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Condensations with extra properties

István Juhász, Jan van Mill, and Lajos Soukup

Abstract. We show that there are locally compact spaces that can be condensed on separable spaces, but not on compact separable spaces. We also show that for every cardinal κ, there is a locally compact topological group of cardinality 2^κ that can be condensed on a compact space but not on a compact topological group. These answer some questions of Arhangel'skii and Buzyakova.

1 Introduction

All topological spaces that we discuss are infinite Tychonoff spaces.

A *condensation* f of a space X on a space Y is a continuous bijection $f : X \to Y$. Clearly, for a topological space X, admitting a continuous bijection on a space Y with a certain property is equivalent to X having a coarser topology with that property. Natural examples of important coarser topologies, and hence of condensations, are, for example, the various weak topologies in functional analysis. Compact spaces do not have interesting condensations, but every locally compact noncompact space *does*; it has a compact condensation by a classical result of Parhomenko [15]. There is quite an extensive literature on condensations, see, for example, [2, 13, 14] for references as well as some old and some new results.

In the recent preprint [1], Arhangel'skii and Buzyakova obtained several results on condensations for ordered spaces and their subspaces. The main aim of this note is to answer their Question 2.7 and the compact case of Question 2.8 in the negative.

2 Preliminaries

For all undefined notions, we refer to Engelking [6] and Juhász [8].

We denote the real line, the closed unit interval, and the integers by $\mathbb{R}$, $\mathbb{I}$, and $\mathbb{Z}$, respectively. For a space X, we let τX denote its topology. Moreover, by $X = \bigoplus_{i\in I} X_i$, we mean that X is the topological sum of the spaces $\{X_i : i \in I\}$. Hence, we implicitly assume that the X_i's are pairwise disjoint, and $\tau X = \{U \subseteq X : (\forall\, i \in I)(U \cap X_i \in \tau X_i)\}$. A space X is *homogeneous* if for all $x, y \in X$, there exists a homeomorphism

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$f : X \to Y$ such that $f(x) = y$. Examples of homogeneous spaces are topological groups. But there are many homogeneous spaces that do not have the structure of a topological group, for example, the Hilbert cube, since it has the fixed-point property, Keller [11].

As usual, we denote the cardinality of the continuum by $\mathfrak{c}$. For any cardinal number κ, we denote by $\log(\kappa)$ the smallest cardinal μ such that $2^\mu \geq \kappa$.

3 Positive results

We present here our main results for detecting if certain topological sums have or do not have a separable, respectively, a compact separable condensation. The results in this section will be used in the next section to present our counterexamples to some questions of Arhangel'skii and Buzyakova.

Theorem 3.1 *Assume that* $X = \bigoplus\{X_\alpha : \alpha < \kappa\}$, *where*

$$\omega \leq \kappa \leq 2^{\mathfrak{c}} \text{ and } \mu = \sup\{w(X_\alpha) : \alpha < \kappa\} \leq \mathfrak{c}.$$

Then, X condenses on a separable space Y of weight at most $\lambda = \max\{\log(\kappa), \mu\}$.

Proof We first consider the case $\lambda = \omega$, i.e., when $\kappa \leq \mathfrak{c}$ and each X_α is second countable. In this case, Y can be chosen to be even second countable, i.e., a subspace of the Hilbert cube $\mathbb{I}^\omega$. Now, it is obvious that $\mathbb{I}^\omega$ can be partitioned into $\mathfrak{c}$ homeomorphic copies of $\mathbb{I}^\omega$, say $\mathbb{I}^\omega = \bigcup\{H_\alpha : \alpha < \mathfrak{c}\}$. Then, for every $\alpha < \kappa \leq \mathfrak{c}$, there is an embedding f_α of X_α into H_α, hence, the map $f = \bigcup\{f_\alpha : \alpha < \kappa\}$ is clearly a condensation on the second countable space $Y = \bigcup\{f_\alpha[X_\alpha] : \alpha < \kappa\}$.

