}, \]
\[ E_{n+1,1}^{(n+1)} = \{ b_j^{(n+1)} : j \in \{0, \ldots, j_{n+1}\}\}. \]

**Step 7:** With these definitions, let us check that property (1) holds true. Of course, all the sets \( E_{i,0}^{(n+1)} \) and \( E_{i,1}^{(n+1)} \) are finite and
\[ \text{ran}(f_{n+1}) = \left( \bigcup_{i=0}^{n+1} E_{i,0}^{(n+1)} \right) \cup \left( \bigcup_{i=0}^{n+1} E_{i,1}^{(n+1)} \right) = E_{n+1,0}^{(n+1)} \cup E_{n+1,1}^{(n+1)}. \]

All the numbers \( b_j^{(n+1)} \) and \( b_j^{(n+1)} \), \( j \in \{0, \ldots, j_{n+1}\} \) are distinct, and for every index \( i \in \{0, \ldots, n\} \), \( J_{i,0}^{(n+1)} \cap J_{i,1}^{(n+1)} = \emptyset \) (because \( E_{i,0}^{(n)} \cap E_{i,1}^{(n)} = \emptyset \)). So \( E_{i,0}^{(n+1)} \cap E_{i,1}^{(n+1)} = \emptyset \) for all \( i \in \{0, \ldots, n\} \). Also clearly \( E_{n+1,0}^{(n+1)} \cap E_{n+1,1}^{(n+1)} = \emptyset \). So property (1) holds true.

**Step 8:** In order to check property (2), let us fix \( i \in \{0, \ldots, n+1\} \), and \( x, y \in C_{n+1} \) such that \( f_{n+1}(x) \in E_{i,0}^{(n+1)} \) and \( f_{n+1}(y) \in E_{i,1}^{(n+1)} \). By Step 5 above, there exist maps
\[ \tau, \tau': F \rightarrow \{0, \ldots, l_{n+1}\}, \text{ integers } k, k' \text{ with } |k|, |k'| \leq M - d, \text{ and maps } \theta, \theta': F \rightarrow \{0, 1\} \text{ such that} \]

\[ f_{n+1}(T^p x) = c^{(n+1)}_{\tau(p), k+p, \theta(p)} \quad \text{and} \quad f_{n+1}(T^p y) = c^{(n+1)}_{\tau'(p), k'+p, \theta'(p)} \quad \text{for every } p \in F. \]

Recall that \(0 \in F\). Since \(E_{i,0}^{(n+1)} \cap E_{i,1}^{(n+1)} = \emptyset\), \(f_{n+1}(x) \neq f_{n+1}(y)\), so that \((\tau(0), k, \theta(0)) \neq (\tau'(0), k', \theta'(0))\). Hence \((\tau, \tau', k, k', \theta, \theta')\) belongs to \(\mathcal{F}\), and

\[ \sum_{p \in F} c_p c^{(n+1)}_{\lambda(p), k+p, \theta(p)} \neq \sum_{p \in F} c_p c^{(n+1)}_{\lambda'(p), k'+p, \theta'(p)}, \]

i.e.

\[ \sum_{p \in F} c_p f_{n+1}(T^p x) \neq \sum_{p \in F} c_p f_{n+1}(T^p y). \]

Thus \(D_{i,0}^{(n+1)} \cap D_{i,1}^{(n+1)} = \emptyset\) for every \(i \in \{0, \ldots, n+1\}\). Once \(\eta_{n+1}\) is fixed (and this will be done only later on in the construction), one can choose \(\eta < \eta_{n+1}\), and then \(\beta_{n+1}\) is fixed (and this will be done only later on in the construction), one can choose \(\eta < \eta_{n+1}\), and then \(\beta_{n+1}\) so small that properties (2a), (2b), and (2c) hold true.

**Step 9:** Our next step is to define the sets \(H_i^{(n+1)}\) for \(i \in \{0, \ldots, n+1\}\) and to prove property (3). We set

\[ H_i^{(n+1)} = H_i^{(n)} \cup \left( \bigcup_{|k| \leq N} T^k E \right) \quad \text{for every } i \in \{0, \ldots, n\} \]

\[ H_{n+1}^{(n+1)} = \emptyset. \]

Then for every \(i \in \{0, \ldots, n\}\), \(\mu(H_i^{(n+1)}) \leq \mu(H_i^{(n)}) + \eta < \alpha_i(1 - 2^{-n}) + \eta\). So, if \(\eta\) is chosen sufficiently small,

\[ \mu(H_i^{(n+1)}) < \alpha_i(1 - 2^{-(n+1)}). \]

Also, \(\mu(H_{n+1}^{(n+1)}) = 0 < \alpha_{n+1}(1 - 2^{-(n+1)})\) whatever the value of \(\alpha_{n+1}\). So (3a) holds. As (3b) is obvious, it remains to check (3c).

Let \(i \in \{0, \ldots, n\}\) and \(x \in Q_i \setminus H_i^{(n+1)}\). Then \(x \in X \setminus \left( \bigcup_{|k| \leq N} T^k E \right)\) so that

\[ g_{n+1}(x) = f_n(x) = c_l^{(n+1)} \quad \text{for some } l \in \{0, \ldots, l_{n+1}\}. \]

Also \(x \in Q_i \setminus H_i^{(n)}\), so \(f_n(x) \in E_i^{(n)}\) by the induction assumption, that is \(c_l^{(n+1)} \in E_i^{(n)}\). We have either

\[ h_{n+1}(x) = c_l^{(n+1)} \quad \text{or} \quad h_{n+1}(x) = c_{l,k}^{(n+1)} \quad \text{for some } |k| \leq M. \]

If we write \(h_{n+1}(x) = b_j^{(n+1)}\) for some \(j \in \{0, \ldots, j_{n+1}\}\), then \(j\) belongs to \(J_{i,0}^{(n+1)}\). So \(b_j^{(n+1)}\) and \(b_j^{(n+1)}\) belong to \(E_i^{(n+1)}\). Since \(f_{n+1}(x)\) is equal to either \(b_j^{(n+1)}\) or \(b_j^{(n+1)}\), it follows that \(f_{n+1}(x)\) belongs to \(E_i^{(n+1)}\). In the same way, if \(x \in (X \setminus Q_i) \setminus H_i^{(n+1)}\), then \(f_{n+1}(x)\) belongs to \(E_i^{(n+1)}\).

Let now \(i = n + 1\). Let \(x \in Q_{n+1}\), and let \(j \in \{0, \ldots, j_{n+1}\}\) be such that \(h_{n+1}(x) = b_j^{(n+1)}\). Then \(f_{n+1}(x) = b_j^{(n+1)}\), and so by definition of the set \(E_{i,0}^{(n+1)}\), \(f_{n+1}(x)\) belongs to \(E_{n+1,0}^{(n+1)}\). Similarly, if \(x \in X \setminus Q_{n+1}\), then \(f_{n+1}(x)\) belongs to \(E_{n+1,1}^{(n+1)}\). This proves property (3c).
Step 10: We now have to check properties (4) and (5). We have $g_{n+1}(x) = f_n(x)$ for every $x \in B$ and $\mu(B) > 1 - \eta$ (the set $B$ has been defined in Step 1). If $\gamma > 0$ is an arbitrarily small positive number, the numbers $c_i^{(n+1)}$, $b_j^{(n+1)}$ and $b_{j,1}^{(n+1)}$ have been chosen so close to $c_i^{(n+1)}$ and $b_j^{(n+1)}$ respectively that $||f_{n+1} - g_{n+1}||_\infty < \gamma$, so that in particular
\[ |f_{n+1}(x) - f_n(x)| < \gamma \quad \text{for every } x \in B. \]
Moreover,
\[ ||f_{n+1} - f_n||_\infty \leq ||f_{n+1}||_\infty + ||f_n||_\infty \]
\[ \leq ||g_{n+1}||_\infty + \gamma + ||f_n||_\infty \]
\[ \leq ||f_n||_\infty + \max_{|k| \leq d_{n+1}} |a_k^{(n+1)}| + \gamma + ||f_n||_\infty \]
\[ \leq 2(||f_n||_\infty + \max_{|k| \leq d_{n+1}} |a_k^{(n+1)}|) \]
if $\gamma < \max_{|k| \leq d_{n+1}} |b_k^{(n+1)}|$. The quantity on the righthand side depends only on the construction until step $n$ and on the vector $u_{n+1}$, but not on the rest of the construction at step $n + 1$. In particular, it does not depend on $\gamma$ nor on $\eta$. We have
\[ \int_X ||f_{n+1}(x) - f_n(x)||^2 d\mu(x) < \gamma^2 + \mu(X \setminus B) ||f_{n+1} - f_n||_\infty^2 \leq \gamma^2 + \eta ||f_{n+1} - f_n||_\infty^2. \]
If both $\gamma$ and $\eta$ are chosen sufficiently small, we can ensure that for instance
\[ ||f_{n+1} - f_n||_{L^2(X,B,\mu)} < 2^{-n-1}. \]
This proves (5a).

Let us now estimate, for $x \in X$,
\[ ||\Phi_{f_{n+1}}(x) - \Phi_{f_n}(x)|| = ||\sum_{k \in Z} (f_{n+1}(T^k x) - f_n(T^k x)) A^{-k} z_0||. \]
The series $\sum_{k \in Z} A^{-k} z_0$ being unconditionally convergent in $Z$, there exists for every $\rho > 0$ a positive integer $k_\rho$ such that, for every bounded sequence $(a_k)_{k \in Z}$ of complex numbers,
\[ \left\| \sum_{|k| \geq k_\rho} a_k A^{-k} z_0 \right\| \leq \rho \sup_{|k| \geq k_\rho} |a_k|. \]
So
\[ ||\Phi_{f_{n+1}}(x) - \Phi_{f_n}(x)|| \leq \sup_{|k| < k_\rho} \left| f_{n+1}(T^k x) - f_n(T^k x) \right| \sum_{|k| < k_\rho} ||A^{-k} z_0|| \]
\[ + \rho \cdot \sup_{|k| \geq k_\rho} \left| f_{n+1}(T^k x) - f_n(T^k x) \right| \]
\[ \leq C_\rho \sup_{|k| < k_\rho} \left| f_{n+1}(T^k x) - f_n(T^k x) \right| + \rho ||f_{n+1} - f_n||_\infty, \]
where $C_\rho = \sum_{|k| < k_\rho} ||A^{-k} z_0||$. We have seen already that $||f_{n+1} - f_n||_\infty$ does not depend on the quantities introduced at step $n + 1$ of the construction, so let us fix $\rho = \rho_{n+1} > 0$ so small that $\rho_{n+1} ||f_{n+1} - f_n||_\infty < \gamma$. Then $k_{n+1} = k_{\rho_{n+1}}$ depends on the construction until step $n$, but not on $\eta$. We set
\[ B_{n+1} = \bigcap_{|k| < k_{n+1}} T^{-k} B. \]
Then $\mu(B_{n+1}) > 1 - (2k_{n+1} - 1)\eta$ which can be made as close to 1 as we wish provided $\eta$ is small enough. We also have

$$\sup_{|k| < k_{n+1}} \left| f_{n+1}(T^k x) - f_n(T^k x) \right| < \gamma \quad \text{for every } x \in B_{n+1}.$$  

It follows that for every $x \in B_{n+1}$, $\|\Phi_{n+1}(x) - \Phi_n(x)\| \leq C_{\rho_{n+1}} \cdot \gamma + \gamma$. So if $\gamma'$ is any positive number, we can ensure by taking $\gamma$ sufficiently small that

$$\|\Phi_{n+1}(x) - \Phi_n(x)\| < \gamma' \quad \text{for every } x \in B_{n+1}.$$  

Thus if $\gamma_{n+1}$ and $\eta_{n+1}$ are any fixed positive numbers, taking $\gamma$ and $\eta$ sufficiently small yields that properties (4a), (4b) and (4c) are true.

Also, we have

$$\int_X \|\Phi_{n+1}(x) - \Phi_n(x)\|^2 d\mu(x) < \gamma'^2 + \mu(X \setminus B_{n+1}) (C_{\rho_{n+1}} + \rho_{n+1})^2 \cdot \|f_{n+1} - f_n\|_\infty^2 \leq \gamma'^2 + (2k_{n+1} - 1) \eta (C_{\rho_{n+1}} + \rho_{n+1}) \cdot \|f_{n+1} - f_n\|_\infty^2.$$  

Since $\eta$ can be chosen as small as we wish compared to $k_{n+1}$, $\rho_{n+1}$, and $\|f_{n+1} - f_n\|_\infty$, we can make the bound above as small as we wish provided $\gamma$ and $\eta$ are sufficiently small. So we can in particular ensure that

$$\|\Phi_{n+1} - \Phi_n\|_{L^2(X, \mathcal{B}, \mu; Z)} < 2^{-(n+1)},$$  

which is (5b).

**Step 11:** It remains to construct the sets $G_i^{(n+1)}$, $i \in \{0, \ldots, n+1\}$, in such a way that property (6) holds true.

We know that for every $i \in \{0, \ldots, n\}$ and every $x \in G_i^{(n)}$, $\Phi_n(x)$ belongs to $U_i$, i.e. $\|\Phi_n(x) - u_i\| < r_i$, and that $\mu(G_i^{(n)}) \geq \delta_i(1 + 2^{-n})$. Let $0 < \kappa < r_i$ be so small that for every $i \in \{0, \ldots, n\}$,

$$\mu(\{x \in G_i^{(n)} : \|\Phi_n(x) - u_i\| < r_i - \kappa\}) \geq \delta_i(1 + \frac{3}{4}2^{-n}).$$  

This number $\kappa$ only depends on the construction until step $n$. We set for $i \in \{0, \ldots, n\}$

$$G_i^{(n+1)} = \{ x \in G_i^{(n)} : \|\Phi_n(x) - u_i\| < r_i - \kappa \} \cap B_{n+1}$$

and $G_{n+1}^{(n+1)} = E$. Then obviously $G_i^{(n+1)} \subseteq G_i^{(n)}$ for $i \in \{0, \ldots, n\}$ and

$$\mu(G_i^{(n+1)}) \geq \delta_i \left( 1 + \frac{3}{4}2^{-n} - (2k_{n+1} - 1) \eta \right) \geq \delta_i \left( 1 + 2^{-(n+1)} \right)$$

if $\eta$ is small enough. Also $\mu(G_{n+1}^{(n+1)}) = \mu(E) \geq \delta_{n+1}(1 + 2^{-(n+1)})$ if $\delta_{n+1}$ is small enough. So properties (6a) and (6b) are true.

If $i \in \{0, \ldots, n\}$ and $x \in G_i^{(n+1)}$, then $\|\Phi_n(x) - u_i\| < r_i - \kappa$. Also $x \in B_{n+1}$ so that $\|\Phi_{n+1}(x) - \Phi_n(x)\| < \gamma'$. If $\gamma'$ is chosen less than $\kappa$ (which is possible since $\kappa$ depends only on the construction until step $n$), we have $\|\Phi_{n+1}(x) - u_i\| < r_i$, i.e. $\Phi_{n+1}(x) \in U_i$.

