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Kyoto University
Equivariant definable homotopy extensions

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Abstract
Let $G$ be a definably compact definable group, $X$ a definable $G$ set and $Y$ a definable closed $G$ subset of $X$. We prove that a pair $(X, Y)$ admits an equivariant definable homotopy extension.

1 Introduction
In this paper we consider equivariant definable homotopy extensions in an o-minimal expansion $\mathcal{N} = (R, +, \cdot, <, ...)$ of a real closed field $R$. It is known that there exist uncountably many o-minimal expansions of the field $\mathbb{R}$ of real numbers([8]).
Definable set and definable maps are studied in [3], [4], and see also [9]. Everything is considered in $\mathcal{N} = (R, +, \cdot, <, ...)$ and definable maps are assumed to be continuous unless otherwise stated.

2 Preliminaries
Let $R$ be a real closed field.
A structure $\mathcal{N}$ is given by the following data.

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1. A set $R$ is called the **universe** or **underlying set** of $\mathcal{N}$.

2. A collection of functions $\{f_i|i \in I\}$, where $f_i : R^{n_i} \to R$ for some $n_i \geq 1$.

3. A collection of relations $\{R_j|j \in J\}$, where $R_j \subset R^{m_j}$ for some $m_j \geq 1$.

4. A collection of distinguished elements $\{c_k|k \in K\} \subset R$, and each $c_k$ is called a **constant**.

Any (or all) of the sets $I, J, K$ may be empty.

We say that $f$ (resp. $L$) is $m$-place function (resp. $m$-place relation) if $f : R^m \to R$ (resp. $L \subset R^m$).

A term is a finite string of symbols obtained by repeated applications of the following three rules:

1. Constants are terms.

2. Variables are terms.

3. If $f$ is an $m$-place function of $\mathcal{N}$ and $t_1, \ldots, t_m$ are terms, then the concatenated string $f(t_1, \ldots, t_m)$ is a term.

A formula is a finite string of symbols $s_1 \ldots s_k$, where each $s_i$ is either a variable, a function, a relation, one of the logical symbols $=, \neg, \lor, \land, \exists, \forall$, one of the brackets $(,)$, or comma $.$. Arbitrary formulas are generated inductively by the following three rules:

1. For any two terms $t_1$ and $t_2$, $t_1 = t_2$ and $t_1 < t_2$ are formulas.

2. If $R$ is an $m$-place relation and $t_1, \ldots, t_m$ are terms, then $R(t_1, \ldots, t_m)$ is a formula.

3. If $\phi$ and $\psi$ are formulas, then the negation $\neg \phi$, the disjunction $\phi \lor \psi$, and the conjunction $\phi \land \psi$ are formulas. If $\phi$ is a formula and $v$ is a variable, then $(\exists v)\phi$ and $(\forall v)\phi$ are formulas.

A subset $X$ of $R^n$ is **definable** (in $\mathcal{N}$) if it is defined by a formula (with parameters). Namely, there exist a formula $\phi(x_1, \ldots, x_n, y_1, \ldots, y_m)$ and elements $b_1, \ldots, b_m \in R$ such that $X = \{(a_1, \ldots, a_n) \in R^n|\phi(a_1, \ldots, a_n, b_1, \ldots, b_m) \text{ is true in } \mathcal{N}\}$. 
For any \(-\infty \leq a < b \leq \infty\), an open interval \((a, b)_R\) means \(\{x \in R|a < x < b\}\), for any \(a, b \in R\) with \(a < b\), a closed interval \([a, b)_R\] means \(\{x \in R|a \leq x < b\}\). We call \(N\) o-minimal (order-minimal) if every definable subset of \(R\) is a finite union of points and open intervals.

A real closed field \((R, +, \cdot, <)\) is an o-minimal structure and every definable set is a semialgebraic set [10], and a definable map is a semialgebraic map [10]. In particular, the semialgebraic category is a special case of the definable one.

The topology of \(R\) is the interval topology and the topology of \(R^n\) is the product topology. Note that \(R^n\) is a Hausdorff space.

