MINICOURSE: BANACH REPRESENTATIONS OF DYNAMICAL SYSTEMS
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MICHAEL MEGRELIŠVILI (BAR-ILAN UNIVERSITY, ISRAEL)

MEGERELI@ MATH.BIU.AC.IL
WWW.MATH.BIU.AC.IL/~MEGERELI

Contents
1. Introduction 1
2. Preliminaries 4
3. Actions and semigroups 10
4. Representations of topological groups I 14
5. Matrix coefficients 19
6. Reflexive spaces and WAP systems 21
7. $L_4 \in \text{Refl}_r \setminus \text{Hilb}_r$ 29
8. Fragmentability and Banach spaces 30
9. Some classes of right topological semigroups and dynamical systems 39
10. HNS-semigroups, dynamical systems and Asplund Banach spaces 39
11. Tame semigroups, tame systems and Rosenthal spaces 41
12. Representations of dynamical systems and of functions 46
13. Some applications 51
14. Representations of topological groups II 53
References 57

1. INTRODUCTION

Banach representations of dynamical systems is a relatively new theory already having several important applications. In the present course we study some hierarchies of topological dynamical systems and topological groups coming from Banach space theory. This allows to find new links between many different research lines. Among others: abstract topological dynamics, geometry of Banach spaces and the theory of Polish topological groups.

During this course I will expose some results and ideas mainly from recent joint works with Eli Glasner (Tel Aviv University). A part of the presented results are joint with Vladimir Uspenskij [30]. We mention also a major influence of several works of Vladimir Pestov. See, for instance, [60].

You can download this lecture, some exercises, as well as, some related papers, from the site www.math.biu.ac.il/~megereli/seminar.html

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First let us ask some intuitive questions.

**Question 1.1. What is common between:**

1. Grothendieck’s Double Limit Property, (weak) almost periodicity and reflexive Banach spaces;
2. Lack of “butterfly effects”, averages of functions on topological groups and Asplund Banach spaces;

By the Fibonacci binary sequence we mean the following particular case of a cutting binary sequence $c_n$ of 0-s and 1-s (with the slope $\phi = \frac{1+\sqrt{5}}{2}$).

It can be defined also by the finite blocks $s_n$ using the Fibonacci substitution: $s_0 = 0, s_1 = 01, s_n = s_{n-1}s_{n-2}$. So, we have 0100101001001···.

One may prove (Theorem 12.6) that the Fibonacci cutting sequence ”lives in a Rosenthal Banach space” as a generalized matrix coefficient. That is, there exist: a Rosenthal Banach space $V$, a linear isometry $\sigma \in \text{Iso}(V)$ and two vectors $v \in V, f \in V^*$ such that $c_n = \langle \sigma^n(v), f \rangle = f(\sigma^n(v)) \ \forall n \in \mathbb{N}$.

It is impossible to choose $V$ reflexive or even Asplund.

Note that even ”simple” bisequences sometimes are not reflexively representable. For example $c = \chi_M : \mathbb{Z} \to \{0,1\}$

\[ \cdots 000111 \cdots \]

is not reflexively representable but it is Asplund representable.

Our aim is to show that Questions like 1.1 can be studied by developing a relatively new tool: representations of dynamical systems on Banach spaces.

Like topological groups, compact dynamical systems, can be represented on (duals of) Banach spaces. We study dynamical analogs of Eberlein, Radon-Nikodým and weakly Radon–Nikodým compacta; that is the classes of dynamical systems which can be represented on reflexive, Asplund and Rosenthal Banach spaces. They correspond to important classes of compact metrizable dynamical systems: weakly almost periodic (WAP), hereditarily nonsensitive (HNS) and tame.
This approach naturally extends some classical research themes and at the same time opens new and sometimes quite unexpected directions. One of the examples is a connection between the lack of chaotic behavior (lack of "butterfly effects") of a dynamical system (HNS systems) and the existence of weak-star continuous representations on the dual of Asplund Banach spaces. The topological concept of the fragmentability (originally coming from Banach spaces) and the famous factorization theorem of Davis-Figiel-Johnson-Pelczyński are the main tools in the present theory.

We provide the necessary background. Besides some new results we give soft geometric proofs of several classical results (like: Teleman’s regular representations of topological groups, Ellis and Ellis-Lawson theorems; Helmer’s theorem about WAP functions; Ryll-Nardzewski’s fixed point theorem, etc.). At the same time we discuss perspectives of the theory and pose several open questions.

1.1. Some concrete questions. To every Banach space $V$ one may associate several important structures. For example: compact spaces $X \subset B^* := (B_{V^*}, w^*)$, topological groups $G \leq \text{Iso} (V)$ and continuous actions $G \times X \to X$, where $G \leq \text{Iso} (V)$ and $X$ is a $G$-subset of $(V^*, w^*)$.

Let $\mathcal{K}$ be a nice subclass of Banach spaces. For example: Hilbert, reflexive, Asplund, Rosenthal. There are several good reasons explaining our interest just to these classes.

**Question 1.2.**

1. Which compact dynamical $G$-systems $X$ can be represented on some $V \in \mathcal{K}$?
2. Which topological groups can be embedded into $\text{Iso} (V)$ where $V \in \mathcal{K}$?

**Remark 1.3.** A classical result of Teleman [70] (see also the survey of Pestov [60] for a detailed discussion (downloadable from the course website)) is that every (Hausdorff) topological group can be embedded into $\text{Iso} (V)$ for some Banach space $V$ (namely, one can take $V := \text{RUC}(G)$). Furthermore, every continuous dynamical system $(G, X)$ has a faithful representation on $V := C(X)$, where one can identify $x \in X$ with the point mass $\delta_x$ viewed as an element of $C(X)^*$. This is true also for semigroup actions. So, any compact dynamical $S$-system $X$ is Banach representable (on $C(X)$). However, the Banach spaces $\text{RUC}(G), C(X)$ very rarely are in a nice class.

For a given topological semigroup $S$, one way to measure the complexity of a compact dynamical $S$-system $X$ is to investigate its representability on nice Banach spaces, [28, 27, 25]. Another way is to ask whether the points of $X$ can be separated by a norm bounded $S$-invariant family $F \subset C(X)$ of continuous functions on $X$, such that $F$ is “small” in some sense or another. More precisely, Questions 1.2 are closely related to the next question. For every $F \subset V$ and a weak-star compact subset $X \subset V^*$ one may consider the evaluation map

$$w : F \times X \to \mathbb{R}$$

induced by the canonical bilinear mapping $V \times V^* \to \mathbb{R}, (v, f) \mapsto f(v)$. For example, $B_V$ separates the points of $V^*$ (hence also of $X$). For every $F \subset C(X)$ the evaluation map $F \times X \to \mathbb{R}$ obviously is represented on $V := C(X)$.

**Question 1.4.** Which abstract evaluation maps can be realized as a part of the canonical bilinear map on a Banach space $V \in \mathcal{K}$?
Usually \( F \) is “small” means that the pointwise closure \( \text{cl}_p(F) \) of \( F \) (the \emph{envelope of} \( F \)) in \( \mathbb{R}^X \) is a “small” topological space. For example, (a) when \( \text{cl}_p(F) \subset C(X) \), or (b) when \( \text{cl}_p(F) \) consists of fragmented functions (Baire 1, when \( X \) is metrizable).

It turns out that the first case (a) characterizes the reflexively representable dynamical systems, (i.e., the dynamical analog of Eberlein compacta) or, for metric dynamical systems \( X \), the class of Weakly Almost Periodic (in short: WAP) systems.

In the second case (b) we get the characterization of Rosenthal representable dynamical systems, or, for metric dynamical systems \( X \), the class of tame systems (a Banach space \( V \) is said to be \emph{Rosenthal} if it does not contain an isomorphic copy of the Banach space \( l_1 \).)

We have the natural intermediate case of Asplund representable or hereditarily non sensitive (HNS) systems. Namely, an \( S \)-system \( X \) is HNS iff there exists a separating bounded family \( F \subset C(X) \) which is a fragmented family.

### 2. Preliminaries

**2.1. Notation.** The closure and the interior operators in topological spaces will be denoted by \( \text{cl} \) and \( \text{int} \), respectively. "Compact" will mean "compact and Hausdorff".

As usual \emph{hereditarily Baire} means that every closed subspace is a Baire space. A function \( f : X \to Y \) is \emph{Baire class 1 function} if the inverse image \( f^{-1}(O) \) of every open set is \( F_\sigma \) in \( X \). A topological space \( X \) is said to be \emph{Polish} if it admits a complete separable metrizable metric. For Polish spaces \( X \) a function \( f : X \to \mathbb{R} \) is Baire 1 iff \( f \) is a pointwise limit of a sequence of continuous functions.

Banach spaces and locally convex vector spaces are over the field \( \mathbb{R} \) of real numbers.

When \( V \) is a Banach space we denote by \( B \), or \( B_V \), the closed unit ball of \( V \). \( B^* = B_V^* \) and \( B^{**} := B_{V^{**}} \) will denote the weak* compact unit balls in the dual \( V^* \) and second dual \( V^{**} \) of \( V \) respectively.

**2.2. From representations to compactifications.** Let \( X \) be a topological space, \( Y \) be a compact Hausdorff space and let \( f : X \to Y \) be a function such that \( f(X) \) is dense in \( Y \). If \( f \) is continuous, then \( Y \) (more precisely, the pair \( (Y, f) \)) is called a \emph{compactification of} \( X \). If \( f \) is a homeomorphic embedding, then \( Y \) is called a \emph{proper compactification of} \( X \). Denote by \( (\mathcal{C}(X), \leq) \) the partially ordered set of all compactifications of \( X \) up to the standard equivalence. For a topological space \( X \) denote by \( C(X) \) the Banach algebra of real valued continuous and bounded functions equipped with the supremum norm. Recall that the unital closed subalgebras of \( C(X) \) determine the compactifications of \( X \).

**Fact 2.1.** (Gelfand-Kolmogoroff) \emph{There exists a natural order preserving bijective correspondence between} \( \mathcal{C}(X) \) (different compactifications of \( X \)) \emph{and closed unital subalgebras of} \( C(X) \). \emph{In particular,} \( C(X) \) \emph{determines the greatest compactification} \( \beta : X \to \beta X \).

**Proof.** (Sketch) Let \( \mathcal{A} \) be a Banach unital subalgebra \( \mathcal{A} \) of \( C(X) \). Denote by \( \mathcal{A}^* \) the dual Banach space of \( \mathcal{A} \). Consider the canonical \( \mathcal{A} \)-compactification \( \alpha_{\mathcal{A}} : X \to X^\mathcal{A} \), where \( X^\mathcal{A} \subset B^* \subset \mathcal{A}^* \) is the Gelfand space (or, the \emph{spectrum}) of the algebra \( \mathcal{A} \). The map

\[ \alpha_{\mathcal{A}} : X \to X^\mathcal{A}, \ x \mapsto \delta_x \]
is defined by the **Gelfand transform**, the evaluation at \( x \) multiplicative functional, that is \( \alpha(x)(f) = \delta_x(f) = f(x) \) and \( X^A \) is the closure of \( \alpha_A(X) \) in \( A^* \) with respect to the weak\(^*\) topology \( w^* \). Therefore \( X_A \) is compact by Alaoglu Theorem.

Conversely, every compactification \( \nu : X \to Y \) is equivalent to the **canonical** \( \mathcal{A}_\nu \)-compactification \( \alpha_{\mathcal{A}_\nu} : X \to X^{\mathcal{A}_\nu} \), where the algebra \( \mathcal{A}_\nu \) (corresponding to \( \nu \)) is defined as the image \( j_\nu(C(Y)) \) of the natural embedding of Banach algebras

\[
j_\nu : C(Y) \to C(X), \quad \phi \mapsto \phi \circ \nu.
\]

If \( \mathcal{A}_1 \subseteq \mathcal{A}_2 \) then the adjoint operator induces the weak-star continuous onto map \( \mathcal{A}_2^* \to \mathcal{A}_1^* \). Its restriction on \( c_2(X) \) gives the desired morphism of compactifications \( c_2 \to c_1 \).

Categorical view: the assignment \( K \mapsto C(K) \) defines an important contravariant functor from the category \( \text{Comp} \) into the categories of Banach spaces \( \text{Ban} \) and Banach algebras.

For every (Tychonoff) space \( X \) and for the algebra \( A = C(X) \) we get the maximal (Chech-Stone) compactification.

\[
\delta : X \to \beta(X) \subset B^* \subset C(X)^*
\]

For every compact space \( K \) we have a topological embedding (Gelfand representation)

\[
\delta : K \hookrightarrow C(K)^*, \ x \mapsto \delta_x.
\]

Its image \( \delta(K) \) affinely generates \( P(K) \) (i.e. \( \overline{\sigma_{w^*}(\delta(K))} = P(K) \)), where

\[
P(K) := \{ \mu \in C(K)^* : \|\mu\| = \mu(1) = 1 \}
\]

the weak-star compact set of all **probability measures** on \( K \). We have \( K := \delta(K) \subset P(K) \subset B_{C(K)^*} \).

2.3. **Topological prototypes.** An important direction in the classical study of (large) compact spaces went via the following general principle: Given a compact space \( X \) find a nice class \( \mathcal{K} \) of Banach spaces such that there always is an element \( V \in \mathcal{K} \) where \( X \) can be embedded into \( V^* \) equipped with its weak-star topology?

**Eberlein compacta** in the sense of Amir and Lindenstrauss are exactly the weakly compact subsets in the class of all (equivalently, reflexive) Banach spaces. If \( X \) is a weak\(^*\) compact subset in the dual \( V^* \) of an Asplund space \( V \) then, following Namioka [56], \( X \) is called a **Radon–Nikodým compactum** (in short: RN). In other words, reflexively representable compact spaces are the Eberlein compacta and Asplund representable compact spaces are the Radon–Nikodým compacta. Hilbert representable compacta are the so-called **uniformly Eberlein** compact spaces. Another interesting class of compact spaces, namely the weakly **Radon–Nikodým** (WRN) compacta, occurs by taking \( \mathcal{K} \) to be the class of Rosenthal Banach spaces (i.e. those Banach spaces which do not contain an isomorphic copy of \( l_1 \)). Comparison of the above mentioned classes of Banach spaces implies the inclusions of the corresponding classes of compact spaces:

\[
\text{(Comp} \cap \text{Metr)} \subset uEb \subset Eb \subset RN \subset WRN \subset \text{Comp}.
\]

Note that this classification makes sense only for large compact spaces, where \( X \) is not metrizable. In fact, any compact metrizable space is even norm embeddable in a separable Hilbert space.
Example 2.2.

(1) For every Hilbert space $H$ the (weak compact) unit ball $(B_H, w)$ is uniformly Eberlein.

(2) 1-point compactification $A(\kappa)$ of a discrete space of cardinality $\kappa$ is uniformly Eberlein.

A topological space $(X, \tau)$ is scattered if every (closed) subset $L \subset K$ has an isolated point in L. $A(\kappa)$ is scattered. For every ordinal $\lambda$ the linearly ordered compact space $[0, \lambda]$ is scattered.

Fact 2.3. (Namioka-Phelps75) Let $K$ be a compact space. The following are equivalent:

1. $K$ is scattered
2. $C(K)$ is an Asplund space.

Example: $c = C(K)$ with $K = A(\omega)$.

Note that infinite dimensional space $C(K)$ never can be reflexive.

Corollary 2.4. Every scattered compact space is RN.

Remark 2.5.

1. $A(\kappa) \in \text{Eberlein}$
2. $[0, \omega_1] \in \text{RN \setminus Eberlein}$
3. Two arrows space $D \in \text{WRN \setminus RN}$

Indeed, every compact linearly ordered space is WRN (a recent result [29]). $D$ is not RN by a result of Namioka [56, Example 5.9].

This was done by Todorčević (private communication).

Remark 2.6. Perhaps the first outstanding feature of this new theory is that, in contrast to the purely topological case (i.e., the case of trivial actions), for dynamical systems, the case of metrizable systems is ”full of life”. Moreover, the main interest of the dynamical theory is just within the class of metrizable dynamical systems. For example, even for $X := [0, 1]$, the unit interval, the action of the cyclic group $\mathbb{Z}$ on $X$ generated by the map $f(x) = x^2$ is RN and not Eberlein. There exists a compact metric $\mathbb{Z}$-system which is reflexively but not Hilbert representable, i.e., Eberlein but not uniformly Eberlein. There are compact metric $\mathbb{Z}$-systems which are WRN but not RN, etc. See Example 11.5.

It turns out that the corresponding classes of metric dynamical systems coincide with well known important classes whose study is well motivated by other independent reasons. For example we have, Eberlein = WAP (weakly almost periodic systems), RN = HNS (hereditarily non-sensitive), WRN = tame systems. The investigation of Hilbert representable (i.e., ”uniformly Eberlein”) systems is closely related to the study of unitary and reflexive representability of groups.

\footnote{dispersed in other terminology}
2.4. **Some connections to Banach space theory.** Another remarkable feature is the fact that the correspondence goes both ways. Thus, for example, to construct some nontrivial examples of Banach spaces. Every metric WRN but not RN $Z$-system leads to an example of a separable Rosenthal Banach space which is not Asplund. One of the important questions in Banach space theory until the mid 70’s was to construct a separable Rosenthal space which is not Asplund. The first counterexamples were constructed independently by James and Lindenstrauss-Stegall.

In view of the representation theorem below we now see that a fruitful way of producing such distinguishing examples comes from dynamical systems. Just consider a compact metric tame $G$-system which is not HNS and then represent it on a (separable) Rosenthal space $V$. Then $V$ is not Asplund (otherwise, $(G,X)$ is HNS). We have several examples of dynamical systems of this type; e.g. $(H_+,[0,1],[0,1])$, the Sturmian cascades, or the projective actions of $GL_n(\mathbb{R})$ on the sphere or the projective space.

One may make this result sharper by using representation theorem. There exists a separable Rosenthal space $V$ without the adjoint continuity property. Indeed, the Polish group $G := H_+([0,1])$, which admits only trivial adjoint continuous representations (and, hence, trivial Asplund or reflexive representations), is however Rosenthal representable.

Finally, let us mention yet another potentially interesting direction, which may lead to a new classification inside Rosenthal Banach spaces induced by topological classification of Rosenthal compacta (Todorcevic trichotomy) applied to the Rosenthal compacta of the form $E(V)$ (enveloping semigroups of Banach spaces $V$).

2.5. **Some typical applications.**

**Theorem 2.7.** [47, 50] Let $V$ be a reflexive space (remains true for PCP spaces). Then

1. norm topology = weak topology on every orbit $Gv$ for every $G \leq \text{Iso}(V)$.
2. WOP=SOP. The weak and the strong operator topologies coincide on $\text{Iso}(V)$.
3. Every weakly continuous (co)homomorphism $h : G \rightarrow \text{Iso}(V)$ is strongly continuous.

**Proof.** It is enough to show (1). Let $z \in X := Gv$. Denote by $\tau$ the weak topology on $X \subset V$. We have to show that for every $\varepsilon > 0$ there exists a $\tau$-neighborhood $O(z)$ of $z$ in $X$ such that $O$ is $\varepsilon$-small. Since $X$ is $(\tau, \text{norm})$-fragmented (non-sensitivity is enough), we can pick a non-void $\tau$-open subset $W \subset X$ such that $W$ is $\varepsilon$-small in $V$. Choose $g_0 \in G$ such that $g_0 z \in W$. Denote by $O$ the $\tau$-open subset $g_0^{-1}W$ of $(X, \tau)$. Then $O$ is a $\tau$-neighborhood of $z$ and is $\varepsilon$-small. □

**Theorem 2.8.** (Shtern, Megrelishvili) If $P$ is a compact semitopological monoid then there exists a reflexive Banach space $V$ and an embedding $P \hookrightarrow \Theta(V)_w$ into the compact semitopological monoid

$$\Theta(V)_w := \{ \sigma \in L(V,V) : ||\sigma|| \leq 1 \}.$$

**Theorem 2.9.**

1. Let $S$ be a compact semitopological monoid and $G$ be its subgroup. Then $G$ is a topological group.
2. Ellis Theorem Every compact semitopological group $G$ is a topological group.
Proof. It is enough to show (1). Combine previous two theorems. By Theorem 2.8,\n\[ G \leq \text{Iso}(V)_w \subset \Theta(V)_w \] for some reflexive \( V \). By Theorem 2.7, WOP=SOP on Iso\((V)\) for every \( V \in PCP \). So, \( G \leq \text{Iso}(V)_w = \text{Iso}(V)_s \) is a topological group. \( \square \)

**Theorem.** ([27], 2012) \( \text{Ros}_r \neq \text{Asp}_r \)

*The Polish topological group \( H_t[0,1] \) is representable on a separable Rosenthal Banach space (and not representable on any Asplund space, [24], 2007).*

\[ \downarrow \]

(Well known) There exists a separable Rosenthal Banach space which is not Asplund.

**Remark 2.10.** Well known but once it was a famous problem, resolving by James (JT space) and Lindenstrauss-Stegall (JF space).

Another corollary: There exists a separable Rosenthal space \( V \) without the adjoint continuity property.

### 2.6. The hierarchy of Banach representations.

With every Banach space \( V \) one may naturally associate several structures which are related to the theories of topological dynamics, topological groups and compact right topological semigroups:

**Definition 2.11.**

1. \( \text{Iso}(V) \) is the group of linear onto self-isometries of \( V \). It is a topological (semitopological) group with respect to the strong (respectively, weak) operator topology. It is naturally included in the semigroup \( \Theta(V) := \{ \sigma \in L(V,V) : ||\sigma|| \leq 1 \} \) of non-expanding linear operators. The latter is a topological (semitopological) monoid with respect to the strong (respectively, weak) operator topology. Notation: \( \Theta(V)_s, \text{Iso}(V)_s \) (respectively, \( \Theta(V)_w, \text{Iso}(V)_w \)) or simply \( \Theta(V) \) and \( \text{Iso}(V) \), where the topology is understood.

2. For every subsemigroup \( S \leq \Theta(V)^{op} \) the pair \( (S,B^*) \) is a dynamical system, where \( B^* \) is the weak star compact unit ball in the dual space \( V^* \), and \( \Theta(V)^{op} \) is the opposite semigroup (which can be identified with the adjoint) to \( \Theta(V) \). The action is jointly (separately) continuous where \( S \) carries the strong (weak) operator topology.

3. The enveloping semigroup \( E(S,B^*) \) of the system \( (S,B^*) \) is a compact right topological semigroup (it can be identified with the pointwise closure of \( S \) in \( B^*B^* \)). In particular, \( E(V) := E(\Theta(V)^{op},B^*) \) will be called the *enveloping semigroup of \( V \).* Its topological center is just \( \Theta(V)^{op}_w \) which is densely embedded into \( E(V) \). Note that \( E(V) = \Theta(V)^{op} \) iff \( V \) is reflexive.

