

DEGREE OF T -EQUIVARIANT MAPS IN \mathbb{R}^n

JOANNA JANCZEWSKA

*Department of Technical Physics and Applied Mathematics
Gdańsk University of Technology
Narutowicza 11/12, 80-952 Gdańsk, Poland
E-mail: janczewska@mif.pg.gda.pl*

MARCIN STYBORSKI

*Department of Technical Physics and Applied Mathematics
Gdańsk University of Technology
Narutowicza 11/12, 80-952 Gdańsk, Poland
and Ph.D. student of the Institute of Mathematics, Polish Academy of Sciences
E-mail: marcins@impan.gov.pl*

Abstract. A special case of G -equivariant degree is defined, where $G = \mathbb{Z}_2$, and the action is determined by an involution $T : \mathbb{R}^p \oplus \mathbb{R}^q \rightarrow \mathbb{R}^p \oplus \mathbb{R}^q$ given by $T(u, v) = (u, -v)$. The presented construction is self-contained. It is also shown that two T -equivariant gradient maps $f, g : (\mathbb{R}^n, S^{n-1}) \rightarrow (\mathbb{R}^n, \mathbb{R}^n \setminus \{0\})$ are T -homotopic iff they are gradient T -homotopic. This is an equivariant generalization of the result due to Parusiński.

1. Introduction. Let Ω be an open bounded subset of \mathbb{R}^n . Consider a continuous map $f : \overline{\Omega} \rightarrow \mathbb{R}^n$ such that f is not equal to 0 at any point on the boundary of Ω . Then an integer $\deg(f, \Omega)$ called the Brouwer degree can be associated to f . The classical works on this subject are [3], [12], [13], and a modern one is [11]. It is well known that the Brouwer degree is an invariant of homotopy. This means that if $h : \overline{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ is a homotopy nowhere vanishing on $\partial\Omega \times [0, 1]$ then $\deg(h_t, \Omega) = \deg(h_0, \Omega)$ for all $t \in [0, 1]$, where $h_t(x) = h(x, t)$.

Let G be a compact Lie group. Assume that V is a real finite-dimensional representation of G and $n = \dim V$. Take $\Omega \subset V$ and $f : \overline{\Omega} \rightarrow V$ as above. In addition, suppose that Ω is G -invariant ($gx \in \Omega$ for all $x \in \Omega$, $g \in G$) and f is G -equivariant ($f(gx) = gf(x)$)

2000 *Mathematics Subject Classification*: 47H11.

Key words and phrases: involution, T -equivariant degree, classification of T -equivariant maps.

Supported by Grant KBN no. 1 P03A 042 29.

The paper is in final form and no version of it will be published elsewhere.

for all $x \in \overline{\Omega}$, $g \in G$). In this case, the G -equivariant degree $\text{Deg}_G(f, \Omega) \in B(G)$ is defined, where $B(G)$ stands for the Burnside ring of G . This degree was introduced by Ize, Massabó and Vignoli in [10]. Up till now, it was considered by many authors. See for instance [6], [11] and [15]. Of course, G -equivariant degree is an invariant of G -equivariant homotopy ($h(gx, t) = gh(x, t)$ for all $x \in \overline{\Omega}$, $t \in [0, 1]$, $g \in G$).

Let G be equal to \mathbb{Z}_2 . The action of \mathbb{Z}_2 on \mathbb{R}^n is determined by a decomposition of \mathbb{R}^n onto the direct sum $\mathbb{R}^p \oplus \mathbb{R}^q$ and the involution $T(u, v) = (u, -v)$, where $n = p + q$, $p, q \in \mathbb{N} \cup \{0\}$ and $u \in \mathbb{R}^p$, $v \in \mathbb{R}^q$. In fact, to define the \mathbb{Z}_2 -equivariant degree we do not need to use the representation theory. In this work we would like to describe a construction of this degree. We will call it T -equivariant degree.