If $i = n + 1$, and $x \in G_{n+1}^{(n+1)} = E$, then $T^k x \in T^k E$ for every $k \in \mathbb{Z}$. Hence

$$\Phi_{g_{n+1}}(x) = \sum_{|k| \leq d_{n+1}} a_k^{(n+1)} A^{-k} z_0 + \sum_{|k| > N} g_{n+1}(T^k x) A^{-k} z_0$$
by the definition of the function \(g_{n+1}\). Thus
\[
\|\Phi_{g_{n+1}}(x) - u_{n+1}\| \leq \left| \sum_{|k| > N} g_{n+1}(T^k x) A^{-k} z_0 \right|.
\]

Let now be \(\rho > 0\) such that \(\rho \|g_{n+1}\|_\infty < r_{n+1}/2\). Since
\[
\|g_{n+1}\|_\infty \leq \|f_n\|_\infty + \max_{|k| \leq d_{n+1}} |a_k^{(n)}|,
\]
the number \(\rho\) only depends on the construction until step \(n\), and we can choose \(N\) so large that \(N > k_\rho\). Then we have for every \(x \in E\)
\[
\|\Phi_{g_{n+1}}(x) - u_{n+1}\| \leq \rho \sup_{|k| > N} |g_{n+1}(T^k x)| \leq \rho \|g_{n+1}\|_\infty < \frac{r_{n+1}}{2}.
\]

Recall that there exists a positive constant \(C\) such that
\[
\left| \sum_{k \in \mathbb{Z}} a_k A^{-k} z_0 \right| \leq C \sup_{k \in \mathbb{Z}} |a_k|
\]
for all bounded sequences \((a_k)_{k \in \mathbb{Z}}\) of complex numbers. Since \(\|f_{n+1} - g_{n+1}\|_\infty < \gamma\), we can assume by taking \(\gamma\) sufficiently small that \(\|f_{n+1} - g_{n+1}\|_\infty < r_{n+1} / (2C)\). Then we have, for every \(x \in X\),
\[
\|\Phi_{f_{n+1}}(x) - \Phi_{g_{n+1}}(x)\| \leq C \|f_{n+1} - g_{n+1}\|_\infty < \frac{r_{n+1}}{2}.
\]
Hence \(\|\Phi_{f_{n+1}}(x) - u_{n+1}\| < r_{n+1}\) for every \(x \in E\), i.e. \(\Phi_{n+1}(x)\) belongs to \(U_{n+1}\) for every \(x \in E = G_{n+1}\). Thus property (6c) is satisfied.

This finishes the construction by induction of the functions \(f_n\).

2.3. Construction of the isomorphism \(\Phi\) and proof of Theorem 1.3. — By property (5b), the sequence \((\Phi_{f_n})_{n \geq 0}\) converges in \(L^2(X, \mathcal{B}, \mu; Z)\) to a function \(\Phi\) which belongs to \(L^2(X, \mathcal{B}, \mu; Z)\). Our aim is now to prove that the probability measure \(\nu\) on \(Z\) defined by \(\nu(B) = \mu(\Phi^{-1}(B))\) for any Borel subset \(B\) of \(Z\) has full support, and that \(\Phi\) is an isomorphism between the two dynamical systems \((X, \mathcal{B}, \mu; T)\) and \((Z, \mathcal{B}_Z, \nu; A)\).

Observe that the property (5a) of the sequence of functions \((f_n)_{n \geq 0}\) implies that \((f_n)_{n \geq 0}\) converges in \(L^2(X, \mathcal{B}, \mu)\) to a certain function \(f \in L^2(X, \mathcal{B}, \mu)\). Obviously, \(f\) does not belong to \(L^\infty(X, \mathcal{B}, \mu)\), and thus it makes no sense to speak of the map \(\Phi_f\) (this is a difference with what happens in the construction of [10]). But a link between \(\Phi\) and \(f\) can be obtained thanks to the assumption (b) of Theorem 1.3: for \(\mu\)-almost every \(x \in X\) and every \(n \geq 0\) we have \((z_0^*, \Phi_{f_n}(x)) = \sum_{p \in F} c_p f_n(T^p x)\), where the set \(F\) is finite. Since there exists a strictly increasing sequence \((n_k)_{k \geq 0}\) of integers such that \(\Phi_{f_{n_k}} \rightarrow \Phi\) and \(f_{n_k} \rightarrow f\) \(\mu\)-almost everywhere, it follows that
\[
\langle z_0^*, \Phi(x) \rangle = \sum_{p \in F} c_p f(T^p x) \quad \mu\text{-almost everywhere}.
\]

- Let us first show that \(\nu\) has full support. By property (4c) we have that for every \(n \geq 0\) and every \(x \in B_n = \bigcap_{k \geq n} B_k\), \(\|\Phi_{f_{k-1}}(x) - \Phi_{f_k}(x)\| < \gamma_k\) for every \(k \geq n\). Observe that
\[
\mu(B_n) \geq 1 - \sum_{k \geq n} \eta_k > 1 - 2\eta_n
\]
if the sequence \((\eta_n)_{n \geq 0}\) decreases sufficiently fast, so that \(\mu(\widetilde{B}_n) \to 1\) as \(n \to +\infty\). For every \(n \geq 0\) and every \(x \in \widetilde{B}_n\) we have in particular
\[
||\Phi f_n(x) - \Phi f_n(x)|| \leq \sum_{j=\eta_n}^{k} ||\Phi f_j(x) - \Phi f_{j-1}(x)|| \leq \sum_{j=\eta_n+1}^{\infty} \gamma_j < 2 \gamma_{n+1}
\]
if the sequence \((\gamma_k)_{k \geq 0}\) is sufficiently rapidly decreasing. As \((\Phi f_k)_{k \geq 0}\) converges to \(\Phi\) in \(L^2(X, \mathcal{B}, \mu; Z)\), there exists a subsequence of \((\Phi f_k)_{k \geq 0}\) which converges to \(\Phi\) \(\mu\)-almost everywhere on \(X\) and thus we have:
\[
\text{for } \mu\text{-almost every } x \in \widetilde{B}_n, \quad ||\Phi(x) - \Phi f_n(x)|| \leq 2 \gamma_{n+1}.
\]
Let us now fix \(i \geq 0\). By property (6c), we have that, for every \(n \geq i\) and every \(x \in G_i^{(n)}\),
\[
||\Phi f_n(x) - u_i|| < r_i.
\]
Let
\[
G_i = \bigcap_{n \geq i} G_i^{(n)}.
\]
As the sequence of sets \((G_i^{(n)})_{n \geq i}\) is decreasing by (6b), we have \(\mu(G_i) = \lim_{n \to +\infty} \mu(G_i^{(n)})\) so that \(\mu(G_i) \geq \delta_i > 0\) by property (6a). Let now \(n \geq i\) be so large that \(\mu(G_i \cap \widetilde{B}_n) > 0\). If \(x \in G_i \cap \widetilde{B}_n\), then
\[
||\Phi(x) - u_i|| \leq ||\Phi(x) - \Phi f_n(x)|| + ||\Phi f_n(x) - u_i|| < 2 \gamma_{n+1} + r_i.
\]
Hence \(\nu(B(u_i, r_i + 2 \gamma_{n+1})) > 0\) for all \(n\) sufficiently large, so that it follows in particular that \(\nu(B(u_i, 2 r_i)) > 0\). This being true for all \(i \geq 0\), the measure \(\nu\) has full support.

Let us observe at this point that the measure \(\nu\) admits a moment of order 2. Indeed
\[
\int_{Z} ||z||^2 d\nu(z) = \int_{X} ||\Phi(x)||^2 d\mu(x) < +\infty
\]
since \(\Phi \in L^2(X, \mathcal{B}, \mu; Z)\).

- **It remains to show that \(\Phi\) is an isomorphism between \((X, \mathcal{B}, \mu; T)\) and \((Z, \mathcal{B}_Z, \nu; A)\).** For this it suffices to prove (see for instance [13, p. 59–60]) that the two transformations \(T\) and \(A\) are conjugated via the map \(\Phi\). First of all, we need to check that \(\Phi(Tx) = A\Phi(x)\) for \(\mu\)-almost every \(x \in X\). Since \(\Phi f_n\) tends to \(\Phi\) in \(L^2(X, \mathcal{B}, \mu; Z)\) as \(n\) tends to infinity, there exists a subsequence \((\Phi f_{k_n})_{k \geq 0}\) of \((\Phi f_n)\) which tends to \(\Phi\) \(\mu\)-almost everywhere. As \(\Phi f_n(Tx) = A\Phi f_n(x)\) \(\mu\)-almost everywhere for each \(n \geq 0\), it follows that \(\Phi(Tx) = A\Phi(x)\) \(\mu\)-almost everywhere.

The second point is to check that for every subset \(Q\) of \(X\), \(Q \in \mathcal{B}\), there exists a subset \(B\) of \(Z\), \(B \in \mathcal{B}_Z\), such that \(\mu(Q \triangle \Phi^{-1}(B)) = 0\). So let \(Q \in \mathcal{B}\). Suppose that we are able to exhibit a Borel subset \(C\) of \(Z\) such that \(Q = \{x \in X; \sum_{p \in F} c_p f(T^p x) \in C\}\) up to a set of measure zero. Setting \(B = \{z \in Z; \langle z_0^*, z \rangle \in C\}\), and remembering that \(\langle z_0^*, \Phi(z) \rangle = \sum_{p \in F} c_p f(T^p x)\) \(\mu\)-almost everywhere, we obtain that \(B\) is a Borel subset of \(Z\) such that \(\Phi^{-1}(B) = Q\) (up to a set of \(\mu\)-measure zero). So it suffices to find \(C\) with the property above.

Let us first introduce some notation: for each \(n \geq 0\) we define the function \(F_n\) on \(X\) by setting \(F_n(x) = \sum_{p \in F} c_p f_n(T^p x)\) and the function \(F\) by setting \(F(x) = \sum_{p \in F} c_p f(T^p x)\). For every \(i \geq 0\), let
\[
C_{i,0} = \bigcap_{n \geq i} F^{(n)}_{i,0} \quad \text{and} \quad C_{i,1} = \bigcap_{n \geq i} F^{(n)}_{i,1}.
\]
These are Borel subsets of $\mathbb{C}$. Recall that $J_i = \{ j \geq i; Q_j = Q_i \}$ is supposed to be infinite. Let

$$\Gamma_{i,0} = \bigcup_{j \geq 0} \bigcap_{k \in J_i} C_{k,0} \quad \text{and} \quad \Gamma_{i,1} = \bigcup_{j \geq 0} \bigcap_{k \in J_i} C_{k,1}.$$  

These two sets are Borel in $\mathbb{C}$. Moreover $\Gamma_{i,0} \cap \Gamma_{i,1} = \emptyset$. Indeed, if it is not the case, we have

$$\left( \bigcap_{k \in J_i} C_{k,0} \right) \cap \left( \bigcap_{k \in J_i} C_{k,1} \right) \neq \emptyset$$

for some integers $j_1$ and $j_2$. In particular, if $k \in J_i$ is such that $k \geq \max(j_1, j_2)$ (and such a $k$ does exist because $J_i$ is infinite), $C_{k,0} \cap C_{k,1} \neq \emptyset$. So for all $n \geq k$, $F_{k,0}^{(n)} \cap F_{k,1}^{(n)} \neq \emptyset$, which is a contradiction with (2c).

For every $i \geq 0$, we consider the subsets of $X$

$$D_i = \bigcap_{p \in F} \left( \bigcap_{k \geq i} T^{-p} B_k \right) \cap \left( \bigcap_{k \geq i} C_k \right),$$

$$H_i = \bigcup_{n \geq i} H_i^{(n)}$$

$$\Omega_i = \bigcap_{k \geq i} (D_k \setminus H_k)$$

$$\Omega = \bigcup_{i \geq 0} \Omega_i.$$

We have $\mu(D_i) \geq 1 - (2d + 2) \sum_{k \geq i} \eta_k \geq 1 - 4(d + 1) \eta_i$ if the sequence $(\eta_i)_{i \geq 0}$ decreases sufficiently fast. Also, (3a) and (3b) imply that $\mu(H_i) \leq \alpha_i$ so that

$$\mu(\Omega_i) \geq 1 - \sum_{k \geq i} (\mu(X \setminus D_k) + \mu(H_k)) \geq 1 - 4(d + 1) \sum_{k \geq i} \eta_k - \sum_{k \geq i} \alpha_k \geq 1 - 8(d + 1)(\alpha_i + \eta_i)$$

if the sequences $(\eta_i)_{i \geq 0}$ and $(\alpha_i)_{i \geq 0}$ decrease to zero sufficiently fast. Thus $(\Omega_i)_{i \geq 0}$ is an increasing sequence of sets such that $\mu(\Omega_i) \to 1$ as $i \to +\infty$. So $\mu(\Omega) = 1$.

For every $n \geq 0$, every $x \in D_n$, every $p \in F$, and every $k \geq n$, by property (4b), $|f_{k+1}(T^p x) - f_k(T^p x)| < \gamma_{k+1}$. Hence $|F_{k+1}(x) - F_k(x)| \leq (\sup_{p \in F} |c_p|) \gamma_{k+1}$. Since $(F_k)_{k \geq 0}$ converges to $F$ in $L^2(X, B, \mu)$, there exists a subsequence $(F_{k_j})_{j \geq 0}$ of $(F_k)_{k \geq 0}$ which converges to $F$ $\mu$-almost everywhere. Hence for $(\mu$-almost) every $x \in D_n$ we have

$$|F(x) - F_n(x)| \leq \sup_{p \in F} |c_p| \sum_{k \geq n} \gamma_{k+1} < \beta_n$$

if $\gamma_{n+1}, \gamma_{n+2}, \ldots$ are chosen at steps $n+1, n+2, \ldots$ sufficiently small with respect to $\beta_n$. Thus $F(x) \in D(F_n(x), \beta_n)$ for every $x \in D_n$.

After these preliminaries, our aim is now to show that for every $i \geq 0$, $F^{-1}(\Gamma_{i,0}) = Q_i$ and $F^{-1}(\Gamma_{i,1}) = X \setminus Q_i$. So, let us fix $i \geq 0$ and $k \in J_i$. Suppose that $x \in Q_i \cap \Omega_k$. Then for every $n \geq k$, $x \in Q_i \cap (D_k \setminus H_k) \cap (D_n \setminus H_n)$ so that $x \in Q_i \cap (D_n \setminus H_k^{(n)}) = Q_k \cap (D_n \setminus H_k^{(n)})$.

By property (3c), $f_n(x) \in E_k^{(n)}$. Since $x \in D_n \subseteq C_n$, this implies that $F_n(x) \in D_k^{(n)}$. It follows that for every $n \geq k$, $F(x) \in F_k^{(n)}$, so that $F(x) \in \bigcap_{n \geq k} F_k^{(n)} = C_{k,0}$. We have thus proved that if $k \in J_i$ and $x \in Q_i \cap \Omega_k$, then $F(x) \in C_{k,0}$.
Let now $j \geq 0$. If $k \geq j$ and $k \in J_i$, then, since $\Omega_j \subseteq \Omega_k$, we have $Q_i \cap \Omega_j \subseteq Q_i \cap \Omega_k$. It follows that if $x \in Q_i \cap \Omega_j$, $F(x) \in C_{k,0}$ for every $k \in J_i$, $k \geq j$, and so

$$F(x) \in \bigcap_{k \geq j} C_{k,0}.$$ 

Suppose now that $x \in Q_i \cap \Omega$: there exists a $j \geq 0$ such that $x \in Q_i \cap \Omega_j$. Hence

$$F(x) \in \bigcup_{j \geq 0} \bigcap_{k \geq j} C_{k,0} = \Gamma_{i,0}.$$ 

In exactly the same way, if $x \in (X \setminus Q_i) \cap \Omega$ then $F(x) \in \Gamma_{i,1}$. Since $\Gamma_{i,0} \cap \Gamma_{i,1} = \emptyset$ and $\mu(\Omega) = 1$, we have proved that

$$F^{-1}(\Gamma_{i,0}) = Q_i, \quad \text{and} \quad F^{-1}(\Gamma_{i,1}) = X \setminus Q_i$$ 

up to sets of $\mu$-measure zero. The proof is now nearly finished. Let

$$Q = \{Q \in \mathcal{B}; \text{there exists a Borel subset } C \text{ of } \mathbb{C} \text{ such that } \mu(Q \Delta F^{-1}(C)) = 0\}.$$ 

Then $Q$ is a $\sigma$-algebra which contains all the sets $Q_i$, $i \geq 0$, and these sets generate $\mathcal{B}$. Thus $Q = \mathcal{B}$. This finishes the proof that $\Phi$ is an isomorphism of dynamical systems, and Theorem 1.3 is proved.

