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LOCALLY H-CLOSED SPACES

BY

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We characterize LHC spaces, study some of their properties and focus on a special class of LHC spaces, the Hausdorff spaces for which any H-closed extension is obtained by adding only a finite set of points. We also establish a theorem for the identification of the LHC extensions of a Hausdorff space.

LHC spaces were studied by O b r e a n u [6], C.T. Liu [4], P o r t e r [8, 9], B l a s z c z y k [1] and O v s e p j a n [7].

As in [3], we denote by X a Hausdorff space, by $\mathrm{Sp}(X)$ the set of filters on X, by $\mathfrak{X}$ the set of filters on X with an open base and no cluster points, by $X^{\vee}$ the set of the maximal elements of $\mathfrak{X}$ and by $i(x)$ the neighbourhood filter of $x \in X$. O_0 denotes the topology of $\mathrm{Sp}(X)$ generated by the sets $O(A) = \{\mathcal{F} \in \mathrm{Sp}(X) : A \in \mathcal{F}$, *$A$ open subset of X*$\}$ and O_1 the topology generated by the sets $\{i(A)$: *A open subset* of $X\}$ and $\{i(A) \cup \{\mathcal{F}\}$: *$A$ open subset of X and $A \in \mathcal{F}$*$\}$. The same notations will be used for the topology induced on different subspaces of $\mathrm{Sp}(X)$. If $A \subset X$, then cA denotes $X \setminus A$.

We shall use extensively the following theorem, proved in [3]:

Theorem 1. *Y is an H-closed extension of X iff it is homeomorphic to a subspace $\mathcal{X}$ of $\mathrm{Sp}(X)$ such that: $i(X) \subset \mathcal{X}$, $\mathcal{X} \setminus i(X) \subset \mathfrak{X}$, any maximal element of $\mathfrak{X}$ has exactly one subfilter in $\mathcal{X}$, and the topology of $\mathcal{X}$ is between O_0 and O_1.*

§ 1. **Characterizations of LHC spaces.** X is locally H-closed (LHC) if every point has an H-closed neighbourhood. If we requested a fundamental system of H-closed neighbourhoods, we should obtain only the class of locally compact spaces. We agreed that any space denoted by X is Hausdorff because there exist non-Hausdorff topological spaces in which every point has an H-closed neighbourhood (and even a fundamental system of compact neighbourhoods [2, I, §9, 7]) but such spaces cannot have H-closed extensions.

X is LHC *iff either $\mathfrak{X}$ has a least element or $\mathfrak{X} = \varnothing$.*

X is LHC *iff either the intersection of all the maximal elements of $\mathfrak{X}$ is in $\mathfrak{X}$ or $\mathfrak{X} = \varnothing$.*

These characterizations are close to those obtained in [6].

The following result is a corollary to Theorem 1 from [3]: a nowhere solvable space is LHC iff $\mathfrak{X}$ contains the intersection of all the non-convergent ultrafilters with open base.

In [3] we proved that X is not H-closed iff there is at least a cover of X such that: it has an open subcover, it contains $\overline{A \cup B}$ whenever it contains A and B and X itself is not an element of the cover Let $\mathcal{C}_0$ denote the family of such covers and $\mathcal{C}$ the subfamily of those which contain all the subsets of a set of the cover. Obviously $\mathcal{C}=\varnothing$ iff $\mathcal{C}_0=\varnothing$.

Theorem 2. *X is LHC iff $\mathcal{C}=\varnothing$ or it has a least element.*

Proof. X is H-*closed iff* $\mathcal{C}=\varnothing$; henceforth we consider that $\mathcal{C}\neq\varnothing$