Our approach is alternative to the one by Granas and Dugundji in [8]. There are two basic differences between our and their approach. Contrary to Granas and Dugundji, from the beginning we work with the family of T -equivariant maps (see Sec. 6, §20, Theorem 1.2, pp. 551–552 in [8], and Lemma 3.2, Conclusion 3.3 here). We also introduce notions of T -equivariant normal maps and homotopies, which are different from ones in [8]. Moreover, the proofs of all lemmas and propositions needed to define the degree are complete.

Our construction is divided into five main steps. Each step is a separate section.

In [14], Parusiński showed that if we have two gradient vector fields on the unit ball in \mathbb{R}^n and nowhere vanishing on the sphere, then they are homotopic if and only if they are gradient homotopic. In the last section we will prove this theorem in T -equivariant case. Namely, consider two T -equivariant gradient vector fields f and g on the unit ball in \mathbb{R}^n and nowhere vanishing on the sphere. It is shown that if there is a T -equivariant homotopy joining f to g then there is a T -equivariant gradient homotopy joining f to g . Our result suggests that there is no interesting generalization of T -equivariant degree on gradient vector fields. The proof is based on the latest results by Ferrario (see [4]) and Dancer, Gęba and Rybicki (see [1]).

2. T -equivariant maps and homotopy. Let $\mathbb{R}^n = \mathbb{R}^p \oplus \mathbb{R}^q$, where $n \in \mathbb{N}$, $p, q \in \mathbb{N} \cup \{0\}$ and $n = p + q$. For every $x \in \mathbb{R}^n$ we write $x = (u, v)$, where $u \in \mathbb{R}^p$ and $v \in \mathbb{R}^q$. Let $T : \mathbb{R}^n \rightarrow \mathbb{R}^n$ be given by

$$T(u, v) := (u, -v).$$

The map T is a linear isomorphism and an involution, i.e. $T^2 = \text{Id}_{\mathbb{R}^n}$.

DEFINITION 2.1. A set $X \subset \mathbb{R}^n$ is T -invariant if $T(X) \subset X$.

If a set X is T -invariant then $T(X) = X$ and $T|_X : X \rightarrow X$ is an involution onto X .

DEFINITION 2.2. Let $X \subset \mathbb{R}^n$ be T -invariant.

1. A map $f : X \rightarrow \mathbb{R}^n$ is called T -equivariant if $f(Tx) = Tf(x)$ for all $x \in X$.
2. $h : X \times [0, 1] \rightarrow \mathbb{R}^n$ is called a T -equivariant homotopy if it is continuous and $h(Tx, t) = Th(x, t)$ for all $x \in X$ and $t \in [0, 1]$.
3. A function $\tau : X \rightarrow \mathbb{R}$ is called T -equivariant if $\tau(Tx) = \tau(x)$ for all $x \in X$.



Remark that if $f = (f_1, f_2)$, where $f_1 : X \rightarrow \mathbb{R}^p$ and $f_2 : X \rightarrow \mathbb{R}^q$, then f is T -equivariant if and only if $f_1(u, -v) = f_1(u, v)$ and $f_2(u, -v) = -f_2(u, v)$ for all $(u, v) \in X$.

From now on, every open bounded T -invariant subset of \mathbb{R}^n is said to be T -admissible.

Assume that $\Omega \subset \mathbb{R}^n$ is T -admissible. It is obvious that $\bar{\Omega}$ is T -invariant. We say that $f : \bar{\Omega} \rightarrow \mathbb{R}^n$ is T -admissible if f is continuous, T -equivariant and $f(x) \neq 0$ for all $x \in \partial\Omega$. We will denote by $\mathcal{A}_T(\Omega)$ the family of all T -admissible maps from $\bar{\Omega}$ into \mathbb{R}^n . In the same spirit we generalize the notion of homotopy. We say that a homotopy $h : \bar{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ is T -admissible if h is T -equivariant and $h(x, t) \neq 0$ for all $x \in \partial\Omega$ and $t \in [0, 1]$. We will denote by $\mathcal{HA}_T(\Omega)$ the family of all T -admissible homotopies from $\bar{\Omega} \times [0, 1]$ into \mathbb{R}^n .