2.4. Proof of Theorem 1.4. — The proof of Theorem 1.4 is exactly similar in spirit, but some technical points need to be adjusted. We briefly list the most important ones. If $(X, \mathcal{B}, \mu; T)$ is an ergodic dynamical system, which is not necessarily invertible, the maps $\Phi_f$, $f \in L^\infty(X, \mathcal{B}, \mu)$ are defined as $\Phi_f(x) = \sum_{k \geq 1} f(T^k x) A^{-k+r} z_0$ for $\mu$-almost every $x \in X$, where $r \in \mathbb{Z}$ is such that $A^r z_0 = 0$. Then

$$\Phi_f(T x) = \sum_{k \in \mathbb{Z}} f(T^k x) A^{-k+1+r} z_0 = \sum_{k \geq 1} f(T^k x) A^{-k+1+r} z_0$$ 

since $A^r z_0 = 0$. Hence $\Phi_f(T x) = A \Phi_f(x)$ $\mu$-almost everywhere. As in the proof of Theorem 1.3, we can suppose by shifting the sequence $(z_n)_{n \in \mathbb{Z}}$ that $0 \in F$ and that there exists a non-zero functional $z_0^* \in Z^*$ such that $c_n = \langle z_0^*, A^{-n+r} z_0 \rangle$ is non-zero if and only if $n \in F$. The vectors $u_n$ are defined as

$$u_n = \sum_{k=0}^{d_n} a_k^{(n)} A^{-k+r} z_0, \quad a_k^{(n)} \in \mathbb{C}.$$ 

The set $E$ and the integer $N$ are chosen in such a way that $\mu(E) > 0$, $\mu(\bigcup_{k=0}^{N} T^{-k} E) < \eta$, and the sets $T^{-k} E$ are pairwise disjoint. This entails a modification of the definition of the function $g_{n+1}$:

$$g_{n+1}(x) = \begin{cases} 
    a_k^{(n+1)} & \text{if } x \in T^{-N-k} E, \quad 0 \leq k \leq d_{n+1} \\
    0 & \text{if } x \in T^{-N-k} E, \quad d_{n+1} < k \leq N \\
    f_n(x) & \text{if } x \in X \setminus \bigcup_{k=0}^{N} T^{-k} E.
\end{cases}$$ 

The set $E'$ and the integer $M$ are chosen so that $\mu(\bigcup_{k=0}^{M-d} T^{-k} E') < 1 - \eta$ and the sets $T^{-k} E'$, $0 \leq k \leq M$, are pairwise disjoint (where $d = \max |F|$). The set $G^{(n+1)}_{n+1}$ needs to be defined as $G^{(n+1)}_{n+1} = T^{-N} E$. Up to these modifications, the proof is the same, and we leave the details to the reader.
2.5. Some remarks. — Now we have carried out the proofs of these two results, a few remarks are in order.

Remark 2.2. — We have seen during the proofs of Theorem 1.3 and 1.4 that the measures \( \nu \) constructed on \( Z \) admit a second order moment. Thus operators satisfying the assumptions of these theorems are 2-universal for (invertible) ergodic systems in the sense of Definition 5.1 (see Section 5). It is not difficult to check that one can ensure that all the measures \( \nu \) actually admit moments of all orders.

Remark 2.3. — If \( A \) is an invertible operator on \( Z \), then it cannot be universal for all ergodic systems: indeed, suppose that \( (X, \mathcal{B}, \mu; T) \) is a dynamical system which is isomorphic to \( (Z, \mathcal{B}_Z, \nu; A) \) for some \( A \)-invariant measure \( \nu \) with full support. Then \( \nu \) is \( A^{-1} \)-invariant too. If \( \Phi : X \rightarrow Z \) is an isomorphism between \( (X, \mathcal{B}, \mu; T) \) and \( (Z, \mathcal{B}_Z, \nu; A) \) then set \( S = \Phi^{-1}A^{-1}\Phi \). The measure \( \mu \) is \( S \)-invariant, and since \( T = \Phi^{-1}A\Phi \), we have \( TS = ST = \text{id}_X \), so that \( T \) is invertible. Thus an invertible operator may only be universal for invertible ergodic systems.

If \( A \) is a universal operator for ergodic systems and \( (X, \mathcal{B}, \mu; T) \) is an invertible ergodic system, there exists a probability measure \( \nu \) on \( Z \) such that \( (X, \mathcal{B}, \mu; T) \) and \( (Z, \mathcal{B}_Z, \nu; A) \) are isomorphic. Hence \( A \) is invertible as a measure-preserving transformation of \( (Z, \mathcal{B}_Z, \nu) \), although, as observed above, it is not invertible as a topological map from \( Z \) into itself. There is no contradiction in this: there indeed exists a Borel subset \( M \) of \( Z \) with \( A(M) = M \) and \( \nu(M) = 1 \) such that \( A : M \rightarrow M \) is an invertible measure-preserving transformation, i.e. there exists a map \( S : M \rightarrow M \) which is measurable and measure-preserving such that \( AS(x) = SA(x) = x \) for every \( x \in M \). But \( M \) being distinct from the whole space \( X \), and \( S \) not necessarily uniformly continuous on \( M \), there is no reason why \( S \) should extend into a topological inverse of \( A \) on \( Z \).

Remark 2.4. — The ergodicity of the system \( (X, \mathcal{B}, \mu; T) \) has been used in the proofs of Theorems 1.3 and 1.4 only via the Rokhlin lemma. So we could have supposed instead that the system was aperiodic, and the operators \( A \) of Theorems 1.3 and 1.4 are in fact universal for (invertible) aperiodic systems.

We finish this section with a generalization of Theorems 1.3 and 1.4, in which assumption (a) is relaxed. This generalization is useful for proving the universality of some operators (see Section 4) for which the (bi)cyclicity assumption (a) is not easily seen to hold true.

Theorem 2.5. — Let \( A \in \mathcal{B}(Z) \) be a bounded operator on \( Z \). Suppose that there exist sequences \( (z_n^{(i)})_{n \in \mathbb{Z}} \) of vectors of \( Z \), \( i \in I \), where either \( I = \{0, \ldots, N\} \) for some integer \( N \geq 0 \), or \( I = \mathbb{Z}^+ \), such that \( Az_n^{(i)} = z_n^{(i)} \) for every \( i \in I \) and \( n \in \mathbb{Z} \). Suppose that the following three properties hold true:

(a') \( \overline{\text{span}} \{ A^{-n}z_0^{(i)} ; \ n \in \mathbb{Z}, \ i \in I \} = Z \);

(b') there exists a finite subset \( F \) of \( \mathbb{Z} \) such that

\[
\overline{\text{span}} \left\{ \{ A^{-n}z_0^{(i)} ; \ n \in \mathbb{Z} \setminus F \} \cup \{ A^{-n}z_0^{(i)} ; \ n \in \mathbb{Z}, \ i \in I \setminus \{0\} \} \right\} \neq Z;
\]

(c') the series \( \sum_{n \in \mathbb{Z}} A^{-n}z_0^{(i)} \), \( i \in I \), are unconditionally convergent in \( Z \).

Then \( A \) is universal for invertible ergodic systems.

The analogue statement for universality for ergodic systems is
Theorem 2.6. — Let $A \in \mathcal{B}(Z)$ be a bounded operator on $Z$. With the notations of Theorem 2.5, suppose that there exist sequences $(z_n^{(i)})_{n \in \mathbb{Z}}$, $i \in I$, of vectors of $Z$ and integers $r^{(i)}$, $i \in I$, where either $I = \{0, \ldots, N\}$ for some integer $N \geq 0$, or $I = \mathbb{Z}^+$, such that $A z_n^{(i)} = z_{n+1}^{(i)}$ for every $n \in \mathbb{Z}$ and $A z_0^{(i)} = 0$, for every $i \in I$.

If assumptions (a'), (b') and (c') of Theorem 2.5 hold true, $A$ is universal for ergodic systems.

Proof. — The proofs are almost the same as those of Theorems 1.3 and 1.4, with the additional complication that several functions $f^{(i)} \in L^2(X, \mathcal{B}, \mu)$, $i \in I$, have to be considered, and several sequences $(\{f_n^{(i)}\})_{n \geq 0}$ of functions of $L^\infty(X, \mathcal{B}, \mu)$ introduced. We sketch here the proof of Theorem 2.5, and leave the proof of Theorem 2.6 to the reader.

Let $(u_n)_{n \geq 0}$ be a sequence of vectors of $Z$ which is dense in $Z$ and has the following property: there exist for each $n \geq 0$ an integer $d_n$ and complex coefficients $a_k^{(i,n)}$, $k \in \{0, \ldots, n+1\}$, $i \in \{0, \ldots, n\}$, such that

$$u_n = \sum_{i=0}^n \sum_{k=0}^{d_n} a_k^{(i,n)} A^{-n} z_0^{(i)}.$$

Let $(r_n)_{n \geq 0}$ be a decreasing sequence of positive radii such that the balls $U_n = B(u_n, r_n)$, $n \geq 0$, form a basis of the topology of $Z$. Let also $z_0^*$ be a non-zero functional and $F$ a finite subset of $Z$ such that $\langle z_0^*, A^{-n} z_0^{(i)} \rangle = 0$ for every $i \in I \setminus \{0\}$ and every $n \in \mathbb{Z}$, $c_n = \langle z_0^*, A^{-n} z_0^{(0)} \rangle = 0$ for every $n \in \mathbb{Z} \setminus F$, and $c_n = \langle z_0^*, A^{-n} z_0^{(0)} \rangle$ is non-zero for every $n \in F$ (the set $F$ can be assumed to contain 0).

Then we construct sequences $(f_n^{(i)})_{n \geq 0}$, $i \in I$, as in the proof of Theorem 1.3: at each step $n$ we construct the functions $f_n^{(i)}$ for $i \in \{0, \ldots, n\}$: for each such $i$, the open set used in the construction is $U_n^{(i)} = B(u_n^{(i)} , 2^{-(i+1)} r_n)$, where

$$u_n^{(i)} = \sum_{k=0}^{d_n} a_k^{(i,n)} A^{-n} z_0^{(i)}$$

if $i \in \{0, \ldots, n\}$, $u_n^{(i)} = 0$ otherwise (if $I$ is finite, $i \in \{0, \ldots, n\}$ means that $i \in \{0, \ldots, \min(|I|, n)\}$). Hence $u_n = \sum_{i \in I} u_n^{(i)}$ for every $n \geq 0$.

We carry out the construction in such a way that properties (1)–(6) hold true for $f_n^{(0)}$, and properties (4)–(6) hold true for $f_n^{(i)}$, $i \in \{1, \ldots, n\}$. The important points in this construction, when compared to the proof of Theorem 1.3 are the following:

- the initial functions $f_i^{(i)}$, $i \in I$, are such that $\|f_i^{(i)}\|_{L^\infty(X, \mathcal{B}, \mu)} < 2^{-(i+1)} r_i^{(i)}$, so that $\|\Phi_i^{(i)}\|_{L^2(X, \mathcal{B}, \mu; Z)} \leq C_i \|f_i^{(i)}\|_{L^\infty(X, \mathcal{B}, \mu)} < 2^{-(i+1)} r_i^{(i)}$, where $C_i$ is a positive constant such that

$$\left| \sum_{k \in \mathbb{Z}} a_k^{(i)} A^{-k} z_0^{(i)} \right| \leq C_i \sup_{k \in \mathbb{Z}} |a_k^{(i)}|$$

for every $(a_k^{(i)})_{k \in \mathbb{Z}} \in \ell_\infty(\mathbb{Z})$.

- at a given step of the construction, the sets $E$ and $E'$ and the parameters $\gamma$ and $\eta$ can be chosen independently of the index $x \in \{0, \ldots, n\}$. It follows that the sets $B_n$ and
$G_i^{(n)}$, which may a priori depend on the index $i$, can be constructed so as not to depend on it, as well as the parameters $\gamma_n, \eta_n, \delta_n$ (the other parameters in the construction, as well as the sets $C_n, D_{i,0}^{(n)}, E_{i,1}^{(n)}, F_{i,0}^{(n)}, F_{i,1}^{(n)}, H_i^{(n)}$ are involved only for the index $i = 0$). More precisely, Step 11 in the proof of the construction becomes: we know that for every $i \in \{0, \ldots, n\}$ and every $x \in G_i^{(n)}$, we have
\[
||\Phi_{f_{i,0}^{(n)}} - u_i^{(i)}|| < 2^{-(i+1)}r_i \quad \text{for every } i \in \{0, \ldots, n\}.
\]
Let $\kappa$ be so small that for every $i \in \{0, \ldots, n\}$,
\[
\mu\left(\{x \in G_i^{(n)} : \text{for every } i \in \{0, \ldots, n\}, ||\Phi_{f_{i,0}^{(n)}}(x) - u_i^{(i)}|| < 2^{-(i+1)}(r_i - \kappa)\}\right) \geq \delta_i\left(1 + \frac{3}{4}2^{-n}\right).
\]
We set for $i \in \{0, \ldots, n\}$
\[
G_i^{(n+1)} = \{x \in G_i^{(n)} : \text{for every } i \in \{0, \ldots, n\}, ||\Phi_{f_{i,0}^{(n)}}(x) - u_i^{(i)}|| < 2^{-(i+1)}(r_i - \kappa)\} \cap B_{n+1}
\]
and $G_i^{(n+1)} = E$. Properties (6a) and (6b) are clearly true. It remains to prove property (6c). It is not difficult to see that for every $i \in \{0, \ldots, n\}$ and every $x \in G_i^{(n+1)} = E$ and every $i \in \{0, \ldots, n\}$, $\Phi_{f_{i,0}^{(n)}}(x) \in U_i^{(i)}$ for every $x \in G_i^{(n+1)}$. We then have to check that for every $i \in \{0, \ldots, n\}$ and every $x \in G_i^{(n+1)}$, $\Phi_{f_{i,0}^{(n)}}(x) \in U_i^{(n+1)}$, i.e. that
\[
||\Phi_{f_{i,0}^{(n+1)}}(x) - u_i^{(n+1)}|| < 2^{-(n+2)}r_i.
\]
But $u_i^{(n+1)} = 0$ and
\[
||\Phi_{f_{i,0}^{(n+1)}}||_{L^\infty(X,B;\mu)} < 2^{-(n+2)}r_{n+1} < 2^{-(n+2)}r_i,
\]
so we do have that $\Phi_{f_{i,0}^{(n+1)}}(x) \in U_i^{(n+1)}$. The last item in the proof of property (6c) is to show that $\Phi_{f_{i,0}^{(n)}}(x) \in U_i^{(i)}$ for every $x \in G_i^{(n+1)} = E$ and every $i \in \{0, \ldots, n\}$, and here the proof is again exactly the same.