If $\mathcal{F}=\{F_i\}_{i\in I}\in\mathcal{X}$, then $\mathcal{A}=\{cF_i\}_{i\in I}\in\mathcal{C}$. Indeed $\bigcap_{i\in I} \mathring{F}_i=\varnothing$ hence $\bigcup_{i\in I} c\mathring{F}_i=X$, hence it has an open subcover ; $c\mathring{F}_i\cup c\mathring{F}_j=c\mathring{F}_i\cup c\mathring{F}_j=c(\mathring{F}_i\cap\mathring{F}_j)$ is in $\mathcal{A}$. If $(D_i)_{i\in I}\in\mathcal{C}$ then $(cD_i)_{i\in I}\in\mathcal{X}$. Indeed, $c(\bar{D}_i\cup\bar{D}_j)=c\bar{D}_i\cap c\bar{D}_j$ and $\bigcap_{i\in I} c\bar{D}_i=\varnothing$ since $\bigcup_{i\in I} cc\bar{D}_i=\bigcup_{i\in I} \bar{D}_i=X$. If $D_i\in\mathcal{L}\in\mathcal{C}$ then $c\mathring{D}_i=c(\bar{D}_i\cup\bar{D}_j)\in\mathcal{L}$.

Therefore it is obvious that $\mathcal{C}$ has a least element iff the filter corresponding in $\mathcal{X}$ is a least element of $\mathcal{X}$, hence iff X is LHC and not H-closed.

A cover is called strictly refinable if it has a refinement other than itself. $\mathcal{A}'\in\mathcal{C}$ refines $\mathcal{A}\in\mathcal{C}$ iff $\mathcal{A}'\subset\mathcal{A}$, because $\mathcal{A}$ contains all the subsets of a set of the cover. Therefore $\mathcal{A}'$ refines $\mathcal{A}$ iff $\mathcal{F}\subset\mathcal{F}'$, where $\mathcal{F}'$ and $\mathcal{F}$ are the filters in $\mathcal{X}$ which correspond to the two covers. This remark suggests another characterization of LHC spaces.

Theorem 3. *X is LHC iff $\mathcal{C}$ contains at most a cover which is not strictly refinable.*

Definition. *The topological space (Y,σ) is a Hausdorff (respectively an H-closed) extension of (X,τ), if (Y,σ) is Hausdorff (respectively H-closed) $X\subset Y$, $\sigma|x=\tau$ and $\bar{X}=Y$. The extension (Y,σ) is called projectively larger than the extension (Z,ρ) if there is a continuous function from Y onto Z which leaves X pointwise fixed. An extension in a set $\mathcal{S}$ of extensions is called a projective maximum (minimum) in $\mathcal{S}$ if it is projectively larger (smaller) than any other extension in $\mathcal{S}$.*

It is known that the Katětov extension $kX=(X\cup X^{\vee}, O_1)$ of X is a projective maximum in the set of all H-closed extensions of X [4].

Theorem 4. *The following conditions are equivalent :*

1) X is LHC but is not H-closed.

2) The set of proper H-closed extensions of X has a projective minimum.

3) The set of proper Hausdorff extensions of X has as a projective minimum an H-closed extension.

4) The set of proper Hausdorff extensions of X has a projective minimum.

Proof. It is obvious that 3) implies 4) and 2).

1) $\Rightarrow$ 3). $\mathcal{X}$ has a least element $\mathcal{G}$ and the extension obtained by adding $\mathcal{G}$ is the projective minimum in the class of Hausdorff extensions. Indeed, if $\mathcal{Y}=i(X)\cup\{\mathcal{F}_j\}_{j\in J}$ is another Hausdorff extension, then as we proved in [3] $\mathcal{F}_j\in\mathcal{X}$ for any $j\in J$, any maximal element of $\mathcal{X}$ has at most a subfilter in $\mathcal{Y}$ and the topology of $\mathcal{Y}$ is between O_0 and O_1. We define the mapping $f:\mathcal{Y}\to i(X)\cup\{\mathcal{G}\}$ which maps $\mathcal{F}_j$ in $\mathcal{G}$ and leaves $i(X)$ pointwise fixed. An open set of $i(X)\cup\{\mathcal{G}\}$ is either $i(A)$ or $i(A)\cup\{\mathcal{G}\}$, where A is an open subset of X, and $A\in\mathcal{G}$ is the second case. Their counterimages are either $i(A)$ or $i(A)\cup\{\mathcal{F}_j\}_{j\in J}$ and $A\in\mathcal{F}_j$ as $\mathcal{G}\subset\mathcal{F}_j$, for any $j\in J$; the set $i(A)\cup\{\mathcal{F}_j\}=O(A)\cap\mathcal{X}$, is open in any topology which is finer than O_0.