A *representation* of a semigroup \( S \) (with identity element \( e \)) on a Banach space \( V \) is a co-homomorphism \( h : S \to \Theta(V) \), where \( \Theta(V) := \{ T \in L(V) : ||T|| \leq 1 \} \) and \( h(e) = \text{id}_V \). Here \( L(V) \) is the space of continuous linear operators \( V \to V \) and \( \text{id}_V \) is the identity operator. This is equivalent to the requirement that \( h : S \to \Theta(V)^{op} \) be a monoid homomorphism, where \( \Theta(V)^{op} \) is the opposite semigroup of \( \Theta(V) \). If \( S = G \), a group then \( h(G) \subset \text{Iso}(V) \), where \( \text{Iso}(V) \) is the group of all linear isometries from \( V \) onto \( V \).

**Definition 2.12.** [50, 23, 24, 25] Let \( X \) be a dynamical \( S \)-system.
(1) A representation of \((S, X)\) on a Banach space \(V\) is a pair
\[ h : S \rightarrow \Theta(V), \quad \alpha : X \rightarrow V^* \]
where \(h : S \rightarrow \Theta(V)\) is a weakly continuous representation (co-homomorphism) of semigroups and \(\alpha : X \rightarrow V^*\) is a weak* continuous bounded \(S\)-mapping with respect to the dual action
\[ S \times V^* \rightarrow V^*, \quad (s\varphi)(v) := \varphi(h(s)(v)). \]
We say that the representation is strongly continuous if \(h\) is strongly continuous. A representation \((h, \alpha)\) is said to be faithful if \(\alpha\) is a topological embedding.

(2) If \(S := G\) is a group then a representation of \((G, X)\) on \(V\) is a pair \((h, \alpha)\), where \(\alpha\) is as above and \(h : G \rightarrow \text{Iso}(V)\) is a group co-homomorphism.

(3) If \(\mathcal{K}\) is a subclass of the class of Banach spaces, we say that a dynamical system \((S, X)\) is \((\text{strongly})\ \mathcal{K}\)-representable if there exists a weakly (respectively, strongly) continuous faithful representation of \((S, X)\) on a Banach space \(V \in \mathcal{K}\).

(4) A dynamical system \((S, X)\) is said to be \((\text{strongly})\ \mathcal{K}\)-approximable if it can be embedded in a product of \((\text{strongly})\ \mathcal{K}\)-representable \(S\)-spaces.

**Remark 2.13.** The notion of a reflexively (Asplund) representable compact dynamical system is a dynamical version of the purely topological notion of an Eberlein (respectively, a Radon-Nikodym (RN, in short)) compactum, in the sense of Amir and Lindenstrauss (respectively, in the sense of Namioka). As in [25], we call Rosenthal representable systems Weakly Radon-Nikodym (WRN) systems.

**Remark 2.14.**

(1) Of course not every \(\mathcal{K}\)-approximable is \(\mathcal{K}\)-representable. Take for example, \((S, X)\) with \(S := \{e\}\) and \(X := [0, 1]^\mathbb{R}\). Then \((S, X)\) is clearly reflexively-approximable but not reflexively-representable (because \(X\), as a compactum, is not Eberlein).

(2) In some particular cases \(\mathcal{K}\)-approximability and \(\mathcal{K}\)-representability are equivalent. This happens for example if \(X\) is metrizable and \(\mathcal{K}\) is closed under countable \(l_2\)-sums.

(3) The classes of Eberlein, RN and WRN compact dynamical systems are closed under countable products.

**Proof.** Use the \(l_2\)-sum of representations \((h_n, \alpha_n)\) of \((S, X_n)\) on \(V_n\) where \(|\alpha_n(x)| \leq 2^{-n}\) for every \(x \in X_n\) and \(n \in \mathbb{N}\) with \(V := (\Sigma_{n=1}^{\infty} V_n)_{l_2}\). \(\square\)

(4) ("building blocks" of dynamical systems) Let \(S \times X \rightarrow X\) be a continuous action on a compact space \(X\). Then the \(S\)-system \(X\) can be \(S\)-embedded into a topological \(S\)-product \(\prod_{f \in F} X_f\) of "cyclic \(S\)-systems" \(X_f\). Here \(F \subset C(X)\) is a point separating family and \(X_f\) is defined as the Gelfand space of the algebra \(\mathcal{A}_f = \{\text{the smallest closed } S\text{-invariant subalgebra generated by } fS \text{ in } C(X)\}\). It follows that if any \(X_f\) is \(S\ \mathcal{K}\)-approximated then \(X\) is \(\mathcal{K}\)-approximated, too.
3. ACTIONS AND SEMIGROUPS

**Definition 3.1.** Let $S$ be a semitopological semigroup with a neutral element $e$. Let $\pi : S \times X \to X$ be a left action of $S$ on a topological space $X$. This means that $ex = x$ and $s_1(s_2x) = (s_1s_2)x$ for all $s_1, s_2 \in S$ and $x \in X$, where as usual, we write $sx$ instead of $\pi(s, x) = \lambda_s(x) = \rho_x(s)$. Let $S \times X \to X$ and $S \times Y \to Y$ be two actions. A map $f : X \to Y$ between $S$-spaces is an $S$-map if $f(sx) = sf(x)$ for every $(s, x) \in S \times X$.

We say that $X$ is a dynamical $S$-system (or an $S$-space or an $S$-flow) if the action $\pi$ is separately continuous (that is, if all orbit maps $\rho_x : S \to X$ and all translations $\lambda_s : X \to X$ are continuous). If otherwise is not stated we assume that $X$ is compact. We sometimes write it as a pair $(S, X)$.

A right system $(X, S)$ can be defined analogously. If $S^{op}$ is the opposite semigroup of $S$ with the same topology then $(X, S)$ can be treated as a left system $(S^{op}, X)$ (and vice versa).

**Fact 3.2.** (J. Lawson [42]) Let $G$ be a Čech-complete (e.g., locally compact or completely metrizable) semitopological group. Then every separately continuous action of $G$ on a compact space $X$ is continuous.

**Notation:** All semigroups $S$ are assumed to be monoids, i.e., semigroups with a neutral element $e$. Also actions are monoidal (meaning $ex = x, \forall x \in X$) and separately continuous. We reserve the symbol $G$ for the case when $S$ is a group.

Let $h : S_1 \to S_2$ be a semigroup homomorphism, $S_1$ act on $X_1$ and $S_2$ on $X_2$. A map $f : X_1 \to X_2$ is said to be $h$-equivariant if $f(sx) = h(s)f(x)$ for every $(s, x) \in S_1 \times X_1$. For $S_1 = S_2$ with $h = 1_S$, we say $S$-map. The map $h : S_1 \to S_2$ is a co-homomorphism if $h : S_1 \to S_2^{op}$ (the same assignment) is a homomorphism.

Given $x \in X$, its orbit is the set $Sx = \{sx : s \in S\}$ A point $x$ with $cl(Sx) = X$ is called a transitive point, and the set of transitive points is denoted by $X_{tr}$. We say that the system is point-transitive when $X_{tr} \neq \emptyset$. The system is called minimal if $X_{tr} = X$. Equivalently: any nonempty closed $S$-subsystem of $X$ is $X$.

By an (invertible) cascade on $X$ we mean a continuous action $S \times X \to X$, where $S := \mathbb{N} \cup \{0\} := \mathbb{N}_0$ is the additive semigroup of all nonnegative integers (respectively, $S = (\mathbb{Z}, +)$).

3.1. Some old and new classes of semigroups. Let $S$ be a semigroup which is also a topological space. By $\lambda_a : S \to S, x \mapsto ax$ and $\rho_a : S \to S, x \mapsto xa$ we denote the left and right $a$-transitions. The subset $\Lambda(S) := \{a \in S : \lambda_a, \rho_a \text{ continuous}\}$ is called the topological center of $S$.

**Definition 3.3.** A semigroup $S$ with a given topology is called:

1. right topological semigroup if every $\rho_a$ is continuous;
2. admissible if $S$ is right topological and $\Lambda(S)$ is dense in $S$;
3. topological if the multiplication $S \times S \to S$ is continuous;
4. topological group if $S$, algebraically, is a group, topological semigroup and if the inversion $s \mapsto s^{-1}$ is continuous.
5. semitopological if the multiplication $m : S \times S \to S$ is separately continuous (i.e., if $S$ is left and right topological);

Define two new classes of compact right topological semigroups.
**Definition 3.4.** [23, 25] A compact admissible right topological semigroup \((P, \tau)\) is said to be:

1. [25] *tame* if the left translation \(\lambda_a : (P, \tau) \to (P, \mu)\) is a fragmented map (Definition 8.1) for every \(a \in P\).
2. *HNS-semigroup* if \(\{\lambda_a : P \to P\}_{a \in P}\) is a fragmented family of maps.

These classes are closed under factors. We have the inclusions:

\(\{\text{compact semitopological semigroups}\} \subset \{\text{HNS-semigroups}\} \subset \{\text{Tame semigroups}\}\)

### 3.2. Functions with small orbits

Let \(S \times X \to X\) be an action. It induces the right action \(C(X) \times S \to C(X)\) and a co-homorphism \(h : S \to \Theta(C(X))\).

A (bounded) function \(f \in C(X)\) is said to be:

(a) *Right uniformly continuous* if the orbit map \(\tilde{f} : S \to C(X)\) is continuous; i.e.

\[ \forall \varepsilon > 0 \ \forall s_0 \in S \ \exists U \in \mathcal{N}(s_0) \ |f(sx) - f(s_0x)| < \varepsilon \ \forall x \in X, s \in U. \]

notation: \(f \in \text{RUC}(X)\). If the action is continuous and \(X\) is compact then \(\text{RUC}(X) = C(X)\).

(b) *Almost periodic* if the norm closure \(\text{cl}(fS)\) of the orbit \(fS\) is norm compact in \(C(X)\); notation: \(f \in \text{AP}(X)\).

(c) *Weakly almost periodic* if the weak closure \(\text{cl}_w(fS)\) of the orbit \(fS\) is weak compact in \(C(X)\); Notation: \(f \in \text{WAP}(X)\).

In particular we have \(\text{WAP}(S)\) for usual left action of \(S\) on itself. Note that for the right action of \(S\) on itself the corresponding (right) version of \(\text{WAP}(S)\) gives the equivalent definition [10, 6].

A compact \(S\)-space \(X\) is said to be *weakly almost periodic* if (resp., \(C(X) = \text{WAP}(X)\)) \(C(X) = \text{AP}(X)\). For any \(S\)-space \(X\) the collections \(\text{WAP}(X)\) and \(\text{AP}(X)\) are \(S\)-invariant subalgebras of \(C(X)\). The corresponding Gelfand spaces and compactifications define \(S\)-equivariant compactifications \(u_{\text{wAP}} : X \to X^{\text{WAP}}\) and \(u_{\text{AP}} : X \to X^{\text{AP}}\). The compactification \(S \to S^{\text{WAP}}\) (for \(X := S\)) is the universal semitopological semigroup compactification of \(S\).

For every topological group \(G\), treated as a \(G\)-space, the corresponding universal \(\text{AP}\) compactification is the classical *Bohr compactification* \(b : G \to bG\), where \(bG\) is a compact topological group.

(d) Let \(X\) be a compact DS. We say that \(f \in C(X)\) is *Asplund* if \(fS\) is a fragmented family (Definition 8.1) of maps \(X \to \mathbb{R}\); notation: \(f \in \text{Asp}(X)\). It is equivalent saying that \(\text{cl}_p(fS)\) is a fragmented family.

Define also, \(\text{Asp}(G) := \text{Asp}(\beta_G G)\).

(e) Let \(X\) be a compact DS. We say that \(f \in C(X)\) is *tame* if \(\text{cl}_p(fS)\) is an eventually fragmented family of maps \(X \to \mathbb{R}\); notation: \(f \in \text{Tame}(X)\). Or, equivalently, if \(fS\) does not contain an independent subsequence (Definition 8.7).

Another equivalent condition is: \(\text{cl}_p(X) \subset \mathcal{F}(X)\), where \(\mathcal{F}(X)\) is the set of all fragmented real valued functions on \(X\). (See Theorem 8.10.)
3.3. Semigroup compactifications. A good introduction to semigroup compactifications of topological groups is a work of Uspenskij [74] (downloadable from the course website). See also a book of Berglund-Junghenn-Milnes [6].

Definition 3.5. Let \( S \) be a semitopological semigroup. [6, p. 105] A right topological semigroup compactification of \( S \) is a pair \((\gamma, T)\) such that \( T \) is a compact right topological semigroup, and \( \gamma \) is a continuous semigroup homomorphism from \( S \) into \( T \), where \( \gamma(S) \) is dense in \( T \) and the left translation \( \lambda_s : T \to T, \ x \mapsto \gamma(s)x \) is continuous for every \( s \in S \), that is, \( \gamma(S) \subset \Lambda(T) \).

It follows that the associated action

\[
\pi_\gamma : S \times T \to T, \quad (s, x) \mapsto \gamma(s)x = \lambda_s(x)
\]
is separately continuous.

Example 3.6.

(1) Maximal (jointly continuous) \( G \)-compactification \( G \hookrightarrow \beta G := G^{\text{RUC}} \) (the greatest ambit). The corresponding algebra is \( \text{RUC}(G) \).

(2) Universal semitopological compactification: \( G \to wG := G^{\text{WAP}} \). The corresponding algebra is \( \text{WAP}(G) \).

(3) universal topological compact group compactification (Bohr compactification): \( G \to bG = G^{\text{AP}} \).

By [53], \( q : G^{\text{RUC}} \to G^{\text{WAP}} \) is a homeomorphism iff \( G \) is precompact.

3.4. Enveloping semigroups. For every (separately continuous) compact \( S \)-system \( X \) we have a (pointwise continuous) monoid homomorphism \( j : S \to C(X, X) \), \( j(s) = \tilde{s} \), where \( \tilde{s} : X \to X, x \mapsto sx = \pi(s, x) \) is the \( s \)-translation \( (s \in S) \).

Definition 3.7. The enveloping semigroup \( E(S, X) \) (or just \( E(X) \)) of the compact dynamical \( S \)-system \( X \) is defined as the pointwise closure \( E(S, X) = \text{cl}_p(j(S)) \) of \( \tilde{S} = j(S) \) in \( X^X \).

The associated homomorphism \( j : S \to E(X) \) is a right topological semigroup compactification (say, Ellis compactification) of \( S \), \( j(e) = \text{id}_X \) and the associated action \( \pi_j : S \times E(X) \to E(X) \) is separately continuous. Furthermore, if the \( S \)-action on \( X \) is continuous then \( \pi_j \) is continuous. \( E(X) \) is always a right topological compact monoid. Algebraic and topological properties of the families \( j(S) \) and \( E(X) \) reflect the asymptotic dynamical behavior of \( (S, X) \).

Exercise 3.8. (A concrete computation) Let \( S := \mathbb{Z} \cup \{-\infty, \infty\} \) be the two-point compactification of \( \mathbb{Z} \). Extend the usual addition by:

\[
n + t = t + n = s + t = t \quad n \in \mathbb{Z}, \ s, t \in \{-\infty, \infty\}
\]

Show:

(1) \((S, +)\) is a noncommutative compact right topological semigroup having dense topological centre \( \Lambda(S) = \mathbb{Z} \).

(2) \( S \) is topologically isomorphic to the enveloping semigroup of the invertible cascade \( (\mathbb{Z}, [0, 1]) \) generated by the homeomorphism \( \sigma : [0, 1] \to [0, 1], \sigma(x) = x^2 \).
Proof. Let $E$ be the enveloping semigroup of $(\mathbb{Z}, [0, 1])$ and $j : \mathbb{Z} \to E$ be the corresponding compactification. Observe that besides the points $j(\mathbb{Z}) = \{\sigma^n : \ n \in \mathbb{Z}\}$ the enveloping semigroup $E(X)$ contains two more points: $a, b$, where $a = \xi_{\{1\}}$ the characteristic function of $\{1\}$ and $b = 1 - \xi_{\{0\}}$, where $\xi_{\{0\}}$ is the characteristic function of $\{0\}$. □

Exercise 3.9. Is it true that $E$ from Example 3.8 is: (a) semitopological; (b) HNS; (c) Tame?

Hint: use the fact that the compactum $E$ is countable.

Remark 3.10.

(1) \{enveloping semigroups $E(S, X)$\} = \{compact right topological admissible semigroups\}.

(2) $(G, X)$ is AP (equiv., equicontinuous) iff $E$ is a group of continuous maps.

(3) (Ellis-Nerurkar [16]) $X$ is a WAP system iff every $p \in E$ is a continuous map $X \to X$.

(4) Enveloping semigroup $E(\mathbb{Z}, \Omega)$ of the Bernoulli shift symbolic system $\Omega := \{0, 1\}^{\mathbb{Z}}$ is $\beta\mathbb{Z}$.

Sketch: To see this recall that the collection $\{\bar{A} : A \subset \mathbb{Z}\}$ is a basis for the topology of $\beta\mathbb{Z}$ consisting of clopen sets. Next identify $\Omega$ with the collection of subsets of $\mathbb{Z}$ in the obvious way: $A \leftrightarrow 1_A$. Now define an “action” of $\beta\mathbb{Z}$ on $\Omega$ by:

$$p * A = \{g \in \mathbb{Z} : g^{-1}p \in \overline{A^{-1}}\}.$$  

This action extends the action of $\mathbb{Z}$ on $\Omega$ and defines an isomorphism of $\beta\mathbb{Z}$ onto $E(\Omega)$.

(5) If $\sigma : [0, 1] \to [0, 1], t \mapsto 4t(1 - t)$ then for the corresponding cascade $\mathbb{N}_0 \times [0, 1] \to [0, 1]$ the enveloping semigroup $E$ topologically contains $\beta\mathbb{N}$. (So, also in this case $E$ is not a Frechet topological space.)

Below we answer the questions: for which compact metrizable dynamical systems the enveloping semigroup is: (a) metrizable; (b) Frechet.

3.5. Enveloping semigroups of Banach spaces.

Definition 3.11. Given a Banach space $V$ we denote by $\mathcal{E}(V)$ the enveloping semigroup of the dynamical system $(\Theta(V)^{op}, B^*)$. We say that $\mathcal{E}(V)$ is the enveloping semigroup of $V$.

In the sequel whenever $V$ is understood we use the following simple notations $\mathcal{E} := \mathcal{E}(V), \Theta := \Theta(V), \Theta^{op} := \Theta(V)^{op}$. By $S_V$ we denote the unit sphere of $V$.

Lemma 3.12. [27] For every Banach space $V$, every $v \in S_V$ and $\psi \in S_{V^*}$ we have

(1) $\Theta v = B$.

(2) $v\mathcal{E} = B^{**}$.

(3) $cl_w(\Theta^{op}\psi) = B^*$.

(4) $\mathcal{E}\psi = B^*$.

(5) $A(\mathcal{E}) = \Theta^{op}$.

(6) $V$ is reflexive iff $\mathcal{E} = \Theta^{op}$ iff $\mathcal{E}$ is semitopological.

Some DS results below will lead us to
Theorem 3.13. Let $V$ be a separable Banach space.
(1) $V$ is Asplund iff $E$ is metrizable.
(2) $V$ is Rosenthal iff $E$ is Frechet.

Theorem 3.14. Let $V$ be a (not necessarily separable) Banach space.
(1) $V$ is Asplund iff $E$ is HNS semigroup.
(2) $V$ is Rosenthal iff $E$ is a tame semigroup.

4. Representations of topological groups I

By a (t-faithful) representation of a topological group $G$ on a Banach space $V$ we mean a continuous homomorphism (resp., topological group embedding) $h : G \to \text{Iso}(V)$ of $G$ into the top. group $\text{Iso}(V)$ of all linear onto isometries of $V$ with SOT.

Every (topological) group is topologically isomorphic to its opposite group by the assignment $g \mapsto g^{-1}$. Hence, $G$ is representable on $V$ iff it is co-representable on $V$.

Problem 4.1. Which (Polish) groups can be represented on nice Banach spaces ?

Let $\mathcal{K} \subset \text{Ban}$ be a subclass of Banach spaces. We write: $G \in \mathcal{K}_r$ if $\exists$ a t-faithful representation of $G$ on $V \in \mathcal{K}$.

\[
\mathcal{TGr} = \text{Ban}_r \supset \text{Ros}_r \supset \text{Asp}_r \supset \text{Ref}_r \supset \text{Hilb}_r \supset \{\text{LC top. gr.}\}
\]

Remark 4.2.
(1) (Teleman’s theorem) Any topological group $G$ is Banach representable.
(2) (Gelfand-Raikov) Every locally compact group is Hilbert representable. If $G$ is a locally compact topological group then the regular representation of $H = L_2(G, \mu)$ (where $\mu$ is the Haar measure) defines an embedding $G \hookrightarrow \text{Iso}(H)$.
(3) (Me [49]) $G := L_4([0,1]) \in \text{Ref}_r \setminus \text{Hilb}_r$ (For proofs see Section 14).
(Glasner-Weiss 2012) $\exists G \in \text{Ref}_r \setminus \text{Hilb}_r$ s.t. $G = l_2/D$ is Polish monothetic.
(4) Unknown if: $\text{Asp}_r = \text{Ref}_r$, $\text{Ban}_r = \text{Ros}_r$.

It is an open question if every Polish group is Rosenthal representable (enough to examine the universal Polish group $G := \text{Homeo}([0,1]^\mathbb{N})$).

Remark 4.3.
(1) (Me 2001) $\mathcal{TGr} \not\supset \text{Ref}_r$, $H_+[0,1] \not\in \text{Ref}_r$.
\[
\forall \text{ representation } h : H_+ \to \text{Iso}(V) \text{ is trivial } \forall V \in \text{Ref}_r.
\]
\[
\forall \text{ metrizable semigroup compactification of } H_+ \text{ is trivial.}
\]
(2) (Gl-Me 2007, independently also by Uspenskij)
\[
\forall \text{ representation } h : H_+ \to \text{Iso}(V) \text{ is trivial } \forall V \in \text{Asp}_r.
\]
\[
\forall \text{ metrizable semigroup compactification of } H_+ \text{ is trivial.}
\]
(3) $\exists$ a proper semigroup compactification $H_+ \to S$ which is Fréchet (in fact, topologically $S \subset M_+([0,1], [0,1] = \text{Helly compactum})$.

Theorem. (Gl-Me 2012) $\text{Ros}_r \not\supset \text{Asp}_r$.
The Polish topological group $H_+[0,1]$ is representable on a separable Rosenthal Banach space (and not representable on any Asplund space – 2007).
(Well known) There exists a separable Rosenthal Banach space which is not Asplund.

**Remark 4.4. (Ferri-Galindo)** The topological group $c_0$ is not reflexively representable.

Note that $c_0$ as a Banach space is Asplund (because, $c_0^* = l_1$ is separable). However the following concrete question is open

**Question 4.5.** Is it true that $c_0$ is Asplund representable?

**Question 4.6. (Ferri-Galindo)** Is it true that for every abelian topological group $G$ there exists a continuous injective representation $h : G \rightarrow \text{Iso}(V)$ with reflexive $V$?

**Question 4.7.** When $G$ can be embedded into a good right topological compact semigroup $P$? For example: when $P$ can be semitopological, metrizable, Frechet, ...?