We thus have
\[
||f_{i}^{(n+1)} - f_{i,1}^{(n+1)}||_{L^2(X,B;\mu)} < 2^{-n} \quad \text{and} \quad ||\Phi_{f_{i}}^{(n+1)} - \Phi_{f_{i,1}^{(n+1)}}||_{L^2(X,B;\mu;Z)} < 2^{-n}
\]
for every $n \geq 1$ and $i \in \{0, \ldots, n\}$ and
\[
||\Phi_{f_{i}}^{(n+1)}(x) - u_{i}^{(n+1)}|| < 2^{-(i+1)}r_n
\]
for every $x \in G_i^{(n)}$, $i \in \{0, \ldots, n\}$, $i \in \{0, \ldots, n\}$. It follows that the sequence $\left(f_{i}^{(n)}\right)_{n \geq 1}$ converges in $L^2(X,B;\mu)$ to a function $f^{(i)}$ which satisfies
\[
||f^{(i)}||_{L^2(X,B;\mu)} \leq ||f_{i}^{(1)}||_{L^2(X,B;\mu)} + \sum_{n \geq 1} ||f_{i}^{(n)} - f_{i,1}^{(n)}||_{L^2(X,B;\mu)} < 2^{-(i+1)} + \sum_{n \geq 1} 2^{-(n+1)} \leq 2^{-(i+1)}.
\]
In the same way, $\left(\Phi_{f_{i}}^{(n+1)}\right)_{n \geq 1}$ converges in $L^2(X,B;\mu;Z)$ to a function $\Phi^{(i)}$ which satisfies $||\Phi^{(i)}||_{L^2(X,B;\mu;Z)} < 2^{-(i+1)}$. In particular, the series $\sum_{i \in I} ||\Phi^{(i)}||_{L^2(X,B;\mu;Z)}$ is convergent.
We now consider the map $\Phi : X \rightarrow Z$ defined as
\[
\Phi = \sum_{i \in I} \Phi^{(i)}.
\]

Since
\[
\int_X \sum_{i \in I} \|\Phi^{(i)}(x)\| \, d\mu(x) \leq \sum_{i \in I} \left( \int_X \|\Phi^{(i)}(x)\|^2 \, d\mu(x) \right)^{1/2} \leq \sum_{i \in I} 2^{-(i-1)} < +\infty,
\]
$\Phi(x)$ is defined $\mu$-almost everywhere.

If $\nu$ is the measure defined on $Z$ by setting $\nu(B) = \mu(\Phi^{-1}(B))$ for every $B \in \mathcal{B}_Z$, then it is clear that $\Phi : (X, \mathcal{B}, \mu; T) \rightarrow (Z, \mathcal{B}_Z, \nu; A)$ is a factor map. It is an isomorphism of dynamical systems for the same reason as in the proof of Theorem 1.3: if $Q$ is any Borel subset of $X$, we know that there exists a Borel subset $C$ of $\mathbb{C}$ such that
\[
\{ x \in X : \sum_{p \in F} c_p f^{(0)}(T^p x) \in C \} = Q.
\]

Let now $B = \{ z \in Z ; \langle z^*_0, z \rangle \in C \}$. We have
\[
\Phi^{-1}(B) = \{ x \in X ; \langle \Phi(x), \Phi(x) \rangle \in C \} = Q.
\]

So $\Phi$ is an isomorphism between $(X, \mathcal{B}, \mu; T)$ and $(Z, \mathcal{B}_Z, \nu; A)$. It remains to prove that the measure $\nu$ has full support: for every $i \geq 0$, every $n \geq i$, every $\ell \in \{0, \ldots, n\}$, and every $x \in G_i = \bigcap_{n \geq i} G_i^{(n)}$, $\|\Phi_{f^{(i)}} - u^{(i)}\| < 2^{-(i-1)} r_i$. We also know that for every $k \geq 0$, every $\ell \in \{0, \ldots, k\}$ and every $x \in B_k$,
\[
\|\Phi_{f^{(i)}}(x) - \Phi_{u^{(i)}}(x)\| < \gamma_k.
\]

So, if $x \in G_i \cap \bigcap_{k \geq n} B_k$ and $\ell \in \{0, \ldots, n\}$,
\[
\|\Phi_{f^{(i)}}(x) - u^{(i)}\| \leq \sum_{k \geq n+1} \|\Phi_{f^{(i)}}(x) - \Phi_{u^{(i)}}(x)\| + \|\Phi_{f^{(i)}}(x) - u^{(i)}\|
\leq \sum_{k \geq n+1} \gamma_k + 2^{-(i+1)} r_i < \gamma_n + 2^{-(i+1)} r_i.
\]

Let us now fix $i \geq 0$. Let $(n_i)_{i \in I}$ be an increasing (finite or infinite) sequence of integers such that $\gamma_{n_i} < 2^{-(i+1)} r_i$ and $\mu(G_i \cap \bigcap_{k \geq n_0} B_k) > 0$. If $x \in G_i \cap \bigcap_{k \geq n_0} B_k$, then $x \in G_i \cap \bigcap_{k \geq n} B_k$ for every $\ell \in I$, so that
\[
\|\Phi_{f^{(i)}}(x) - u^{(i)}\| < 2^{-\ell} r_i
\]
for every $\ell \in I$.

Hence
\[
\|\sum_{i \in I} \Phi_{f^{(i)}}(x) - \sum_{i \in I} u^{(i)}\| < 2 r_i
\]
for every $x \in G_i \cap \bigcap_{k \geq n_0} B_k$,
i.e. $\Phi(x) \in B(u_i, 2r_i)$. This being true for every $i \geq 0$, it follows that the measure $\nu$ has full support.

3. Universal unilateral and bilateral weighted shifts

The easiest class of operators to which the criteria of Theorems 1.3 and 1.4 can be applied is the class of weighted shifts on $\ell_p(\mathbb{N})$ or $\ell_p(\mathbb{Z})$, $1 \leq p < \infty$, or on $c_0(\mathbb{N})$ or $c_0(\mathbb{Z})$. We first give the proof of Theorem 1.5.

3.1. Proof of Theorem 1.5. — Suppose that $B_w$ is a unilateral weighted shift with weights $(w_n)_{n \geq 1}$ on one of the spaces $\ell_p(\mathbb{N})$, $1 \leq p < \infty$, or $c_0(\mathbb{N})$, with $B_w e_0 = 0$ and $B_w e_n = w_n e_{n-1}$ for every $n \geq 1$. Let us set $z_0 = e_0$ and $z_{-n} = 1/(w_1 \ldots w_n) e_n$ for every $n \geq 1$. Then

$$B_w z_{-n} = \frac{1}{w_1 \ldots w_n} w_n e_{n-1} = z_{-(n-1)}$$

for every $n \geq 1$, and $B_w z_0 = 0$.

If we write $z_{-n} = B_w^{-n} e_0$ for every $n \geq 1$, then the vectors $B_w^{-n} z_0$, $n \geq 0$, span a dense subset of $\ell_p(\mathbb{N})$ (or $c_0(\mathbb{N})$). Also, the linear span of the vectors $B_w^{-n} z_0$, $n \geq 1$, is not dense, so that assumption (b) of Theorem 1.4 always holds true with $F = \{0\}$.

The series $\sum_{n \geq 0} B_w^{-n} e_0$ is unconditionally convergent in $\ell_p(\mathbb{N})$ (resp. $c_0(\mathbb{N})$) if and only if the series $\sum_{n \geq 1} 1/|w_1 \ldots w_n|^p$ is convergent (resp. if and only if $|w_1 \ldots w_n| \to +\infty$ as $n \to +\infty$). So if this last condition is satisfied, $B_w$ is universal on $\ell_p(\mathbb{N})$ (resp. $c_0(\mathbb{N})$) for ergodic systems.

This condition is also necessary for $B_w$ to be universal for either ergodic or invertible ergodic systems, but the arguments are different depending on whether $B_w$ acts on $\ell_p(\mathbb{N})$ for some $1 \leq p < +\infty$ or on $c_0(\mathbb{N})$.

- if $B_w$ acts on $\ell_p(\mathbb{N})$, $1 \leq p < +\infty$, and is universal for ergodic systems, then $B_w$ is necessarily frequently hypercyclic, and by the characterization of frequently hypercyclic weighted shifts on $\ell_p(\mathbb{N})$ of [6], the series $\sum_{n \geq 1} 1/|w_1 \ldots w_n|^p$ is convergent;

- if $B_w$ acts on $c_0(\mathbb{N})$, then the same argument does not apply since the condition $|w_1 \ldots w_n| \to +\infty$ as $n \to +\infty$ does not characterize frequently hypercyclic backward weighted shifts on $c_0(\mathbb{N})$ (see [3] and [6] for details). But if $B_w$ is universal for (invertible) ergodic systems, then it is necessarily strongly mixing with respect to some invariant measure with full support, hence in particular topologically mixing. So, for every $\varepsilon > 0$, there exists an integer $n_\varepsilon$ such that, for every $n \geq n_\varepsilon$, there exists a vector $x^{(n, \varepsilon)} \in c_0(\mathbb{N})$ with $||x^{(n, \varepsilon)}||_\infty < \varepsilon$ such that $||B_w^n x^{(n, \varepsilon)} - e_0||_\infty < 1/2$. In particular, $|x^{(n, \varepsilon)}_n|w_1 \ldots w_n - 1| < 1/2$, so that $|x^{(n, \varepsilon)}_n w_1 \ldots w_n| > 1/2$. Thus $\varepsilon |w_1 \ldots w_n| > 1/2$ for every $n \geq n_\varepsilon$. It follows that $|w_1 \ldots w_n| \to +\infty$ as $n \to +\infty$.

The arguments for bilateral weighted shifts are exactly the same and we leave them to the reader.

3.2. Proof of Theorem 1.6. — The proof of Theorem 1.6 relies on the following simple idea: suppose that $Z$ is a Banach space admitting a biorthogonal system $(u_n, u^*_n)_{n \geq 0}$ having the following property:

there exists a bounded sequence $(\omega_n)_{n \geq 1}$ of non-zero weights such that $B_\omega$ defined by $B_\omega u_n = \omega_n u_{n-1}$ for every $n \geq 1$ and $B_\omega u_0 = 0$ is a bounded operator on $Y$ and

$$\sum_{n \geq 1} \frac{||u_n||}{|\omega_1 \ldots \omega_n|} < +\infty.$$
Then $B_\alpha$ is a universal operator for ergodic systems on $Z$. The proof of this statement is exactly similar to that of Theorem 1.5: we set $z_0 = u_0$ and $z_{-n} = (1/\omega_1 \ldots \omega_n) u_n$. Then span $[z_{-n}; n \geq 0] = Z$, $\langle u_0^*, z_{-n} \rangle = 0$ for every $n \geq 1$ so that span $[z_{-n}; n \geq 1]$ is not equal to $Z$, and lastly the series $\sum_{n \geq 0} z_{-n}$ is unconditionally convergent since $\sum_{n \geq 0} ||z_{-n}|| < +\infty$. So Theorem 1.4 applies.

Suppose that $Z$ can be decomposed as a topological sum $Z = E \oplus Y$ where $E$ has a sub-symmetric basis $(e_n)_{n \geq 0}$ (i.e. the basis $(e_n)_{n \geq 0}$ is unconditional and equivalent to each of its subsequences). Let $(e_n^*)_{n \geq 0}$ denote the family of biorthogonal functionals on $E$, which we extend to $Z$ by setting $\langle e_n^*, y \rangle = 0$ for every $y \in Y$. Let also $(y_n, y_n^*)_{n \geq 0}$ be a bounded biorthogonal system for $Y$, where each $y_n^*$ is extended to $Z$ by setting $\langle y_n^*, e \rangle = 0$ for every $e \in E$. We denote by $P_E$ and $P_Y$ the projections of $Z$ onto $E$ and $Y$ respectively, associated to the decomposition $Z = E \oplus Y$, and we let $M = \max(||P_E||, ||P_Y||)$. Since the basis $(e_n)_{n \geq 0}$ is sub-symmetric, $B_\alpha$ defined by $B_\alpha e_n = \alpha_n e_{n-1}$ for every $n \geq 1$ and $B_\alpha e_0 = 0$ is a bounded operator on $E$ for any bounded sequence of weights $(\alpha_n)_{n \geq 1}$. Let $(n_k)_{k \geq 0}$ be a strictly increasing sequence of integers with $n_0 = 0$. Consider the biorthogonal system $(u_n, u_n^*)$ of $Z$ defined by setting

$$
\begin{align*}
 u_n &= \begin{cases} 
 y_k & \text{if } n = n_k \text{ for some } k \geq 0 \\
 e_{n-k-1} & \text{if } n \in \{n_k + 1, \ldots, n_{k+1} - 1\} \text{ for some } k \geq 0
\end{cases} \\
 u_n^* &= \begin{cases} 
 y_k^* & \text{if } n = n_k \text{ for some } k \geq 0 \\
 e_{n-k-1}^* & \text{if } n \in \{n_k + 1, \ldots, n_{k+1} - 1\} \text{ for some } k \geq 0.
\end{cases}
\end{align*}
$$

With this definition, $\{u_n; n_k < n < n_{k+1}\} = \{e_n; n_k - k < n < n_{k+1} - (k + 1)\}$, and $\{u_n; n \in \{n_k; k \geq 0\}\} = \{y_n; n \geq 0\}$, so that $(u_n, u_n^*)_{n \geq 0}$ is indeed a bounded biorthogonal system of $Z$.

We define an operator $A$ on $Z$ by setting for every $z \in Z$

$$
Az = \sum_{k \geq 1} u_n^*(z) w_k u_{n_k-1} + 2 \sum_{k \geq 0} \left( \sum_{n=n_k+2}^{n_{k+1}-1} u_n^*(z) u_{n-1} \right) + \sum_{k \geq 0} u_n^*(z) w'_k u_{n_k}
$$

where the weights $w_k$ and $w'_k$ are defined by

$$
\begin{align*}
 w_k &= 2^{-k} \frac{1}{||y_k||} & \text{and} & \\
 w'_k &= 2^{-k} \frac{1}{||y_k||}, & k \geq 0.
\end{align*}
$$

Observe that these weights do not depend on the sequence $(n_k)_{k \geq 0}$.