If A is an open subset of X, $i(A)$ is open in any Hausdorff extension $\mathcal{Y}$. Indeed, any $x\in A$ has an H-closed neighbourhood V_x which no filter in $\mathcal{X}$ contains (see the proof of Theorem 2). Hence $\mathring{V}_x\cap A$ which is an unempty open subset of X is not contained by any filter belonging to $\mathcal{X}$; thus $O(A\cap\mathring{V}_x)\cap\mathcal{Y}=i(A\cap\mathring{V}_x)$ is open. $i(A)=\bigcup_{x\in A} i(A\cap\mathring{V}_x)$ is therefore an open subset of $\mathcal{Y}$.

4) $\Rightarrow$ 1) X has proper Hausdorff extensions, hence it is not H-closed. Since $i(X)\cup\{\mathcal{G}_1\}$, where $\mathcal{G}_1$ is minimal in $\mathcal{X}$, which is unempty, is a Hausdorff extension [3], the projective minimum $\mathcal{Y}$ must be $i(X)\cup\{\mathcal{F}\}$, for a certain $\mathcal{F}$ in $\mathcal{X}$, otherwise there is no map from $i(X)\cup\{\mathcal{G}_1\}$ onto $\mathcal{Y}$ which leaves $i(X)$ pointwise fixed. If $F\in\mathcal{F}$, the counterimage of $i(F)\cup\{\mathcal{F}\}$ which is $i(F)\cup\{\mathcal{G}_1\}$ must be the union of some sets belonging to the base of the topology of $i(X)\cup\{\mathcal{G}_1\}$; one of them must contain $\mathcal{G}_1$, hence it must be $i(G)\cup\{\mathcal{G}_1\}$ for some $G\in\mathcal{G}_1$; but this implies $G\subset F$ because $i(G)\cup\{\mathcal{G}_1\}$ is in the union which gives $i(F)\cup\{\mathcal{G}_1\}$, and it follows that $F\in\mathcal{G}_1$. Hence $\mathcal{F}\subset\mathcal{G}_1$ and as $\mathcal{G}_1$ is a minimal element of $\mathcal{X}$, we proved that $\mathcal{F}=\mathcal{G}_1$. As $\mathcal{G}_1$ was chosen arbitrary among the minimal elements of $\mathcal{X}$, we can conclude that these coincide, therefore X is LHC.

2) $\Rightarrow$ 1). This has been proved by Liu [4] and by Porter [9].

Theorem 5. *X is LHC iff it is an open set in every Hausdorff extension.*

Proof. The necessity was shown in the second paragraph of the proof of Theorem 4 ; the sufficiency follows from the fact that X is LHC iff it is an open set in every H-closed extension [8].

Corollary. *A regular space is locally compact iff it is an open set in every Hausdorff extension.*

The fact that a regular space is locally compact iff it is an open set in all its compactifications is well-known.

§ 2. **Properties of LHC spaces. Proposition 1.** *The image of an LHC space under a continuous open mapping into a Hausdorff space is* LHC.

Proof. The image of an H-closed space under a continuous mapping into a Hausdorff space is H-closed. If X is LHC and $y\in f(X)$, then $x\in X$ exists so that $y=f(x)$. If V_x is an H-closed neighbourhood of x, $f(V_x)$ is H-closed and is a neighbourhood of y, since f is open.

The condition that f is open is essential in the case of LHC spaces, although it does not appear in the case of H-closed spaces. Indeed, let X be a countable set with the discrete topology, hence LHC. If f is a function from X onto Q it must be continuous but Q is not LHC as it is regular but it is not locally compact.

Proposition 2. *If X is LHC and $F\subset X$ such that $F\cap Y$ is H-closed whenever Y is an H-closed subset of X, then F is closed in X.*

Proof. The interiors of the H-closed subsets of X form a cover of X; and it is known the fact that if $(A_i)_{i\in I}$ is a family of subsets of X whose interiors cover X, then a subset F of X is closed if each of the sets $F\cap A_i$ is closed in A_i ([2] ch. I. §3.1).