4.1. **Elementary observations.**

**Exercise 4.8.** Every locally compact topological group is closed in every Hausdorff topological group.

For example, $\mathbb{Z}$ and $\mathbb{R}$ cannot be embedded into compact groups. In particular, such groups do not admit finite dimensional orthogonal representations $h : G \hookrightarrow O_n(\mathbb{R})$ where $h$ is an embedding. More precisely, we have

**Fact 4.9.** Let $G$ be a topological group. The following are equivalent:

1. $G$ can be embedded into a compact topological semigroup.
2. $G$ can be embedded into a compact group (i.e., the Bohr compactification $b : G \rightarrow bG$ is an embedding).
3. $G$ is embedded into a product of finite dimensional orthogonal group $O_n(\mathbb{R})$.

The equivalence of (1) and (3) is a consequence of Peter-Weyl theorem. The equivalence of (1) and (2) easily follows from the following

**Exercise 4.10.** If $S$ is a compact topological semigroup and if $G$ is a subgroup of $S$ then $cl(G)$ is a (compact) topological group.

**Exercise 4.11.** Let $(G, \cdot, \tau)$ be a locally compact non-compact Hausdorff topological group. Denote by $S := G \cup \{\infty\}$ the 1-point compactification of $G$. Recall the topology

$$
\tau_\infty := \tau \cup \{S \setminus K : K \text{ is compact in } G\}.
$$

Show that $(S, \cdot, \tau_\infty)$ is a semitopological but not a topological semigroup.

**Corollary 4.12.** Let $G$ be a locally compact group. Then

1. $G$ is embedded into a topological semigroup iff $G$ is compact.
2. $G$ is embedded into a compact semitopological semigroup.

**Theorem 4.13. (Ellis thm)** Every (locally) compact semitopological group is a topological group.
4.2. Examples of topological (semi)groups.

Exercise 4.14. Prove that:

1. for every metric space \((M, d)\) the semigroup \(S := \Theta(M, d)\) of all contractive maps \(f : X \to X\) (that is, \(d(f(x), f(y)) \leq d(x, y)\)) is a topological monoid with respect to the topology of pointwise convergence;
2. the group \(\text{Iso}(M)\) of all onto isometries is a topological group;
3. the evaluation map \(S \times M \to M\) is a continuous monoidal action.

Exercise 4.15. Let \(Y\) be a compact space. Show that:

1. The semigroup \(C(Y, Y)\) endowed with the compact open topology is a topological monoid;
2. The subset \(H(Y)\) in \(C(Y, Y)\) of all homeomorphisms \(Y \to Y\) is a topological group;
3. For every subsemigroup \(S \subset C(Y, Y)\) the induced action \(S \times Y \to Y\) is continuous;
4. Furthermore, it satisfies the following remarkable minimality property. If \(\tau_0\) is an arbitrary topology on \(S\) such that \((S, \tau_0) \times Y \to Y\) is continuous then \(\tau_{co} \subset \tau_0\).

4.3. Operator topologies.

Definition 4.16. Let \(V\) be a Banach space. The strong operator topology (SOT) on \(L(V, V)\) is the pointwise topology inherited from \((V, \| \cdot \|)^V\). That is, a net \(s_i\) converges to \(s\) iff \(s_i(v)\) converges to \(s(v)\) in the norm topology for every \(v \in V\).

Replacing the norm topology of \(V\) by its weak topology we obtain the weak operator topology (WOT). A net \(s_i\) in \((L(V, V), \text{WOT})\) converges to \(s\) iff \(f(s_i(v))\) converges to \(f(s(v))\) in \(\mathbb{R}\) for every given pair of vectors \((v, f) \in V \times V^*\).

Exercise 4.17. Prove that:

1. \(\Theta(V)\) and \(L(V, V)\) are semitopological monoids with respect to WOT.
2. The semigroup \(\Theta(V)\) endowed with the SOT is a topological monoid. The subspace \(\text{Iso}(V)\) of all linear onto isometries is a topological group.

Recall that (by Theorem 2.7) WOT=SOT on \(\text{Iso}(V)\) for reflexive \(V\). Below in Theorem 13.3 we show this for a large class of Banach spaces (PCP).

It is well known (de Leeuw-Glicksberg [13]) that \(\Theta(V)_w\) is a compact (semitopological) semigroup for every reflexive \(V\). One may show that this property characterizes reflexive spaces.

Lemma 4.18. For any Banach space \(V\) and any given norm 1 vector \(v \in S_V\) the map

\[\Theta(V)_w \to (B, w), \ s \mapsto sv\]

is onto (and continuous).

Proof. Take \(f \in S_{V^*}\) such that \(f(v) = 1\). For every \(z \in B\) define the rank 1 operator \(z \otimes f : V \to V, \ x \mapsto f(x)z\).

Then \(z \otimes f(v) = z\) and \(z \otimes f \in \Theta\) since \(\|z \otimes f\| = \|f\| \cdot \|z\| = \|z\| \leq 1\). □

\(^2\)In another terminology: Lipschitz 1 maps
Proposition 4.19. The following are equivalent:

1. $V$ is reflexive;
2. $B := B_V$ is weakly compact;
3. $\Theta(V)_w$ is compact.

Proof. (1) $\iff$ (2) is a well known criterion.

(2) $\implies$ (3) $\Theta(V) \subset (B, w)_B$ is a closed subset. Apply now Tychonoff Theorem.

(3) $\implies$ (2) Is a corollary of Lemma 4.18. □

Every left action $\pi : S \times X \to X$ induces the co-homomorphism $h_\pi : S \to C(X)$ and the right action $C(X) \times S \to C(X)$ where $(fs)(x) = f(sx)$. While the translations $\tilde{s} : V \to V$ are continuous, the orbit maps $\tilde{f} : S \to C(X)$ are not necessarily norm (even weakly) continuous and require additional assumptions for their continuity. As before denote by $\text{RUC}(X)$, the set of all functions $f \in C(X)$ such that the orbit map $\tilde{f}$ is norm continuous.

For every normed space $V$ the usual adjoint map $\text{adj} : L(V) \to L(V^*)$, $s \mapsto s^*$ is an injective co-homomorphism of monoids. Sometimes we write simply $s$ instead of $s^*$.

Lemma 4.20. For every normed space $V$ the injective map 
$$\gamma : \Theta(V)^{\text{op}} \to C(B^*, B^*)$$
induced by the adjoint map $\text{adj} : L(V) \to L(V^*)$, is a topological (even uniform) monoid embedding. In particular,
$$\Theta(V)^{\text{op}} \times B^* \to B^*$$
is a jointly continuous monoidal action of $\Theta(V)^{\text{op}}$ on the compact space $B^*$.

Proof. The strong uniformity on $\Theta(V)$ is generated by the family of pseudometrics
$$\{ p_v : v \in V \}$$
where $p_v(s, t) = ||sv - tv||$. On the other hand the family of pseudometrics
$$\{ q_v : v \in V \}$$
where $q_v(s, t) = \sup\{|(fs)(v) - (ft)(v)| : f \in B^*\}$ generates the natural uniformity inherited from $C(B^*, B^*)$. Now observe that $p_v(s, t) = q_v(s, t)$ by the Hahn-Banach theorem. This proves that $\gamma$ is a uniform (and hence, also, topological) embedding. □

Corollary 4.21. Let $V$ be a Banach space. Suppose that $\pi : V \times S \to V$ is a right action of a topologized semigroup $S$ by linear contractive operators. The following are equivalent:

(i) The co-homomorphism $h : S \to \Theta(V)$, $h(s)(v) := vs$ is strongly continuous.
(ii) The induced affine action $S \times B^* \to B^*$, $(s \psi)(v) := \psi(vs)$ is jointly continuous.

For a compact space $X$ we denote by $H(X)$ the topological group of all self-homeomorphisms of $X$ endowed with the compact open topology.

Lemma 4.22. Let $X$ be a compact $G$-space, where $G$ is a topological subgroup of $H(X)$. Assume that $(h, \alpha)$ is a faithful representation (that is, $\alpha : X \to (V^*, w^*)$ is an embedding) of $(G, X)$ on a Banach space $V$. Then $h$ is a topological group embedding.
4.4. **Theorems of Teleman and Uspenskij.** Teleman’s theorem below 4.25 shows that any topological group is represented on a Banach space by linear isometries.

For example, every finite group $G$ can be represented on $\mathbb{R}^n$ with $n = |G|$. Indeed, take

$$G \hookrightarrow S_n \hookrightarrow \text{Iso}(\mathbb{R}^n) = O_n(\mathbb{R}).$$

**Exercise 4.23.** Every discrete group $G$ admits an effective isometric representation on the Banach space $l_\infty(G)$ and also on the Hilbert space $H := l_2(G)$. So, on $l_\infty := l_\infty(\mathbb{N})$ and on $l_2 := l_2(\mathbb{N})$ if $G$ is countable.

For every compact space $K$ we have the Gelfand representation $\delta : K \hookrightarrow C(K)^\ast$. Now let $S \times K \to K$ be a continuous action. The induced action $C(K)^\ast \times S \to C(K)^\ast$ is linear, norm-preserving and continuous. We obtain a natural representation $(h, \delta)$, where $h : S \to \Theta(V)$ is a strongly continuous co-homomorphism of monoids. Call it the Teleman’s representation. This is a dynamical version of Gelfand’s representation.

**Theorem 4.24.** [70] Let $S \times K \to K$ be a continuous action on a compact space $K$. Then

1. Teleman’s representation $(h, \delta)$ of the dynamical system $(S, K)$ on the Banach space $V = C(K)$ is faithful and strongly continuous. That is, $h : S \to \Theta(V)^\ast_s$ is continuous. If $S = G$ is a group then $h$ is a co-homomorphism of groups $h : G \to \text{Iso}(V)^\ast_s$;

2. Moreover, if $S$ carries the compact open topology inherited from $C(K, K)$ then the homomorphisms $S \to C(B^\ast, B^\ast)$ and $h : S \to \Theta(V)^\ast_{op}$ are topological embeddings.

**Proof.** (1) The induced right linear action $C(K)^\ast \times S \to C(K)^\ast$ is continuous (because the orbit maps are norm continuous). This action is contractive ($||fs|| \leq 1||$ for every $f \in C(X)$). It follows that $h : S \to \Theta(V)^\ast_{op}$ is a well defined strongly continuous homomorphism. Clearly, $B^\ast$ is an $S$-subset under the dual action. By Lemma 4.20 we obtain that the action $S \times B^\ast \to B^\ast$ is continuous. Furthermore, $h$ is injective (because, if $s_1 \neq s_2$ are distinct elements of $S \subset C(X, X)$ then $s_1x \neq s_2x$ for some $x \in X$). Choose $f \in C(X)$ such that $f(s_1x) \neq f(s_2x)$. Then $f(s_1) \neq f(s_2)$. It is straightforward to see that $\alpha(sx) = h(s)(\alpha(x))$ for every $s \in S, x \in X$. So, $(h, \alpha)$ is equivariant.

(2) Let $S \subset C(K, K)$. Denote by $\tau_0$ the induced topology on $S$. The action $S \times K \to K$ can be treated as a restriction of the bigger action $S \times B^\ast \to B^\ast$, where $K$ naturally is embedded into $B^\ast$ via Gelfand’s map. Then the topology $\tau$ on $S$ inherited from $C(B^\ast, B^\ast)$ majors the original topology $\tau_0$. Hence, $\tau_0 \subset \tau$.

On the other hand, the continuity of $(S, \tau_0) \times B^\ast \to B^\ast$ easily implies (minimality property in Exercise 4.15.4) that $\tau \subset \tau_0$ on $S$. Summing up we conclude that $\tau = \tau_0$ on $S$.

**Theorem 4.25.** (Teleman’s theorems) Let $G$ be a topological group. Then

1. $G$ is embedded into $\text{Iso}(V)$ for some Banach space $V$.
2. $G$ is embedded into $\text{Iso}(M, d)$ for some metric space $(M, d)$.
3. $G$ is embedded into $\text{Homeo}(K)$ for some compact space $K$.

**Proof.** Clearly, (1) $\Rightarrow$ (2). By Theorem 4.24, (3) $\Rightarrow$ (1). So it is enough to show (3).
The left action $G \times G \to G$ is $G$-compactifiable. The algebra $RUC(G)$ separates the points and closed subsets. Then the maximal $G$-compactification $G \to \beta_G G$ is an embedding and $G \hookrightarrow H(K)$, where $K := \beta_G G$.

**Theorem 4.26.** [51] (universal small actions) Let $K := [0,1]^N$ be the Hilbert cube. Denote by $U := C(K,K)$ the topological monoid and the natural action $U \times K \to K$. Then this action is universal for all monoidal actions on compact metrizable spaces. The pair $(H(K),K)$ is universal for continuous group actions on compact metrizable spaces.

[That is, for every compact metrizable $X$ and a topological submonoid $S$ of $U$ there exists an equivariant pair $(h,\alpha) : (S,X) \Rightarrow (U,I^\omega)$ such that $h : S \hookrightarrow U$ is an embedding of topological semigroups and $\alpha : X \hookrightarrow I^\omega$ is a topological embedding.]

**Proof.** Use Equivariant Teleman’s representation on $V := C(K)$ and the fact that by Keller’s theorem $B^\ast = (B^\ast \ast, w^\ast)$ is homeomorphic to the Hilbert cube $K$ for every separable $V$.

**Corollary 4.27.** (Uspenskij [73]) $H([0,1]^N)$ is a universal Polish topological group.

5. **Matrix coefficients**

For every $h : S \to L(V,V)$ and any pair of vectors $v \in V$ and $\psi \in V^\ast$, we have a canonically associated (generalized) matrix coefficient

$$m_{v,\psi} : S \to \mathbb{R}, \quad s \mapsto <vs,\psi> = <v,s\psi>$$

![Diagram](https://via.placeholder.com/150)

Easy to adopt this definition for any bilinear mappings $V \times W \to \mathbb{R}$ and a pair of compatible (co)-homomorphisms from $S$ to $L(V,V)$ and to $L(W,W)$.

**Remark 5.1.** In order to justify the name ”matrix coefficient” note the following. For $V = \mathbb{R}^n$ (rows $1 \times n$) consider $V^\ast$ (columns $n \times 1$) and $v = e_i \in V$ and $w = e_j^\prime \in V^\ast$ taken from the standard basis.

Then for a matrix $A = (a_{ij})_{n \times n}$ we have

$$a_{ij} = <e_i \cdot A, e_j^\prime> = e_i \cdot A \cdot e_j^\prime$$

(where $<v, w> := v \cdot w$ matrix multiplication).

**Exercise 5.2.** Let $h : S \to \Theta(V)$ be a co-homomorphism. The following are equivalent:

1. $h$ is weakly continuous;
2. The action $S \times B^\ast \to B^\ast$ is separately continuous (where $B^\ast := (B^\ast, w^\ast)$);
3. Every (matrix coefficient) $m_{v,\psi} : S \to \mathbb{R}, \quad s \mapsto <vs,\psi>$ is continuous for any $(v,\psi) \in V \times V^\ast$. 

It is natural to expect that matrix coefficients reflect good properties of flow representations. We recall two well-known facts. The first example is the case of Hilbert representations. Let $h : G \to \mathrm{Iso}(H)$ be a continuous homomorphism, where $H$ is Hilbert with its scalar product $H \times H \to \mathbb{R}$. Then the corresponding matrix coefficient $m_{u,v}$ is the so-called Fourier-Stieltjes functions on $G$. If $u = v$, then we get positive definite functions on $G$. The converse is also true: every continuous positive definite function comes from some continuous Hilbert representation. Recall that a continuous bounded function $f : G \to \mathbb{R}$ is said to be positive definite if $\sum \alpha_i \alpha_j f(g_i^{-1}g_j) \geq 0$ for all $\alpha_1, \ldots, \alpha_n \in \mathbb{R}$, $g_1, \ldots, g_n \in G$. Every positive definite function is WAP.

The second example comes from Eberlein (see [6, Examples 1.2.f]). If $V$ is reflexive, then every bounded $V$-representation $(h, \alpha)$ and arbitrary pair $(v, \psi)$ lead to a weakly almost periodic function $m_{v,\psi}$ on $S$. This follows easily by the (weak) continuity of the natural operators defined by the following rule. For every fixed $\psi \in V^*$ $(v \in V)$ define

$$ L_\psi : V \to C(S) \text{ and } R_\psi : V^* \to C(S), \text{ where } L_\psi(v) = R_\psi(\psi) = m_{v,\psi}. $$

We say that a vector $v \in V$ is strong (weak) continuous if the corresponding orbit map $\tilde{v} : S \to V, \tilde{v}(s) = vs$, defined through $h : S \to \Theta(V)$, is strongly (weakly) continuous.

**Fact 5.3.** Let $h : S \to \Theta(V)$ be a weakly continuous co-homomorphism (homomorphism). Then

1. $L_\psi : V \to C(S)$ is a linear bounded $S$-operator between right (left) $S$-actions.
2. If $v \in V$ is strong continuous, then $m_{v,\psi}$ is right uniformly continuous on $S$.
   If $\psi$ is norm continuous then $m_{v,\psi}$ is left uniformly continuous on $S$.

**Proof.** (1) Is straightforward.

(2) In order to establish that $m_{v,\psi} \in \text{RUC}(S)$, observe that

$$ |m_{v,\psi}(st) - m_{v,\psi}(s_0t)| = |<vst, \psi> - <vs_0t, \psi>| = |<vs, t\psi> - <vs_0, t\psi>| \leq ||vs - vs_0|| \cdot ||t\psi|| = ||vs - vs_0||. $$

The second case is similar. \hfill \Box

**Fact 5.4.** Let $(h, \alpha) : (S, X) \Rightarrow (\Theta(V)^{opp}, B^*)$ be an equivariant pair with weak* continuous $\alpha$.

1. The map $T : V \to C(X), v \mapsto T(v)$, where $T(v) : X \to \mathbb{R}$ is defined by

$$ T(v)(x) = < v, \alpha(x) > $$

is a linear $S$-operator (between right $S$-actions) with $||T|| \leq 1$.
2. $T(v_0) \in \text{RUC}(X)$ for every strongly continuous vector $v_0$ in $V$. Hence, if $h$ is strongly continuous then $T(V) \subset \text{RUC}(X)$.
3. If $V$ is reflexive, then $T(V) \subset \text{WAP}(X)$.

**Proof.** (i) Is straightforward.

(ii) Observe that $||\alpha(x)|| \leq 1$ for every $x \in X$. We get

$$ ||T(v_0)s - T(v_0)s_0|| = \sup\{|<v_0s - v_0s_0, \alpha(x)> : x \in X\} \leq ||v_0s - v_0s_0|| \cdot ||\alpha(x)|| \leq ||v_0s - v_0s_0||. $$

This implies that $T(v_0) \in \text{RUC}(X)$.
(iii) If $V$ is reflexive, the orbit $vS$ is relatively weakly compact for each $v \in V$. By the (weak) continuity of the $S$-operator $T$, the same is true for the orbit of $T(v)$ in $C(X)$. Therefore we get $T(v) \in \text{WAP}(X)$.

Proposition 5.5. For every $S$-flow $X$ the following are equivalent:

1. $f \in \text{RUC}(X)$.
2. There exist: a Banach space $V$, a strongly continuous antihomomorphism $h : S \to \Theta(V)$, a weak* continuous equivariant map $\alpha : X \to B^*$, and a vector $v \in V$ such that
   
   $$f(x) = <v, \alpha(x)> = T(v)(x).$$

Proof. (1) $\implies$ (2) The function $f$ belongs to an $S$-invariant Banach subalgebra $\mathcal{A}$ of $\text{RUC}_S(X)$. The right action of $S$ on $V := \mathcal{A}$ is jointly continuous. Then by Corollary 4.21, corresponding left action of $S$ on the dual ball $(B^*, w^*)$ is jointly continuous. Then the naturally associated map $\alpha : X \to B^*$ and the vector $v := f$ satisfy the desired property.

(1) $\iff$ (2) Immediate by Fact 5.4 (ii).

Proposition 5.6. For every semitopological monoid $S$ the following are equivalent:

1. $f \in \text{RUC}(S)$.
2. There exist: a Banach space $V$, a strongly continuous antihomomorphism $h : S \to \Theta(V)$, and a pair of vectors $v \in V$ and $\psi \in V^*$ such that $f = m_{v,\psi}$.

If $G$ is a topological group then $h(G) \subset \text{Is}(V)$.

Proof. (1) $\implies$ (2) Consider the Gelfand compactification $u_R : S \to S^{\mathcal{R}}$ defined by $\text{RUC}(S) = C(S^{\mathcal{R}})$. Then the action $S \times S^{\mathcal{R}} \to S^{\mathcal{R}}$ is jointly continuous. Now define: $V := C(S^{\mathcal{R}})$, corresponding strongly continuous $h : S \to \Theta(V)$ (induced by the right action of $S$ on $C(S^{\mathcal{R}})$), $v := f \in V$ and $\psi = u_R(e) \in V^*$.

(1) $\iff$ (2) Immediate by Fact 5.3.2.

So we see that every right uniformly continuous function on a (semi)group can be represented as a matrix coefficient $m_{v,\psi}$ of some strongly continuous Banach representation. We mentioned also that a positive definite function on a topological group $G$ is a matrix coefficient of some Hilbert representation. One of our aims is to understand the role of matrix coefficients for reflexive, Asplund and Rosenthal representations. We show that wap functions are exactly the reflexive matrix coefficients. In the “Asplund case” this approach leads to a definition of Asplund functions. For ”Rosenthal case” we will get the so-called tame (regular (Kohler [41]) functions.

6. Reflexive spaces and WAP systems

6.1. Double Limit Property. Let $F, X, Y$ be topological spaces and $w : F \times X \to Y, w(f, x) := f(x)$ be a function. We say that $F$ has the Double Limit Property (DLP) on $X$ if for every sequence $\{f_n\} \subset F$ and every sequence $\{x_m\} \subset X$ the limits

$$\lim_n \lim_m f_n(x_m) \quad \text{and} \quad \lim_m \lim_n f_n(x_m)$$

are equal whenever they both exist.

Example 6.1. Let $V$ be a reflexive space. Then $B$ has DLP on $B^*$.
Proof. By Eberlein-Shmuelian theorem $B$ and $B^*$ in their weak topologies are sequentially compact. □

**Theorem 6.2.** (Raynaud [62, Prop. 1.1], Krivine-Maurey [40, Theorem II.3] for metrizable $X$, $F$) Let $w : F \times X \to \mathbb{R}$ be a separately continuous bounded function with compact spaces $F$ and $X$. Then it can be represented on a reflexive space. That is, there exists a reflexive space $V$ and weak continuous maps $\nu : F \to V$, $\alpha : X \to V^*$ such that $<\nu(f), \alpha(x)> = w(f, x)$.

**Remark 6.3.** One may refine these results (even keeping the general action setting) as follows. The fundamental DFJP-factorization construction from [11] has an “isometric modification” [43]. Taking into account this modification note that we can prove a little bit more. Namely, if the given family $F \subset C(X)$ is bounded by constant 1, then we can assume that $\nu(F) \subset B$ and $\alpha(X) \subset B^*$. Hence the following sharper diagram commutes:

$$
\begin{array}{c}
F \times X \quad \xrightarrow{\nu} \quad [-1,1] \\
\downarrow \quad \downarrow \quad \downarrow \\
B \times B^* \quad \xrightarrow{id} \quad [-1,1]
\end{array}
$$

For more details see [27].