Now, assume that $\lambda > \omega$. Since $\lambda \leq \mathfrak{c}$, the Tychonoff cube $\mathbb{I}^\lambda$ is separable, so let $D = \{d_n : n < \omega\}$ be a faithfully indexed countable dense subset of $\mathbb{I}^\lambda$. Let $E \subset \lambda$ be countably infinite such that $\pi_E \restriction D$ is 1-1, where $\pi_E : \mathbb{I}^\lambda \to \mathbb{I}^E$ is the projection. Let $p \in \mathbb{I}^E \setminus \pi_E(D)$. For each $n < \omega$, let $S_n = \pi_E^{-1}(\{\pi_E(d_n)\})$. Similarly, $T_p = \pi_E^{-1}(\{p\})$. Then, $\lambda > \omega$ implies that each member of $\{S_n : n < \omega\} \cup \{T_p\}$ is homeomorphic to $\mathbb{I}^\lambda$. Since $\mathbb{I}^\lambda \times \mathbb{I}^\lambda \approx \mathbb{I}^\lambda$, we can split T_p into a pairwise disjoint family $\{K_\alpha : \alpha < 2^\lambda\}$ consisting of closed sets each homeomorphic to $\mathbb{I}^\lambda$. Note also that $\lambda \geq \log(\kappa)$ implies $\kappa \leq 2^\lambda$.

Note that for every $\alpha < \kappa$, we have $w(X_\alpha) \leq \mu \leq \lambda$, hence, X_α embeds into $\mathbb{I}^\lambda$. For each $n < \omega$, let $f_n : X_n \to S_n$ be an embedding. Since $\mathbb{I}^\omega$ is homogeneous by Keller [11], so is S_n, hence, we may assume that f_n has the property that $d_n \in f_n(X_n)$. For each α with $\omega \leq \alpha < \kappa$, let $f_\alpha : X_\alpha \to K_\alpha$ be any embedding. Now, the map $f = \bigcup\{f_\alpha : \alpha < \kappa\}$ is clearly a condensation on the space $Y = \bigcup\{f_\alpha[X_\alpha] : \alpha < \kappa\} \subset \mathbb{I}^\lambda$ that is separable because $D \subset Y$. ∎

Let X and Y be spaces. We say that X and Y are *somewhere homeomorphic* if there are nonempty $U \in \tau X$ and $V \in \tau Y$ such that U and V are homeomorphic.

Theorem 3.2 *Let* $X = \bigoplus_{n<\omega} X_n$, *where each* X_n *is* σ*-compact and assume that X condenses on a Baire space Y. Then:*

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(1) *there exists $n < \omega$ such that X_n and Y are somewhere homeomorphic;*
(2) *if each X_n is compact, then there are infinitely many n such that X_n and Y are somewhere homeomorphic;*
(3) *if Y is compact and each X_n is a continuum, then there are infinitely many n such that X_n is homeomorphic to a component of Y that is clopen in Y.*

Proof Let $f : X \to Y$ be a condensation.

For (1), write X_n as $\bigcup_{m<\omega} X_n^m$, where each X_n^m is compact. Since $Y = \bigcup_{n<\omega} \bigcup_{m<\omega} f[X_n^m]$, by the Baire Category Theorem, there are $n, m < \omega$ such that $f[X_n^m]$ contains a nonempty open subset U of Y. Since the restriction of f to X_n^m is a homeomorphism and f is a condensation, we are done.

For (2), for a fixed $n < \omega$, take $y \in f[X_{n+1}]$, and let U be an open neighborhood of y such that $\overline{U} \cap \bigcup_{m\leq n} f_m[X_m] = \varnothing$. Since $\overline{U} \subseteq \bigcup_{m>n} f_m[X_m]$, by the Baire Category Theorem, there exist $m > n$ and V such that $V \subseteq \overline{U} \cap f_m[X_m]$ is nonempty and open in $\overline{U}$. Then, $V \cap U$ is nonempty and open in U, hence open in Y.

For (3), first observe that by Kuratowski [12, Theorem 6a, p. 174], $\mathcal{C} = \{f[X_n] : n < \omega\}$ is the collection of all components of Y. Hence, $\mathcal{C}$ is an upper semicontinuous decomposition of Y and if we collapse each $C \in \mathcal{C}$ to a single point, the resulting space is a countably infinite compact Hausdorff space. See Kuratowski [12, Theorem 4, p. 151] for details. Being countable and compact, the decomposition space has infinitely many isolated points. But this means that infinitely many $C \in \mathcal{C}$ are clopen in Y. ∎

It is a natural question whether case (1) of Theorem 3.2 remains true for classes larger than σ-compact spaces. A natural and interesting case is that of Lindelöf spaces. We do not know the answer to the following question.