The field \(\mathbb{R}\) of real numbers, \(\mathbb{R}_{alg} = \{x \in \mathbb{R}|x\text{ is algebraic over }\mathbb{Q}\}\) are Archimedean real closed fields.

The Puiseux series \(\mathbb{R}[X]^{\wedge}\), namely \(\sum_{i=k}^{\infty}a_iX^\frac{i}{q}, k \in \mathbb{Z}, q \in \mathbb{N}, a_i \in \mathbb{R}\) is a non-Archimedean real closed field.

**Fact 2.1.** (1) The characteristic of a real closed field is 0.

(2) For any cardinality \(\kappa \geq \aleph_0\), there exist \(2^\kappa\) many non-isomorphic real closed fields whose cardinality is \(\kappa\).

(3) In a general real closed field, even for a \(C^\infty\) function, the intermediate value theorem, existence theorem of maximum and minimum, Rolle's theorem, the mean value theorem do not hold. Even for a \(C^\infty\) function \(f\) in one variable, the result that \(f' > 0\) implies \(f\) is increasing does not hold.

**Definition 2.2.** Let \(X \subset R^n, Y \subset R^m\) be definable sets.

(1) A continuous map \(f : X \to Y\) is a **definable map** if the graph of \(f\) \((\subset R^n \times R^m)\) is definable.

(2) A definable map \(f : X \to Y\) is a **definable homeomorphism** if there exists a definable map \(f' : Y \to X\) such that \(f \circ f' = id_Y, f' \circ f = id_X\).

**Definition 2.3.** A group \(G\) is a **definable group** if \(G\) is definable and the group operations \(G \times G \to G, G \to G\) are definable.

As in the field \(\mathbb{R}\), for any real closed field \(R\), we can define the \(n\)-th general linear \(G(n, R)\), the \(n\)-th orthogonal group \(O(n)\).

Let \(G, G'\) be definable groups. A group homomorphism \(f : G \to G'\) is a **definable group homomorphism** if \(f\) is definable. A definable group homomorphism \(f : G \to GL(n, R)\) is called a **definable G representation**. A definable group homomorphism \(f : G \to O(n)\) is called a **definable orthogonal**
$G$ representation and $R^n$ with the orthogonal action induced from an orthogonal $G$ representation is called a \textit{definable orthogonal $G$ representation space}.

**Definition 2.4.** (1) A $G$ invariant definable subset of a definable orthogonal $G$ representation space is a \textit{definable $G$ set}.

Let $X, Y$ be definable $G$ sets.

(2) A definable map $f : X \to Y$ is a \textit{definable $G$ map} if for any $x \in X, g \in G$, $f(gx) = gf(x)$.

(3) A definable $G$ map $f : X \to Y$ is a \textit{definable $G$ homeomorphism} if there exists a definable $G$ map $h : Y \to X$ such that $f \circ h = id_Y$, $h \circ f = id_X$.

**Definition 2.5.** (1) A definable set $X \subset R^n$ is \textit{definably compact} if for any definable map $f : (a, b)_R \to X$, there exist the limits $\lim_{x \to a^+} f(x), \lim_{x \to b^-} f(x)$ in $X$.

(2) A definable set $X \subset R^n$ is \textit{definably connected} if there exist no definable open subsets $U, V$ of $X$ such that $X = U \cup V, U \cap V = \emptyset, U \neq \emptyset, V \neq \emptyset$.

A compact (resp. a connected) definable set is definably compact (resp. definably connected). But a definably compact (resp. a definably connected) definable set is not always compact (resp. connected). For example, if $R = \mathbb{R}_{alg}$, then $[0, 1]_{\mathbb{R}_{alg}} = \{x \in \mathbb{R}_{alg} | 0 \leq x \leq 1\}$ is definably compact and definably connected, but it is neither compact nor connected.

**Theorem 2.6 ([7]).** For a definable set $X \subset R^n$, $X$ is definably compact if and only if $X$ is closed and bounded.

The following is a definable version of the fact that the image of a compact (resp. a connected) set by a continuous map is compact (resp. connected).

**Proposition 2.7.** Let $X \subset R^n$, $Y \subset R^m$ be definable set, $f : X \to Y$ a definable map. If $X$ is definably compact (resp. definably connected), then $f(X)$ is definably compact (resp. definably connected).