**Corollary 6.4.** Let $F$ and $X$ are compact spaces and $w : F \times X \to \mathbb{R}$ be a separately continuous bounded function. Then:

1. $F$ has DLP on $X$;
2. The induced (bounded) images $j_1(F) \subset C_p(X)$ and $j_2(X) \subset C_p(F)$ are Eberlein compacta (hence, Frechet and sequentially compact).

Note that (1) admits also a direct proof easily reducing the proof to the case of metrizable $F$, $X$.

**Lemma 6.5.** (Grothendieck) Let $X$ be a compact space. Then a bounded subset $F$ of $C(X)$ is weakly compact iff $F$ is pointwise compact.

**Proof.** By Lebesgue dominated convergence theorem it follows that any pointwise converging bounded sequence in $C(X)$ is weakly converging. So, $id : (F, p) \to (F, w)$ is sequentially continuous. The evaluation map $(F, p) \times X \to \mathbb{R}$ is separately continuous. Therefore, $(F, p)$ is a Frechet compactum (Corollary 6.4). So we obtain that the pointwise and weak topologies on $F \subset C(X)$ are the same. □

**Lemma 6.6.** (Grothendieck; see for example [6, Appendix A]) Let $F$ be a bounded subset in a Banach space $V$. The following are equivalent:

1. The weak closure of $F$ in $V$ is weakly compact;
2. $F$ has DLP on $B^*$.

**Theorem 6.7.** Let $V$ be a Banach space. The following conditions are equivalent:

1. $V$ is reflexive.
2. $B$ has DLP on $B^*$.
3. every bounded subset $F \subset V$ has DLP on every bounded $X \subset V^*$.
4. $B \subset V$ is weakly compact.
Proof. (1) ⇒ (2) As in Example 6.1 use Eberlein-Shmulian theorem.

(2) ⇒ (3) Is trivial.

(3) ⇒ (4) Apply Lemma 6.6.

(4) ⇒ (1) $B_V$ is $w^*$-closed in $V^{**}$. By Goldstine’s theorem the $w^*$-closure of $B_V$ in $V^{**}$ is $B^{**} := B_{V^{**}}$. Hence, $B = B^{**}$. This implies directly that $V = V^{**}$. □

Exercise 6.8. Let $X$ be a compact space and $F \subset C(X)$ be a bounded subset. Show that $F$ has DLP on $X$ iff $F$ has DLP on $B^*$, where $B^* = B_{C(X)^*}$.

6.2. WAP dynamical systems. Given a function $f \in C(X)$ we consider its orbit $fS := \{f \circ \tilde{s} : s \in S\} \subset C(X)$. For every $f \in C(X)$ the function $E \to \mathbb{R}^X$, $s \mapsto fs$ is pointwise continuous. So we have $fE = \text{cl}_p(fS)$.

One may estimate the dynamical complexity of $f$ by considering the pointwise compact subset $\text{cl}_p(fS)$ in $\mathbb{R}^X$. Various kinds of “smallness” of this compactum leads to a natural hierarchy. The classical example is (weakly) almost periodic functions.

Definition 6.9. Let $X$ be a compact $S$-system.

(1) $f \in C(X)$ is said to be WAP if one of the following equivalent conditions is satisfied:
   
   (a) $fS$ is weakly precompact in $C(X)$;
   
   (b) $\text{cl}_p(fS) \subset C(X)$;
   
   (c) $fS$ has DLP on $X$.

(2) $(S, X)$ is said to be WAP if one of the following equivalent conditions is satisfied:

   (a) every member $p \in E(S, X)$ is a continuous function $X \to X$;
   
   (b) WAP$(X) = C(X)$.

The equivalences can be verified using Grothendieck’s classical results. See for example, [6, Theorem A4] and [6, Theorem A5]. If $X$ is metrizable (or, sequentially compact) then (a) and (b) in (2) are equivalent to the condition: (c) $S \times X \to X$ has DLP.

The following characterization of WAP dynamical systems is due to Ellis and Nerurkar [16].

Theorem 6.10. Let $X$ be a compact $S$-dynamical system. The following conditions are equivalent.

(1) $(S, X)$ is WAP.

(2) The enveloping semigroup $E(S, X)$ consists of continuous maps. That is, $E(S, X) \subset C(X, X)$.

Proof. (1) ⇒ (2) By Definition 6.9, $\text{cl}_p(fS) \subset C(X)$ for every $f \in C(X) = \text{WAP}(X)$. Therefore, $fp : X \to \mathbb{R}$ is continuous for every $f \in C(X)$ and $p \in E(X)$. Since $X$ is compact this guarantees that every $p : X \to X$ is continuous.

(2) ⇒ (1) If $E \subset C(X, X)$ then $fE = \text{cl}_p(fS) \subset C(X)$. By Grothendieck’s Lemma 6.5, $\text{cl}_p(fS)$ is weakly compact. Hence, $f \in \text{WAP}(X)$. □

Corollary 6.11. When $(S, X)$ is WAP the enveloping semigroup $E(X)$ is a semi-topological semigroup. The converse holds if in addition we assume that $(S, X)$ is point transitive.

Example 6.12.
(1) (Eberlein, see for example [6, Examples 1.2.f]) If $V$ is reflexive, then every weakly continuous representation $(h, \alpha)$ of an $S$-system $X$ on $V$ and every pair $(v, \psi) \in V \times V^*$ lead to a weakly almost periodic function $m_{v, \psi}$ on $S$. This follows easily by the (weak) continuity of the bounded operator $L_\psi : V \to C(S)$, where $L_\psi(v) = m_{v, \psi}$.

(2) Analogously, every $v \in V$ (with reflexive $V$) defines a WAP function $T_v : X \to \mathbb{R}$ on the $G$-system $X$ which naturally comes from the given dynamical system representation $(h, \alpha)$. Precisely, define

$$T(V) = T_v : X \to \mathbb{R}, \quad x \mapsto \langle v, \alpha(x) \rangle.$$ 

Then the set of functions $\{T_v\}_{v \in V}$ is a subset of $WAP(X)$.

**Proof.** (1) If the orbit of $vS$ is relatively weakly compact in $V$. Then $L_\psi(vS) = m_{v, \psi}S$ is relatively weakly compact in $C(S)$. Thus, $m_{v, \psi} \in WAP(S)$.

For the case when $h$ is a "homomorphism" recall (see [10] or [6]) that $fS$ is weakly precompact iff $Sf$ is weakly precompact in $C(S)$.

(2) Is similar. □

If in (2) $\alpha$ is an embedding (which implies that $X$ is reflexively representable) then it follows that the collection $\{T_v\}_{v \in V}$ (and hence also $WAP(X)$) separates the points of $X$. If, in addition, $X$ is compact it follows that $WAP(X) = C(X)$ (because $WAP(X)$ is always a closed subalgebra of $C(X)$). That is, in this case $(S, X)$ is WAP in the sense of Ellis and Nerurkar.

The converses of Example 6.12 is also true as we show below.

**Theorem 6.13.** [50] Let $S \times X \to X$ be a separately continuous action of a semitopological semigroup $S$ on a compact space $X$. For every $f \in WAP(X)$ there exist: a reflexive space $V$, a functional $\phi \in V^*$ and an equivariant pair

$$(h, \alpha) : (S, X) \to (\Theta(V), B_V)$$

such that $h : S \to \Theta(V)$ is a weakly continuous homomorphism, $\alpha : X \to B_V$ is a weakly continuous $S$-map, and $f(x) = \langle \phi, \alpha(x) \rangle = \phi(\alpha(x))$ for every $x \in X$.

If $S = G$ is a semitopological group then one can assume in addition that $h(G) \subset Iso(V)$ and $h : G \to Iso(V)$ is strongly continuous.

**Theorem 6.14.** [50, section 4] Let $S$ be a semitopological semigroup.

(1) A compact (continuous) $S$-space $X$ is WAP if and only if $(S, X)$ is weakly (respectively, strongly) reflexively approximable.

(2) A compact (continuous) metric $S$-space $X$ is WAP if and only if $(S, X)$ is weakly (respectively, strongly) reflexively representable.

(3) Every $f \in WAP(S)$ is a matrix coefficient of a reflexive representation.

It is important to take into account the following characterization of reflexive spaces.

**Lemma 6.15.** Let $V$ be a Banach space. The following conditions are equivalent:

(1) $V$ is reflexive.

(2) The semitopological semigroup $\Theta(V)_w$ is compact.

(3) The compact right topological semigroup $\mathcal{E}(V)$ is semitopological.

(4) $(\Theta^{op}, B^*)$ is a WAP system.
Proof. (1) ⇒ (2) Always, $\Theta(V)$ is a closed subset of the product $(B, w)^B$. So, if $V$ is reflexive then by Theorem 6.7 $(B, w)^B$ is compact. Hence, we obtain by Tychonoff theorem that $\Theta(V)$ is compact.

(2) ⇒ (3) Use the fact that $\Theta(V)^{op}$ is dense in $E(V)$ (Lemma 3.12).

(3) ⇒ (4) One may apply Corollary 6.11 because $(\Theta(V)^{op}, B^*)$ is transitive.

(4) ⇒ (1) Choose any $v \in S_V$ and treat it as a (continuous) function on the dynamical $\Theta^{op}$-system $B^*$. Then $v \in \text{WAP}(B^*)$. Then its orbit has DLP on $B^*$. So, $v\Theta^{op} = \Theta v = B$ has DLP on $B^*$.

Another consequence of Theorem 6.14 (taking into account Lemma 6.15) is

**Theorem 6.16.** ([68] and [47]) Every compact semitopological semigroup $S$ can be embedded into $\Theta(V)$ for some reflexive $V$.

Thus, compact semitopological semigroups $S$ can be characterized as closed subsemigroups of $E(V)$ for reflexive Banach spaces $V$.

6.3. DFJP factorization for WAP dynamical systems.

**Theorem 6.17.** Let $X$ be a compact $S$-space and $F \subset C(X)$ a norm bounded $S$-invariant subset of $C(X)$. The following are equivalent:

1. $(F, S, X)$ admits a reflexive representation.
2. $\text{cl}_{\text{p}}(F) \subset C(X)$.
3. $F$ has DLP on $X$.

Proof. (1) ⇒ (3) If $V$ is a reflexive space then every bounded subset $F$ of the dual $V^*$ has DLP on every bounded subset $X \subset V$. This follows from the Eberlein-Šmulian theorem. See Theorem 6.7.

(2) ⇒ (1) Theorem 6.19 below.

(2) ⇔ (3) It can be found for example in [6, Theorem A.4].

**Theorem 6.18.** $(S, X)$ is a WAP (continuous) system if and only if $(S, X)$ is weakly (respectively, strongly) reflexively-approximable. If $X$ is metrizable then “approximable” can be replaced by “representable”. Moreover, the corresponding Banach space can be assumed to be separable.

Proof. The “only if” part: Use the fact that $(\Theta^{op}, B^*)$ is a WAP system (Theorem 11.4) for every reflexive space $V$.

The “if” part: (1) For every $f \in C(X) = \text{Tame}(X)$ the orbit $fS$ has DLP (being weakly precompact) family for $X$. Applying Theorem 12.4 below we conclude that every $f \in C(X) = \text{Tame}(X)$ on a compact $S$-space $X$ comes from a reflexive representation. Since continuous functions separate points of $X$, this implies that reflexive representations of $(S, X)$ separate points of $X$. So, it is enough to prove the following result which gives a proof of Theorem 6.17.

**Theorem 6.19.** Let $X$ be a compact $S$-space and let $F \subset C(X)$ be a bounded $S$-invariant pointwise compact family. Then there exist: a reflexive Banach space $V$, an injective mapping $\nu : F \rightarrow B_V$ and a representation

$$h : S \rightarrow \Theta(V), \quad \alpha : X \rightarrow V^*$$
of \((S, X)\) on \(V\) such that \(h\) is weakly continuous, \(\alpha\) is a weak* (in fact, weakly) continuous map and
\[
f(x) = \langle \nu(f), \alpha(x) \rangle \quad \forall \ f \in F \ \forall \ x \in X.
\]

Thus the following diagram commutes
\[
\begin{array}{ccc}
F \times X & \xrightarrow{\nu} & \mathbb{R} \\
\downarrow{\alpha} & & \downarrow{id} \\
V \times V^* & \xrightarrow{id} & \mathbb{R}
\end{array}
\]

If \(X\) is metrizable then in addition we can suppose that \(V\) is separable.
If the action \(S \times X \to X\) is continuous we may assume that \(h\) is strongly continuous.
If \(S = G\) is a group then \(h(G) \subset \text{Iso}(V)\).
If \(F\) separates points of \(X\) then \(\alpha : X \to (V^*, w^*)\) is a topological embedding.

**Proof. Step 1:** The construction of \(V\).

For brevity of notation let \(\mathcal{A} := C(X)\) denote the Banach space \(C(X)\), \(B\) will denote its unit ball, and \(B^*\) will denote the weak* compact unit ball of the dual space \(\mathcal{A}^* = C(X)^*\). Let \(W\) be the symmetrized convex hull of \(F\); that is, \(W := \text{co}(F \cup -F)\).

Consider the sequence of sets
\[
M_n := 2^n W + 2^{-n} B.
\]
Then \(W\) is convex and symmetric. We apply the construction of Davis-Figiel-Johnson-Pelczyński [11] as follows. Let \(\| \cdot \|_n\) be the Minkowski functional of the set \(M_n\), that is,
\[
\|v\|_n = \inf \{ \lambda > 0 \mid v \in \lambda M_n \}.
\]
Then \(\| \cdot \|_n\) is a norm on \(\mathcal{A}\) equivalent to the given norm of \(\mathcal{A}\). For \(v \in \mathcal{A}\), set
\[
N(v) := \left( \sum_{n=1}^{\infty} \|v\|_n^2 \right)^{1/2}
\]
and let \(V := \{ v \in \mathcal{A} \mid N(v) < \infty \}\).

Denote by \(j : V \to \mathcal{A}\) the inclusion map. Then \((V, N)\) is a Banach space, \(j : V \to \mathcal{A}\) is a continuous linear injection and

\[
W \subset j(B_V) = B_V \subset \bigcap_{n \in \mathbb{N}} M_n = \bigcap_{n \in \mathbb{N}} (2^n W + 2^{-n} B)
\]

Indeed, if \(v \in W\) then \(2^n v \in M_n\), hence \(\|v\|_n \leq 2^{-n}\) and \(N(v)^2 \leq \sum_{n \in \mathbb{N}} 2^{-2n} < 1\). This proves \(W \subset j(B_V)\). In order to prove the second inclusion recall that the norms \(\| \cdot \|_n\) on \(\mathcal{A}\) are equivalent to each other. It follows that if \(v \in B_V\) then \(\|v\|_n < 1\) for all \(n \in \mathbb{N}\). That is, for every \(n \in \mathbb{N}\), \(v \in \lambda_n M_n\) for some \(0 < \lambda_n < 1\). By the construction \(M_n\) is a convex subset containing the origin. This implies that \(\lambda_n M_n \subset M_n\). Hence \(j(v) = v \in M_n\) for every \(n \in \mathbb{N}\).

**Step 2:** The construction of the representation \((h, \alpha)\) of \((S, X)\) on \(V\).
The given action \( S \times X \to X \) induces a natural linear norm preserving continuous right action \( C(X) \times S \to C(X) \) on the Banach space \( A = C(X) \). It follows by the construction that \( W \) and \( B \) are \( S \)-invariant subsets in \( A \). This implies that \( V \) is an \( S \)-invariant subset of \( A \) and the restricted natural linear action \( V \times S \to V \), \( (v, g) \mapsto vg \) satisfies \( N(vs) \leq N(v) \). Therefore, the co-homomorphism \( h : S \to \Theta(V) \), \( h(s)(v) := vs \) is well defined.

Let \( j^* : A^* \to V^* \) be the adjoint map of \( j : V \to A \). Define \( \alpha : X \to V^* \) as follows. For every \( x \in X \subset C(X)^* \) set \( \alpha(x) = j^*(x) \). Then \( (h, \alpha) \) is a representation of \( (S, X) \) on the Banach space \( V \).

By the construction, \( F \subset W \subset B_V \). Define \( \nu : F \hookrightarrow B_V \) as the natural inclusion. Then
\[
(6.4) \quad f(x) = \langle \nu(f), \alpha(x) \rangle \quad \forall \ f \in F \ \forall \ x \in X.
\]

**Step 3:** Weak continuity of \( h : S \to \Theta(V) \).

By our construction \( j^* : C(X)^* \to V^* \), being the adjoint of the bounded linear operator \( j : V \to C(X) \), is a norm and weak* continuous linear operator. By [17, Lemma 1.2.2] we obtain that \( j^*(C(X)^*) \) is norm dense in \( V^* \). Since \( V \) is Rosenthal, Haydon’s theorem (Fact 8.11.4) gives \( Q := cl_{w^*}(co(Y)) = cl_{norm}(co(Y)) \), where \( Y := j^*(X) \). Now observe that \( j^*(P(X)) = Q \). Since \( S \times X \to X \) is separately continuous, every orbit map \( \tilde x : S \to X \) is continuous, and each orbit map \( j^*(x) : S \to j^*(X) \) is weak* continuous. Then also \( j^*(z) : S \to V^* \) is weak* continuous for each \( z \in cl_{norm}(co(j^*(X))) = Q \). Since \( sp(Q) \) is norm dense in \( V^* \) (and \( ||h(s)|| \leq 1 \) for each \( s \in S \)) it easily follows that \( j^*(z) : S \to V^* \) is weak* continuous for every \( z \in V^* \). This is equivalent to the weak continuity of \( h \).

If the action \( S \times X \to X \) is continuous we may assume that \( h \) is strongly continuous. Indeed, by the definition of the norm \( N \), we can show that the action of \( S \) on \( V \) is norm continuous (use the fact that, for each \( n \in \mathbb{N} \), the norm \( ||-||_n \) on \( A \) is equivalent to the given norm on \( A \)).

**Step 4:** \( V \) is a reflexive space.

*Proof.* See [11]. Sketch: \( j^{**}(B_{V^{**}}) \subset A \). Hence, \( j^{**} \) is 1-1 and \( (j^{**})^{-1}(A) = V \). It follows that \( V^{**} \subset V \) (reflexivity).

If the compact space \( X \) is metrizable then \( C(X) \) is separable and it is also easy to see that \( (V, N) \) is separable. □

This proves Theorem 12.4 and hence also Theorem 12.3.1.

Finally note that if \( X \) is metrizable then “approximable” can be replaced by “representable” using an \( l_2 \)-sum of a sequence of separable reflexive spaces (see Lemma ??3).

6.4. Applications.

**Theorem 6.20.** (WAP Representation Theorem) Let \( X \) be a compact semitopo- logical \( S \)-system and \( f \in C(X) \). The following conditions are equivalent:
Theorem 6.23. \( f : X \to \mathbb{R} \) is weakly almost periodic.

(ii) There exist: a representation \((h, \alpha)\) of \((S, X)\) into reflexive \(V\) with a weak continuous antihomomorphism \(h : S \to \Theta(V)\), weak (eq., weak-star) continuous \(\alpha : X \to B^*\), and a vector \(v \in V\) such that \(f(x) = <v, \alpha(x)>\).

If either: a) \(S = G\) is a semitopological group; or b) \(X\) is compact and the action \(S \times X \to X\) is jointly continuous, then in (ii) we can suppose that \(h\) is strongly continuous.

Proof. Recall that a continuous function \(f \in C(X)\) is WAP iff the orbit \(fS\) is relatively weakly compact in \(C(X)\). That is, \(cl_w(fS)\) is weakly compact. Apply Theorem for \(F := cl_w(fS)\).

Theorem 6.21. A compact \(S\)-system \(X\) is WAP iff \(X\) is reflexively approximable.

Proof. If \(X\) is REFL-approximable then \(X\) is wap by Fact 5.4 (iii) (in fact, WAP separates points but since WAP(X) is an algebra and \(X\) is compact it is enough).

The nontrivial part follows from Theorem 6.20 because if \(X\) has sufficiently many wap functions, then \((S, X)\) has sufficiently many reflexive representations.

Corollary 6.22. Every metrizable compact WAP system is Eberlein.

Theorem 6.23. For every semitopological monoid \(S\) the function \(f : S \to \mathbb{R}\) is wap iff \(f\) is a matrix coefficient of a weak continuous antihomomorphism \(S \to \Theta(V)\) for a reflexive \(V\). That is, there exist \(v \in V\) and \(\psi \in V^*\) such that \(f(s) = <v, \alpha(s)>\).

If \(S = G\) is a group then \(h(G) \subset Iso(V)\) (and \(h\) is strongly continuous).

Proof. Apply Theorem 6.20 to the flow \((S, S)\). Then for \(f \in WAP(S)\) there exists a reflexive \(V\) and a representation \(h : S \to \Theta(V)\), \(\alpha : S \to B(V^*)\) such that \(f(s) = <v, \alpha(s)>\) for a suitable \(v \in V\). Denote by \(e\) the identity of \(S\). Then \(f = m_{v, \psi}\), where \(\psi = \alpha(e)\).

Fact 6.24. ([68] and [47]) Let \(S\) be a semitopological semigroup. The following are equivalent:

(i) \(S\) is embedded into a compact semitopological monoid.

(ii) There exists a reflexive space \(E\) such that \(S\) is embedded (as a semitopological subsemigroup) into \(\Theta(E)^w\).

Therefore, compact semitopological semigroups are exactly the class of all closed subsemigroups of \(\Theta(E)^w\) for some reflexive \(V\).

Proof. (i) \(\implies\) (ii) We can suppose that \(S\) is a monoid. Consider \(X := S^W\) the universal semitopological compactification of \(S\). Then the corresponding universal map \(u_W : S \to S^W\) is a topological embedding by (i) and hence, the action \((S, S^W)\) is left strict. That is, there is no strictly coarser topology on \(S\) under which \(S\) is a semitopological semigroup and \(S^W\) is still a semitopological \(S\)-flow. By Theorem 6.20 there exists a separating family \((h_i, \alpha_i)\) of reflexive \(V_i\)-representations \((i \in I)\) of \((S, S^W)\). Then the \(l_2\)-sum of these representations defined on the Banach space \(V := (\sum_{i} V_i)_{l_2}\) will induce a weakly continuous antihomomorphism \(h : S \to \Theta(V)\). Since the original action is left strict, it is easy to show that \(h\) must be a topological
embedding. Define $E := V^*$. It is clear that the antihomomorphism $h$ defines the desired homomorphism $h : S \to \Theta(V)^{\text{opp}} = \Theta(V^*) = \Theta(E)$.

(ii) $\implies$ (i) Use Lemma 6.15.

By Theorem 2.7, $\text{Iso}(V)_s = \text{Iso}(V)_w$ for every reflexive $V$. Therefore we obtain

**Fact 6.25.** Let $G$ be a topological group. The following are equivalent:

(i) $G \to G^w$ is an embedding.