Question 3.3 *For each $n < \omega$, let X_n be a Lindelöf space of weight at most $\mathfrak{c}$ and let $X = \bigoplus_{n<\omega} X_n$. Assume that X condenses on a separable compact space Y. Is there an $n < \omega$ such that X_n is somewhere separable?*

But we do know that some condition on the X_n's is necessary, as we will now demonstrate.

Remark 3.4 By Dow, Gubbi, and Szymánski [5, Theorem 1], there exists a crowded countable extremally disconnected space X such that $X^* = \beta X \backslash X$ is ω-bounded, that is, for every countable $A \in [X^*]^\omega$, the closure of A in βX is contained in X^*. Observe that X^* is also crowded. For if p is an isolated point of X^*, then there is a clopen subset C of βX such that $C \cap X^* = \{p\}$. But then βX would contain a compact countably infinite subset, hence a nontrivial convergent sequence, which contradicts βX being extremally disconnected. By Comfort and García-Ferreira [4, Theorem 6.9], X^* is ω-resolvable, that is, there is a partition $\{S_n : n < \omega\}$ of X^* such that each S_n is dense in X^*. Since X^* is ω-bounded, each S_n is nowhere separable. List X faithfully as $\{x_n : n < \omega\}$, and, for each $n < \omega$, put $T_n = S_n \cup \{x_n\}$. Then, $\bigoplus_{n<\omega} T_n$ condenses on the compact separable space βX, yet every T_n is nowhere separable, hence in case (1) of Theorem 3.2, the assumption on σ-compactness cannot be dropped completely.

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4 Negative results

We first deal with Question 2.7 in Arhangel'skii and Buzyakova [1]: *If X is locally compact space that can be condensed on a separable space, can X be condensed on a compact separable space?*

The counterexamples to this question that we shall present will actually be topological sums of compacta. We actually consider topological sums of compact spaces of increasing topological complexity.

4.1 Consistent discrete counterexamples

To begin with, we consider discrete spaces, i.e., topological sums of points. It does not come as a surprise that in this case we have to deal with purely set-theoretic considerations. We shall denote the (infinite) discrete space of cardinality κ by $D(\kappa)$.

Clearly, $D(\kappa)$ condenses on a separable space iff $\omega \leq \kappa \leq 2^{\mathfrak{c}}$. Moreover, $D(\kappa)$ condenses on a separable compact space iff there is a separable compact space of cardinality κ. In other words, our task is to determine the possible cardinalities of separable compact spaces. This turns out to be a highly non-trivial problem that is very sensitive to what model of set theory we are in.

Let us denote by $\mathbf{S}$ the set of possible cardinalities of separable compact spaces. Clearly, we have $\mathbf{S} \subset [\omega, 2^{\mathfrak{c}}]$. The following two conditions on $\mathbf{S}$ are easily established in ZFC:

$(*)$ $[\omega, \mathfrak{c}] \cup \{2^{\kappa} : \omega < \kappa \leq 2^{\mathfrak{c}}\} \subset \mathbf{S}$;
$(**)$ if $A \subset \mathbf{S}$ is countable, then $\sup A \in \mathbf{S}$, i.e., $\mathbf{S}$ is ω-closed.

Condition $(*)$ holds because for any infinite $\kappa \leq \mathfrak{c}$, the one-point compactification of the Ψ-space determined by an almost disjoint subfamily of $[\omega]^{\omega}$ of size κ is a witness, moreover, if $\omega \leq \kappa \leq \mathfrak{c}$, then the Cantor cube of weight κ is a witness. Condition $(**)$ holds because the one-point compactification of the topological sum of countably many separable compact spaces is again separable and compact.

Note that under CH, i.e., when $\mathfrak{c} = \omega_1$, $(*)$ reduces to $\{\omega, \omega_1, 2^{\omega_1}\} \subset \mathbf{S}$ and $\max \mathbf{S} = 2^{\omega_1}$, hence the real problem is to determine $(\omega_1, 2^{\omega_1}) \cap \mathbf{S}$.

It turns out that much more can be said about $\mathbf{S}$ under CH. This is because then

$$\mathbf{S} = \{|X| : X \text{ is compact with } w(X) \leq \omega_1\}.$$

Indeed, this is immediate from Parovichenko's theorem in [16] saying that every compact space X of weight ω_1 is a remainder of $D(\omega)$, hence $|X| = |X| + \omega \in \mathbf{S}$. Also, under CH, every separable space has weight $\leq \omega_1$.