DEFINITION 2.3. We say that f is homotopic to g in $\mathcal{A}_T(\Omega)$ and write $f \sim g$ in $\mathcal{A}_T(\Omega)$ if there exists $h \in \mathcal{HA}_T(\Omega)$ joining f to g , i.e. $h(x, 0) = f(x)$ and $h(x, 1) = g(x)$ for all $x \in \bar{\Omega}$.

It is easy to check that \sim is an equivalence relation in $\mathcal{A}_T(\Omega)$. The homotopy class of $f \in \mathcal{A}_T(\Omega)$ under \sim will be denoted by $[f]$. Finally, the set of all homotopy classes of the relation \sim will be denoted by $\mathcal{A}_T[\Omega]$.

3. T -equivariant generic maps. Let $\Omega \subset \mathbb{R}^n$ be T -admissible. Here and subsequently,

$$\begin{aligned} \mathcal{A}_T^\infty(\Omega) &:= \{f \in \mathcal{A}_T(\Omega) : f|_\Omega \text{ is smooth}\}, \\ \mathcal{HA}_T^\infty(\Omega) &:= \{h \in \mathcal{HA}_T(\Omega) : h_{t|\Omega} \text{ is smooth for } t \in [0, 1]\}, \end{aligned}$$

where $h_t : \bar{\Omega} \rightarrow \mathbb{R}^n$ is defined by $h_t(x) := h(x, t)$.

DEFINITION 3.1. We say that f is homotopic to g in $\mathcal{A}_T^\infty(\Omega)$ and write $f \simeq g$ in $\mathcal{A}_T^\infty(\Omega)$ if there exists $h \in \mathcal{HA}_T^\infty(\Omega)$ joining f to g .

The relation \simeq is easily seen to be an equivalence relation in $\mathcal{A}_T^\infty(\Omega)$.

A map $f \in \mathcal{A}_T^\infty(\Omega)$ is said to be generic if $0 \in \mathbb{R}^n$ is a regular value of $f|_\Omega$, i.e. the derivative $Df(x) : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is an isomorphism for all $x \in f^{-1}(\{0\})$.

In this section we show that under some restrictions on Ω , every homotopy class in $\mathcal{A}_T[\Omega]$ possesses a T -equivariant generic map. For this purpose we prove now a few lemmas.

Let K be a compact subset of \mathbb{R}^n . A map $f : K \rightarrow \mathbb{R}^n$ is called smooth if there exists an open set $X \subset \mathbb{R}^n$ such that $K \subset X$ and there exists a smooth map $\tilde{f} : X \rightarrow \mathbb{R}^n$ such that $\tilde{f}|_K = f$. Let $\{U_i\}_{i=1}^k$ be an open covering of K . Set $U = \bigcup_{i=1}^k U_i$. We call a family of smooth functions $\lambda_i : U \rightarrow [0, 1]$, where $i = 1, 2, \dots, k$, a smooth partition of unity subordinate to the covering $\{U_i\}_{i=1}^k$, if this family satisfies the following conditions:

- $\text{supp } \lambda_i = \overline{\{x \in \mathbb{R}^n : \lambda_i(x) \neq 0\}} \subset U_i$ for every $i = 1, 2, \dots, k$,
- $\sum_{i=1}^k \lambda_i(y) = 1$ for every $y \in K$.

It is well known that such a partition exists (see [16]). Additionally, if K and every U_i are T -invariant sets and every λ_i is a T -equivariant function then we say that $\{U_i\}_{i=1}^k$ is a T -invariant covering of K and $\{\lambda_i\}_{i=1}^k$ is a T -equivariant partition of unity.

