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Universal autohomeomorphisms of $\mathbb{N}^*$

Klaas Pieter Hart and Jan van Mill

To the memory of Cor Baayen, who taught us many things

Abstract

We study the existence of universal autohomeomorphisms of $\mathbb{N}^*$. We prove that the Continuum Hypothesis (CH) implies there is such an autohomeomorphism and show that there are none in any model where all autohomeomorphisms of $\mathbb{N}^*$ are trivial.

Introduction

This paper is concerned with universal autohomeomorphisms on $\mathbb{N}^*$, the Čech-Stone remainder of $\mathbb{N}$.

In very general terms we say that an autohomeomorphism $h$ on a space $X$ is universal for a class of pairs $(Y, g)$, where $Y$ is a space and $g$ is an autohomeomorphism of $Y$, if for every such pair there is an embedding $e : Y \to X$ such that $h \circ e = e \circ g$, that is, $h$ extends the copy of $g$ on $e[Y]$.

In 1, Section 3.4 one finds a general way of finding universal autohomeomorphisms. If $X$ is homeomorphic to $X^\omega$ then the shift mapping $\sigma : X^\mathbb{Z} \to X^\mathbb{Z}$ defines a universal autohomeomorphism for the class of all pairs $(Y, g)$, where $Y$ is a subspace of $X$. One embeds $Y$ into $X^\mathbb{Z}$ by mapping each $y \in Y$ to the sequence $\langle g^n(y) : n \in \mathbb{Z} \rangle$.

Thus, the Hilbert cube carries an autohomeomorphism that is universal for all autohomeomorphisms of separable metrizable spaces and the Cantor set carries one for all autohomeomorphisms of zero-dimensional separable metrizable spaces. Likewise the Tychonoff cube $[0, 1]^\kappa$ carries an autohomeomorphism that is universal for all autohomeomorphisms
of completely regular spaces of weight at most \( \kappa \), and the Cantor cube \( 2^\kappa \) has a universal autohomeomorphism for all zero-dimensional such spaces.

Our goal is to have an autohomeomorphism \( h \) on \( \mathbb{N}^* \) that is universal for all autohomeomorphisms of all \textit{closed} subspaces of \( \mathbb{N}^* \). The first result of this paper is that there is no trivial universal autohomeomorphism of \( \mathbb{N}^* \), and hence no universal autohomeomorphism at all in any model where all autohomeomorphisms of \( \mathbb{N}^* \) are trivial. On the other hand, the Continuum Hypothesis implies that there is a universal autohomeomorphism of \( \mathbb{N}^* \). The proof of this will have to be different from the results mentioned above because \( \mathbb{N}^* \) is definitely not homeomorphic to its power \( (\mathbb{N}^*)^\omega \); it will use group actions and a homeomorphism extension theorem.

We should mention the dual notion of universality where one requires the existence of a surjection \( s : X \to Y \) such that \( g \circ s = s \circ h \). For the space \( \mathbb{N}^* \) this was investigated thoroughly in 2 for general group actions.

1. Some preliminaries

Our notation is standard. For background information on \( \mathbb{N}^* \) we refer to 5.

We denote by \( \text{Aut} \) the autohomeomorphism group of \( \mathbb{N}^* \). We call a member \( h \) of \( \text{Aut} \) trivial if there are cofinite subsets \( A \) and \( B \) of \( \mathbb{N} \) and a bijection \( b : A \to B \) such that \( h \) is the restriction of \( \beta b \) to \( \mathbb{N}^* \).

In both sections we shall use the \( G_\delta \)-topology on a given space \( (X, \tau) \); this is the topology \( \tau_\delta \) on \( X \) generated by the family of all \( G_\delta \)-subsets in the given space. It is well-known that \( \omega(X, \tau_\delta) \leq \omega(X, \tau)^\omega \); we shall need this estimate in Section 3.

2. What if all autohomeomorphisms are trivial?

To begin we observe that fixed-point sets of trivial autohomeomorphism of \( \mathbb{N}^* \) are clopen. Therefore, to show that no trivial autohomeomorphism is universal it would suffice to construct a compact space that can be embedded into \( \mathbb{N}^* \) and that has an autohomeomorphism whose fixed-point set is not clopen.
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The example

We let $L$ be the ordinal $\omega_1 + 1$ endowed with its $G_\delta$-topology. Thus all points other than $\omega_1$ are isolated and the neighbourhoods of $\omega_1$ are exactly the co-countable sets that contain it. Then $L$ is a $P$-space of weight $\mathbb{N}_1$ and hence, by the methods in 4, Section 2, its Čech-Stone compactification $\beta L$ can be embedded into $\mathbb{N}^*$.