(ii) $G$ is a topological subgroup of the group Is$(V)_s$ (endowed with the strong operator topology) of all linear isometries for a suitable reflexive $V$.

It is well known (as noted for example by Arhangelskij or Namioka-Wheeler that a compact space is Eberlein iff it can be included into some right strict duality. Theorem 6.19 provides “a flow version”.

We next recall a version of Lawson’s theorem and a soft geometric proof using representations of dynamical systems on reflexive spaces.

**Theorem 6.26.** (Ellis-Lawson Joint Continuity Theorem) Let $G$ be a subgroup of a compact semitopological monoid $S$. Suppose that $S \times X \to X$ is a separately continuous action with compact $X$. Then the action $G \times X \to X$ is jointly continuous (and $G$ is a topological group).

**Proof.** A sketch of the proof from [50]: We show the joint continuity of $G \times X \to X$ (for the last part take $X := S$ and the natural action $G \times S \to S$). It is easy to see by Grothendieck’s Lemma (Theorem 6.5) that $C(X) = \text{WAP}(X)$. Hence $(S,X)$ is a weakly almost periodic system. By Theorem 6.14 the proof can be reduced to the particular case where $(S,X) = (\Theta(V)^{\text{op}},B_{V^*})$ for some reflexive Banach space $V$ with $G := \text{Iso}(V)$, where $\Theta(V)^{\text{op}}$ is endowed with the weak operator topology. By Theorem 2.7, the weak and strong operator topologies coincide on $\text{Iso}(V)$ for reflexive $V$. In particular, $G$ acts continuously on $B_{V^*}$. (For the last part apply our assertion to the following action $G \times X \to X$ where $X = S$) □

As a corollary one gets the classical result of Ellis.

**Theorem 6.27.** (Ellis’ Theorem) Every compact semitopological group is a topological group.

7. $L_4 \in \text{Ref}_r \setminus \text{Hilb}_r$

**Theorem 7.1.**

(1) $L_4[0,1] \in \text{Ref}_r$;

(2) $L_4[0,1] \notin \text{Hilb}_r$.

[Chaatit 1996] The additive group of every separable stable (Krivine-Maurey [40]) Banach sp. $\in \text{Ref}_r$.

$\implies$ (1)

(direct) proof of (1):

$\phi : L_{2k} \to \mathbb{R}$, $v \mapsto e^{-\|v\|}$ is wap.

**Exercise 7.2.** If $G$ admits a left invariant metric with DLP then $G \in \text{Ref}_r$. 
Lemma (Grothendieck’s DLP) A function \( f \in C^b(G) \) is \( \text{wap} \) iff 
\[
\lim_{m} \lim_{n} f(g_nh_m) = \lim_{n} \lim_{m} f(g_nh_m)
\]
whenever all the limits exist.

- \((L_{2k}(\mu), |||) \ (k \in \mathbb{N})\) has the DLP.

\[
\| u_n + v_m \|^2 = \| u_n \|^2 + \sum_{i=1}^{2k-1} C^i_{2k} \int u_{n}^{2k-i} v_{m}^{i} dt + \| v_m \|^2
\]

\[
\int u_{n}^{2k-i} v_{m}^{i} dt = < u_{n}^{2k-i}, v_{m}^{i} >
\]

\[v_{n}^{2k-i} \in L^*_2 \frac{1}{2k-i}, \quad v_{m}^{i} \in L^*_2 \frac{1}{2k-i}.
\]

- Use DLP for \( B(V) \times B(V^*) \rightarrow [-1, 1] \) with reflexive \( V \).

(2) \( L_{2}[0, 1] \not\subset \text{Hilb}_{p} \)

Theorem 7.3 (Aharoni-Maurey-Mityagin 1985). For \( 2 < p < \infty \), an infinite-dimensional \( L_{p}(\mu) \) space is not uniformly embedded into a Hilbert space.

Lemma \( \forall \) metric subgroup \( G \) of \( Is(H) \)

\[ \exists (G, \mathcal{L}) \overset{\text{unif}}{\hookrightarrow} H. \]

(a): \( \| v_n \| = \frac{1}{2^n} \)

(b): \( \{ \tilde{v}_n : Is(H) \rightarrow H, \ g \mapsto g v_n \}_{n \in \mathbb{N}} \) generates the left uniformity on \( Is(H) \).

\[ Is(H) \overset{\text{unif}}{\hookrightarrow} \prod_{n} (H)_{unif} \overset{\text{unif}}{\hookrightarrow} \overset{l_2-\text{sum}}{\hookrightarrow} H \]

\[ \Rightarrow \quad L_{p}[0, 1] \not\subset \text{Hilb}_{r} \quad p > 2 \quad \Rightarrow \quad \text{(II)} \]

8. Fragmentability and Banach spaces

The concept of fragmentability originally comes from Banach space theory and has several applications in Topology, and more recently also in Topological Dynamics.

Definition 8.1. Let \((X, \tau)\) be a topological space and \((Y, \mu)\) a uniform space.

(1) [36] \( X \) is \((\tau, \mu)\)-fragmented by a (typically, not continuous) function \( f : X \rightarrow Y \)
if for every nonempty subset \( A \) of \( X \) and every \( \varepsilon \in \mu \) there exists an open subset \( O \) of \( X \) such that \( O \cap A \) is nonempty and the set \( f(O \cap A) \) is \( \varepsilon \)-small in \( Y \). We also say in that case that the function \( f \) is fragmented. Notation:
\( f \in \mathcal{F}(X, Y) \), whenever the uniformity \( \mu \) is understood. If \( Y = \mathbb{R} \) then we write simply \( \mathcal{F}(X) \).

(2) [23] We say that a family of functions \( F = \{ f : (X, \tau) \rightarrow (Y, \mu) \} \) is fragmented
if condition (1) holds simultaneously for all \( f \in F \). That is, \( f(O \cap A) \) is \( \varepsilon \)-small
for every \( f \in F \).

(3) [29] We say that \( F \) is an eventually fragmented family if every infinite subfamily \( C \subset F \) contains an infinite fragmented subfamily \( K \subset C \).
In Definition 8.1.1 when $Y = X, f = \text{id}_X$ and $\mu$ is a metric uniform structure, we get the usual definition of fragmentability (more precisely, $(\tau, \mu)$-fragmentability) in the sense of Jayne and Rogers [37]. Implicitly it already appears in a paper of Namioka and Phelps [57].

**Remark 8.2.** [23, 25]

1. It is enough to check the condition of Definition 8.1 for closed subsets $A \subset X$ and for $\varepsilon \in \mu$ from a subbase $\gamma$ of $\mu$ (that is, the finite intersections of the elements of $\gamma$ form a base of the uniform structure $\mu$).
2. When $X$ and $Y$ are Polish spaces, $f : X \to Y$ is fragmented iff $f$ is a Baire class 1 function.
3. When $X$ is compact and $(Y, \rho)$ metrizable uniform space then $f : X \to Y$ is fragmented iff $f$ has a point of continuity property (i.e., for every closed nonempty $A \subset X$ the restriction $f|_A : A \to Y$ has a continuity point).
4. When $Y$ is compact with its unique compatible uniformity $\mu$ then $p : X \to Y$ is fragmented if and only if $f \circ p : X \to \mathbb{R}$ has a point of continuity property for every $f \in C(Y)$.
5. A topological space $(X, \tau)$ is scattered iff $X$ is $(\tau, \mu)$-fragmented, for every uniform structure $\mu$ on the set $X$.
6. Let $(X, \tau)$ be a separable metrizable space and $(Y, \rho)$ a pseudometric space. Suppose that $f : X \to Y$ is a fragmented onto map. Then $Y$ is separable.

The first assertion in the following lemma can be proved using Namioka’s joint continuity theorem.

**Lemma 8.3.**

1. Suppose $F$ is a compact space, $X$ is Čech-complete, $Y$ is a uniform space and we are given a separately continuous map $w : F \times X \to Y$. Then the naturally associated family $\tilde{F} := \{\tilde{f} : X \to Y\}_{f \in F}$ is fragmented, where $\tilde{f}(x) = w(f, x)$.
2. Suppose $F$ is a compact metrizable space, $X$ is hereditarily Baire and $M$ is separable and metrizable. Assume we are given a map $w : F \times X \to M$ such that every $\tilde{x} : F \to M, f \mapsto w(f, x)$ is continuous and $y : X \to M$ is continuous at every $\tilde{y} \in Y$ for some dense subset $Y$ of $F$. Then the family $\tilde{F}$ is fragmented.
3. (version of Osgood’s theorem) Let $f_n : X \to \mathbb{R}$ be a pointwise convergent sequence of continuous functions on a hereditarily Baire space $X$. Then $F := \{f_n\}_{n \in \mathbb{N}}$ is a fragmented family.

**Proof.** (1): There exists a collection of uniform maps $\{\varphi_i : Y \to M_i\}_{i \in I}$ into metrizable uniform spaces $M_i$ which generates the uniformity on $Y$. Now for every closed subset $A \subset X$ apply Namioka’s joint continuity theorem to the separately continuous map $\varphi_i \circ w : F \times A \to M_i$ and take into account Remark 8.2.1.

(2): Since every $\tilde{x} : F \to M$ is continuous, the natural map $j : X \to C(F, M), j(x) = \tilde{x}$ is well defined. Every closed nonempty subset $A \subset X$ is Baire. By [30, Proposition 2.4], $j|_A : A \to C(F, M)$ has a point of continuity, where $C(F, M)$ carries the sup-metric. Hence, $\tilde{F}_A = \{\tilde{f} |_A : A \to M\}_{f \in F}$ is equicontinuous at some point $a \in A$. This implies that the family $\tilde{F}$ is fragmented.

(3) follows from (2) applied to the evaluation map $w : F \times X \to \mathbb{R}$, where $F := \{f\} \cup \{f_n : n \in \mathbb{N}\} \subset \mathbb{R}^X$ with $f := \lim f_n$, the pointwise limit.
Remark 8.4. Let us briefly describe one of the ideas linking fragmentability and dynamical systems. Suppose that $X$ is a weak* compact dual ball of some Banach space $V$. One of the major themes in Banach space theory is the study of the relationship between the norm and the weak* topologies on $X \subset V^*$. When these two coincide, we say that $X$ is a Kadec subset of $V^*$. If moreover $X$ is a subsystem (under some action by linear isometries) then $X$, as a dynamical system, is equicontinuous. In general, as an attempt to measure “the level of equicontinuity”, we can ask how close are the two natural topologies on $X$ inherited from $V^*$. A more concrete, but sufficiently flexible, question is: for which dynamical system representations is the natural mapping $1_X : (X, \text{weak}^*) \to (X, \text{norm})$ fragmented? The latter means that every nonempty subset of $X$ admits relatively weak* open nonempty subsets with arbitrarily small diameters. Every point of continuity of $1_X$ is a point of equicontinuity of the dynamical system $X$.

8.1. Banach spaces defined by fragmentability. We recall the definitions of three important classes of Banach spaces: Asplund, Rosenthal and PCP. Each of them can be characterized in terms of fragmentability.

8.1.1. Asplund Banach spaces. Recall that a Banach space $V$ is an Asplund space if the dual of every separable linear subspace is separable.

In the following result the equivalence of (1), (2) and (3) is well known and (4) is a reformulation of (3) in terms of fragmented families.

**Theorem 8.5.** [57, 56] Let $V$ be a Banach space. The following conditions are equivalent:

1. $V$ is an Asplund space.
2. $V^*$ has the Radon-Nikodým property.
3. Every bounded subset $A$ of the dual $V^*$ is (weak*, norm)-fragmented.
4. $B$ is a fragmented family of real valued maps on the compactum $B^*$.

Reflexive spaces and spaces of the type $c_0(\Gamma)$ are Asplund. By [57] the Banach space $C(K)$ for compact $K$ is Asplund iff $K$ is a scattered compactum (see also Lemma 8.2.4). Namioka’s Joint Continuity Theorem implies that every weakly compact set in a Banach space is norm fragmented, [56]. This explains why every reflexive space is Asplund.

8.1.2. Banach spaces not containing $l_1$.

**Definition 8.6.** Let $f_n : X \to \mathbb{R}$ be a uniformly bounded sequence of functions on a set $X$. Following Rosenthal we say that this sequence is an $l_1$-sequence on $X$ if there exists a real constant $a > 0$ such that for all $n \in \mathbb{N}$ and choices of real scalars $c_1, \ldots, c_n$ we have

$$a \cdot \sum_{i=1}^{n} |c_i| \leq ||\sum_{i=1}^{n} c_i f_i||.$$ 

This is the same as requiring that the closed linear span in $l_\infty(X)$ of the sequence $f_n$ be linearly homeomorphic to the Banach space $l_1$. In fact, in this case the map

$$l_1 \to l_\infty(X), \quad (c_n) \to \sum_{n \in \mathbb{N}} c_n f_n$$
is a linear homeomorphic embedding.

**Definition 8.7.** A sequence \( f_n \) of real valued functions on a set \( X \) is said to be independent if there exist real numbers \( a < b \) such that
\[
\bigcap_{n \in P} f_n^{-1}(-\infty, a) \cap \bigcap_{m \in M} f_m^{-1}(b, \infty) \neq \emptyset
\]
for all finite disjoint subsets \( P, M \) of \( \mathbb{N} \).

**Definition 8.8.** A Banach space \( V \) is said to be Rosenthal if it does not contain an isomorphic copy of \( l_1 \).

Every Asplund space \( V \) is Rosenthal (because \( l_1^1 \) is the nonseparable space \( l_\infty \)).

**Definition 8.9.** Let \( X \) be a topological space. We say that a subset \( F \subset C(X) \) is a Rosenthal family (for \( X \)) if \( F \) is norm bounded and the pointwise closure \( \text{cl}_p(F) \) of \( F \) in \( \mathbb{R}^X \) consists of fragmented maps, that is, \( \text{cl}_p(F) \subset \mathcal{F}(X) \).

The following useful result synthesizes some known results.

It is based on results of Rosenthal [64], Talagrand [69, Theorem 14.1.7] and van Dulst [12]. In [25, Prop. 4.6] we show why eventual fragmentability of \( F \) can be included in the following list.

**Theorem 8.10.** Let \( X \) be a compact space and \( F \subset C(X) \) a bounded subset. The following conditions are equivalent:

1. \( F \) does not contain an independent subsequence.
2. \( F \) does not contain a subsequence equivalent to the unit basis of \( l_1 \).
3. Each sequence in \( F \) has a pointwise convergent subsequence in \( \mathbb{R}^X \).
4. \( F \) is a Rosenthal family for \( X \).
5. \( F \) is an eventually fragmented family.

We need also some characterizations of Rosenthal spaces.

**Theorem 8.11.** Let \( V \) be a Banach space. The following conditions are equivalent:

1. \( V \) is a Rosenthal Banach space.
2. (E. Saab and P. Saab [66]) Each \( x^{**} \in V^{**} \) is a fragmented map when restricted to the weak* compact ball \( B^* \). Equivalently, \( B^{**} \subset \mathcal{F}(B^*) \).
3. \( B \) is a Rosenthal family for the weak* compact unit ball \( B^* \).
4. \( B \) is an eventually fragmented family of maps on \( B^* \).
5. (Haydon [34, Theorem 3.3]) For every weak* compact subset \( Y \subset V^* \) the weak* and norm closures of the convex hull \( \text{co}(Y) \) in \( V^* \) coincide: \( \text{cl}_{w^*}(\text{co}(Y)) = \text{cl}_{\text{norm}}(\text{co}(Y)) \).

Condition (2) is a reformulation (in terms of fragmented maps) of a criterion from [66] which was originally stated in terms of the point of continuity property. The equivalence of (1), (3) and (4) follows from Theorem 8.10.

8.1.3. Banach spaces with PCP. A Banach space \( V \) is said to have the point of continuity property (PCP for short) if every bounded weakly closed subset \( C \subset V \) admits a point of continuity of the identity map \( (C, \text{weak}) \to (C, \text{norm}) \) (see for example Edgar-Wheeler [14] and [37]). Every Banach space with RNP has PCP. In particular, this is true for the duals of Asplund spaces and for reflexive spaces. This concept was
studied, among others, by Bourgain and Rosenthal. They show, for instance, that there are separable Banach spaces with PCP which do not satisfy RNP.

**Theorem 8.12.** (Jayne and Rogers [37]) Let $V$ be a Banach space. The following conditions are equivalent:

1. $V$ has PCP.
2. Every bounded subset $A \subset V$ is (weak, norm)-fragmented.

8.2. More properties of fragmented families. Here we demonstrate a general principle: the fragmentability of a family of continuous maps on a compact space is “countably-determined”. Formally the following theorem is new, though its proof (the part (3) $\Rightarrow$ (1)) is inspired by a result of Namioka [56, Theorem 3.4].

**Theorem 8.13.** Let $F = \{f_i : X \to Y\}_{i \in I}$ be a bounded family of continuous maps from a compact (not necessarily metrizable) space $(X, \tau)$ into a pseudometric space $(Y, d)$. The following conditions are equivalent:

1. $F$ is a fragmented family of functions on $X$.
2. Every countable subfamily $K$ of $F$ is fragmented.
3. For every countable subfamily $K$ of $F$ the pseudometric space $(X, \rho_{K,d})$ is separable, where

$$\rho_{K,d}(x_1, x_2) := \sup_{f \in K} d(f(x_1), f(x_2)).$$

**Proof.** (1) $\Rightarrow$ (2) is trivial.

(2) $\Rightarrow$ (3): Let $K$ be a countable subfamily of $F$. Consider the natural map

$$\pi : X \to Y^K, \quad \pi(x)(f) := f(x).$$

By (2), $K$ is a fragmented family. Thus by Lemma 8.2.6 the map $\pi$ is $(\tau, \mu_K)$-fragmented, where $\mu_K$ is the uniformity of $d$-uniform convergence on $Y^K := \{ f : K \to (Y, d) \}$. Then the map $\pi$ is also $(\tau, d_K)$-fragmented, where $d_K$ is the pseudometric on $Y^K$ defined by

$$d_K(z_1, z_2) := \sup_{f \in K} d(z_1(f), z_2(f)).$$

Since $d$ is bounded, $d_K(z_1, z_2)$ is finite and $d_K$ is well-defined. Denote by $(X_K, \tau_p)$ the subspace $\pi(X) \subset Y^K$ in pointwise topology. Since $K \subset C(X)$, the induced map $\pi_0 : X \to X_K$ is a continuous map onto the compact space $(X_K, \tau_p)$. Denote by $i : (X_K, \tau_p) \to (Y^K, d_K)$ the inclusion map. So, $\pi = i \circ \pi_0$, where the map $\pi$ is $(\tau, d_K)$-fragmented. Then by Lemma 8.2.7 we obtain that $i$ is $(\tau_p, d_K)$-fragmented. It immediately follows that the identity map $id : (X_K, \tau_p) \to (X_K, d_K)$ is $(\tau_p, d_K)$-fragmented.

Since $K$ is countable, $(X_K, \tau_p) \subset Y^K$ is metrizable. Therefore, $(X_K, \tau_p)$ is second countable (being a metrizable compactum). Now, since $d_K$ is a pseudometric on $Y^K$, and $id : (X_K, \tau_p) \to (X_K, d_K)$ is $(\tau_p, d_K)$-fragmented, we can apply Lemma 8.2.5. It directly implies that the set $X_K$ is a separable subset of $(Y^K, d_K)$. This means that $(X, \rho_{K,d})$ is separable.

(3) $\Rightarrow$ (1): Suppose that $F$ is not fragmented. Thus, there exists a non-empty closed subset $A \subset X$ and an $\varepsilon > 0$ such that for each non-empty open subset $O \subset X$ with $O \cap A \neq \emptyset$ there is some $f \in O$ such that $f(O \cap A)$ is not $\varepsilon$-small in $(Y, d)$. Let $V_1$ be an arbitrary non-empty relatively open subset in $A$. There are $a, b \in V_1$ and
$f_1 \in F$ such that $d(f_1(a), f_1(b)) > \varepsilon$. Since $f_1$ is continuous we can choose relatively open subsets $V_2, V_3$ with $\text{cl}(V_2 \cup V_3) \subset V_1$ such that $d(f(x), f(y)) > \varepsilon$ for every $(x, y) \in V_2 \times V_3$.

By induction we can construct a sequence \( \{V_n\}_{n \in \mathbb{N}} \) of non-empty relatively open subsets in $A$ and a sequence $K := \{f_n\}_{n \in \mathbb{N}}$ in $F$ such that:

(i) $\text{cl}(V_{2n} \cup V_{2n+1}) \subset V_n$ for each $n \in \mathbb{N}$;
(ii) $d(f_n(x), f_n(y)) > \varepsilon$ for every $(x, y) \in V_{2n} \times V_{2n+1}$.

We claim that $(X, \rho_{K,d})$ is not separable, where

$$
\rho_{K,d}(x_1, x_2) := \sup_{f \in K} d(f(x_1), f(x_2)).
$$

In fact, for each branch

$$
\alpha := V_1 \supset V_{n_1} \supset V_{n_2} \cdots
$$

where for each $i, n_{i+1} = 2n_i$ or $2n_i + 1$, by compactness of $X$ one may choose an element

$$
x_\alpha \in \bigcap_{i \in \mathbb{N}} \text{cl}(V_{n_i}).
$$

If $x = x_\alpha$ and $y = x_\beta$ come from different branches, then there is an $n \in \mathbb{N}$ such that $x \in \text{cl}(V_{2n})$ and $y \in \text{cl}(V_{2n+1})$ or (vice versa). In any case it follows from (ii) and the continuity of $f_n$ that $d(f_n(x), f_n(y)) \geq \varepsilon$, hence $\rho_{K,d}(x, y) \geq \varepsilon$. Since there are uncountably many branches we conclude that $A$ and hence also $X$ are not $\rho_{K,d}$-separable.

**Definition 8.14.** [17, 50] Let $X$ be a compact space and $F \subset C(X)$ a norm bounded family of continuous real valued functions on $X$. Then $F$ is said to be an Asplund family for $X$ if for every countable subfamily $K$ of $F$ the pseudometric space $(X, \rho_{K,d})$ is separable, where

$$
\rho_{K,d}(x_1, x_2) := \sup_{f \in K} |f(x_1) - f(x_2)|.
$$

Any Asplund family for a compact space $X$ can be viewed, by [17, Lemma 1.5.3], as a particular case of the more general concept of an Asplund set in the Banach space $C(X)$.

**Corollary 8.15.** Let $X$ be a compact space and $F \subset C(X)$ a norm bounded family of continuous real valued functions on $X$. Then $F$ is fragmented if and only if $F$ is an Asplund family for $X$.

**Theorem 8.16.** Let $F = \{f_i : X \to Y\}_{i \in I}$ be a family of continuous maps from a compact (not necessarily metrizable) space $(X, \tau)$ into a pseudouniform space $(Y, \mu)$. Then $F$ is fragmented if and only if every countable subfamily $A \subset F$ is fragmented.