This operator is a backward weighted shift with respect to the biorthogonal system $(u_n, u_n^*)_{n \geq 0}$: $Aw_n = \omega_n u_{n-1}$ where

$$
\omega_n = \begin{cases} 
 w_k & \text{if } n = n_k \text{ for some } k \geq 1 \\
 2 & \text{if } n \in \{n_k + 2, \ldots, n_{k+1} - 1\} \text{ for some } k \geq 0 \\
 w'_k & \text{if } n = n_k + 1 \text{ for some } k \geq 1.
\end{cases}
$$

Let us first check that $A$ is bounded. We have for every $z \in Z$

$$
Az = \sum_{k \geq 1} y_k^*(z) w_k e_{n_{k-1}-k} + \sum_{k \geq 0} \left( \sum_{n=n_k+2}^{n_{k+1}-1} e_{n-k-1}^*(z) 2 e_{n-k-2} \right) + \sum_{k \geq 0} e_{n_k-k}^*(z) w'_k y_k.
$$
NEW EXAMPLES OF UNIVERSAL HYPERCYCLIC OPERATORS

Since the basis \((e_n)_{n \geq 0}\) is sub-symmetric, there exists a positive constant \(C\) such that for every \(z \in \mathbb{Z}\),
\[
\left\| \sum_{k \geq 0} \left( \sum_{n=n_k+2}^{n_k+1} e_{n_k-1}(z) e_{n-2} \right) \right\| \leq C \|z\|.
\]
Hence
\[
\|Az\| \leq \|z\| \sum_{k \geq 1} \|y^*_k\| \|w_k e_{n_k-1-k}\| + 2C \|z\| + \|z\| \sum_{k \geq 0} \|e_{n_k-k}\| \|w'_k\| \|y_k\|.
\]
Since \(\sup_{n \geq 0} \|e_n\|\) and \(\sup_{n \geq 0} \|e^*_n\|\) are finite, the conditions on the weights \(w_k\) and \(w'_k\) imply that \(A\) is bounded.

In order to show that \(A\) is universal for ergodic systems, it remains to choose the sequence \((n_k)_{k \geq 0}\) in such a way that the series
\[
\sum_{n \geq 1} \|u_n\| \omega_1 \ldots \omega_n
\]
is convergent. We have
\[
\sum_{n \geq 1} \|u_n\| \omega_1 \ldots \omega_n = \sum_{k \geq 0} \sum_{n=n_k+1}^{n_k+1} \frac{\|u_n\|}{\omega_1 \ldots \omega_n} = \sum_{k \geq 1} \frac{1}{w_1 \ldots w_k w'_1 \ldots w'_k 2^{n_k-2k}} \left( \sum_{n=n_k+1}^{n_k+1} \frac{\|u_n\|}{2^{n-(n_k+1)}} + \frac{\|u_{n_k+1}\|}{2^{(n_k+1)-(n_k+1)w_k+1}} \right).
\]
If we write \(C_k = \max\{\|u_n\| : n_k + 1 \leq n \leq n_{k+1}\}\), this yields
\[
\sum_{n \geq 1} \frac{\|u_n\|}{\omega_1 \ldots \omega_n} \leq \sum_{k \geq 1} \frac{C_k}{w_1 \ldots w_k w'_1 \ldots w'_k 2^{n_k-k}} \left( 2 + \frac{1}{2^{n_k+1-n_k-2} w_{k+1}} \right).
\]
Since the weights \(w_k\) and \(w'_k\) are defined independently of the sequence \((n_k)_{k \geq 0}\), we can choose this sequence growing so fast that
\[
2^{n_k} > \max \left( \frac{2^{n_k-1+2}}{w_k}, \frac{2^{2k} C_k}{w_1 \ldots w_k w'_1 \ldots w'_k} \right) \text{ for every } k \geq 1.
\]
Then
\[
\frac{\|u_n\|}{\omega_1 \ldots \omega_n} \leq \sum_{k \geq 1} \frac{C_k}{w_1 \ldots w_k w'_1 \ldots w'_k 2^{n_k-k}} \leq 3 \cdot 2^{-k} \text{ for every } k \geq 1,
\]
from which it follows that the series
\[
\sum_{n \geq 1} \frac{\|u_n\|}{\omega_1 \ldots \omega_n}
\]
is convergent. This terminates the proof of Theorem 1.6.

4. Unimodular eigenvectors and universality

We begin this section with the proof of Theorem 1.7, which gives a straightforward criterion in terms of unimodular eigenvectors for an operator to be universal for (invertible) ergodic systems.
4.1. Proof of Theorem 1.7. — Let $A$ be a bounded operator on the complex separable infinite-dimensional Banach space $Z$, admitting a unimodular eigenvectorfield $E$ satisfying assumptions (i), (ii), and (iii) of Theorem 1.7. Set, for each $n \in \mathbb{Z}$, $z_n = \hat{E}(-n)$. Then $Az_n = z_{n+1}$ for every $n \in \mathbb{Z}$. The vectors $z_n$, $n \in \mathbb{Z}$, span a dense subspace of $Z$. Indeed, suppose that $z^* \in Z^*$ is such that $\langle z^*, z_n \rangle = 0$ for every $n \in \mathbb{Z}$. Then the function $\langle z^*, E(.) \rangle$ is zero almost everywhere, and by (i) it follows that $z^* = 0$. So $z_0$ is bicyclic for $A$. Let now $F$ be the spectrum of the polynomial $q$ defined by $q(e^{i\theta}) = \sum_{n \in \mathbb{Z}} \hat{p}(-n)e^{i\theta}$. For every $n \in \mathbb{Z} \setminus F$, we have

$$\langle z_0^*, z_n \rangle = \int_{\mathbb{T}} \lambda^n \langle z_0^*, E(\lambda) \rangle d\lambda = \hat{q}(n) = 0.$$ 

Since $z_0^*$ is non-zero, it follows that the linear span of the vectors $z_n$, $n \in \mathbb{Z} \setminus F$, is not dense in $Z$. Lastly, assumption (iii) of Theorem 1.7 states that the series $\sum_{n \in \mathbb{Z}} z_n$ is unconditionally convergent. So the hypotheses of Theorem 1.3 are satisfied, and $A$ is universal for invertible ergodic systems. If $\hat{E}(-r) = 0$ for some integer $r \in \mathbb{Z}$, then $A^*z_0 = 0$, and Theorem 1.4 applies.

Theorem 1.8 can now be obtained as a consequence of Theorem 1.7.

4.2. Proof of Theorem 1.8. — Suppose that $A \in \mathcal{B}(Z)$ admits a unimodular eigenvectorfield $E$ which is analytic in a neighborhood $\Omega$ of $\mathbb{T}$, and such that the vectors $E(\lambda)$, $\lambda \in \mathbb{T}$, span a dense subspace of $Z$. Then the restriction of $E$ to $\mathbb{T}$ is $\sigma$-spanning for any measure $\sigma$ with infinite support. In particular, it is $d\lambda$-spanning, where $d\lambda$ is the normalized Lebesgue measure on $\mathbb{T}$.

Let $z_0^*$ be any non-zero element of $Z^*$. The function $\varphi$ defined on $\Omega$ by setting

$$\varphi(\lambda) = \langle z_0^*, E(\lambda) \rangle, \quad \lambda \in \mathbb{T},$$

is analytic on $\Omega$, and not identically zero since the span of the vectors $E(\lambda)$, $\lambda \in \mathbb{T}$, is dense in $Z$. Thus $\varphi$ admits only finitely many zeroes $z_1, \ldots, z_r$ on $\mathbb{T}$, with respective multiplicities $d_1, \ldots, d_r$. Let $p(z) = \prod_{j=1}^{r} (z - z_j)^{d_j}$. There exists a function $\psi$, which is analytic on $\Omega$ and does not vanish on a neighborhood $\Omega'$ of $\mathbb{T}$ such that $\varphi(z) = p(z)\psi(z)$ for every $z \in \Omega'$.

Consider the eigenvectorfield $F : \Omega' \rightarrow Z$ defined by $F(\lambda) = E(\lambda)/\psi(\lambda)$. The span of the vectors $F(\lambda)$, $\lambda \in \mathbb{T}$, is dense in $Z$. Moreover, for every $\lambda \in \mathbb{T}$,

$$\langle z_0^*, F(\lambda) \rangle = \frac{1}{\psi(\lambda)} \langle z_0^*, E(\lambda) \rangle = p(\lambda).$$

Lastly, since $F$ is analytic on a neighborhood of $\mathbb{T}$, there exists $a \in (0, 1)$ such that

$$||\hat{F}(n)|| = O(a^{||n||}) \quad \text{as} \quad |n| \rightarrow +\infty.$$ 

Hence the series $\sum_{n \in \mathbb{Z}} \hat{F}(n)$ is unconditionally convergent. The assumptions of Theorem 1.7 are thus satisfied, and $A$ is universal for invertible ergodic systems.

If $E$ is analytic in a neighborhood of $\mathbb{D}$, the same kind of reasoning applies: if $z_1, \ldots, z_r$ are the zeroes of $\varphi(\lambda) = \langle z_0^*, E(\lambda) \rangle$ on $\mathbb{D}$ with multiplicities $d_1, \ldots, d_r$, and if $p(z) = \prod_{j=1}^{r} (z - z_j)^{d_j}$, then $\varphi(z) = p(z)\psi(z)$ on a neighborhood of $\mathbb{D}$, where $\psi$ is an analytic function on this neighborhood which does not vanish. If we consider again the eigenvectorfield $F$ defined by $F(\lambda) = E(\lambda)/\psi(\lambda)$, then $F$ is analytic in a neighborhood of $\mathbb{D}$ so that $\hat{F}(n) = 0$ for every $n < 0$. So Theorem 1.7 applies again and $A$ is universal for ergodic systems.
Let us mention here that, using Theorems 2.5 and 2.6, Theorems 1.7 and 1.8 can be generalized to the case where $A$ admits several eigenvectorfields.

4.3. Examples and applications. — We present in this section several examples of operators which can be shown to be universal thanks to Theorems 1.7 and 1.8. First, one can easily retrieve the universality of some of the weighted shifts considered in Theorem 1.5 above.

**Example 4.1.** — Let $\alpha B$, $|\alpha| > 1$, be a multiple of the unweighted backward shift on $\ell_p(\mathbb{N})$, $1 \leq p < +\infty$, or $c_0(\mathbb{N})$. Then $\alpha B$ admits an eigenvectorfield $E$ defined on the disk of radius $|\alpha|$ by

$$E(\lambda) = \sum_{n \geq 0} \left( \frac{\lambda}{\alpha} \right)^{n-1} e_n.$$ 

So $E$ is analytic on $\mathbb{D}(0, |\alpha|)$, and it is easy to check that the eigenvectors $E(\lambda)$, $\lambda \in \mathbb{T}$, span a dense subspace of $\ell_p(\mathbb{N})$ or $c_0(\mathbb{N})$. Thus Theorem 1.8 applies, and $\alpha B$ is universal for ergodic systems. The same argument applies for instance to the weighted shift $S_w$ on $\ell_p(\mathbb{Z})$ or $c_0(\mathbb{Z})$, where the weight $w$ is given by $w_n = 2$ if $n \geq 1$ and $w_n = 1/2$ if $n \leq 0$: $S_w$ is universal for invertible ergodic systems.

Our second class of examples is given by adjoints of multipliers $M^*_{\varphi}$ on $H^2(\mathbb{D})$. This is a natural class of operators to consider here, since their dynamical properties (hypercyclicity, frequent hypercyclicity, ergodicity) are rather well understood. See for instance [4] for details.

**Example 4.2.** — Denoting by $\mathbb{D}$ the open unit disk, let $\varphi : \mathbb{D} \rightarrow \mathbb{C}$ be an analytic map belonging to $H^\infty(\mathbb{D})$, and consider the adjoint $M^*_{\varphi}$ of the multiplier $M_{\varphi}$ defined on the Hardy space $H^2(\mathbb{D})$ by setting $M_{\varphi} f = \varphi f$ for every $f \in H^2(\mathbb{D})$. If $\mathbb{T} \subseteq \varphi(\mathbb{D})$, then $M^*_{\varphi}$ is universal for invertible ergodic systems.

**Proof of Example 4.2.** — Suppose that the analytic map $\varphi : \mathbb{D} \rightarrow \mathbb{C}$ is such that $\varphi(\mathbb{D})$ contains the unit circle. Since $\varphi$ is open, $K = \varphi^{-1}(\mathbb{T})$ is a compact subset of $\mathbb{D}$, and there exists $\rho \in (0, 1)$ such that $K \subseteq D(0, \rho)$. The derivative $\varphi'$ of $\varphi$ can vanish only finitely many times on $K$, and we denote by $z_1, \ldots, z_r$ the distinct zeroes of $\varphi'$ on $K$, with respective multiplicities $m_1, \ldots, m_r$. There exists for every $j \in \{1, \ldots, r\}$ a disk $D(z_j, \varepsilon_j)$ with $\varepsilon_j > 0$ and two holomorphic functions $\psi_j$ and $\sigma_j$ on $D(z_j, \varepsilon_j)$ which do not vanish here such that for every $z \in D(z_j, \varepsilon_j)$,

$$\varphi(z) = \lambda_j + (z - z_j)^{d_j} \psi_j(z) \quad \text{and} \quad \varphi'(z) = (z - z_j)^{m_j} \sigma_j(z)$$

where $d_j = m_j + 1$ and $\lambda_j = \varphi(z_j)$. Also, there exists a holomorphic function $\beta_j$ on $D(z_j, \varepsilon_j)$ such that $\psi_j = \beta_j^{d_j}$. If we set $\alpha_j(z) = (z - z_j)^{\beta_j}$ for $z \in D(z_j, \varepsilon_j)$, we can assume that $\alpha_j$ is a biholomorphism from a certain open neighborhood $V_j$ of $z_j$ contained in $D(z_j, \varepsilon_j)$ onto an open disk $D(0, \delta_j)$. Let

$$\Omega_{j, 0} = D(0, \delta_j^{d_j}) \setminus [0, \delta_j^{d_j}]$$

and let $\gamma_{j, 0}$ be an holomorphic determination of the $d_j$-th root of $z$ on $\Omega_{j, 0}$: $\gamma_{j, 0}(z)^{d_j} = z$ for every $z \in \Omega_{j, 0}$. We also set $V_{j, 0} = \{ z \in V_j; \, \alpha_j(z)^{d_j} \in \Omega_{j, 0} \}$, $U_{j, 0} = \lambda_j + \Omega_{j, 0}$ and $U_j = D(\lambda_j, \delta_j^{d_j})$. Observe that $U_{j, 0} \cap \mathbb{T}$ contains a set of the form $\Gamma_j \setminus \{ \lambda_j \}$, where $\Gamma_j$ is an open arc containing the point $\lambda_j$. 

NEW EXAMPLES OF UNIVERSAL HYPERCYCLIC OPERATORS 29
We now claim that $\varphi$ is a biholomorphism from $V_{j,0}$ onto $U_{j,0}$. Let us first check that $\varphi(V_{j,0}) = U_{j,0}$: $z \in V_j$ belongs to $V_{j,0}$ if and only if $\alpha_j(z)^d_j = \varphi(z) - \lambda_j$ belongs to $\Omega_{j,0}$, i.e. if and only if $\varphi(z)$ belongs to $U_{j,0}$.