Since the weight of the topological sum of ω_1 many spaces of weight $\leq \omega_1$ is ω_1, it follows that under CH $(**)$ can be strengthened to

$(***)$ if $A \subset \mathbf{S}$ with $|A| \leq \omega_1$, then $\sup A \in \mathbf{S}$, i.e., $\mathbf{S}$ is both ω- and ω_1-closed.

On the other hand, compact spaces of weight $\leq \omega_1$ are just the closed subspaces of $\mathbb{I}^{\omega_1}$, and so it is easy to see that

$$\mathbf{S} = \{|br(T)| : T \text{ is a tree with } ht(T) = |T| = \omega_1\},$$

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where $br(T)$ is the set of all cofinal branches of T. For a closed subspace X of $\mathbb{I}^{\omega_1}$ and $\alpha < \omega_1$, we have $T_\alpha = \{x \restriction \alpha : x \in X\}$ as the αth level of the tree T corresponding to X. That each $|T_\alpha| \leq \omega_1$ follows from CH.

Luckily for us, **S** in this guise had been thoroughly investigated by set theorists under CH. In fact, a rather complete description of **S** in this guise under CH had been obtained by Poór and Shelah in [17]. It turns out that $(*)$ and $(***)$ are the only conditions that **S** has to satisfy, except that if in addition to CH, we also have $\omega_2 < 2^{\omega_1}$, then whether $\omega_2 \in \mathbf{S}$ requires special attention.

The characterization of **S** given by Poór and Shelah in [17] may be summarized as follows: The consistency of ZFC implies that any set of infinite cardinals satisfying $(*)$ and $(***)$ and containing ω_2 may be realized in a model of ZFC + CH as **S**. If, on the other hand, there is also an inaccessible cardinal, then in this statement, the condition $\omega_2 \in \mathbf{S}$ can be dropped.

The assumption about the inaccessible cardinal above is also necessary. Indeed, as was observed by Kunen, if $\omega_2 \notin \mathbf{S}$, then the "real" ω_2 is a regular limit cardinal in the constructible subuniverse L, hence it is inaccessible in L (see, e.g., Theorem 4.1 of [17]).

Actually, a much more easily accessible but relevant result is Theorem 4.8(i) in [9], also due to Kunen. This states that if there is an inaccessible cardinal, then there is a model of CH in which $\mathbf{S} = \{\omega, \omega_1, \lambda = 2^{\omega_1}\}$, where λ is any regular cardinal above ω_1.

So, from both of these results, we can deduce the consistency of having many cardinals κ with $\mathfrak{c} = \omega_1 < \kappa < 2^{\omega_1}$ such that $D(\kappa)$ does not admit any condensation on a separable compact space, while it obviously does admit a condensation on a separable space.

Let us now consider the case when CH fails. While in this case much less is known about the possible behavior of **S**, we can again deduce from known results the consistency of having many cardinals κ with $\mathfrak{c} < \kappa < 2^{\mathfrak{c}}$ such that $D(\kappa)$ does not admit any condensation on a separable compact space.

Indeed, Theorem 38 of [10] implies that if the combinatorial principle $\mathrm{D}(\mathfrak{c})$ together with $2^{<\mathfrak{c}} = \mathfrak{c}$ holds then $\mathbf{S} = [\omega, \mathfrak{c}] \cup \{2^{\mathfrak{c}}\}$. Moreover, it follows from Theorem 25 (or 26) of [10] that if κ is any regular cardinal such that GCH holds below κ in V and we add κ Cohen reals to V, then in the generic extension $V[G]$, we have $\mathrm{D}(\mathfrak{c})$ together with $2^{<\mathfrak{c}} = \mathfrak{c} = \kappa$, while

$$2^{\mathfrak{c}} = (2^{\kappa})^{V} = (2^{\kappa})^{V[G]}.$$

So again, in these forcing extensions, $D(\kappa)$ does not admit a condensation on a separable compact space whenever $\mathfrak{c} < \kappa < 2^{\mathfrak{c}}$.

4.2 Nondiscrete spaces

A discrete space is a topological sum of very uninteresting topological spaces, namely, singleton sets. If in topological sums, we consider more complex spaces, it is conceivable that topological arguments will become important. This is what we will see in this section.

Since $\log(\omega) = \omega$, by Theorems 3.1 and 3.2, all we need for a negative answer to [1, Question 2.7] is a compact space X of weight at most $\mathfrak{c}$ which is nowhere separable.