**Proof.** The proof can be reduced to Theorem 8.13. Every pseudouniform space can be uniformly approximated by pseudometric spaces. Using Lemma 8.2.1 we can suppose that $(Y, \mu)$ is pseudometrizable; i.e. there exists a pseudometric $d$ such that $\text{unif}(d) = \mu$. Moreover, replacing $d$ by the uniformly equivalent metric $\frac{d}{1+d}$ we can suppose that $d \leq 1$. \qed
8.3. The natural affine extension map $T : bB_1(X) \to bB_1(B^*)$.

**Definition 8.17.** Let $X$ be a topological space.

1. A function $f : X \to \mathbb{R}$ is said to be Baire 1 if $f^{-1}(O)$ is an $F_\sigma$ in $X$ for every open $O \subset X$. Notation: $f \in B_1(X)$.

2. Denote by $B^1_1(X)$ the set of all pointwise limits of sequences of continuous functions on $X$.

3. Bounded functions in $B_1(X)$ and $B^1_1(X)$ are denoted by $bB_1(X)$ and $bB^1_1(X)$.

Always, $B^1_1(X) \subset B_1(X)$ (van Dulst p. 137 for every $X$) and $B_1(X) \subset \mathcal{F}(X)$, for every hereditarily Baire space [8, Lemma 1C(c)].

Below $X$ be a compact space. It naturally is embedded into $(C(X)^*, w^*)$. This embedding induces a natural injective map

$$T : bB^1_1(X) \to bB^1_1(B^*),$$

where $B^*$, as before, is the weak* compact unit ball of $C(X)^*$. In the definition of $T$ below we will use Riesz representation theorem and Lebesgue’s Dominated Convergence Theorem.

For compact $X$ we have $\mathcal{F}(X) = B^3_1$ in terms of [8]. Each $f \in \mathcal{F}(X)$ is universally measurable for every compact space $X$ (see for example [8, Prop. 1F])). Therefore, for every measure $\mu \in B^*$ we can define

$$(Tf)(\mu) := \int f d\mu.$$

This map is well defined. Indeed, first note that when $f \in C(X)$, $T(f) = i(f)$, where

$$i : C(X) \hookrightarrow C(B^*), \quad i(f)(\mu) := \langle f, \mu \rangle = \int f d\mu$$

is the canonical isometric inclusion of the corresponding Banach spaces and

$$\langle \cdot, \cdot \rangle : C(X) \times C(X)^* \to \mathbb{R}$$

is the canonical bilinear mapping. Now if $f \in bB^1_1(X)$ then by definition $f$ is a pointwise limit of a sequence of continuous functions $h_n \in C(X)$. Since $f : X \to \mathbb{R}$ is a bounded function we can assume in addition that the sequence $h_n$ is uniformly bounded. By Lebesgue’s Convergence Theorem it follows that $T(f)$ is a pointwise limit of the sequence $T(h_n) = i(h_n)$, $n \in \mathbb{N}$. Since every $i(h_n) \in C(B^*)$ we conclude (by Definition 8.17) that $T(f) \in B^1_1(B^*)$. The sequence $i(h_n)$ is uniformly bounded in $C(B^*)$ hence $T(f)$ is a bounded function. This means that $T(f) \in bB^1_1(B^*)$.

The map $T$ is injective because $T(f)(\delta_x) = f(x)$ for every point mass $\delta_x \in B^*$ ($x \in X$).

**Remark 8.18.** Each $T(f)$ for $f \in bB^1_1(X)$ can be treated as an element of the second dual $C(X)^{**}$ of $C(X)$. Moreover the pointwise topology of $B^1_1(B^*)$ and the weak*-topology on $C(X)^{**}$ agree on $T(bB^1_1(X))$.

**Lemma 8.19.** Let $X$ be a compact space. For every uniformly bounded subset $A \subset bB^1_1(X)$ the restriction $T|_A$ of the natural injective map

$$T : bB^1_1(X) \to bB^1_1(B^*) \cap C(X)^{**}$$

on $A$ is sequentially continuous. Furthermore, $T(A)$ is also uniformly bounded.
Proof. Lebesgue’s Convergence Theorem implies that \( T \) is sequentially continuous. The boundedness of \( T(A) \) is easy.

Namioka [56] gave a kind of duality between uniform separability and pointwise metrizability.

**Theorem 8.20.** (Namioka [56, Theorem 4.1]) Let \( F \subset \mathbb{R}^X \) be a bounded set of maps. The following are equivalent:

1. The pseudometric space \((X, \rho_F)\) is separable, where \( \rho_F(x_1, x_2) := \sup\{|f(x_1) - f(x_2)| : f \in F\} \).
2. The pointwise closure \( \text{cl}_p(F) \) is a metrizable subspace of \( \mathbb{R}^X \).

Proof. (1) \( \Rightarrow \) (2) \( F \) is an equicontinuous family on the pseudometric space \((X, \rho_F)\). Then its pointwise closure \( \text{cl}_p(F) \) is also equicontinuous. So, it follows that the topology of pointwise convergence on \( X \) for \( \text{cl}_p(F) \) is the same as the topology of pointwise convergence on a countable \( \rho_F \)-dense subset of \( X \). Hence, \( \text{cl}_p(F) \) is metrizable.

(2) \( \Rightarrow \) (1) Let \( K := \text{cl}_p(F) \) be pointwise metrizable. Then \( C(K) \) is norm separable. Denote by \( \varphi : X \to C(K) \) the induced map defined by \( \varphi(x)(f) := f(x) \) for every \( f \in C(K) \). Then \( \varphi(X) \subset C(K) \) is norm separable. In particular (since \( F \subset K \)) we obtain that \((X, \rho_F)\) is separable.

**Lemma 8.21.** (Namioka [56, Theorem 4.4]) Let \( F \subset C(K) \) be a bounded family of continuous functions on a compact space \( K \). The following are equivalent:

1. \( F \) is a fragmented family of functions on \( K \).
2. The pseudometric space \((K, \rho_A)\) is separable for every countable \( A \subset F \).
3. The pointwise closure \( \text{cl}(A) \) is a metrizable subspace of \( \mathbb{R}^K \) for every countable \( A \subset F \).

Proof. Combine Theorem 8.21 and Corollary 8.15.

**Proposition 8.22.** If \( F \subset C(X) \) is a countable bounded fragmented family on a compact space \( X \) then

1. \( \text{cl}_p(F) \) is a metrizable subset of \( bB_1^*(X) \).
2. The restriction of \( T \) on \( \text{cl}_p(F) \) induces a homeomorphism

\[ \text{cl}_p(F) \to \text{cl}_p(T(F)) \subset bB_1^*(B^*) \cap C(X)^{**}. \]

Proof. (1) \( \text{cl}_p(F) \) is a uniformly bounded subset of \( \mathbb{R}^X \) because \( F \) is bounded. Since \( F \) is fragmented we obtain that \((X, \rho_F)\) is separable. So, by Lemma 8.21, \( \text{cl}_p(F) \) is metrizable in \( \mathbb{R}^X \). Therefore, every \( \phi \in \text{cl}_p(F) \) is a pointwise closure of a subsequence in \( F \). Hence, \( \phi \in bB_1^*(X) \).

(2) In view of Lemma 8.19 the restricted (injective) map \( T : \text{cl}_p(F) \to bB_1^*(B^*) \) is sequentially continuous. This restriction is even continuous because \( \text{cl}_p(F) \) is metrizable by (1). We conclude that the map \( T : \text{cl}_p(F) \to bB_1^*(B^*) \) is a continuous injection, and therefore a homeomorphism, of \( \text{cl}_p(F) \) onto its image in \( bB_1^*(B^*) \).

**Proposition 8.23.** Let \( X \) be a compact space and \( F \subset C(X) \) be bounded family. The following conditions are equivalent:

1. \( F \) is a (eventually) fragmented family for \( X \) iff \( F_{B^*} \) is a (resp., eventually) fragmented family for \( B^* \).
(2) $F$ is a Rosenthal family for $X$ iff $F_{B^*}$ is a Rosenthal family for $B^*$.

Proof. (1) Let $A$ be a countable subfamily of $F$. Then since $A$ is fragmented, Lemma 8.21 implies that $cl\,(A_X) \subset bB_1^1(X)$ is metrizable. By Proposition 8.22.2 $cl\,(A_{B^*})$ is homeomorphic to $cl\,(A_X)$. Therefore, $cl\,(A_{B^*}) \subset bB_1^1(B^*)$ is metrizable, too. Now again by Lemma 8.21 we obtain that $A_{B^*}$ is fragmented. It is true for every countable subfamily of $F_{B^*}$. Thus, $F_{B^*}$ is fragmented. This proves the "fragmented case". The "eventually fragmented case" is verbatim the same.

(2) is a reformulation of the eventually fragmented case of (1). □

Of course if $F_{B^*}$ is fragmented then $F_{P(X)}$ is fragmented, too.

**Corollary 8.24.** $C(K)$ is Asplund iff the compact space $K$ is scattered.

Proof. Let $K$ is scattered. Then it is fragmented by any uniformity, in particular with respect to the norm of $C(K)^*$. Then Proposition 8.23 guarantees that $B^*$ is also fragmented by the norm. Therefore, $C(K)$ is Asplund.

Second direction comes from the following Exercise. □

**Exercise 8.25.** Let $K$ be a compact space which is norm-fragmented in $C(K)^*$ . Show that $K$ is scattered.

Hint: the norm uniformity on $X \subset C(K)^*$ is discrete.

**Theorem 8.26.** Let $F \subset V$ be a norm bounded subset and $K \subset V^*$ be a weak-star compact subset. Then $F$ is a fragmented family on $K$ iff $F$ is a fragmented family on $Q := cl\,p(F)$.

Proof. Consider the restriction operator

$$r_K : V \to C(K), \quad r_K(v)(x) = <v, x> \quad \forall x \in K$$

$F_K := r_K(F)$ is a fragmented family on $K$. Then by Proposition 8.23, $F_Q$ is also fragmented on $P(K) \subset B^*$. Now consider the adjoint $r_K^* : C(K)^* \to V^*$. Then $r_K^*(P(K)) = Q$. □

**Corollary 8.27.** (Namioka [56, Thm 2.5]) Let $K \subset V^*$ be a weak-star compact subset which is norm fragmented. Then $\overline{\sigma}(K)$ is also norm fragmented.

Proof. Take $F := BV$. □

**Lemma 8.28.** (Fabian’s Lemma [17, Lemma 1.5.3]) Let $K$ be a compact space, let $F \subset B_{C(K)}$ be a nonempty set, and consider on $C(K)^*$ the pseudometric $\rho_F$ defined as

$$\rho_F(\lambda, \mu) = sup_{f \in F} <\lambda - \mu, f> \quad \lambda, \mu \in C(K)^*.$$

Assume that $(K, \rho_F)$ (as a subset of $C(K)^*$) is separable. Then $(C(K)^*, \rho_F)$ is also separable.

Proof. By Theorem 8.20, $cl_p(F) \subset bB_1^1(X)$ is metrizable. Since $T : cl_p(F) \subset bB_1^1(X) \to bB_1^1(B^*)$ is sequentially continuous we obtain that this map is a homeomorphic embedding. Hence, $T(cl_p(F)) \subset bB_1^1(B^*)$ is also metrizable. Again by Theorem 8.20 we obtain that $(B^*, \rho_F)$ is separable. This implies that $(C(K)^*, \rho_F)$ is also separable. □
Lemma 8.29. Let $F$ be a fragmented family of real valued functions on $(X, \mu)$. Then $\text{co}(F)$ is also fragmented.

Proof. If $f_i(D)$ is $\varepsilon$-small for every $i = 1, \cdots, n$ and $\sum_{i=1}^{n} c_i = 1$, $c_i > 0$ then $\sum_{i=1}^{n} c_i f_i(D)$ is $\varepsilon$-small. \qed

9. SOME CLASSES OF RIGHT TOPOLOGICAL SEMIGROUPS AND DYNAMICAL SYSTEMS

To the basic classes of right topological semigroups listed in 3.3 above, we add the following two which have naturally arisen in the study of tame and HNS dynamical systems.

Definition 9.1. [23, 25] A compact admissible right topological semigroup $P$ is said to be:

(1) [25] tame if the left translation $\lambda_a : P \rightarrow P$ is a fragmented map for every $a \in P$.

(2) HNS-semigroup if $\{\lambda_a : P \rightarrow P\}_{a \in P}$ is a fragmented family of maps.

These classes are closed under factors. We have the inclusions:

\{compact semitopological semigroups\} $\subset$ \{HNS-semigroups\} $\subset$ \{Tame semigroups\}

Lemma 9.2.

(1) Every compact semitopological semigroup $P$ is a HNS-semigroup.

(2) Every HNS-semigroup is tame.

(3) If $P$ is a metrizable compact right topological admissible semigroup then $P$ is a HNS-semigroup.

Proof. (1) Apply Lemma 8.3.1 to $P \times P \rightarrow P$.

(2) is trivial.

(3) Apply Lemma 8.3.2 to $P \times P \rightarrow P$. \qed

If $P$ is Fréchet, as a topological space, then $P$ is a tame semigroup by Corollary 11.7 below.

10. HNS-SEMIGROUPS, DYNAMICAL SYSTEMS AND ASPLUND BANACH SPACES

Definition 10.1. We say that a compact $S$-system $X$ is hereditarily non-sensitive (HNS, in short) if one of the following equivalent conditions are satisfied:

(1) For every closed nonempty subset $A \subset X$ and for every entourage $\varepsilon$ from the unique compatible uniformity on $X$ there exists an open subset $O$ of $X$ such that $A \cap O$ is nonempty and $s(A \cap O)$ is $\varepsilon$-small for every $s \in S$.

(2) The family of translations $\tilde{S} := \{\tilde{s} : X \rightarrow X\}_{s \in S}$ is a fragmented family of maps.

(3) $E(S, X)$ is a fragmented family of maps from $X$ into itself.

The equivalence of (1) and (2) is evident from the definitions. Clearly, (3) implies (2). As to the implication (2) $\Rightarrow$ (3), observe that the pointwise closure of a fragmented family is again a fragmented family, [25, Lemma 2.8].
Note that if $S = G$ is a group then in Definition 10.1.1 one may consider only closed subsets $A$ which are $G$-invariant (see the proof of [23, Lemma 9.4]).

**Lemma 10.2.**

1. For every $S$ the class of HNS compact $S$-systems is closed under subsystems, arbitrary products and factors.

2. For every HNS compact $S$-system $X$ the corresponding enveloping semigroup $E(X)$ is HNS both as an $S$-system and as a semigroup.

3. Let $P$ be a HNS-semigroup. Assume that $j : S \to P$ be a continuous homomorphism from a semitopological semigroup $S$ into $P$ such that $j(S) \subset \Lambda(P)$. Then the $S$-system $P$ is HNS.

4. \{HNS-semigroups\} = \{enveloping semigroups of HNS systems\}.

**Theorem 10.3.** Let $V$ be a Banach space. The following are equivalent:

1. $V$ is an Asplund Banach space.

2. $(\Theta^{op}, B^*)$ is a HNS system.

3. $E$ is a HNS-semigroup.

**Proof.** (1) $\Rightarrow$ (2): Use Definition 10.1.2 and the following well known characterization of Asplund spaces: $V$ is Asplund iff $B^*$ is $(w^*, \text{norm})$-fragmented (Fact 8.5).

(2) $\Rightarrow$ (1) By Fact 8.5 we have to show that $B$ is a fragmented family for $B^*$. Choose a vector $v \in S_V$. Since $\Theta^{op}$ is a fragmented family of self-maps on $B^*$ and as $v : B^* \to \mathbb{R}$ is uniformly continuous we get that the system $v\Theta^{op} = \Theta v$ of maps from $B^*$ to $\mathbb{R}$ is also fragmented. Now recall that $\Theta v = B$ by Lemma 3.12.1.

(2) $\Rightarrow$ (3): Follows from Lemma 10.2.2 and the fact that $E$ is the enveloping semigroup $E(\Theta^{op}, B^*)$.

(3) $\Rightarrow$ (1): $\Lambda(E) = \Theta^{op}$ (Lemma 3.12.5) and $E$ is a HNS-semigroup. So, $(S, E)$ is HNS by Lemma 10.2.3 with $S = \Theta^{op}$. Take $\psi \in B^*$ with $||\psi|| = 1$. The map $q : E \to B^*, p \mapsto p\psi$ defines a continuous homomorphism of $\Theta^{op}$-systems. By Lemma 3.12.4, we have $E\psi = B^*$. So $q$ is onto. Now observe that the HNS property is preserved by factors of $S$-systems (Lemma 10.2.1). \hfill $\Box$

Our next two theorems are based on ideas from Glasner-Megrelisvili-Uspenskij [30].

**Theorem 10.4.** Let $V$ be a Banach space. The following are equivalent:

1. $V$ is a separable Asplund space.

2. $E$ is homeomorphic to the Hilbert cube $[-1, 1]^N$ (for infinite-dimensional $V$).

3. $E$ is metrizable.

**Proof.** (1) $\Rightarrow$ (2) Since $E$ is a compact affine subset in the Fréchet space $\mathbb{R}^N$ we can use Keller’s Theorem [9, p. 100].

(2) $\Rightarrow$ (3) Is trivial.

(3) $\Rightarrow$ (1) $E$ is a HNS-semigroup by Lemma 9.2.3. Now Theorem 10.3 implies that $V$ is Asplund. It is also separable; indeed, by Lemma 3.12.4, $B^*$ is a continuous image of $E$, so that $B^*$ is also $w^*$-metrizable, which in turn yields the separability of $V$. \hfill $\Box$

**Theorem 10.5.** Let $X$ be a compact $S$-system. Consider the following assertions:

(a) $E(X)$ is metrizable.

(b) $(S, X)$ is HNS.
Then:

(1) \((a) \Rightarrow (b)\).
(2) If \(X\), in addition, is metrizable then \((a) \Leftrightarrow (b)\).

Proof. (1) By Definition 10.1 we have to show that \(E(X)\) is a fragmented family of maps from \(X\) into itself. The unique compatible uniformity on the compactum \(X\) is the weakest uniformity on \(X\) generated by \(C(X)\). Using Remark 8.2.1 one may reduce the proof to the verification of the following claim: \(E^f := \{f \circ p : p \in E(X)\}\) is a fragmented family for every \(f \in C(X)\). In order to prove this claim apply Lemma 8.3.2 to the induced mapping \(E(X) \times X \to \mathbb{R}, (p, x) \mapsto f(px)\) (using our assumption that \(E(X)\) is metrizable).

(2) If \(X\) is a metrizable HNS S-system then by Theorem 12.3 below, \((S, X)\) is representable on a separable Asplund space \(V\). We can assume that \(X\) is \(S\)-embedded into \(B^*\). The enveloping semigroup \(E(S, B^*)\) is embedded into \(E\) The latter is metrizable by virtue of Theorem 10.4. Hence \(E(S, X)\) is also metrizable, being a continuous image of \(E(S, B^*)\). □

**Theorem 10.6.** For a compact metric \(S\)-space \(X\) the following conditions are equivalent:

1. the dynamical system \((S, X)\) is RN (that is, Asplund representable);
2. \((S, X)\) is HNS;
3. the enveloping semigroup \(E(S, X)\) is metrizable.

**Theorem 10.7.** Every scattered (e.g., countable) compact \(S\)-space \(X\) is HNS

Proof. Recall that \(C(X)\) is Asplund if (and only if) the compactum \(X\) is scattered. □

11. Tame semigroups, tame systems and Rosenthal spaces

**Definition 11.1.** A compact separately continuous \(S\)-system \(X\) is said to be tame if the translation \(\lambda_a : X \to X, x \mapsto ax\) is a fragmented map for every element \(a \in E(X)\) of the enveloping semigroup.

**Lemma 11.2.** Every WAP system is HNS and every HNS is tame.

Proof. If \((S, X)\) is WAP then \(E(X) \times X \to X\) is separately continuous. By Lemma 8.3.1 we obtain that \(E\) is a fragmented family of maps from \(X\) to \(X\). In particular, its subfamily \(\{\tilde{s} : X \to X\}_{s \in S}\) of all translations is fragmented. Hence, \((S, X)\) is HNS.

Directly from the definitions we conclude that every HNS is tame. □

Another proof of Lemma 11.2 comes also from Banach representations theory for dynamical systems because every reflexive space is Asplund and every Asplund is Rosenthal.

By [29], a compact metrizable \(S\)-system \(X\) is tame if \(S\) is eventually fragmented on \(X\), that is, for every infinite (countable) subset \(C \subset G\) there exists an infinite subset \(K \subset C\) such that \(K\) is a fragmented family of maps \(X \to X\).

**Lemma 11.3.**

1. For every \(S\) the class of tame \(S\)-systems is closed under closed subsystems, arbitrary products and factors.
(2) For every tame compact $S$-system $X$ the corresponding enveloping semigroup $E(X)$ is tame both as an $S$-system and as a semigroup.

(3) Let $P$ be a tame right topological compact semigroup and let $\nu : S \to P$ be a continuous homomorphism from a semitopological semigroup $S$ into $P$ such that $\nu(S) \subseteq \Lambda(P)$. Then the $S$-system $P$ is tame.

(4) $\{\text{tame semigroups}\} = \{\text{enveloping semigroups of tame systems}\}$.

**Theorem 11.4.** Let $V$ be a Banach space. The following are equivalent:

1. $V$ is a Rosenthal Banach space.
2. $(\Theta^{\text{op}}, B^*)$ is a tame system.
3. $p : B^* \to B^*$ is a fragmented map for each $p \in \mathcal{E}$.
4. $\mathcal{E}$ is a tame semigroup.

**Proof.** (2) $\iff$ (3): Follows from the definition of tame flows because $\mathcal{E} = E(\Theta^{\text{op}}, B^*)$.

(2) $\Rightarrow$ (1): By a characterization of Rosenthal spaces [25, Prop. 4.12] (see also Fact 8.11) it suffices to show that $B^{**} \subseteq \mathcal{F}(B^*)$. Since $(\Theta^{\text{op}}, B^*)$ is tame, $p : B^* \to B^*$ is fragmented for every $p \in E(\Theta^{\text{op}}, B^*) = \mathcal{E}$. Pick an arbitrary $v \in B_V$ with $\|v\| = 1$. Then $v\mathcal{E}$ is exactly $B^{**}$ by Lemma 3.12.2. So every $\phi \in B^{**}$ is a composition $v \circ p$, where $p$ is a fragmented map. Since $v : B^* \to \mathbb{R}$ is weak* continuous we conclude that $\phi : B^* \to B^*$ is fragmented.