Let us set for $z \in U_{j,0}$,

$$\varphi_{j,0}^{-1}(z) = \alpha_j^{-1} \circ \gamma_{j,0}(z - \lambda_j).$$

This definition makes sense: if $z \in U_{j,0}$, $z - \lambda_j \in \Omega_{j,0}$, so that $\gamma_{j,0}(z - \lambda_j) \in D(0, \delta_j)$, and $\alpha_j$ is a biholomorphism from $V_j$ onto $D(0, \delta_j)$. This function $\varphi_{j,0}^{-1}$ is thus well-defined and holomorphic on $U_{j,0}$, and we have for every $z \in U_{j,0}$

$$\varphi(\varphi_{j,0}^{-1}(z)) = \lambda_j + \alpha_j(\varphi_{j,0}^{-1}(z))^{d_j} = \lambda_j + (\gamma_{j,0}(z - \lambda_j))^{d_j} = \lambda_j + z - \lambda_j = z$$

since $z - \lambda_j$ belongs to $\Omega_{j,0}$ and $\gamma_{j,0}(z - \lambda_j)^{d_j} = z$ for every $z \in \Omega_{j,0}$. It follows from this that $\varphi : V_{j,0} \rightarrow U_{j,0}$ is a biholomorphism, the inverse of which is $\varphi_{j,0}^{-1}$. Restricting the sets $V_{j,0}$ and $U_{j,0}$, we can and do assume that $U_{j,0} \cap T = \Gamma_j \setminus \{\lambda_j\}$, where $\Gamma_j$ is an open subarc of $T$ containing the point $\lambda_j$, and that the arcs $\gamma_j$, $j \in \{1, \ldots, r\}$, do not intersect.

If $z \in K$ is such that $\varphi(z) \notin \{\lambda_1, \ldots, \lambda_r\}$ and $\varphi'(z) \neq 0$, $\varphi$ is a biholomorphism in a neighborhood of $z$. For every such $z$, let $V_z$ be an open neighborhood of $z$, and $U_z$ a disk centered at $\varphi(z)$ of radius $\rho_z > 0$ such that $\varphi : V_z \rightarrow U_z$ is a biholomorphism, $\varphi'$ does not vanish on $V_z$, and the closure of the set $U_z$ contains none of the points $\lambda_j$, $j \in \{1, \ldots, r\}$. The disks $U_{\varphi^{-1}(T \setminus \{\lambda_1, \ldots, \lambda_r\})}$ and $U_{\gamma_j}$, $j \in \{1, \ldots, r\}$, form an open covering of $T$, so one can extract from it a finite covering of the form $U_{\xi_1}, \ldots, U_{\xi_s}, U_1, \ldots, U_r$, $s \geq 1$. Denote by $(\Omega_l)_{l \in \Lambda}$ the finite family of open subsets of $\mathbb{D}$ consisting of the sets $U_\xi$, $1 \leq j \leq s$, and $U_{j,0}$, $1 \leq j \leq r$. For every $l \in \Lambda$, $\Omega'_l = \Omega_l \cap T$ is either an open subarc of $T$ whose closure is contained in $T \setminus \{\lambda_1, \ldots, \lambda_r\}$ (when $\Omega_l = U_\xi$, for some $i \in \{1, \ldots, s\}$) or an open subarc minus one point (when $\Omega_l = U_{j,0}$ for some $j \in \{1, \ldots, r\}$, in which case $\Omega'_l = \Gamma_j \setminus \{\lambda_j\}$). We have

$$\bigcup_{l \in \Lambda} \Omega'_l \cap T = T \setminus \{\lambda_1, \ldots, \lambda_r\}.$$

Observe that for every $j \in \{1, \ldots, r\}$, the only set $\Omega'_l$ which contains the point $\lambda_j$ in its closure is $\Omega'_l = \Gamma_j \setminus \{\lambda_j\}$.

Let $(v_l)_{l \in \Lambda}$ be a finite $C^1$-partition of the unity associated to the finite covering $(\Omega_l')_{l \in \Lambda}$ of $T \setminus \{\lambda_1, \ldots, \lambda_r\}$, with $v_l$ supported on $\Omega'_l$ for every $l \in \Lambda$. If $\Omega'_l = \Gamma_j \setminus \{\lambda_j\}$ for some $j \in \{1, \ldots, r\}$, the observation above shows that $v_l$ is the only function of the partition which does not vanish on a neighborhood of the point $\lambda_j$. Hence $v_l$ is equal to 1 on a neighborhood of $\lambda_j$, and it follows that $v_l$ can be extended into a $C^1$ function on the whole circle $T$. This is obviously the case too if $\Omega'_l = U_\xi \cap T$ for some $i \in \{1, \ldots, s\}$, and thus we can assume that all the functions $v_l$, $l \in \Lambda$, are defined and of class $C^1$ on $T$. For every $l \in \Lambda$, we denote by $\varphi_l^{-1}$ the inverse of $\varphi$ defined on the set $\Omega_l$.

For every $z \in \mathbb{D}$, we denote by $k_z$ the reproducing kernel of the space $H^2(\mathbb{D})$ at the point $z$:

$$k_z(\xi) = \sum_{n \geq 0} z^n \xi^n = \frac{1}{1 - z \bar{\xi}}, \quad \xi \in \mathbb{D},$$
and \( k_z \) is characterized by the property that \( \langle f, k_z \rangle = f(z) \) for every \( f \in H^2(\mathbb{D}) \). We have \( M_z^* k_z = \varphi(z) k_z \) for every \( z \in \mathbb{D} \). We then introduce the polynomial

\[
p(z) = \prod_{j=1}^{r} (z - \lambda_j)^2
\]

and the maps \( F : \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \to H^2(\mathbb{D}) \) and \( E : \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \to H^2(\mathbb{D}) \) defined by

\[
\forall \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\}, \quad F(\lambda) = \frac{1}{p(\lambda)} \sum_{l \in \Lambda} v_l(\lambda) k_{\varphi_l^{-1}(\lambda)}
\]

and

\[
\forall \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\}, \quad E(\lambda) = F(\lambda).
\]

Observe that the quantity \( k_{\varphi_l^{-1}(\lambda)} \) in the expression of \( F(\lambda) \) above only makes sense when \( \lambda \) belongs to \( \Omega_i' \). But since \( v_l \) is supported on \( \Omega_i' \), the function \( \lambda \mapsto v_l(\lambda) k_{\varphi_l^{-1}(\lambda)} \) extends into a \( C^\infty \) function on \( \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \) by defining it to be zero outside the set \( \Omega_i' \), so that \( F \) is a well-defined \( C^\infty \) function on \( \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \).

For every \( \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \) we have

\[
M_z^* F(\lambda) = \frac{1}{p(\lambda)} \sum_{l \in \Lambda} v_l(\lambda) \varphi(\varphi_l^{-1}(\lambda)) k_{\varphi_l^{-1}(\lambda)}
\]

so that \( M_z^* F(\lambda) = \overline{\lambda} F(\lambda) \). It follows that \( E : \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \to H^2(\mathbb{D}) \) is a unimodular eigenvector field for \( M_z^* \).

Our aim is to show that the assumptions of Theorem 1.7 are satisfied. Assumptions (i) and (ii) are easy to check: suppose that \( f \in H^2(\mathbb{D}) \) is such that \( \langle f, E(\lambda) \rangle = 0 \) for every \( \lambda \in B \) where \( B \subseteq \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \) is a Borel subset of \( \mathbb{T} \) of full Lebesgue measure. Then by continuity

\[
\overline{p(\lambda)} \sum_{l \in \Lambda} v_l(\lambda) f(\varphi_l^{-1}(\lambda)) = 0 \quad \text{for every } \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\},
\]

so that

\[
\sum_{l \in \Lambda} v_l(\lambda) f(\varphi_l^{-1}(\lambda)) = 0 \quad \text{for every } \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\}.
\]

It follows that for every \( \lambda \in \Gamma, \ f(\varphi_{l_0}^{-1}(\lambda)) = 0 \). Since \( \varphi_{l_0}^{-1}(\Gamma) \) has accumulation points in \( \mathbb{D} \), \( f = 0 \), and span \( \{E(\lambda) : \lambda \in B\} \) is dense in \( H^2(\mathbb{D}) \). Assumption (i) is thus satisfied. Assumption (ii) is obviously satisfied: if \( f \equiv 1 \), then \( \langle f, E(\lambda) \rangle = \overline{p(\lambda)} = q(\lambda) \) for every \( \lambda \in \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \), where \( q(e^{i\theta}) = \sum_{n \in \mathbb{Z}} \overline{\bar{E}(n)} e^{in\theta} \). The main difficulty is to check that the series \( \sum_{n \in \mathbb{Z}} \bar{E}(n) \), or equivalently the series \( \sum_{n \in \mathbb{Z}} F(n) \), is unconditionally convergent. Since \( H^2(\mathbb{D}) \) does not contain a copy of \( c_0 \), it suffices to prove that for every \( f \in H^2(\mathbb{D}) \), the series \( \sum_{n \in \mathbb{Z}} |\langle f, F(n) \rangle| \) is convergent.

We are going to show that for every \( f \in H^2(\mathbb{D}) \), the function \( \phi_f \) defined on \( \mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\} \) by

\[
\phi_f(\lambda) = \langle f, F(\lambda) \rangle = \overline{p(\lambda)} \sum_{l \in \Lambda} v_l(\lambda) f(\varphi_l^{-1}(\lambda))
\]
extends into a function of class $C^1$ on $\mathbb{T}$. Bernstein’s Theorem will then imply that the series $\sum_{n \in \mathbb{Z}} \|f, \hat{F}(n)\|$ is convergent.

The function $F$ is clearly of class $C^\infty$ on $\mathbb{T} \setminus \{\lambda_1, \ldots, \lambda_r\}$. Since, for every $l \in \Lambda$, $\sup \{|\varphi_l^{-1}(\lambda)|; \lambda \in \Omega_l\} \leq \rho < 1$, the quantity $\sup \{|k_{\varphi_l^{-1}(\lambda)}|; \lambda \in \Omega_l\}$ is finite for every $l \in \Lambda$. Now $p(\lambda_j) = 0$ for every $j \in \{1, \ldots, r\}$, and since each function $v_l$, $l \in \Lambda$, is uniformly bounded on $\mathbb{T}$ it follows that $F$ can be extended into a continuous map on $\mathbb{T}$ by setting $F(\lambda_j) = 0$ for every $j \in \{1, \ldots, r\}$. So $\phi_f$ is actually continuous on $\mathbb{T}$ for every $f \in H^2(\mathbb{D})$. Let us now compute the derivative of $\phi_f$. Writing, for $0 \leq \theta < 2\pi$, $\lambda = e^{i\theta}$ and

$$\phi_f(e^{i\theta}) = p(e^{i\theta}) \sum_{l \in \Lambda} v_l(e^{i\theta}) f(\varphi_l^{-1}(e^{i\theta}))$$

we have

$$\frac{d\phi_f}{d\theta}(e^{i\theta}) = -i \varphi_l(e^{i\theta}) \sum_{l \in \Lambda} v_l(e^{i\theta}) f(\varphi_l^{-1}(e^{i\theta})) + p(e^{i\theta}) \sum_{l \in \Lambda} i e^{i\theta} \frac{dv}{d\theta}(e^{i\theta}) f(\varphi_l^{-1}(e^{i\theta}))$$

$$+ p(e^{i\theta}) \sum_{l \in \Lambda} v_l(e^{i\theta}) (i e^{i\theta})^2 \frac{1}{\varphi_l'(\varphi_l^{-1}(e^{i\theta}))} f'(\varphi_l^{-1}(e^{i\theta}))$$

(the notation $\frac{d}{d\theta}$ is used for the derivative of a function on $\mathbb{T}$ with respect to the real variable $\theta$, while the sign ‘ is used for the complex derivative of a holomorphic function).

The same argument as above, using the facts that $\Lambda$ is finite, that the functions $v_l$ are of class $C^1$ on $\mathbb{T}$ (and hence have uniformly bounded derivatives on $\mathbb{T}$), and that $p(\lambda_j) = p'(\lambda_j) = 0$ for every $j \in \{1, \ldots, r\}$, shows that the first two terms in this expression tend to 0 as $\lambda = e^{i\theta}$ tends to $\lambda_j$, $j \in \{1, \ldots, r\}$. So it remains to deal with the last term. Again, $\sup \{|f'(\varphi_l^{-1}(\lambda))|; \lambda \in \Omega_l\}$ is finite for every $l \in \Lambda$, and we concentrate on the behaviour of the quantities $1/\varphi'(\varphi_l^{-1}(\lambda))$ as $d\lambda, \{\lambda_1, \ldots, \lambda_r\} \to 0$, $l \in \Lambda$. For every $j \in \{1, \ldots, r\}$ and every $z \in D(z_j, \varepsilon_j)$, we have seen that $\varphi'(z) = (z - z_j)^{m_j} \sigma_j(z)$, where $\sigma_j$ is an holomorphic function which does not vanish on $D(z_j, \varepsilon_j)$. Hence the quantity

$$\sup \left\{ \frac{|z - z_j|^{m_j}}{|\varphi'(z)|}; z \in D(z_j, \varepsilon_j) \setminus \{z_j\} \right\}$$

is finite. So by definition of the sets $\Omega_l$, $l \in \Lambda$, the following holds true: there exists a positive constant $C$ such that for every $l \in \Lambda$ there exists a $j \in \{1, \ldots, r\}$ such that

$$\sup \left\{ \frac{|\varphi_l^{-1}(\lambda) - z_j|^{m_j}}{|\varphi'(\varphi_l^{-1}(\lambda))|}; \lambda \in \Omega_l \right\} \leq C$$

(if $\Omega_l$ is of the form $U_{z_i}$ for some $i \in \{1, \ldots, s\}$, then this estimate is true for any $j \in \{1, \ldots, r\}$ since $|\varphi'|$ is bounded away from 0 on $\varphi_l^{-1}(\Omega_l)$). Let now $l \in \Lambda$ be such that $\lambda_j \in \Omega_l$. Then $\Omega_l$ is equal to $U_{z_j, 0}$. We have

$$p(\lambda) = p(\varphi(\varphi_l^{-1}(\lambda))) = p(\lambda_j + (\varphi_l^{-1}(\lambda) - z_j)^d_j \psi_j(\varphi_l^{-1}(\lambda)))$$
for every $\lambda \in \Omega_t$. Thus $p(\lambda) = (\varphi^{-1}_t(\lambda) - z_j)^{2d_j} q_j(\varphi^{-1}_t(\lambda))$ for $\lambda \in \Omega_t$, where $q_j$ is an holomorphic function which is bounded on $\varphi^{-1}_t(\Omega_t)$. We have

$$
\left| \frac{p(\lambda)}{\varphi'(\varphi^{-1}_t(\lambda))} \right| = \left| \frac{(\varphi^{-1}_t(\lambda) - z_j)^{2d_j}}{(\varphi^{-1}_t(\lambda) - z_j)^{m_j}} \cdot |q_j(\varphi^{-1}_t(\lambda))| \cdot \left| \frac{(\varphi^{-1}_t(\lambda) - z_j)^{m_j}}{\varphi'(\varphi^{-1}_t(\lambda))} \right| \right|
\leq C' \cdot |\varphi^{-1}_t(\lambda) - z_j|^{2d_j - m_j}
$$

which tends to 0 as $\varphi^{-1}_t(\lambda)$ tends to $z_j$ since $2d_j = 2(m_j + 1) > m_j$. We now claim that if $\lambda$ tends to $\lambda_j$, then $\varphi^{-1}_t(\lambda)$ tends to $z_j$. Indeed, since $\Omega_t = U_{j,0}$, $\varphi^{-1}_t(\lambda) = \varphi_{j,k}^{-1}(\lambda) = \alpha_j^{-1}(\gamma_{j,0}(\lambda - \lambda_j))$. If $\lambda \rightarrow \lambda_j$, then $\gamma_{j,0}(\lambda - \lambda_j) \rightarrow 0$. Now $\alpha_j : D(z_j, \varepsilon_j) \rightarrow D(0, \delta_j)$ is a biholomorphism such that $\alpha_j(z_j) = 0$. Thus $\alpha_j^{-1}(\gamma_{j,0}(\lambda - \lambda_j)) \rightarrow z_j$, and this proves our claim.