In [8] it is shown that any LHC subspace of a Hausdorff space is locally closed. If in these results we replace the words H-closed by compact and LHC by locally compact, we obtain familiar statements.

Theorem 1 applied to LHC spaces proves results from [6] and [8] in a unified manner. Indeed if X is not H-closed it has one-point H-closed extensions iff $\mathcal{H}$ has a filter which is a subfilter of all the maximal elements of $\mathcal{H}$, hence iff the intersection $\mathcal{J}$ of all the maximal elements of $\mathcal{H}$ has a subfilter in $\mathcal{H}$, hence iff $\mathcal{J} \in \mathcal{H}$, hence iff X is LHC.

If X is LHC but not H-closed, $\mathcal{H}$ has a least element $\mathcal{G}$, and by Theorem 1 it follows that the only one-point H-closed extensions are $i(X) \cup \{\mathcal{L}\}$, for some $\mathcal{L}$ satisfying $\mathcal{G} \subset \mathcal{L} \subset \mathcal{J}$, $\mathcal{L} \in \mathcal{H}$.

On the set of one-point H-closed extensions, O_0 and O_1 coincide. As the open sets are $i(A)$, A open in X and $i(A) \cup \{\mathcal{L}\}$, $A \in \mathcal{L}$, A open in X, it follows that the extension with the filter $\mathcal{G}$ is a projective minimum and the extension with $\mathcal{J}$ is a projective maximum in the set of all one-point H-closed extensions.

§ 3. **Katětov extension with a finite set.** In [5] O b r e a n u described an H-closed extension which has the same underlying set as kX, i.e. $X \cup X^*$ but its topology is O_0. This extension was also described by F o m i n. Obviously when X^* is finite the topologies O_0 and O_1 coincide on $X \cup X^*$. Therefore, in the title and every where in this section we can replace kX by the Obreanu extension.

If Q is the set of rational numbers, then $kQ \setminus Q$ is at least countable. If $F \subset kQ$ has n elements then $kQ \setminus F$ provides an example of topological space for which X^* has exactly n elements. By Theorem 1, X is not H-closed; kQ is an H-closed extension of X. Since kQ is the projective maximum in the set of all H-closed extensions of Q, it follows that $kX = kQ$; therefore X^* has n elements.

Definition. X *is said to be almost H-closed* (AHC) *if for every pair of disjoint open sets, the closure of one of them is H-closed.*

AHC spaces are defined in [8] and it is shown there that if X is not H-closed, then kX is a one-point H-closed extension iff X is AHC. Theorem 6 generalizes this result.

Theorem 6. X *has n points iff among any* $n+1$ *mutually disjoint open unempty subsets of* X *one has an H-closed closure, and* $n+1$ *is the least number with this property.*

Proof. Let $\mathcal{M}_1, \ldots, \mathcal{M}_n$ be the maximal elements of $\mathcal{H}$ and $U_1, \ldots, U_{n+1}$ mutually disjoint open unempty sets. Any maximal element contains either U_i or cU_i, for every $i = \overline{1, n+1}$. No maximal element contains two of the sets $U_1, \ldots, U_{n+1}$, as they are mutually disjoint. We can find $i_0 \in N$, $1 \leq i_0 \leq n+1$ such that $cU_{i_0} \in \mathcal{M}_i$ for every $i = \overline{1, n}$. Hence $cU_{i_0} \in \mathcal{J} = \bigcap_{i=1}^{n} \mathcal{M}_i$ and it follows that $\overline{U}_{i_0}$ is H-closed, since the open sets which belong to $\mathcal{J}$ are exactly those sets A for which $c\overset{\circ}{A}$ is H-closed, as shown in [8].