(1) $\Rightarrow$ (3): We have to show that $\mathcal{E} \subseteq \mathcal{F}(B^*, B^*)$ for every Rosenthal space $V$. Let $p \in \mathcal{E}$. Then $p \in \Theta(V^*)$. That is, $p$ is a linear map $p : V^* \to V^*$ with norm $\leq 1$. Then, for every vector $f \in V$, the composition $f \circ p : V^* \to \mathbb{R}$ is a linear bounded functional on $V^*$. That is, $f \circ p \in V^{**}$ belongs to the second dual. Again, by the above mentioned characterization of Rosenthal spaces, the corresponding restriction $f \circ p|_{B^*} : B^* \to \mathbb{R}$ is a fragmented function for every $f \in V$. Since $V$ separates points of $B^*$ we can apply [25, Lemma 2.3.3]. It follows that $p : B^* \to B^*$ is fragmented for every $p \in \mathcal{E}$.

\[ \square \]

### 11.1. Some concrete examples of systems and families.

**Example 11.5.**

1. Let $X = [0, 1]$ be the unit interval. Consider the cascade $(\mathbb{Z}, X)$ generated by the homeomorphism $\sigma(x) = x^2$. Then $(\mathbb{Z}, X)$, as a dynamical system, is RN and not Eberlein. To see this observe that the pair of sequences $x_n = 1 - \frac{1}{n}$ in $X = [0, 1]$ and $\sigma^m \in G$ with $\sigma^m(x) = x^{2^m}$ does not satisfy DLP. The corresponding limits are 0 and 1. This means that $(\mathbb{Z}, [0, 1])$ is not Eberlein. The enveloping semigroup $E([0, 1])$ is metrizable being homeomorphic to the two-point compactification of $\mathbb{Z}$. Hence, by [30], $(\mathbb{Z}, [0, 1])$ is RN. The sequence $\{\sigma^m : [0, 1] \to [0, 1]\}_{m \in \mathbb{N}}$ is a fragmented family which does not satisfy DLP.

2. The natural action of the Polish group $H_+[0, 1]$ of all increasing homeomorphisms of $[0, 1]$ on $[0, 1]$ is tame but not HNS. The family $H_+[0, 1]$ of functions (or its dense subsequence) is eventually fragmented but not fragmented.

3. The Bernoulli shift system $(\mathbb{Z}, \{0, 1\}^\mathbb{Z})$ is not WRN (equivalently, nontame). In fact, it is well known that the enveloping semigroup of this system can be
identified with $\beta\mathbb{Z}$. Now use the dynamical version of BFT dichotomy (Fact 11.9).

Another way to see that the shift system is not tame is the well known fact that the sequence of projections 
$$\{\pi_m : \{0,1\}^\mathbb{N} \to \{0,1\}\}_{m \in \mathbb{N}}$$
is independent. Hence by Theorem 8.10 this family fails to be eventually fragmented.

11.2. A dynamical BFT dichotomy. Recall that a topological space $K$ is a Rosenthal compactum if it is homeomorphic to a pointwise compact subset of the space $B_1(X)$ of functions of the first Baire class on a Polish space $X$. All metric compact spaces are Rosenthal. An example of a separable non-metrizable Rosenthal compactum is the Helly compact of all nondecreasing selfmaps of $[0,1]$ in the pointwise topology. Recall that a topological space $K$ is Fréchet (or, Fréchet-Urysohn) if for every $A \subset K$ and every $x \in cl(A)$ there exists a sequence of elements of $A$ which converges to $x$. Every Rosenthal compact space $K$ is Fréchet by a result of Bourgain-Fremlin-Talagrand [8, Theorem 3F], generalizing a result of Rosenthal.

Theorem 11.6. If the enveloping semigroup $E(X)$ is a Fréchet (e.g., Rosenthal) space, as a topological space, then $(S,X)$ is a tame system (and $E(X)$ is a tame semigroup).

Proof. Let $p \in E(X)$. We have to show that $p : X \to X$ is fragmented. By properties of fragmented maps [25, Lemma 2.3.3] it is enough to show that $f \circ p : X \to \mathbb{R}$ is fragmented for every $f \in C(X)$. By the Fréchet property of $E(X)$ we may choose a sequence $s_n$ in $S$ such that the sequence $j(s_n)$ converges to $p$ in $E(X)$. Hence the sequence of continuous functions $f \circ s_n = f \circ j(s_n)$ converges pointwise to $f \circ p$ in $\mathbb{R}^X$. Apply Lemma 8.3.2 to the evaluation map $F \times X \to \mathbb{R}$, where $F := \{f \circ p\} \cup \{f \circ j(s_n)\}_{n \in \mathbb{N}} \subset \mathbb{R}^X$ carries the pointwise topology. We conclude that $F$ is a fragmented family. In particular, $f \circ p$ is a fragmented map. ($E(X)$ is a tame semigroup by Lemma 11.3.2.)

Corollary 11.7. Let $P$ be a compact right topological admissible semigroup. If $P$ is Fréchet (e.g., when it is Rosenthal), as a topological space, then $P$ is a tame semigroup.

Proof. Applying Theorem 11.6 to the system $(S,P)$, with $S := \Lambda(P)$ we obtain that $E(S,P) = P$ is a tame semigroup.

The following theorem is due to Bourgain-Fremlin-Talagrand [8, Theorem 3F], generalizing a result of Rosenthal. The second assertion (BFT dichotomy) is presented as in the book of Todorčević [71] (see Proposition 1 of Section 13).

Theorem 11.8. (1) Every Rosenthal compact space $K$ is Frechet.

(2) (BFT dichotomy) Let $X$ be a Polish space and let $\{f_n\}_{n \in \mathbb{N}}$ be a sequence of continuous real valued functions on $X$ which is bounded. Then, either the sequence $\{f_n\}_{n \in \mathbb{N}}$ contains a pointwise convergent subsequence, or it contains a subsequence whose closure in $\mathbb{R}^X$ is homeomorphic to $\beta\mathbb{N}$, the Stone-Čech compactification of $\mathbb{N}$. 

The following result was proved in [23, Theorem 3.2] using the Bourgain-Fremlin-Talagrand (BFT) dichotomy in the setting of continuous group actions. The same arguments work also for separately continuous semigroup actions. For the sake of completeness we include a simplified proof.

**Fact 11.9** (A dynamical BFT dichotomy). [23, Theorem 3.2] Let $X$ be a compact metric dynamical $S$-system and let $E = E(X)$ be its enveloping semigroup. We have the following alternative. Either

1. $E$ is a separable Rosenthal compact, hence $\text{card } E \leq 2^{\aleph_0}$; or
2. the compact space $E$ contains a homeomorphic copy of $\beta \mathbb{N}$, hence $\text{card } E = 2^{2^{\aleph_0}}$.

The first possibility holds iff $X$ is a tame $S$-system.

**Proof.** For every $f \in C(X)$ define $E^f := \{f \circ p : p \in E\}$. Then $E^f$ is a pointwise compact subset of $\mathbb{R}^X$, being a continuous image of $E$ under the map $q_f : E \to E^f$, $p \mapsto f \circ p$. Since $X$ is metrizable by the separability of $E$ there exists a sequence $\{s_m\}_{m=1}^{\infty}$ in $S$ such that $\{j(s_m)\}_{m=1}^{\infty}$ is dense in $E(X)$. In particular, the sequence of real valued functions $\{f \circ s_m\}_{m=1}^{\infty}$ is pointwise dense in $E^f$. Choose a sequence $\{f_n\}_{n \in \mathbb{N}}$ in $C(X)$ which separates the points of $X$. For every pair $s,t$ of distinct elements of $E$ there exist a point $x_0 \in X$ and a function $f_{n_0}$ such that $f_{n_0}(sx_0) \neq f_{n_0}(tx_0)$. It follows that the continuous diagonal map

$$\Phi : E \to \prod_{n \in \mathbb{N}} E^{f_n}, \quad p \mapsto (f_1 \circ p, f_2 \circ p, \ldots)$$

separates the points of $E$ and hence is a topological embedding. Now if for each $n$ the space $E^{f_n}$ is a Rosenthal compactum then so is $E \cong \Phi(E) \subset \prod_{n=1}^{\infty} E^{f_n}$, because the class of Rosenthal compacta is closed under countable products and closed subspaces. On the other hand if at least one $E^{f_n} = \text{cl}_p(\{f_n \circ s_m\}_{m=1}^{\infty})$ is not Rosenthal then, by BFT-dichotomy it contains a homeomorphic copy of $\beta \mathbb{N}$ and it is easy to see that so does its preimage $E$. In fact if $\beta \mathbb{N} \cong Z \subset E^{f_n}$ then any closed subset $Y$ of $E$ which projects onto $Z$ and is minimal with respect to these properties is also homeomorphic to $\beta \mathbb{N}$.

Now we show the last assertion. If $X$ is tame then every $p \in E(X)$ is a fragmented self-map of $X$. Hence every $f \circ p \in E^f$ is fragmented. By Remark 8.2.2 this is equivalent to saying that every $f \circ p$ is Baire 1. So $E^f \subset \mathcal{B}_1(X)$ is a Rosenthal compactum. Therefore, $E \cong \Phi(E) \subset \prod_{n \in \mathbb{N}} E^{f_n}$ is also Rosenthal. Conversely, if $E$ is a Rosenthal compactum then $(S, X)$ is tame by Theorem 11.6. \hfill $\Box$

**Theorem 11.10** (BFT dichotomy for Banach spaces). Let $V$ be a separable Banach space and let $E = E(V)$ be its (separable) enveloping semigroup. We have the following alternative. Either

1. $E$ is a Rosenthal compactum, hence $\text{card } E \leq 2^{\aleph_0}$; or
2. the compact space $E$ contains a homeomorphic copy of $\beta \mathbb{N}$, hence $\text{card } E = 2^{2^{\aleph_0}}$.

The first possibility holds iff $V$ is a Rosenthal Banach space.

**Proof.** Recall that $E = E(\Theta^p, B^*)$. By Theorem 11.4, $V$ is Rosenthal iff $(\Theta^p, B^*)$ is tame. Since $V$ is separable, $B^*$ is metrizable. So we can apply Fact 11.9. \hfill $\Box$
11.3. **Some topological corollaries.** Answering a question of Talagrand [69, Problem 14-2-41], R. Pol [59] gave an example of a separable compact Rosenthal space \( K \) which cannot be embedded in \( \mathbb{B}_1(X) \) for any compact metrizable \( X \). In [25] we say that a compact space \( K \) is **strongly Rosenthal** if it is homeomorphic to a subspace of \( \mathbb{B}_1(X) \) for a compact metrizable \( X \); and that it is **admissible** if there exists a metrizable compact space \( X \) and a bounded subset \( Z \subset C(X) \) with \( K \subset \text{cl}_p(Z) \), such that the pointwise closure \( \text{cl}_p(Z) \) of \( Z \) in \( \mathbb{R}^X \) consists of Baire 1 functions. Clearly every admissible compactum is strongly Rosenthal.

**Theorem 11.11.** [25] Let \( X \) be a compact metrizable \( S \)-system. Then \((S,X)\) is tame iff the compactum \( K := E(X) \) is Rosenthal iff \( E(X) \) is admissible.

Thus, Pol’s separable compactum mentioned above cannot be of the form \( E(X) \). We do not know if every separable strongly Rosenthal space is admissible. If the answer to this question is in the negative, then this will yield another topological obstruction on being an enveloping semigroup.

Finally, as a consequence of the representation theorem 12.3.1 below we obtain the following result: A compact space \( K \) is an admissible Rosenthal compactum iff it is homeomorphic to a weak* closed bounded subset in the second dual of a separable Rosenthal Banach space \( V \).

Essentially the same result (using different terminology and setting) was obtained earlier by Marciszewski (see Marciszewski [44, Section 6.2] and also Marciszewski-Pol [45, Theorem 8.2]).

11.4. **Some classes of functions.**

**Definition 11.12.** Let \( f \in C(X) \) on a (not necessarily, compact) \( S \)-system \( X \).

1. We say that \( f \) *comes* from the \( S \)-compactification \( q : X \to Y \) (where the action of \( S \) on \( Y \) is at least separately continuous) if there exists a continuous function \( f' : Y \to \mathbb{R} \) such that \( f = f' \circ q \).

2. We say that \( f \in C(X) \) is \( \text{RMC} \) (right multiplicatively continuous) if \( f \) comes from some \( S \)-compactification \( q : X \to Y \). For every compact \( S \)-system \( X \) we have \( \text{RMC}(X) = C(X) \).

3. If we consider only jointly continuous \( S \)-actions on \( Y \) then the functions \( f : X \to \mathbb{R} \) which come from such \( G \)-compactifications \( q : X \to Y \) are **right uniformly continuous**. Notation: \( f \in \text{RUC}(X) \).

4. \( f \) is said to be: a) \( \text{WAP} \); b) \( \text{Asplund} \); c) **tame** if \( f \) comes from an \( S \)-compactification \( q : X \to Y \) such that \((S,Y)\) is: \( \text{WAP} \), \( \text{HNS} \) or tame respectively. For the corresponding classes of functions we use the notation: \( \text{WAP}(X), \text{Asp}(X), \text{Tame}(X) \), respectively. Each of these is a norm closed \( S \)-invariant subalgebra of the \( S \)-algebra \( \text{RMC}(X) \subset C(X) \) and

\[
\text{WAP}(X) \subset \text{Asp}(X) \subset \text{Tame}(X).
\]

For more details see [27, 28].

5. Note that as a particular case of (3) we have defined the algebras \( \text{WAP}(S) \), \( \text{Asp}(S), \text{Tame}(S) \) corresponding to the left action of \( S \) on \( X := S \).

**Definition 11.13.** [23, 27] We say that a compact dynamical \( S \)-system \( X \) is **cyclic** if there exists \( f \in C(X) \) such that \((S,X)\) is topologically \( S \)-isomorphic to the Gelfand
space \( X_f \) of the \( S \)-invariant unital subalgebra \( A_f \subset C(X) \) (generated by the orbit \( fS \)).

**Remark 11.14.** Let \( X \) be a (not necessarily compact) \( S \)-system and \( f \in \text{RMC}(X) \). Then, as was shown in [27], there exist: a cyclic \( S \)-system \( X_f \), a continuous \( S \)-compactification \( \pi_f : X \to X_f \), and a continuous function \( \tilde{f} : X_f \to \mathbb{R} \) such that \( f = \tilde{f} \circ \pi_f \); that is, \( f \) comes from the \( S \)-compactification \( \pi_f : X \to X_f \). The collection of functions \( fS \) separates points of \( X_f \). Finally, \( f \in \text{RUC}(X) \) iff the action of \( S \) on \( X_f \) is jointly continuous.

As expected the cyclic \( S \)-systems \( X_f \) provide “building blocks” for compact \( S \)-systems. That is, every compact \( S \)-space can be embedded into the \( S \)-product of \( S \)-spaces \( X_f \), where \( f \in C(X) \).

**Proposition 11.15.** Let \( X \) be a compact \( S \)-space and \( f \in C(X) \).

1. \( f \in WAP(X) \) iff \( fS \) has DLP on \( X \).
2. \( f \in \text{Asp}(X) \) iff \( fS \) is a fragmented family.
3. \( f \in \text{Tame}(X) \) iff \( fS \) is eventually fragmented iff \( fS \) does not contain an \( l_1 \)-sequence.

12. **Representations of dynamical systems and of functions**

Next we deal with the representability of families of real-valued functions on compact systems. This topic is closely related to the “smallness” of the family \( F \) in terms of its pointwise closure in the spirit of Theorem 8.10.

**Definition 12.1.** Let \( \mathcal{K} \subset \text{Ban} \) be a subclass of Banach spaces.

1. Let \( X \) be a compact \( S \)-system and \((h, \alpha)\) a representation of \((S,X)\) on a Banach space \( V \). Let \( F \subset C(X) \) be a bounded \( S \)-invariant family of continuous functions on \( X \) and \( \nu : F \to V \) a bounded mapping. We say that \((\nu, h, \alpha)\) is an \( F \)-representation of the triple \((F,S,X)\) if \( \nu \) is an \( S \)-mapping (i.e., \( \nu(fs) = \nu(f)s \) for every \((f, s) \in F \times S\)) and

\[
\text{f}(x) = \langle \nu(f), \alpha(x) \rangle \quad \forall \ f \in F, \ \forall \ x \in X.
\]

In other words, the following diagram commutes

\[
\begin{array}{ccc}
F \times X & \xrightarrow{\nu} & \mathbb{R} \\
\downarrow & & \downarrow \text{id}_\mathbb{R} \\
V \times V^* & \xrightarrow{\alpha} & \mathbb{R}
\end{array}
\]

(12.1)

2. We say that a family \( F \subset C(X) \) is \( \mathcal{K} \)-representable if there exists a Banach space \( V \in \mathcal{K} \) and a representation \((\nu, h, \alpha)\) of the triple \((F,S,X)\). A function \( f \in C(X) \) is said to be \( \mathcal{K} \)-representable if the orbit \( fS \) is \( \mathcal{K} \)-representable.

Note that we do not assume in (1) or (2) that \( \alpha \) is injective. However, when the family \( F \) separates points on \( X \) it follows that the map \( \alpha \) is necessarily an injection.

3. In particular, we obtain the definitions of reflexively, Asplund and Rosenthal representable families of functions on dynamical systems.
Clearly, every bounded $S$-invariant $F \subset C(X)$ on an $S$-system $X$ is Banach representable via the canonical representation on $V = C(X)$.

12.1. **Representation theorems.** Let $S$ be a semitopological semigroup and $X$ a compact $S$-system with a separately continuous action.

**Theorem 12.2.** *(Small families of functions)*

Let $F \subset C(X)$ be a norm bounded $S$-invariant subset of $C(X)$.

1. $(F, S, X)$ admits a Rosenthal representation iff $F$ is an eventually fragmented family iff $\text{cl}_p(F) \subset F(X)$.
2. $(F, S, X)$ admits an Asplund representation iff $F$ is a fragmented family iff the envelope $\text{cl}_p(F)$ of $F$ is a fragmented family.
3. $(F, S, X)$ admits a reflexive representation iff $\text{cl}_p(F) \subset C(X)$ iff $F$ has DLP on $X$.

**Proof.** (3) Already was proved in Section 6.3.

(1) and (2): The “only if part” is a consequence of the characterizations of Asplund and Rosenthal spaces in terms of fragmented and eventually fragmented families, Theorems 8.5.4 and 8.11.4. □

**Theorem 12.3.**

1. $(S, X)$ is a tame (continuous) system if and only if $(S, X)$ is weakly (respectively, strongly) Rosenthal-approximable.
2. $(S, X)$ is a HNS (continuous) system if and only if $(S, X)$ is weakly (respectively, strongly) Asplund-approximable.

If $X$ is metrizable then in (1) and (2) “approximable” can be replaced by “representable”. Moreover, the corresponding Banach space can be assumed to be separable.

**Proof.** “only if” part: For (1) use the fact that $(\Theta^\text{op}, B^*)$ is a tame system (Theorem 11.4) for every Rosenthal $V$ and for (2), the fact that $(\Theta^\text{op}, B^*)$ is HNS (Theorem 10.3) for Asplund $V$.

“if” part: (1) For every $f \in C(X) = \text{Tame}(X)$ the orbit $fS$ is a Rosenthal family for $X$ (Proposition 11.15). Applying Theorem 12.4 below we conclude that every $f \in C(X) = \text{Tame}(X)$ on a compact $G$-space $X$ comes from a Rosenthal representation. Since continuous functions separate points of $X$, this implies that Rosenthal representations of $(S, X)$ separate points of $X$. So, for (1) it is enough to prove the following result which gives a proof of Theorem 12.2.1. The proof of (2) is similar.

**Theorem 12.4.** Let $F \subset C(X)$ be a Rosenthal family (Asplund family) for $X$ such that $F$ is $S$-invariant; that is, $fS \subset F \, \forall f \in F$. Then there exist: a Rosenthal (respectively, Asplund) Banach space $V$, an injective mapping $\nu : F \rightarrow B_V$ and a representation

$$h : S \rightarrow \Theta(V), \quad \alpha : X \rightarrow V^*$$

of $(S, X)$ on $V$ such that $h$ is weakly continuous, $\alpha$ is a weak* continuous map and

$$f(x) = \langle \nu(f), \alpha(x) \rangle \quad \forall \, f \in F \, \forall \, x \in X.$$

Thus the following diagram commutes.
If $X$ is metrizable then in addition we can suppose that $V$ is separable.
If the action $S \times X \to X$ is continuous we may assume that $h$ is strongly continuous.

Proof. Step 1: The construction of $V$.

For brevity of notation let $A := C(X)$ denote the Banach space $C(X)$, $B$ will denote its unit ball, and $B^*$ will denote the weak* compact unit ball of the dual space $A^* = C(X)^*$. Let $W$ be the symmetrized convex hull of $F$; that is, $W := \operatorname{co} (F \cup -F)$. Consider the sequence of sets

$$M_n := 2^n W + 2^{-n} B.$$  

Then $W$ is convex and symmetric. We apply the construction of Davis-Figiel-Johnson-Pelczyński [11] as follows. Let $\|\|_n$ be the Minkowski functional of the set $M_n$, that is,

$$\| v \|_n = \inf \{ \lambda > 0 \mid v \in \lambda M_n \}.$$  

Then $\|\|_n$ is a norm on $A$ equivalent to the given norm of $A$. For $v \in A$, set

$$N(v) := \left( \sum_{n=1}^{\infty} \| v \|_n^2 \right)^{1/2}$$  

and let $V := \{ v \in A \mid N(v) < \infty \}$.

Denote by $j : V \to A$ the inclusion map. Then $(V, N)$ is a Banach space, $j : V \to A$ is a continuous linear injection and

$$W \subset j(B_V) = B_V \subset \bigcap_{n \in \mathbb{N}} M_n = \bigcap_{n \in \mathbb{N}} (2^n W + 2^{-n} B)$$  

Indeed, if $v \in W$ then $2^n v \in M_n$, hence $\| v \|_n \leq 2^{-n}$ and $N(v)^2 \leq \sum_{n \in \mathbb{N}} 2^{-2n} < 1$. This proves $W \subset j(B_V)$. In order to prove the second inclusion recall that the norms $\|\|_n$ on $A$ are equivalent to each other. It follows that if $v \in B_V$ then $\| v \|_n < 1$ for all $n \in \mathbb{N}$. That is, for every $n \in \mathbb{N}$, $v \in \lambda_n M_n$ for some $0 < \lambda_n < 1$. By the construction $M_n$ is a convex subset containing the origin. This implies that $\lambda_n M_n \subset M_n$. Hence $j(v) = v \in M_n$ for every $n \in \mathbb{N}$.

Step 2: The construction of the representation $(h, \alpha)$ of $(S, X)$ on $V$.

The given action $S \times X \to X$ induces a natural linear norm preserving continuous right action $C(X) \times S \to C(X)$ on the Banach space $A = C(X)$. It follows by the construction that $W$ and $B$ are $S$-invariant subsets in $A$. This implies that $V$ is an $S$-invariant subset of $A$ and the restricted natural linear action $V \times S \to V, (v, g) \mapsto vg$ satisfies $N(vg) \leq N(v)$. Therefore, the co-homomorphism $h : S \to \Theta(V), h(s)(v) := vs$ is well defined.
Let \( j^* : A^* \to V^* \) be the adjoint map of \( j : V \to A \). Define \( \alpha : X \to V^* \) as follows. For every \( x \in X \subset C(X)^* \) set \( \alpha(x) = j^*(x) \). Then \((h, \alpha)\) is a representation of \((S, X)\) on the Banach space \( V \).