LEMMA 3.1. *Assume that $K \subset \mathbb{R}^n$ is compact and T -invariant, and $\{U_i\}_{i=1}^k$ is an open T -equivariant covering of K . Then there exists a smooth T -equivariant partition of unity subordinate to the covering $\{U_i\}_{i=1}^k$.*

Proof. Let $\{\lambda_i\}_{i=1}^k$ be a smooth partition of unity subordinate to the covering $\{U_i\}_{i=1}^k$ of K . For every $i = 1, 2, \dots, k$, let $\widehat{\lambda}_i$ be given by $\widehat{\lambda}_i = \frac{1}{2}(\lambda_i + \lambda_i T)$. It is obvious that each function $\widehat{\lambda}_i$ is smooth and T -equivariant. The family $\{\widehat{\lambda}_i\}_{i=1}^k$ is a desired one. ■

Let $K \subset \mathbb{R}^n$ be compact and T -invariant. We say that T acts freely on K if $Tx \neq x$ for every $x \in K$, i.e. $K \cap \mathbb{R}^p = \emptyset$. Then

$$\text{dist}(K, \mathbb{R}^p) := \inf\{|x - y| : x \in K, y \in \mathbb{R}^p\}$$

is a positive number.

LEMMA 3.2. *Let $K \subset \mathbb{R}^n$ be a compact T -invariant set such that T acts freely on K . If a map $f : K \rightarrow \mathbb{R}^n$ is continuous and T -equivariant then for every $\varepsilon > 0$ there is a smooth T -equivariant map $g : K \rightarrow \mathbb{R}^n$ such that*

$$\sup_{x \in K} |f(x) - g(x)| < \varepsilon.$$

From now on, $B(a, r)$ stands for an open ball of radius r , centered at a point $a \in \mathbb{R}^n$.

Proof. Fix $\varepsilon > 0$. Since K is compact, f is uniformly continuous. Hence, there is $\delta > 0$ such that if $|x - y| < \delta$ then $|f(x) - f(y)| < \varepsilon$. Set $\delta' = \min\{\delta, \text{dist}(K, \mathbb{R}^p)\}$, and $U_x = B(x, \delta')$ for every $x \in K$. Then

- $TU_x = B(Tx, \delta')$,
- $U_x \cap TU_x = \emptyset$,
- $K \subset \bigcup_{x \in K} (U_x \cup TU_x)$.

The compactness of K implies that there exist points $x_1, x_2, \dots, x_k \in K$ such that $K \subset \bigcup_{i=1}^k (U_i \cup TU_i)$, where $U_i = U_{x_i}$. Consider a smooth T -equivariant partition of unity $\{\lambda_i\}_{i=1}^k$ subordinate to the covering $\{U_i \cup TU_i\}_{i=1}^k$ of K . Set $U = \bigcup_{i=1}^k (U_i \cup TU_i)$. For every $i \in \{1, 2, \dots, k\}$, let $\pi_i : U \rightarrow \mathbb{R}^n$ be a map such that $\pi_i(U_i) = \{x_i\}$ and $\pi_i(TU_i) = \{Tx_i\}$. The function $g : U \rightarrow \mathbb{R}^n$ is defined by

$$g(x) = \sum_{i=1}^k \lambda_i(x) f(\pi_i(x)).$$

Take $x \in U$. If $x \in U_i \cup TU_i$ then in a sufficiently small neighbourhood of x the map $f \circ \pi_i$ is constant. If $x \in \partial U_i \cup \partial TU_i$ then in a sufficiently small neighbourhood of x the function λ_i is equal to 0. Hence g is smooth.