So we have proved that if $\lambda \in \Lambda$ is such that $\lambda_j \in \Omega_t$, and if $\lambda \in \Omega_t$ tends to $\lambda_j$, then

$$
\left| \frac{p(\lambda)}{\varphi'(\varphi^{-1}_t(\lambda))} \right| = \left| \frac{p(\lambda)}{\varphi'(\varphi^{-1}_t(\lambda))} \right| \rightarrow 0.
$$

This shows that the third term in the expression of $\frac{d\phi_j}{d\theta}(e^{i\theta})$ given above tends to 0 as $d(e^{i\theta}, \{\lambda_1, \ldots, \lambda_t\})$ tends to 0. So $\phi_j$ is a map of class $C^1$ on $T$, and this finishes the proof of Example 4.2.

**Example 4.3.** — Using the notation of Example 4.1, the operator $\alpha B^2$ is universal on $\ell_p(\mathbb{N})$ or $c_0(\mathbb{N})$ for any $\alpha$ with $|\alpha| > 1$.

This can be proved in several ways. One of these is to observe that $\alpha B^2$ admits two eigenvectorfields $E_1$ and $E_2$ which are analytic on $D(0, |\alpha|)$:

$$
E_1(\lambda) = \sum_{n \geq 0} \left( \frac{\lambda}{\alpha} \right)^n e_{2n+1} \quad \text{and} \quad E_2(\lambda) = \sum_{n \geq 0} \left( \frac{\lambda}{\alpha} \right)^n e_{2n}.
$$

We have $\overline{\text{span}} \left[ E_1(\lambda), E_2(\lambda) ; \lambda \in T \right] = Z$. Using the generalization of Theorem 1.8 following from Theorem 2.6, we obtain that $\alpha B^2$ is universal for ergodic systems.

If one is interested only in the universality of $\alpha B^2$ for invertible ergodic systems, one can use simply Theorem 1.7 and the following argument: let $\varphi$ be a function of class $C^\infty$ on $T$ such that $0 \leq \varphi \leq 1$ and the support of $\varphi$ is a non-trivial closed sub-arc $\Gamma$ of $T$. Consider the $C^\infty$ eigenvectorfield of $\alpha B^2$ defined by

$$
E(\lambda) = \varphi(\lambda) E_1(\lambda) + (1 - \varphi(\lambda)) E_2(\lambda), \ \lambda \in T.
$$

Let us show that $\overline{\text{span}} \left[ E(\lambda) ; \lambda \in T \right] = Z$: if $x^*$ is a functional such that $\langle x^*, E(\lambda) \rangle = 0$ for every $\lambda \in T$, then $\langle (1 - \varphi(\lambda)) \langle x^*, E_2(\lambda) \rangle = 0 \rangle$ for every $\lambda \in T \setminus \Gamma$. Hence by analyticity of $E_2$, $\langle x^*, E_2(\lambda) \rangle = 0$ for every $\lambda \in T$. It follows that $\varphi(\lambda) \langle x^*, E_1(\lambda) \rangle = 0$ for every $\lambda \in T$. And the same argument shows that $\langle x^*, E_1(\lambda) \rangle = 0$ for every $\lambda \in T$. Since $\overline{\text{span}} \left[ E_1(\lambda), E_2(\lambda) ; \lambda \in T \right] = Z$, $x^* = 0$, and thus $\overline{\text{span}} \left[ E(\lambda) ; \lambda \in T \right] = Z$. Moreover, $\langle e_0^* + e_1^*, E(\lambda) \rangle = 1$ for every $\lambda \in T$ (where $e_i^*$ is the functional on $\ell_p(\mathbb{N})$ or $c_0(\mathbb{N})$ mapping a vector $x$ of the space on its $i^{th}$ coordinate). Lastly, $E$ being of class $C^\infty$ on $T$, the series

$$
\sum_{n \in \mathbb{Z}} ||\hat{E}(n)||
$$
is convergent. So Theorem 1.7 applies. If we consider $\alpha B^2$ as acting on $\ell_2(\mathbb{N})$, Example 4.2 applies directly since $\alpha B^2$ is unitarily similar to $M_{\varphi}^*$ where $\varphi(z) = \pi z^2$, $z \in \mathbb{D}$.

Many other examples can be obtained along these lines (such as $\bigoplus \ell_p \alpha B$ on the infinite direct sum $\bigoplus \ell_p$, $1 \leq p < +\infty$, $|\alpha| > 1, \ldots$).

One can observe that all the universal operators presented until now admit eigenvectorfields which are analytic in a neighborhood of some points of $T$, and in particular have a rather large spectrum. So one may naturally wonder whether this condition is necessary for $A$ to be universal. Our last example, which is rather unexpected, shows that it is not the case. It is to be found within the class of Kalish-type operator on $L^2(\mathbb{T})$ (see [4] for details).

**Example 4.4.** — Let $A$ be the operator defined on $L^2(\mathbb{T})$ by setting for every $f \in L^2(\mathbb{T})$ and every $0 \leq \theta < 2\pi$,

$$Af(e^{i\theta}) = e^{i\theta}f(e^{i\theta}) - \int_0^\theta ie^{it}f(e^{it})dt.$$  

Then $A$ is universal for invertible ergodic systems.

It is not difficult to check that for every $\lambda = e^{i\theta} \in \mathbb{T}$, $0 \leq \theta < 2\pi$, $\ker(A - \lambda) = \text{span}[E(\lambda)]$ where $E(\lambda) = \chi(\lambda, 1)$. Here $\chi(\lambda, 1)$ denotes the indicator function of the arc $\Gamma_\lambda = \{e^{i\tau}; \theta < \tau < 2\pi\}$. The eigenvectorfield $E$ is $1/2$-Hölderian on $\mathbb{T}$. Since the spectrum of $A$ coincides with $\mathbb{T}$, $A$ does not admit any eigenvectorfield which is analytic in a neighborhood of some point of $\mathbb{T}$.

**Proof of Example 4.4.** — The most obvious idea is to try to apply Theorem 1.7. Setting

$$y_n(e^{it}) = \int_0^{2\pi} e^{-in\theta}E(e^{i\theta})(e^{it})\frac{d\theta}{2\pi}$$

for every $n \in \mathbb{Z}$, we have

$$y_0(e^{it}) = \frac{t}{2\pi} \quad \text{and} \quad y_n(e^{it}) = \frac{1 - e^{-int}}{2i\pi n} \quad \text{for every} \quad n \in \mathbb{Z} \setminus \{0\}.$$  

The series $\sum_{n \in \mathbb{Z}} y_n$ is obviously not unconditionally convergent in $L^2(\mathbb{T})$, and Theorem 1.7 cannot be applied this way. So we consider instead of $E$ the unimodular eigenvectorfield $F$ defined by $F(\lambda) = (1 - \lambda)E(\lambda)$, and we set

$$z_n(e^{it}) = \int_0^{2\pi} e^{-in\theta}F(e^{i\theta})(e^{it})\frac{d\theta}{2\pi} = \int_0^{2\pi} \left(e^{-in\theta} - e^{-i(n-1)\theta}\right)E(e^{i\theta})(e^{it})\frac{d\theta}{2\pi}.$$  

Thus $z_n = y_n - y_{n-1}$ for every $n \in \mathbb{Z}$. We have for every $n \in \mathbb{Z} \setminus \{0, 1\}$

$$z_n(e^{it}) = \frac{1}{2i\pi} \left(\frac{e^{-i(n-1)t}}{n-1} - \frac{e^{-int}}{n} - \frac{1}{n(n-1)}\right).$$  

Since the series $\sum_{|n| \geq 2} 1/(n(n-1))$ is convergent, and the series $\sum_{|n| \geq 2} e^{-int}/n$ is unconditionally convergent in $L^2(\mathbb{T})$, it follows that the series $\sum_{|n| \geq 2} z_n$ (and hence the series $\sum_{n \in \mathbb{Z}} z_n$) is unconditionally convergent in $L^2(\mathbb{T})$.  


Let us now check that the functions $z_n, n \in \mathbb{Z}$, span a dense subspace of $L^2(\mathbb{T})$. Suppose that $f \in L^2(\mathbb{T})$ is such that $\langle f, z_n \rangle = 0$ for every $n \in \mathbb{Z}$. Then

$$\frac{\hat{f}(n)}{n} = \frac{\hat{f}(n-1)}{n-1} + \hat{f}(0)\left(\frac{1}{n} - \frac{1}{n-1}\right) \text{ for every } n \notin \{0, 1\}.$$ 

Summing these equalities for $n \geq 2$, we obtain

$$\sum_{n \geq 2} \frac{\hat{f}(n)}{n} = \hat{f}(1) + \sum_{n \geq 2} \frac{\hat{f}(n)}{n} - \hat{f}(0), \text{ i.e. } \hat{f}(1) = \hat{f}(0).$$

As

$$\hat{f}(n) = \frac{n}{n-1} \hat{f}(n-1) - \frac{1}{n-1} \hat{f}(0)$$

for every $n \geq 2$, $\hat{f}(2) = 2\hat{f}(1) - \hat{f}(0) = \hat{f}(0)$. By induction $\hat{f}(n) = \hat{f}(0)$ for every $n \geq 2$, so that $\hat{f}(n) = 0$ for every $n \geq 0$. So

$$\hat{f}(n-1) = \frac{n-1}{n} \hat{f}(n) \text{ for every } n \geq 1,$$

which implies that $\hat{f}(-n) = n\hat{f}(-1)$ for every $n \geq 1$. Hence $f = 0$. So $\text{span} \{z_n; n \in \mathbb{Z}\} = L^2(\mathbb{T})$ (we have actually proved that $\text{span} \{z_n; n \in \mathbb{Z} \setminus \{0, 1\}\} = L^2(\mathbb{T})$).

Lastly, observe that if we set $f_0(e^{i\theta}) = e^{i\theta}$, then $\langle f_0, z_n \rangle = 0$ for every $n$ with $|n| \geq 2$, $\langle f_0, z_1 \rangle = -\langle f_0, z_{-1} \rangle = -1/2i\pi$ and a simple computation shows that $\langle f_0, z_0 \rangle = 0$. So $\langle f_0, F(e^{i\theta}) \rangle = (e^{i\theta} - e^{-i\theta})/2i\pi$, and all the assumptions of Theorem 1.7 (or, directly, Theorem 1.3) are satisfied. So $A$ is universal for invertible ergodic systems. 

5. Miscellaneous results and comments

We begin by investigating necessary conditions for an operator to be universal. We have already seen some such necessary conditions: a universal operator must be frequently hypercyclic, and topologically mixing. If it is universal for all ergodic systems, it cannot be invertible. Without any additional assumption, it seems difficult to say more. But looking at the examples of universal operators presented in Sections 3 and 4, we observe that all of them admit continuous unimodular eigenvectorfields, and that every $\lambda \in \mathbb{T}$ is an eigenvalue. This is not completely a coincidence: if $A \in B(\mathbb{Z})$ satisfies the assumptions of Theorem 1.3, then $A$ admits a continuous unimodular eigenvectorfield defined as

$$E(\lambda) = \sum_{n \in \mathbb{Z}} \lambda^n A^{-n} z_0.$$ 

If $A$ satisfies the assumptions of Theorem 1.4 with $r = 1$ for instance, then $A$ admits a continuous eigenvectorfield on $\mathbb{W}$ defined as $E(\lambda) = \sum_{n \in \mathbb{N}} \lambda^n A^{-n} z_0$. In both cases assumption (b) implies that all $\lambda \in \mathbb{T}$ except possibly finitely many are eigenvectors of $A$. Indeed, there exists a finite subset $F$ of $\mathbb{Z}$ and a non-zero functional $z_0^* \in Z^*$ such that

$$\langle z_0^*, E(\lambda) \rangle = \sum_{n \in F} \lambda^n \langle z_0^*, A^{-n} z_0 \rangle.$$ 

The function $\langle z_0^*, E(\cdot) \rangle$ is a non-zero trigonometric polynomial, so it has only finitely many zeroes on $\mathbb{T}$. This implies that $E(\lambda)$ is non-zero for all $\lambda \in \mathbb{T}$ except possibly finitely many.
So it comes as a natural question to ask whether a universal operator necessarily admits some (or many) unimodular eigenvectors. It is possible to answer this question in the affirmative under two additional assumptions: first that the operator lives on a Hilbert space, and, second, that we add in the definition of the universality the requirement that all the measures $\nu$ on $Z$ involved in the definition have a moment of order 2.

**Definition 5.1.** — A bounded operator $A$ on $Z$ is said to be 2-universal for (invertible) ergodic systems if for every (invertible) ergodic dynamical system $(X, \mathcal{B}, \mu; T)$ there exists a Borel probability measure $\nu$ on $Z$ which is $A$-invariant, has full support, has a moment of order 2 (i.e. $\int_Z ||z||^2 d\nu(z) < +\infty$), and is such that the two dynamical systems $(X, \mathcal{B}, \mu; T)$ and $(Z, \mathcal{B}_Z, \nu; A)$ are isomorphic.

We have seen in Section 2 that operators satisfying the assumptions of Theorems 1.3, 1.4, 2.5 or 2.6 are 2-universal. Thus all the universal operators presented in Sections 3 and 4 above are 2-universal. A first necessary condition for an operator on a Hilbert space to be 2-universal is

**Proposition 5.2.** — Let $H$ be a complex separable infinite-dimensional Hilbert space, and let $A$ be a 2-universal operator on $H$. Then $A$ admits a perfectly spanning (and even a $U_0$-perfectly spanning) set of unimodular eigenvectors.

**Proof.** — The proof is an easy consequence of some results of [3] and [5] concerning the ergodic theory of linear dynamical systems (see also [4]). Since $A$ is 2-universal, it is weakly mixing with respect to some probability measure $\nu$ with full support which has a moment of order 2. Consider the centered Gaussian probability measure $m$ on $H$ whose covariance operator $S$ is given by

$$\langle Sx, y \rangle = \int_H \langle x, z \rangle \overline{\langle y, z \rangle} d\nu(z) \quad \text{for every } x, y \in H.$$ 

Then

$$\int_H \langle x, z \rangle \overline{\langle y, z \rangle} dm(z) = \langle Sx, y \rangle = \int_H \langle x, z \rangle \overline{\langle y, z \rangle} d\nu(z)$$

for every $x, y \in H$. Hence $m$ is $A$-invariant and has full support. Moreover, since $A$ is weakly mixing with respect to $\nu$,

$$\frac{1}{N} \sum_{n=0}^{N-1} \left| \int_H \langle x, A^n z \rangle \overline{\langle y, z \rangle} d\nu(z) \right|^2 = \frac{1}{N} \sum_{n=0}^{N-1} \left| \int_H \langle x, A^n z \rangle \overline{\langle y, z \rangle} dm(z) \right|^2$$

tends to 0 as $N$ tends to infinity for every $x, y \in H$, and this implies (see [2] or [4] for details) that $A$ is weakly mixing with respect to $m$. Since it is proved in [3] that any operator on a space of cotype 2 which is weakly mixing with respect to some Gaussian measure with full support has perfectly spanning unimodular eigenvectors, the first part of the result follows. The second part is proved in exactly the same way: $A$ is necessarily strongly mixing with respect to some probability measure on $Z$ with full support, and is hence strongly mixing with respect to some Gaussian probability measure on $Z$ with full support. It is proved in [5] that this implies that the unimodular eigenvectors of $A$ are $U_0$-perfectly spanning (i.e. for any Borel set $B \subseteq T$ which is a set of extended uniqueness, $\text{span} \left[ \ker(T - \lambda) ; \lambda \in T \setminus B \right] = H$. See [5] for more about these questions).
If $A$ is supposed to be 2-universal for ergodic systems (and not only for invertible ones), we can moreover prove that the unimodular point spectrum of $A$ is a subset of $\mathbb{T}$ of full Lebesgue measure. These are the contents of Theorem 1.9, which we now prove.