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Indeed, then the topological sum of ω copies of X condenses on a separable space but not on a compact (somewhere) separable space.

Now, the Čech–Stone remainder of the discrete space ω does the job, for example. Or so does the ωth power of the 1-point compactification of an uncountable discrete space of size at most $\mathfrak{c}$. There are even first countable, compact linearly orderable spaces that are nowhere separable, even continua. Among ccc spaces, such examples are also easy to find. For example, the Stone space of the reduced measure algebra of $\mathbb{I}$, or its cone if one wants a connected example.

4.3 Topological groups

We now turn to the compact case of Question 2.8 in Arhangel'skii and Buzyakova [1]: *If G is locally compact topological group that can be condensed on a compact space, can G be condensed on a compact topological group?*

The answer to this question is again in the negative. Let G be the discrete group of the integers. Then, G is a topological group and condenses on a compact space (for example, a nontrivial convergent sequence). But it does not condense on a compact topological group, since the cardinality of such a group is of the form 2^τ for certain τ (Comfort [3, Theorem 3.1]). So perhaps the right version of Question 2.8 in [1] is whether every topological group of the right cardinality that condenses on a compact space, actually condenses on a compact topological group.

Proposition 4.1 *The topological group $\mathbb{R}$ of the reals condenses on a compact space, but not on a compact homogeneous space.*

Proof That $\mathbb{R}$ condenses on a compact space follows from Parhomenko's theorem from [15]. In fact, it can be shown quite easily by drawing a picture that $\mathbb{R}$ condenses on the figure eight.

Assume that $f : \mathbb{R} \to X$ is a condensation, where X is any compact homogeneous space. Then, $X = \bigcup_{n<\omega} f([-n, n])$, hence by the Baire Category Theorem, there exists $n < \omega$ such that $f([-n, n])$ has nonempty interior in X. But $f \restriction [-n, n]$ is a homeomorphism, hence this implies that there is an open interval (r, s) in $\mathbb{R}$ such that $f[(r, s)]$ is homeomorphic to (r, s) and open in X. By compactness and homogeneity of X, this implies that X has a finite open cover consisting of sets homeomorphic to the interval (r, s). This easily implies that X is second countable and hence metrizable.

Thus, X is a compact metrizable 1-manifold without boundary and hence is homeomorphic to the circle (= 1-sphere) $\mathbb{S}^1$ (this is well-known, see, e.g., Gale [7]). Hence, we may assume that $X = \mathbb{S}^1$. That this is impossible since f is 1–1 is well-known and can be shown in many ways, we present an elementary one for the sake of completeness below.

Let (u, v) be a nontrivial interval in $\mathbb{R}$. Then, $f[(u, v)]$ is a nontrivial connected proper subset of $\mathbb{S}^1$, hence is either an open interval (s, t), or a half-open interval $[s, t)$ (or $(s, t]$) or a closed interval $[s, t]$. We claim that the last two possibilities are impossible, so only the first one remains from which it follows that f is open and hence a homeomorphism, which obviously is a contradiction. So assume that $f[(u, v)]$ is the interval $[s, t)$. Take $p \in (u, v)$ such that $f(p) = s$. Then, $f[(u, p)]$ is a nontrivial

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connected subset of $[s, t)$ that has p in its closure. Similarly, for $f[(p, v)]$. But then $f[(u, p)] \cap f[(p, v)] \neq \varnothing$, which contradicts f being 1–1. ∎

Hence, Proposition 4.1 gives a counterexample of cardinality $\mathfrak{c}$. Counterexamples of cardinality 2^τ for an arbitrary $\tau \geq \omega$ are also easily found. Consider such a cardinal τ, and let G be the topological group $\mathbb{Z} \times (\mathbb{S}^1)^\tau$. G is locally compact, hence condenses on a compact space by the classical result of Parhomenko [15].

We claim that it does not condense on a compact homogeneous space. Suppose it does condense on the compact homogeneous space X. Then, by Theorem 3.2(3), X has infinitely many clopen components homeomorphic to $(\mathbb{S}^1)^\tau$. But this contradicts homogeneity and compactness, since if there is one clopen component, then all components are clopen by homogeneity and so there are only finitely many of them by compactness.

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HUN-REN Alfréd Rényi Institute of Mathematics, Hungary
e-mail: juhasz@renyi.hu soukup@renyi.hu

University of Amsterdam, Netherlands
e-mail: j.vanmill@uva.nl

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