**Theorem 2.8.** (1) (The intermediate value theorem) For a definable function $f$ on a definably connected set $X$, if $a, b \in X$, $f(a) \neq f(b)$ then $f$ takes all values between $f(a)$ and $f(b)$.

(2) (Existence theorem of maximum and minimum) Every definable function on a definably compact set attains maximum and minimum.
Let $f : [a, b]_R \to R$ be a definable function such that $f$ is differentiable on $(a, b)_R$ and $f(a) = f(b)$. Then there exists $c$ between $a$ and $c$ with $f'(c) = 0$.

(4) (The mean value theorem) Let $f : [a, b]_R \to R$ be a definable function which is differentiable on $(a, b)_R$. Then there exists $c$ between $a$ and $b$ with $f'(c) = \frac{f(b) - f(a)}{b - a}$.

(5) Let $f : (a, b)_R \to R$ be a differentiable definable function. If $f' > 0$ on $(a, b)_R$, then $f$ is increasing.

Example 2.9. (1) Let $\mathcal{N}$ be $(\mathbb{R}_{alg}, +, \cdot, <)$. Then $f : \mathbb{R}_{alg} \to \mathbb{R}_{alg}, f(x) = 2^x$ is not defined.

(2) Let $\mathcal{N}$ be $(\mathbb{R}, +, \cdot, <)$. Then $f : \mathbb{R} \to \mathbb{R}, f(x) = 2^x$ is defined but not definable, and $h : \mathbb{R} \to \mathbb{R}, h(x) = \sin x$ is defined but not definable.

3 Equivariant definable homotopy extensions

Let $X, Y$ be definable sets and $f : X \to Y$ a definable map. We say that $f$ is definably proper if for any definably compact subset $C$ of $Y$, $f^{-1}(C)$ is a definably compact subset of $X$.

Let $A \subset \mathbb{R}^n, S \subset \mathbb{R}^m$ be definable sets, and let $f : S \to A$ be a definable map. We say that $f$ is definably trivial if there exist a definable set $F \subset \mathbb{R}^N$ for some $N \in \mathbb{N}$, and a definable map $h : S \to F$ such that $(f, h) : S \to A \times F$ is a definable homeomorphism. In this case, each fiber $f^{-1}(a)$ of $f$ over $a$ is definably homeomorphic to $F$.

In o-minimal expansions of real closed fields, the following five theorems are known.

Theorem 3.1. (1) (Monotonicity theorem (e.g. 3.1.2, 3.1.6. [3])). Let $f : (a, b)_R \to R$ be a function with the definable graph. Then there exist finitely many points $a = a_0 < a_1 < \cdots < a_k = b$ such that on each subinterval $(a_j, a_{j+1})_R$, the function is either constant, or strictly monotone and continuous. Moreover for any $c \in (a, b)_R$, the limits $\lim_{x \to c+0} f(x), \lim_{x \to c-0} f(x)$ exist in $\mathbb{R} \cup \{\infty\} \cup \{-\infty\}$.

(2) (Cell decomposition theorem (e.g. 3.2.11. [3])). For any definable subsets $A_1, \ldots, A_k$ of $\mathbb{R}^n$, there exists a cell decomposition of $\mathbb{R}^n$ partitioning each $A_1, \ldots, A_k$. 

Let $A$ be a definable subset of $R^n$ and $f : A \to R$ a function with the definable graph. Then there exists a cell decomposition $D$ of $R^n$ partitioning $A$ such that each $B \subset A, B \in D$, $f|B : B \to R$ is continuous.

(3) (Triangulation theorem (e.g. 8.2.9. [3])). Let $S \subset R^n$ be a definable set and let $S_1, S_2, \ldots, S_k$ be definable subsets of $S$. Then $S$ has a triangulation in $R^n$ compatible with $S_1, \ldots, S_k$.

(4) (Piecewise trivialization theorem (e.g. 8.2.9. [3])). Let $f : S \to A$ be a definable map between definable sets $S$ and $A$. Then there is a finite partition $A_1, \ldots, A_k$ of $A$ into definable sets $A_i$ such that each $f|f^{-1}(A_i) : f^{-1}(A_i) \to A_i$ is definably trivial.