We can find $M_i^j \in \mathcal{M}_i$, $i = \overline{1, n}$, $j = \overline{1, n}$ such that $M_i^j \cap M_j^i = \emptyset$ (otherwise $\mathcal{M}_i \cup \mathcal{M}_j$ generates a filter which belongs to $\mathcal{H}$). As $\mathcal{M}_i$ is a filter, $\bigcap_{j=1}^{n} M_i^j = M_i \neq \emptyset$ for any $i = \overline{1, n}$ and clearly M_i are n mutually disjoint open sets. As $M_i \in \mathcal{M}_i$, $i = \overline{1, n}$, this sets cannot be H-closed, because any filter from $\mathcal{H}$ contains the complements of the H-closed subsets of X [6].

Conversely, we can find mutually disjoint open unempty sets, none of them with H-closed closure, hence by what we have proved, $\mathcal{H}$ has at least n maximal elements. If we suppose that it has more, we can choose $\mathcal{M}_1, \ldots, \mathcal{M}_{n+1}$ among them and we can find as above the mutually disjoint sets $M_i \in \mathcal{M}_i$, $i = \overline{1, n+1}$, none of which with H-closed closure.

Corollary. AHC *spaces are* LHC.

We can describe precisely the open non-convergent ultrafilter of an AHC space which is not H-closed. The maximal element of $\mathcal{H}$ will be the filter which it generates.

Theorem 7. *A space* X *which is not H-closed is* AHC *iff the family* $\mathcal{U}$ *of the open unempty sets which are not contained in an H-closed subspace of* X *is an open non-convergent ultrafilter.*

Proof. Let X be AHC but not H-closed and A an open set of X. If A is dense in X it is obviously in $\mathcal{U}$. If A is not dense, then one and only one of the sets A and cA has H-closed closure, otherwise X would be H-closed as the union of two H-closed subspaces. The other belongs to $\mathcal{U}$ since an open set contained in an H-closed subspace must have and H-closed closure. $\mathcal{U}$ is a filter subbase because by the definition of AHC spaces, A and B cannot be both in $\mathcal{U}$, if they are disjoint. Clearly, the open sets containing a set which is in $\mathcal{U}$ are also in $\mathcal{U}$. The intersection of two sets belongs to $\mathcal{U}$, whenever both of them do: if $A, B \in \mathcal{U}$ and A is dense, then $B \subset \overline{A \cap B}$ and therefore $\overline{A \cap B}$ cannot be H-closed; if neither A nor B is dense then $c\overline{A}$ and $c\overline{B}$ are H-closed as X is AHC and $\overline{A \cap B}$ is not H-closed as $\overline{A \cap B} \cup c\overline{A} \cup c\overline{B} = X$ which is not H-closed. $\mathcal{U}$ is not convergent as any $x \in X$ has an H-closed neighbourhood $V_x \neq X$ and then $\overset{\circ}{V}_x \in \mathcal{U}$ and it is not dense hence $c\overset{\circ}{V}_x \in \mathcal{U}$. Conversely, if $\mathcal{U}$ is a filter subbase then if A and B are disjoint open sets one is missing from $\mathcal{U}$ and thus has an H-closed closure.

In [8] it is shown that a LHC space which is not H-closed has a unique one-point H-closed extension iff every nowhere dense closed subset is contained in an H-closed subspace of X.

Theorem 8. *An* LHC *space* X *which is not H-closed has a unique H-closed extension iff either* U *or* cU *is contained in an H-closed subspace of* X, *for every set* U *which has the property that there is no open subset of* X *in which both* U *and* cU *are dense.*

Proof. If X is LHC but it is not H-closed it has one-point H-closed extensions. If it has a unique H-closed extension, then kX is a one-point H-closed extension, hence the space is AHC. Let U have the property that in any open subset of X either U or cU is not dense. Then $\mathrm{Fr}\, U$ is a nowhere dense closed set, therefore an H-closed subspace W of X exists such that $\mathrm{Fr}\, U \subset W$. Suppose for instance that U is not dense in X. If $\overset{\circ}{U} = \emptyset$, then $U \subset \mathrm{Fr}\, U \subset W$. If $\overset{\circ}{U} \neq \emptyset$, the definition of AHC spaces applied to $\overset{\circ}{U}$ and $c\overline{U}$ ensures that either $\overline{\overset{\circ}{U}}$ or $\overline{c\overline{U}}$ is H-closed. We have $U \subset \overline{\overset{\circ}{U}} \cup W$ and $cU \subset \overline{c\overline{U}} \cup W$ and the union of two H-closed subspaces of a Hausdorff space is H-closed.