\textbf{Proof of Theorem 1.9.} — Let $A$ be a 2-universal operator on $H$ for ergodic systems. Consider the dynamical system $T$ defined on $([0, 1], \mathcal{B}_{[0, 1]}, dx)$, where $dx$ is the Lebesgue measure on $[0, 1]$, by $Tx = 2x \mod 1$. Then $T$ is strongly mixing, and has the following property of decay of correlations: for any $f, g \in L^2([0, 1])$ and $n \geq 0$, define the $n$-th correlation between $f$ and $g$ as

$$C_n(f, g) = \int_0^1 f(T^n x) \overline{g(x)} \, dx - \left( \int_0^1 f \right) \cdot \left( \int_0^1 g \right).$$

Then we have for every $f \in L^2([0, 1]), g \in C^1([0, 1])$, and $n \geq 0$

$$|C_n(f, g)| \leq 2^{-n} \frac{||f||_2 \cdot ||g||_\infty}{\sqrt{3}}.$$

Thus the correlations decay exponentially fast provided one of the two functions $f$ and $g$ is sufficiently smooth.

Since $A$ is 2-universal for ergodic systems, there exists an $A$-invariant measure $\nu$ on $H$ with full support and with a moment of order 2, for which there exists an isomorphism $\Phi$ between the two dynamical systems $([0, 1], \mathcal{B}_{[0, 1]}, dx; T)$ and $(H, \mathcal{B}_H, \nu; A)$. We denote by $L^2_0([0, 1])$ (resp. $L^2(H, \mathcal{B}_H, \nu)$) the set of functions $f \in L^2([0, 1])$ (resp. $f \in L^2(H, \mathcal{B}_H, \nu)$) such that $f^1_0 f(x) \, dx = 0$ (resp. $\int_H f(z) \, d\nu(z) = 0$). For every functions $F, G \in L^2_0(H, \mathcal{B}_H, \nu)$ such that $G = g \circ \Phi^{-1}$ for some function $g \in C^1([0, 1]) \cap L^2_0([0, 1])$, there exists a positive constant $c(F, G)$ such that if we denote for every $n \geq 0$ by $C_n(F, G)$ the correlation

$$C_n(F, G) = \int_Z F(A^n z) \overline{G(z)} \, d\nu(z),$$

then $|C_n(F, G)| \leq c(F, G) 2^{-n}$. Since the measure $\nu$ has a moment of order 2, one can consider its covariance operator $S$ on $H$ defined as:

$$\langle Sx, y \rangle = \int_Z \langle x, z \rangle \langle y, z \rangle \, d\nu(z)$$

for every $x, y \in H$. The operator $S$ is self-adjoint, positive, and of trace class. Since $\nu$ has full support, $S$ has dense range. Hence there exist an orthonormal basis $(e_l)_{l \geq 1}$ of $H$ and a sequence $(\sigma^2_l)_{l \geq 1}$ of positive numbers with $\sum_{l \geq 1} \sigma^2_l < +\infty$ such that $S e_l = 2\sigma^2_l e_l$ for every $l \geq 1$. Also it follows from the orthogonality of the vectors $e_l$ in $H$ that the functions $\langle e_l, . \rangle$ are orthogonal in $L^2(H, \mathcal{B}_H, \nu)$. Let $\mathcal{E} = \text{span} \{ \langle e_l, . \rangle : l \geq 1 \}$, where the closed linear span is taken in $L^2(H, \mathcal{B}_H, \nu)$: $\mathcal{E}$ is a closed subspace of $L^2(H, \mathcal{B}_H, \nu)$ which consists of all functions $F \in \mathcal{E}$ which can be written as a convergent series in $L^2(H, \mathcal{B}_H, \nu)$ of the form

$$F = \sum_{l \geq 1} a_l \langle e_l, . \rangle, \quad \text{where} \quad \sum_{l \geq 1} |a_l|^2 \sigma^2_l < +\infty.$$

Remark that the function $\langle x, . \rangle$ belongs to $\mathcal{E}$ for every $x \in H$. We denote by $\iota$ the injection operator $\iota : H \rightarrow \mathcal{E}$ defined by $\iota(x) = \langle x, . \rangle$. If $U_A$ denotes the Koopman operator associated to $(H, \mathcal{B}_H, \nu; A)$, then $U_A(\mathcal{E}) \subseteq \mathcal{E}$. Proceeding as in the proof of [3, Th. 4.1], we apply the spectral decomposition theorem to $U_A$, which is an isometry on $L^2(H, \mathcal{B}_H, \nu)$: there exists a finite or countable family $(H_l)_{l \in I}$ of Hilbert spaces, with...
either \( H_i = H^2(\mathbb{T}) \) or \( H_i = L^2(\mathbb{T}, \sigma_i) \) for some probability measure on \( \mathbb{T} \), and an invertible isometry \( J : \bigoplus_{i \in I} H_i \to L^2(H, B_H, \nu) \) such that \( U_A J = JM \). Here \( M \) acts on \( \bigoplus_{i \in I} H_i \) as \( M = \bigoplus_{i \in I} M_i \), where \( M_i \) is the multiplication operator by \( \lambda \) on \( H_i \); \( (M_i f_i)(\lambda) = \lambda f_i(\lambda) \) for every \( f_i \in H_i \).

Let now \( K : \bigoplus_{i \in I} H_i \to H \) be the operator defined as \( K = \iota^* J \). For every \( x \in H \), we have
\[
\langle S x, x \rangle = \int_H |\langle x, z \rangle|^2 \, d\nu(z) = ||\iota(x)||^2 = ||K^* x||^2.
\]
It follows that \( K^* \) is a Hilbert-Schmidt operator, and so there exists for each \( i \in I \) a unimodular eigenvectorfield \( E_i \in L^2(\mathbb{T}, \sigma_i; H) \) such that \( K^* x = \bigoplus_{i \in I} \langle x, E_i(.) \rangle \) (see [14], [3] or [4] for more details). We have thus for every \( x, y \in H \),
\[
\langle S x, y \rangle = \langle K^* x, K^* y \rangle = \sum_{i \in I} \int_T \langle x, E_i(\lambda) \rangle \langle y, E_i(\lambda) \rangle \, d\sigma_i(\lambda).
\]
Let now \( G \in L^2_0(H, B_H, \nu) \) be a function of the form \( G = g \circ \Phi^{-1} \) with \( g \in L^2_0([0, 1] \cap C^1([0, 1]) \), which is such that its orthogonal projection on \( \mathcal{E} \), we which we denote by \( F \), is non-zero. Such a function \( G \) does exist because \( \{g \circ \Phi^{-1}; \ g \in L^2_0([0, 1] \cap C^1([0, 1]) \) is dense in \( L^2(H, B_H, \nu) \). For every \( n \geq 0 \) we have
\[
\mathcal{C}_n(F, G) = \int_Z F(A^n z) \overline{G(z)} \, d\nu(z) = \langle U^n_A F, G \rangle = \langle U^n_A F, F \rangle = \langle U^n_A F, G - F \rangle.
\]
Since \( U_A(\mathcal{E}) \subseteq \mathcal{E} \) and \( G - F \) is orthogonal to \( \mathcal{E} \), the second term vanishes and
\[
\mathcal{C}_n(F, G) = \mathcal{C}_n(F, F) = \int_Z F(A^n z) \overline{F(z)} \, d\nu(z) \quad \text{for every } n \geq 0.
\]
Hence there exists a positive constant \( C \) such that for every \( n \geq 0 \), \( |\mathcal{C}_n(F, F)| \leq C 2^{-n} \).

Writing \( F \) as \( F = \sum_{l \geq 1} a_l \langle e_l, . \rangle \), where \( \sum_{l \geq 1} |a_l| \sigma_l^2 < +\infty \) and one at least of the coefficients \( a_l \) is non-zero, we can write \( \mathcal{C}_n(F, F) \) as
\[
\mathcal{C}_n(F, F) = \sum_{k, l \geq 1} a_k a_l \langle SA^n e_k, e_l \rangle
= \sum_{k, l \geq 1} a_k a_l \sum_{i \in I} \int_T \langle A^n e_k, E_i(\lambda) \rangle \overline{\langle e_l, E_i(\lambda) \rangle} \, d\sigma_i(\lambda)
= \int_T \lambda^n \sum_{i \in I} \left( \sum_{k, l \geq 1} a_k a_l \langle e_k, E_i(\lambda) \rangle \overline{\langle e_l, E_i(\lambda) \rangle} \right) \, d\sigma_i(\lambda)
= \int_T \lambda^n \sum_{i \in I} \left( \sum_{k \geq 1} a_k \langle e_k, E_i(\lambda) \rangle \right)^2 \, d\sigma_i(\lambda).
\]
All these computations make sense because
\[
\int_T \sum_{i \in I} \lambda^n \sum_{k \geq 1} a_k \langle e_k, E_i(\lambda) \rangle^2 \, d\sigma_i(\lambda) = \int_Z |F(z)|^2 \, d\nu(z) < +\infty.
\]
Let us denote by \( \sigma \) the positive finite measure
\[
\sigma = \sum_{i \in I} \left( \sum_{k \geq 1} a_k \langle e_k, E_i(.) \rangle \right)^2 \sigma_i.
\]
Then $|\hat{\sigma}(n)| \leq C.2^{-n}$ for every $n \geq 0$, and since $\sigma$ is a positive measure, $\hat{\sigma}(-n) = \hat{\sigma}(n)$ for every $n \geq 0$, so that $|\hat{\sigma}(n)| \leq C.2^{-|n|}$ for every $n \in \mathbb{Z}$. Hence there exists a function $\varphi$ which is analytic in $\mathbb{A}_{1/2} = \{ \lambda \in \mathbb{C}; \; 1/2 < |\lambda| < 2 \}$ such that $d\sigma = \varphi d\lambda$, where $d\lambda$ is the normalized Lebesgue measure on $\mathbb{T}$. Since $C_0(F,F) = \hat{\sigma}(0) > 0$ (recall that the function $F$ is non-zero), the function $\varphi$ cannot be identically zero. If $E$ is a subset of $\mathbb{T}$ of positive Lebesgue measure, it is thus impossible that $E_i(\lambda) = 0$ for every $\lambda \in E$ and every $i \in I$. So the unimodular point spectrum of $A$ has full Lebesgue measure in $\mathbb{T}$. This proves Theorem 1.9.

The proof of Theorem 1.9 does not extend to operators which are 2-universal for invertible ergodic systems: the proof uses in a crucial way that the correlations $C_n(f,g)$ of the system $x \mapsto 2x \mod 1$ on $[0,1]$ decay exponentially fast for all $f \in L^2([0,1])$ and sufficiently smooth $g \in L^2([0,1])$. This system is not invertible, and this seems to be in the nature of things that for an invertible system, the correlations decay exponentially fast only for sufficiently smooth functions $f$ and $g$ (see [1] for more on these questions). So the following question remains open:

**Question 5.3.** — If $A$ is a 2-universal operator for invertible ergodic systems on a Hilbert space, is it true that the unimodular point spectrum of $A$ has full Lebesgue measure?

We do not know any example of a 2-universal operator whose unimodular point spectrum is not the whole unit circle:

**Question 5.4.** — If $A$ is a 2-universal operator for (invertible) ergodic systems on a Hilbert space, is it true that the unimodular point spectrum of $A$ is equal to $\mathbb{T}$?

If an affirmative answer to this question could be obtained, it would be a first step towards a characterization of symbols $\varphi \in H^\infty(\mathbb{D})$ such that $M_\varphi^*$ acting on $H^2(\mathbb{D})$ is 2-universal for invertible ergodic systems.

**Question 5.5.** — Let $\varphi \in H^\infty(\mathbb{D})$. Is it true that $M_\varphi^* \in B(H^2(\mathbb{D}))$ is 2-universal for invertible ergodic systems if and only if $\mathbb{T} \subseteq \varphi(\mathbb{D})$?

It would also be interesting to obtain a characterization of adjoints of multipliers on $H^2(\mathbb{D})$ which are universal for ergodic systems.

**Question 5.6.** — Let $\varphi \in H^\infty(\mathbb{D})$. If $\overline{\mathbb{D}} \subseteq \varphi(\mathbb{D})$ (where $\overline{\mathbb{D}}$ denotes the closure of the unit disk $\mathbb{D}$), is $M_\varphi^*$ universal for ergodic systems? Is it true that $M_\varphi^*$ is 2-universal for ergodic systems if and only if $\overline{\mathbb{D}} \subseteq \varphi(\mathbb{D})$?

Of course things would be simpler if we knew that a universal operator is necessarily 2-universal, but this does not seem easy to prove. It is not even known whether a frequently hypercyclic operator on a reflexive space admits an invariant measure with full support having a moment of order 2, although it is known that it admits invariant measures with full support (see [9]).

**Question 5.7.** — Does there exist a universal operator which is not 2-universal?

This brings us back to questions about the existence of unimodular eigenvectors for universal operators.

**Question 5.8.** — Does there exist universal (or 2-universal) operators admitting no unimodular eigenvalue? What about universal operators on a Hilbert space?
The second half of this question seems hard, again because we do not know whether a frequently hypercyclic operator on a Hilbert space necessarily has some unimodular eigenvalue. The first half of Question 5.8 may be more tractable, and a potential example would be the Kalish-type operator $A$ of Example 4.4 acting on the space $C_0([0, 2\pi])$ of continuous functions on $[0, 2\pi]$ vanishing at 0. It is proved in [3] that although this operator has no unimodular eigenvalue, it admits a Gaussian invariant measure with full support with respect to which it is strongly mixing. We have seen that $A$ acting on $L^2(\mathbb{T})$ is universal for invertible ergodic systems, so one may naturally wonder about the following:

**Question 5.9.** — Let $A$ be the bounded operator on $C_0([0, 2\pi])$ defined by setting, for every $f \in C_0([0, 2\pi])$ and every $\theta \in [0, 2\pi]$,

$$Af(\theta) = e^{i\theta} f(\theta) - \int_0^\theta ie^{it} f(e^{it}) \, dt.$$ 

Is $A$ a universal (or 2-universal) operator for invertible ergodic systems on $C_0([0, 2\pi])$?

A positive answer to Question 5.9 cannot be obtained via an application of Theorem 1.3, or any variant of it, since we have seen that assumption (c) of Theorem 1.3 for instance implies that $A$ admits a continuous unimodular eigenvectorfield $E$ which is such that $\text{span}\{E(\lambda); \lambda \in \mathbb{T}\} = \mathbb{Z}$. So we finish the paper with this last question:

**Question 5.10.** — Does there exist any universal operator for invertible ergodic systems which does not satisfy the assumptions of Theorem 1.3?

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