By the construction, \( F \subset W \subset B_V \). Define \( \nu : F \hookrightarrow B_V \) as the natural inclusion. Then

\[
(12.5) \quad f(x) = \langle \nu(f), \alpha(x) \rangle \quad \forall \ f \in F \ \forall \ x \in X.
\]

**Step 3:** Weak continuity of \( h : S \to \Theta(V) \).

By our construction \( j^* : C(X)^* \to V^* \), being the adjoint of the bounded linear operator \( j : V \to C(X) \), is a norm and weak* continuous linear operator. By [17, Lemma 1.2.2] we obtain that \( j^*(C(X)^*) \) is norm dense in \( V^* \). Since \( V \) is Rosenthal, Haydon’s theorem (Fact 8.11.4) gives \( Q := cl_{\text{norm}} (co(Y)) = cl_{\text{norm}} (co(Y)) \), where \( Y := j^*(X) \). Now observe that \( j^*(P(X)) = Q \). Since \( S \times X \to X \) is separately continuous, every orbit map \( \hat{x} : S \to X \) is continuous, and each orbit map \( \widehat{j^*(x)} : S \to j^*(X) \) is weak* continuous. Then also \( \widehat{j^*(z)} : S \to V^* \) is weak* continuous for each \( z \in cl_{\text{norm}} (co(j^*(X))) \). Since \( sp(Q) \) is norm dense in \( V^* \) (and \( ||h(s)|| \leq 1 \) for each \( s \in S \)) it easily follows that \( j^*(z) : S \to V^* \) is weak* continuous for every \( z \in V^* \). This is equivalent to the weak continuity of \( h \).

If the action \( S \times X \to X \) is continuous we may assume that \( h \) is strongly continuous. Indeed, by the definition of the norm \( N \), we can show that the action of \( S \) on \( V \) is norm continuous (use the fact that, for each \( n \in \mathbb{N} \), the norm \( ||\cdot||_n \) on \( A \) is equivalent to the given norm on \( A \)).

**Step 4:** \( V \) is a Rosenthal space.

*Proof.* If \( F \) is an eventually fragmented family for \( X \) then \( W := co (F \cup -F) \) is an eventually fragmented family for \( X \) and even for \( B^* \) (Proposition 8.23). By the construction of DFJP we get \( j : V \to A \) such that \( cl_{\text{norm}} j^*(A^*) = V^* \) (Fabian). Denote by \( M := \cap \{2^n W + \frac{1}{n} B \} \). Then \( j(B_V) \subset M \). It is easy to see that \( M \) is eventually weakly fragmented on \( X \). Since \( \mathbb{R} \) is a metrizable uniform space by diagonal arguments we obtain that \( M \) is eventually fragmented on \( X \). Therefore \( M \) is eventually fragmented also on \( B^* \) (again Proposition 8.23). In order to show that \( V \) is Rosenthal it is equivalent to show that \( B_V \) is eventually fragmented on \( B_{V^*} \). (Fact 8.11.) It is equivalent to show that for every infinite subset \( C_0 \subset B_V \) there exists a (countable) infinite subset \( C \subset C_0 \) which is fragmented on \( B_{V^*} \), or equivalently, that \( (B_{V^*}, \rho_C) \) is separable. Equivalently, that \( (V^*, \rho_C) \) is separable. Since \( j(C_0) \subset M \) is an infinite subset (recall that \( j \) is injective) we obtain that there exists an infinite subset \( j(C) \) which is a fragmented family on \( B_{A^*} \). Equivalently, \( (B_{A^*}, \rho_{j(C)}) \) is separable. Equivalently, \( (A^*, \rho_{j(C)}) \) is separable (Theorem 8.13). By the definition of the adjoint operator \( \langle < j(c), v^* >, < c, j^*(v^*) > \rangle \) we obtain that \( (j^*(A^*), \rho_C) \) is separable. Then its closure is also separable. That is, \( cl_{\rho_C}(j^*(A^*)) \) is also \( \rho_C \)-separable. Since \( C \) is a bounded subset, clearly, \( cl_{\rho_C}(j^*(A^*)) \supset cl_{\text{norm}}(j^*(A^*)) = V^* \). Therefore, \( (V^*, \rho_C) \) is separable, as desired. \( \square \)
If the compact space $X$ is metrizable then $C(X)$ is separable and it is also easy to
see that $(V, N)$ is separable.

This proves Theorem 12.4 and hence also Theorem 12.3.1.

For the “Asplund case” (when $F$ is fragmented on $X$) use

**Step 4’:** $V$ is an Asplund space.

The main idea is that the corresponding results of [50, Section 7] and [23, Section
9] can be adopted here, thus obtaining a modification of Theorem 12.4 which
replaces a Rosenthal space by an Asplund space, and a “Rosenthal family $F$” for
$X$ by an “Asplund set”. The latter means that for every countable subset $A \subset F$ the
pseudometric $\rho_A$ on $X$ defined by

$$\rho_A(x, y) := \sup_{f \in A} |f(x) - f(y)|, \ x, y \in X$$

is separable. By [17, Lemma 1.5.3] this is equivalent to saying that $(C(X)^*, \rho_A)$ is
separable. Now $\text{co}(F \cup -F)$ is an Asplund set for $B^*$ by [17, Lemma 1.4.3]. The rest
is similar to the proof of [50, Theorem 7.7]. Checking the weak continuity of $h$ one
can apply a similar idea (using again Haydon’s theorem as in (1)).

Finally note that if $X$ is metrizable then in (1) and (2) “approximable” can be
replaced by “representable” using an $l_2$-sum of a sequence of separable Banach spaces.

Note that, in Definition 12.1, when the family $F$ separates points on $X$ it follows
that the map $\alpha$ is necessarily an injection. In view of this remark, Theorem 12.2
implies Theorem 12.3 and also the following useful result.

**Theorem 12.5.** A compact $S$-system $X$ is RN (WRN, Eberlein) iff there exists a
norm bounded $S$-invariant fragmented (resp.: eventually fragmented, DLP) family
$F \subset C(X)$ which separates points of $X$.

Similar to Theorem 6.23 one may show

**Theorem 12.6.** Let $G$ be a topological group and $f \in \text{RUC}(G)$. The following are
equivalent:

1. $f \in \text{Asp}(G)$ iff $f$ is a matrix coefficient of a strongly continuous Asplund
   co-representation of $G$.
2. $f \in \text{Tame}(G)$ iff $f$ is a matrix coefficient of a strongly continuous Rosenthal
   co-representation of $G$.

12.2. **The purely topological case.** Note that the definitions and results of Section
12 (for instance, Theorem 12.2) make sense in the purely topological setting, for trivial
$S = \{e\}$ actions, yielding characterizations of “small families” of functions, and of
RN, WRN and Eberlein compact spaces.

The “only if” parts of these results, in the cases of Eberlein and RN compact spaces
(with trivial actions), are consequences of known characterizations of reflexive and
Asplund spaces. The Eberlein case yields a well-known result: a compact space $X$
is Eberlein iff there exits a pointwise compact subset $Y \subset C(X)$ which separates the
points of $X$. The RN case is very close to some results of Namioka [56] (up to some
reformulations). The case of WRN spaces seems to be new.
Recall that (answering to a question posed by Lindenstrauss) by a classical result of Benjamini-Rudin-Wage, continuous surjective maps preserve the class of Eberlein compact spaces. The same is true for uniformly Eberlein (that is, Hilbert representable) compacta. Recently, Aviles and Koszmider [3] proved that this is not the case for the class RN of Asplund representable compacta, answering a long standing open problem posed by Namioka [56]. The following question seems to be interesting.

**Question 12.7.** Is it true that the class of WRN (e.g., Rosenthal representable) compact spaces is closed under continuous onto maps (in the realm of Hausdorff spaces)?

**Remark 12.8.**

1. An example of a compact space which is not WRN is $\beta N$. This was done by Todorčević (private communication).
2. Two arrows space is WRN but not RN. More precisely, as we recently established, every compact linearly ordered space is WRN. On the other hand, two arrows space is not RN as it was established by Namioka [56, Example 5.9].
3. One may show that a compact space $K$ is WRN iff the Banach space $C(K)$ is Rosenthal generated (meaning that there exists a Rosenthal space $V$ and a linear dense (injective) operator $V \rightarrow C(K)$). It is a WRN analog of Stegall's result for RN compacts.

13. Some applications

13.1. **When does weak imply strong?** Recall that a Banach space $V$ has the Kadec property if the weak and norm topologies coincide on the unit (or some other) sphere of $V$. Let us say that a subset $X$ of a $V$ is a Kadec subset (light subset in [47]) if the weak topology coincides with the norm topology. Light linear subgroups $G \leq GL(V)$ (with respect to the weak and strong operator topologies) can be defined Analogously. Clearly, if $G$ is orbitwise Kadec on $V$ that is, all orbits $Gv$ are light in $V$, then $G$ is necessarily light. The simplest examples are the spheres (orbits of the unitary group $\text{Iso}(H)$) in Hilbert spaces $H$.

**Exercise 13.1.** Show that in every Hilbert space $H$ on any sphere $S_r$ the weak and norm topologies are the same.

In general, $\text{Iso}(V)$ need not be light. Indeed, $\text{Iso}(C([0,1]^2))$ is not light, [47]. The following results show that linear actions frequently are “orbitwise Kadec” in the presence of fragmentability properties.

A not necessarily compact $G$-system $X$ is called quasiminimal if $\text{int(cl}(Gz)) \neq \emptyset$ for every $z \in X$. 1-orbit systems and compact minimal $G$-systems are quasiminimal.

**Theorem 13.2.** Let $G \leq GL(V)$ be a bounded subgroup, $X$ a bounded, (weak, norm)-fragmented $G$-invariant subset of a Banach space $V$. Then every, not necessarily closed, quasiminimal $G$-subspace (e.g., the orbits) $Y$ of $X$ is a Kadec subset.

**Proof.** Let $z \in X$. We have to show that for every $\varepsilon > 0$ there exists a $w$-neighborhood $O(z)$ of $z$ in $X$ such that $O$ is $\varepsilon$-small. Choose $\delta > 0$ such that $(y_1, y_2) \in \varepsilon$ for every $(y_1, y_2) \in \delta$ and $g \in G$. Since $X$ is quasiminimal, the set $A := \text{int(cl}(Gz))$ is non-void. Since $X$ is $(\tau, \text{norm})$-fragmented, we can pick a non-void $\tau$-open subset $W$ of $X$ such that $W \subset A$ and $W$ is $\delta$-small in $X$. Clearly, $W \cap Gz \neq \emptyset$. One can choose
$g_0 \in G$ such that $g_0 z \in W \cap G z$. Denote by $O$ the open subset $g_0^{-1} W$ of $(X, \tau)$. Then $O$ is a $\tau$-neighborhood of $z$ and is $\varepsilon$-small. \hfill \qed

This result together with a characterization of PCP (Theorem 8.12) yield:

**Theorem 13.3.** [47, 50] Let $V$ be a Banach space with PCP (e.g., reflexive, RNP, or the dual of Asplund). Then

1. norm topology = weak topology on every orbit $G v$ for every norm bounded $G \leq \text{Aut}(V)$.
2. The weak and the strong operator topologies coincide on $\text{Iso}(V)$.
3. Every weakly continuous (co)homomorphism $h : G \to \text{Iso}(V)$ is strongly continuous.

Some boundedness condition is necessary even for $l_2$. In fact, $\text{GL}(l_2)$ is not light. The group $G$ may not be replaced in general by semigroups. Indeed, the semigroup $\Theta(l_2)$ is weakly compact but not strongly compact.

**13.2. Adjoint continuity property of Asplund spaces.** Now we turn to the weak* version of the lightness concept. Let $V$ be a Banach space. Let’s say that a subset $A$ of the dual $V^*$ is weak* light if the weak* and the norm topologies coincide on $A$. If $G$ is a subgroup of $\text{GL}(V^*)$, then the weak* (resp., norm*) topology on $G$ is the weakest topology which makes all orbit maps $\{ \tilde{\psi} : G \to V^* : \psi \in V^* \}$ weak* (resp., norm) continuous.

**Definition 13.4.** Let $\pi : G \times V \to V$ be a continuous left action of $G$ on $V$ by linear operators. The adjoint (or, dual) right action $\pi^* : V^* \times G \to V^*$ is defined by $\psi g(v) := \psi(g v)$. The corresponding adjoint (dual) left action is $\pi^* : G \times V^* \to V^*$, where $g \psi(v) := \psi(g^{-1} v)$.

A natural question here is whether the dual action $\pi^*$ of $G$ on $V^*$ is jointly continuous with respect to the norm topology on $V^*$. When this is the case we say that the action $\pi$ (and, also the corresponding representation $h : G \to \text{Iso}(V)$, when $\pi$ is an action by linear isometries) is adjoint continuous.

**Theorem 13.5.** [50] Suppose that $V$ is an Asplund space, $G \leq \text{GL}(V)$ is a bounded subgroup, and $X \subset V^*$ is a bounded $G$-invariant subset.

1. If $(X, w^*)$ is a quasiminimal (e.g., 1-orbit) $G$-subset, then $X$ is weak* light.
2. The weak* and strong* operator topologies coincide on $G$ (e.g., on $\text{Iso}(V)$).
3. Any weakly (hence, also, strongly) continuous group representation $h : G \to \text{Iso}(V)$ on an Asplund space $V$ is adjoint continuous.

More generally, this is true for any continuous linear topological group action (not necessarily by isometries).

**Theorem 13.6.** [50, Corollary 6.9] Let $V$ be an Asplund Banach space and $\pi : G \times V \to V$ a linear jointly continuous action. Then the dual action $\pi^* : G \times V^* \to V^*$ is also jointly continuous.

The regular representation $T \to \text{Iso}(V)$ of the circle group $G := T$ on $V := C(T)$ is continuous but not adjoint continuous. Consider the Banach space $V := l_1$ and the topological subgroup $G := S(\mathbb{N})$ ("permutations of coordinates") of $\text{Iso}(l_1)$. Then we have a natural continuous representation of the symmetric topological group $S(\mathbb{N})$ on $l_1$ which is not adjoint continuous.
13.3. **Helmer’s theorem.** One more application is a quick proof of $\text{WAP}(G) \subset \text{UC}(G) := \text{LUC}(G) \cap \text{RUC}(G)$, Helmer’s theorem. In fact, we can show more.

**Theorem 13.7.** [50] $\text{WAP}(G) \subset \text{Asp}(G) \subset \text{UC}(G)$ for every topological group $G$.

**Proof.** Let $f \in \text{Asp}_s(G)$. The function $f$ coincides with a matrix coefficient $m_{v,\psi}$ for a suitable strongly continuous antihomomorphism $h : G \to \text{Iso}(V)_s$, where $V$ is Asplund. In particular, $v$ is a norm continuous vector. By Theorem 13.5 (or, 13.6) the orbit $G\psi$ is light. Hence, $\psi$ is a norm continuous vector. By Fact 5.3.2, $f = m_{v,\psi}$ is both left and right uniformly continuous. □

13.4. **Ryll-Nardzewski fixed point Theorem.**

**Theorem 13.8.** (Ryll-Nardzewski) Let $V$ be a locally convex vector space equipped with its uniform structure $\xi$. Let $(Q,\tau)$ be an affine compact $S$-system such that

1. $(Q,\tau)$ is a weakly compact subset in $V$.
2. $S$ is $\xi$-distal on $Q$.

Then $Q$ contains a fixed point.

**Proof.** (Sketch) We can suppose that $Q = \text{cl}(\text{co}X)$, where $X$ is a compact minimal $S$-system. Weakly compact set $X$ is $\xi$-fragmented. By Theorem 13.2, on $X$ the topologies induced by $\tau$ and the uniformity $\xi$ agree. So, $(S,X)$ is distal. Therefore, the proof can be reduced to the following theorem of H. Furstenberg.

**Theorem 13.9.** (Furstenberg) Every distal compact dynamical system admits an invariant probability measure. □

### 14. Representations of Topological Groups II

**Theorem 14.1.** The group $G := H_+[0,1]$ is Rosenthal representable.

**Proof.** Consider the natural action of $G$ on the closed interval $X := [0,1]$ and the corresponding enveloping semigroup $E = E(G,X)$. Every element of $G$ is a (strictly) increasing self-homeomorphism of $[0,1]$. Hence every element $p \in E$ is a nondecreasing function. It follows that $E$ is naturally homeomorphic to a subspace of the Helly compact space (of all nondecreasing selfmaps of $[0,1]$ in the pointwise topology). Hence $E$ is a Rosenthal compactum. So by the dynamical BFT dichotomy, Fact 11.9, the $G$-system $X$ is tame. By Theorem 12.3 we have a faithful representation $(h,\alpha)$ of $(G,X)$ on a separable Rosenthal space $V$. Therefore we obtain a $G$-embedding $\alpha : X \hookrightarrow (V^*,w^*)$. Then the strongly continuous homomorphism $h : G \to \text{Iso}(V)^{op}$ is injective. Since $h(G) \times \alpha(X) \to \alpha(X)$ is continuous (and we may identify $X$ with $\alpha(X)$) it follows, by the minimality properties of the compact open topology, that $h$ is an embedding. Thus $h \circ \text{inv} : G \to \text{Iso}(V)$ is the required topological group embedding. □

**Theorem 14.2.** The group $G := H_+[0,1]$ is Asplund trivial (hence, also reflexive and WAP-trivial).
Proof. Let $X$ be a compact dynamical system with the jointly continuous action. Then for every point $x_0 \in X$ the corresponding orbit map $\tilde{x}_0 : G \to X$ is RUC. If it is also left uniformly continuous then we say that $(G, X)$ is strongly uniformly continuous (SUC).

We are going to show that $H_+[0,1]$ is SUC-trivial. This will imply that this system is adjoint trivial (by Fact 5.3). Which in turn implies by Theorem 13.5 that it is Asplund-trivial. Very readable proofs of WAP-triviality of $H_+[0,1]$ can be found in [60] and [74].

Definition 14.3. Let $X$ be a compact $G$-space. We say that two points $a, b \in X$ are SUC-proximal if there exist nets $s_i$ and $g_i$ in $G$ and a point $x_0 \in X$ such that $s_i$ converges to the neutral element $e$ of $G$, the net $g_is_i x_0$ converges to $a$ and the net $g_is_ix_0$ converges to $b$.

Lemma 14.4. If the points $a$ and $b$ are SUC-proximal in a $G$-space $X$ then $a \sim_{SUC} b$.

Theorem 14.5. Let $G = H_+[0,1]$ be the topological group of orientation-preserving homeomorphisms of $[0,1]$ endowed with the compact open topology. Then $G$ is SUC-trivial.

Proof. Denote by $j : G \to G^{SUC}$ and $i : G \to G^{UC}$ the $G$-compactifications ($i$ necessarily is proper because $UC(G)$ separates the points and closed subsets) induced by the Banach $G$-algebras $SUC(G) \subset UC(G)$. There exists a canonical onto $G$-map $\pi : G^{UC} \to G^{SUC}$ such that the following diagram of $G$-maps is commutative:

$$
\begin{align*}
G & \xrightarrow{i} G^{UC} \\
& \downarrow j \quad \quad \downarrow \pi \\
G^{SUC} & 
\end{align*}
$$

We have to show that $G^{SUC}$ is trivial for $G = H_+[0,1]$. One of the main tools for the proof is the following identification.

Lemma 14.6. [Uspenskij] The dynamical system $G^{UC}$ is isomorphic to the $G$-space $(G, \Omega)$. Here $\Omega$ denotes the compact space of all curves in $[0,1] \times [0,1]$ which connect the points $(0,0)$ and $(1,1)$ and “never go down”, equipped with the Hausdorff metric. These are the relations $\omega \subset [0,1] \times [0,1]$ where for each $t \in [0,1]$, $\omega(t)$ is either a point or a vertical closed segment.

Moreover, the natural action of $G = H_+[0,1]$ on $\Omega$ is $(g\omega)(t) = g(\omega(t))$ (by composition of relations on $[0,1]$).

We first note that every “zig-zag curve” (i.e. a curve $z$ which consists of a finite number of horizontal and vertical pieces) is an element of $\Omega$. In particular the curves $\gamma_c$ with exactly one vertical segment defined as $\gamma_c(t) = 0$ for every $t \in [0, c)$, $\gamma_c(c) = \{c\} \times [0,1]$ and $\gamma(t) = 1$ for every $t \in (c,1]$, are elements of $\Omega = G^{UC}$. Note that the curve $\gamma_1$ is a fixed point for the left $G$ action. We let $\theta = \pi(\gamma_1)$ be its image in $G^{SUC}$. Of course $\theta$ is a fixed point in $G^{SUC}$. We will show that $\theta = j(e)$ and since the $G$-orbit of $j(e)$ is dense in $G^{SUC}$ this will show that $G^{SUC}$ is a singleton.

The idea is to show that zig-zag curves are SUC-proximal in $G^{UC}$. Then Lemma 14.4 will ensure that their images in $G^{SUC}$ coincide. Choosing a sequence $z_n$ of zig-zag
curves which converges in the Hausdorff metric to $i(e)$ in $G^{UC}$ we will have $\pi(z_n) = \pi(\gamma_1) = \theta$ for each $n$. This will imply that indeed $j(e) = \pi(i(e)) = \pi(\lim_{n \to \infty} z_n) = \lim_{n \to \infty} \pi(z_n) = \theta$.

First we show that $\pi(\gamma_1) = \pi(\gamma_c)$ for any $0 < c < 1$. As indicated above, since $G^{SUC}$ is the Gelfand space of the algebra $SUC(G)$, by Lemma 14.4, it suffices to show that the pair $\gamma_1, \gamma_c$ is SUC-proximal in $G^{UC}$. Since $X^{SUC} = X$ for $X := G^{SUC}$ we conclude that $\pi(\gamma_1) = \pi(\gamma_c)$.

Let $p \in G^{UC}$ be the curve defined by $p(t) = t$ in the interval $[0, c]$ and by $p(t) = c$ for every $t \in [c, 1)$. Pick a sequence $s_n$ of elements in $G$ such that $s_n$ converges to $e$ and $s_n c < c$. It is easy to choose a sequence $g_n$ in $G$ such that $g_n s_n c$ converges to $0$ and $g_n c$ converges to $1$. Then the sequences $s_n$ and $g_n$ are the desired sequences; that is, $g_n p \to \gamma_c$, $g_n s_n p \to \gamma_1$ (see the picture below).
Denote $\theta = \pi(\gamma_1) = \pi(\gamma_c)$. Using similar arguments (see the picture below, where $a \sim b$ means $\pi(a) = \pi(b)$) construct a sequence $z_n \in G^{UC}$ of zig-zag curves which converges to $i(e)$ and such that $\pi(z_n) = \theta$ for every $n$.

In view of the discussion above this construction completes the proof of the theorem.

As a corollary we get

**Theorem 14.7.** $H_+[0, 1]$ is Asplund-trivial (in particular, reflexive-trivial).
References


DEPARTMENT OF MATHEMATICS, BAR-ILAN UNIVERSITY, 52900 RAMAT-GAN, ISRAEL
E-mail address: megereli@math.biu.ac.il
URL: http://www.math.biu.ac.il/~megereli