We define $f : L \to L$ such that $\omega_1$ is the only fixed point of $\beta f$. We put

$$f(\omega_1) = \omega_1,$$
$$f(2 \cdot \alpha) = 2 \cdot \alpha + 1,$$
and
$$f(2 \cdot \alpha + 1) = 2 \cdot \alpha.$$

This defines a continuous involution on $L$.

If $p \in \beta L \setminus L$ then $p \in \mathrm{cl} \alpha$ for some $\alpha < \omega_1$ and then either $E = \{2 \cdot \beta : \beta < \alpha\}$ or $O = \{2 \cdot \beta + 1 : \beta < \alpha\}$ belongs to the ultrafilter $p$. But $f[E] \cap E = \emptyset = f[O] \cap O$, hence $\beta f(p) \neq p$.

Since $\omega_1$ is not an isolated point of $\beta L$, no matter how this space is embedded into $\mathbb{N}^*$ there is no trivial autohomeomorphism of $\mathbb{N}^*$ that would extend $\beta f$.

3. The Continuum Hypothesis

Under the Continuum Hypothesis the space $\mathbb{N}^*$ is generally very well-behaved and one would expect it to have a universal autohomeomorphism as well. We shall prove that this is indeed the case. We need some well-known facts about closed subspaces of $\mathbb{N}^*$.

First we have Theorem 1.4.4 from 5 which characterizes the closed subspaces of $\mathbb{N}^*$ under CH: they are the compact zero-dimensional $F$-spaces of weight $c$, and, in addition: every closed subset of $\mathbb{N}^*$ can be re-embedded as a nowhere dense closed $P$-set.

Second we have the homeomorphism extension theorem from 3 : CH implies that every homeomorphism between nowhere dense closed $P$-sets of $\mathbb{N}^*$ can be extended to an autohomeomorphism of $\mathbb{N}^*$.
Step 1.

We consider the natural action of $\text{Aut}$ on $\mathbb{N}^*$; the map $\sigma : \text{Aut} \times \mathbb{N}^* \to \mathbb{N}^*$ given by $\sigma(f, p) = f(p)$. This action is continuous when $\text{Aut}$ carries the compact-open topology $\tau$ and hence also when $\text{Aut}$ carries the $G_\delta$-modification $\tau_\delta$ of $\tau$. For the rest of the construction we consider the topology $\tau_\delta$.

Using this action we define an autohomeomorphism $h : \text{Aut} \times \mathbb{N}^* \to \text{Aut} \times \mathbb{N}^*$ by $h(f, p) = (f, f(p))$. The map $h$ is continuous because its two coordinates are and it is a homeomorphism because its inverse $(f, p) \mapsto (f, f^{-1}(p))$ is continuous as well.

Now if $X$ is a closed subset of $\mathbb{N}^*$ and $g : X \to X$ is an autohomeomorphism then we can re-embed $X$ as a nowhere dense closed $P$-set and we can then find an $f \in \text{Aut}$ such that $f \upharpoonright X = g$. We transfer this embedded copy of $X$ to $\{f\} \times \mathbb{N}^*$ in $\text{Aut} \times \mathbb{N}^*$; for this copy of $X$ we then have $h \upharpoonright X = g$. It follows that $h$ satisfies the universality condition.

Step 2.

We embed $\text{Aut} \times \mathbb{N}^*$ into $\mathbb{N}^*$ in such a way that there is an autohomeomorphism $H$ of $\mathbb{N}^*$ such that $H \upharpoonright (\text{Aut} \times \mathbb{N}^*) = h$. Then $H$ is the desired universal autohomeomorphism of $\mathbb{N}^*$.

To this end we list a few properties of this product.

Weight

The weight of the product is equal to $\mathfrak{c}$, as both factors have weight $\mathfrak{c}$. For $\mathbb{N}^*$ this is clear and for $\text{Aut}$ this follows because the topology $\tau$ has weight $\mathfrak{c}$ and one obtains a base for $\tau_\delta$ by taking the intersections of all countable subfamilies of a base for $\tau$.