(5) (Existence of definable quotients (e.g. 10.2.18 [3])). Let $G$ be a definably compact definable group and $X$ a definable $G$ set. Then the orbit space $X/G$ exists as a definable set and the orbit map $\pi : X \to X/G$ is surjective, definable and definably proper.

**Question 3.2.** Let $X, Y$ be definable sets and $A$ a definable subset of $X$.

1. (Extensions of definable maps) Let $f : A \to Y$ be a definable map. When does $f : A \to Y$ extend a definable map $F : X \to Y$?

2. (Definable homotopy extensions) Let $f : X \to Y$ be a definable map and a definable homotopy $F : A \times [0, 1]_R \to Y$ such that $F(x, 0) = f(x)$ for any $x \in A$. When does a definable homotopy $H : X \times [0, 1]_R \to Y$ exist such that $H(x, 0) = f(x)$ for any $x \in X$ and $H[A \times [0, 1]_R] = F$?

**Theorem 3.3** (Definable Tietze extension theorem [1]). Let $X, Y$ be definable sets, $A$ a definable closed subset of $X$ and $f : A \to R$ a definable function. Then there exists a definable function $F : X \to R$ such that $F|A = f$.

**Theorem 3.4** (Definable homotopy extension theorem [2]). Let $X, Y$ be definable sets and $A$ a definable closed subset of $X$. For any definable map $f : X \to Y$ and for any definable homotopy $F : A \times [0, 1]_R \to Y$ such that $F(x, 0) = f(x)$ for any $x \in A$, there exists a definable homotopy $H : X \times [0, 1]_R \to Y$ such that $H(x, 0) = f(x)$ for any $x \in X$ and $H[A \times [0, 1]_R] = F$.

To consider Question 3.2, we need to construct an obstruction theory in the definable category.

The following question is an equivariant version of Question 3.2.

**Question 3.5.** Let $G$ be a definable group, $X, Y$ a definable $G$ sets and $A$ a definable $G$ subset of $X$. 


(1) (Extensions of definable $G$ maps) Let $f : A \to Y$ be a definable $G$ map. When does $f : A \to Y$ extend a definable $G$ map $F : X \to Y$?

(2) (Equivariant definable homotopy extensions) Let $f : X \to Y$ be a definable $G$ map and an equivariant definable homotopy $F : A \times [0, 1]_R \to Y$ such that $F(x, 0) = f(x)$ for any $x \in A$. When does an equivariant definable homotopy $H : X \times [0, 1]_R \to Y$ exist such that $H(x, 0) = f(x)$ for any $x \in X$ and $H|A \times [0, 1]_R = F$?

We have the following result.

**Theorem 3.6** ([6]). Let $G$ be a definably compact definable group, $X$ a definable $G$ set and $A$ a definable closed $G$ subset of $X$. For any definable $G$ map $f : X \to Y$ and for any equivariant definable homotopy $F : A \times [0, 1]_R \to Y$ such that $F(x, 0) = f(x)$ for any $x \in A$, there exists an equivariant definable homotopy $H : X \times [0, 1]_R \to Y$ such that $H(x, 0) = f(x)$ for any $x \in X$ and $H|A \times [0, 1]_R = F$.

Theorem 3.6 is proved in the case where $R = \mathbb{R}$ ([5]).

To prove Theorem 3.6, we need the following results.

**Theorem 3.7** ([6]). Let $G$ be a definably compact definable group and $Y$ a definable closed $G$ subset of a definable $G$ set $X$. Then there exists a $G$ invariant definable open neighborhood $U$ of $Y$ in $X$ such that $Y$ is a definable strong $G$ deformation retract of both $U$ and of the closure $\text{cl} U$ of $U$ in $X$.

**Proposition 3.8** ([6]). Let $G$ be a definably compact definable group and $A, B$ disjoint definable closed $G$ subsets of a definable $G$ set $X$. Then there exists a $G$ invariant definable map $f : X \to [0, 1]_R$ with $A = f^{-1}(0)$ and $B = f^{-1}(1)$.

**References**