Conversely, any nowhere dense closed set is contained in an H-closed subspace since the closure of its complement is the entire space, which is not H-closed. Hence the space has a unique one-point H-closed extension.

Let U and V be open disjoint unempty sets. As $V \subset cU$, either U or V is contained in an H-closed subspace of X, hence its closure is H-closed. Therefore kX is a one-point H-closed extension and this concludes the proof, as kX is the projective maximum in the set of all H-closed extensions.

Corollary. *An LHC space X which is not H-closed has a unique proper Hausdorff extension iff either U or cU is contained in an H-closed subspace of X, for every set U which has the property that there is no open subset of X in which both U and cU are dense.*

Proof. If X has a unique (proper) Hausdorff extension this must be an H-closed extension also as such extensions exist. Conversely, the preceding proof shows that $X^{\vee}$ has only one point M. By [3] it follows that any proper Hausdorff extension is homeomorphic with $i(X)\cup\{\mathcal{L}\}$, where $\mathcal{G} \subset \mathcal{L} \subset \mathcal{M}$, hence it is an H-closed extension too. Theorem 8 shows that this is unique.

§ 4. The LHC and AHC extensions of a Hausdorff space. Theorem 9. *A Hausdorff extension of X with trace filter $\mathcal{X}$ is an LHC extension of X iff whenever there exist maximal elements of $\mathcal{H}$ with no subfilter in $\mathcal{X}$, their intersection belongs to $\mathcal{H}$.*

Proof. If all the maximal elements of $\mathcal{H}$ have subfilters in $\mathcal{X}$, then $\mathcal{X}$ is even an H-closed extension of X. We shall not consider this case henceforth.

Let an LHC extension of X have the trace filter $\mathcal{X}$. Let $\mathcal{Y} = \mathcal{X} \cup \{\mathcal{F}\}$ be a one-point H-closed extension of $\mathcal{X}$. It follows that $i(X)$ is dense in $\mathcal{Y}$ and moreover $\mathcal{Y}$ is an H-closed extension of X. By Theorem 1, $\mathcal{F} \in \mathcal{H}$ and all the maximal elements of $\mathcal{H}$ which have no subfilter in $\mathcal{X}$ are finer than $\mathcal{F}$ as they must have a subfilter in $\mathcal{Y}$. Therefore their intersection belongs to $\mathcal{H}$.

Conversely, let $\mathcal{L}$ be the intersection of all the maximal elements of $\mathcal{H}$ which have no subfilter in $\mathcal{X}$, then $\mathcal{X} \cup \{\mathcal{L}\}$ is an H-closed extension as Theorem 2 of [3] and Theorem 1 prove that a Hausdorff extension of X with trace filter $\mathcal{X}$ is an H-closed extension of X iff all the maximal elements of $\mathcal{H}$ have a subfilter in $\mathcal{X}$.

Theorem 10. *A Hausdorff extension of X with trace filter $\mathcal{X}$ is an* AHC *extension of X iff there is at most one maximal element of $\mathcal{H}$ which has no subfilter in $\mathcal{X}$.*

Proof. As an H-closed extension of X includes $\mathcal{X}$ iff it is also an H-closed extension of $\mathcal{X}$, it follows that $\mathcal{X}$ has only one-point H-closed extensions (i.e. $\mathcal{X}$ is AHC) iff X has no H-closed extension which contains besides $\mathcal{X}$ two or more distinct filters, hence iff there is at most a maximal element of $\mathcal{H}$ with no subfilter in $\mathcal{X}$ (Theorem 1).

Corollary. *The following statements are equivalent* : 1) X *is* AHC 2) X *has no proper* LHC *extensions which are not H-closed extensions* 3) X *has no proper* AHC *extensions which are not H-closed extensions.*

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