Zero-dimensional and $F$

The product is a zero-dimensional $F$-space as the product of the $P$-space $\text{Aut}$ and the compact zero-dimensional $F$-space $\mathbb{N}^*$, see 6, Theorem 6.1.
Strongly zero-dimensional

The product $\text{Aut} \times \mathbb{N}^*$ is not compact, but we shall construct a compactification of it that is also a zero-dimensional $F$-space of weight $\mathfrak{c}$.

For this we need to prove that $\text{Aut} \times \mathbb{N}^*$ is actually strongly zero-dimensional. We prove more: the product is ultraparacompact, meaning that every open cover has a *pairwise disjoint* open refinement.

Let $\mathcal{U}$ be an open cover of the product consisting of basic clopen rectangles.

For each $f \in \text{Aut}$ there is a finite subfamily $\mathcal{U}_f$ of $\mathcal{U}$ that covers $\{f\} \times \mathbb{N}^*$, say $\mathcal{U}_f = \{C_i \times D_i : i < k_f\}$. Let $C_f = \bigcap_{i < k_f} C_i$ and $D_{f,i} = D_i \setminus \bigcup_{j < i} D_j$ for $i < k_f$. Then $C_f = \{C_f \times D_{f,i} : i < k_f\}$ is a disjoint family of clopen rectangles that covers $\{f\} \times \mathbb{N}^*$ and refines $\mathcal{U}$.

Because $\text{Aut}$ has weight $\mathfrak{c}$, and we assume CH, there is a sequence $(f_\alpha : \alpha \in \omega_1)$ in $\text{Aut}$ such that $\{C_{f_\alpha} : \alpha \in \omega_1\}$ covers $\text{Aut}$. Next we let $V_\alpha = C_{f_\alpha} \setminus \bigcup_{\beta < \alpha} C_{f_\beta}$ for all $\alpha$. Because $\text{Aut}$ is a $P$-space the family $\{V_\alpha : \alpha \in \omega_1\}$ is a disjoint open cover of $\text{Aut}$.

The family $\{V_\alpha \times D_{f_\alpha,i} : i < k_{f_\alpha}, \alpha \in \omega_1\}$ then is a disjoint open refinement of $\mathcal{U}$.

A compactification

To complete Step 2 we construct a compactification of $\text{Aut} \times \mathbb{N}^*$ that is a zero-dimensional $F$-space of weight $\mathfrak{c}$ and that has an autohomeomorphism that extends $h$. The Čech-Stone compactification would be the obvious candidate, were it not for the fact that its weight is equal to $2^\mathfrak{c}$. More precisely, using some continuous onto function from $(\text{Aut}, \tau)$ onto $[0, 1]$ one obtains a clopen partition of $(\text{Aut}, \tau_\delta)$ of cardinality $\mathfrak{c}$. This shows that $\beta(\text{Aut} \times \mathbb{N}^*)$ admits a continuous surjection onto the space $\beta\mathfrak{c}$ (where $\mathfrak{c}$ carries the discrete topology).

To create the desired compactification we build, either by transfinite recursion or by an application of the Löwenheim-Skolem theorem, a subalgebra $\mathcal{B}$ of the algebra of clopen subsets of $\text{Aut} \times \mathbb{N}^*$ that is closed under $h$ and $h^{-1}$, of cardinality $\mathfrak{c}$, and that has the property that for every pair of countable subsets $A$ and $B$ of $\mathcal{B}$ such that $a \cap b = \emptyset$ whenever $a \in A$
and $b \in B$ there is a $c \in \mathcal{B}$ such that $a \subseteq c$ and $c \cap b = \emptyset$ for all $a \in A$ and $b \in B$. The latter condition can be fulfilled because $\text{Aut} \times \mathbb{N}^*$ is an $F$-space — $\bigcup A$ and $\bigcup B$ have disjoint closures — and strongly zero-dimensional — the closures can be separated using a clopen set.

The Stone space $\text{St}(\mathcal{B})$ of $\mathcal{B}$ is then a compactification of $\text{Aut} \times \mathbb{N}^*$ that is a compact zero-dimensional $F$-space of weight $\mathfrak{c}$, with an autohomeomorphism $\tilde{h}$ that extends $h$. We embed $\text{St}(\mathcal{B})$ into $\mathbb{N}^*$ as a nowhere dense $P$-set and extend $\tilde{h}$ to an autohomeomorphism $H$ of $\mathbb{N}^*$.

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