Take $x \in K$. If $x \in U_i$ then $\pi_i(x) = x_i$ and $|\pi_i(x) - x| < \delta$. If $x \in TU_i$ then $\pi_i(x) = Tx_i$ and $|\pi_i(x) - x| < \delta$. Finally, if $x \notin U_i \cup TU_i$ then $\lambda_i(x) = 0$. From this it follows that

$$|g(x) - f(x)| = \left| \sum_{i=1}^k \lambda_i(x) f(\pi_i(x)) - \sum_{i=1}^k \lambda_i(x) f(x) \right| \leq \sum_{i=1}^k \lambda_i(x) |f(\pi_i(x)) - f(x)| < \varepsilon.$$

Moreover,

$$g(Tx) = \sum_{i=1}^k \lambda_i(Tx) f(\pi_i(Tx)) = \sum_{i=1}^k \lambda_i(x) f(T\pi_i(x)) = \sum_{i=1}^k \lambda_i(x) T f(\pi_i(x)) = Tg(x),$$

which completes the proof. ■

CONCLUSION 3.3. *Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set such that T acts freely on $\overline{\Omega}$. Then for every $f \in \mathcal{A}_T(\Omega)$ there exists $g \in \mathcal{A}_T^\infty(\Omega)$ such that $f \sim g$ in $\mathcal{A}_T(\Omega)$.*

Proof. By the assumption, $\overline{\Omega}$ is a T -invariant compact set and T acts freely on $\overline{\Omega}$. Set $d = \inf\{|f(x)| : x \in \partial\Omega\}$. From Lemma 3.2 it follows that there exists $g \in \mathcal{A}_T^\infty(\Omega)$ such that

$$\sup_{x \in \overline{\Omega}} |f(x) - g(x)| < d.$$

Consider the linear homotopy $h : \overline{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ joining f to g , i.e.

$$h(x, t) = tg(x) + (1 - t)f(x).$$

It is trivial that h is continuous and $h(Tx, t) = Th(x, t)$ for all $x \in \overline{\Omega}$ and $t \in [0, 1]$. Take $x \in \partial\Omega$ and $t \in [0, 1]$. Then

$$|h(x, t)| = |f(x) - t(f(x) - g(x))| \geq |f(x)| - t|f(x) - g(x)| \geq |f(x)| - |f(x) - g(x)| > 0.$$

Hence $h \in \mathcal{HA}_T(\Omega)$. ■

Let $U \subset \mathbb{R}^n$ be an open bounded set, and $K \subset U$ be compact. It is well known that there exists a smooth function $\eta : \mathbb{R}^n \rightarrow [0, 1]$ such that

$$\eta(x) = \begin{cases} 1 & \text{for } x \in K, \\ 0 & \text{for } x \in \mathbb{R}^n \setminus U. \end{cases}$$

In the mathematical literature, η is called *the Urysohn function* (see [8]).

LEMMA 3.4. *Let U and U_0 be T -admissible subsets of \mathbb{R}^n . Assume that $\overline{U_0} \subset U$. Then there exists a smooth T -equivariant function $\tilde{\eta} : \mathbb{R}^n \rightarrow [0, 1]$ such that $\tilde{\eta}(x) = 1$ for every $x \in \overline{U_0}$ and $\tilde{\eta}(x) = 0$ for every $x \in \mathbb{R}^n \setminus U$.*

The proof is similar to that of Lemma 3.1. We leave it to the reader.

LEMMA 3.5. *Let Ω_0 and Ω be T -admissible subsets of \mathbb{R}^n such that $\Omega_0 \subset \Omega$. Suppose that $f_0 \simeq g_0$ in $\mathcal{A}_T^\infty(\Omega_0)$ and there is an $f \in \mathcal{A}_T^\infty(\Omega)$ such that $f|_{\Omega_0} = f_0$. Then there exist a map $g \in \mathcal{A}_T^\infty(\Omega)$ and a T -admissible set $U_0 \subset \Omega_0$ satisfying the following conditions:*

1. $f \simeq g$ in $\mathcal{A}_T^\infty(\Omega)$,
2. $g(x) = f(x)$ for every $x \in \overline{\Omega} \setminus \Omega_0$,
3. $g(x) = g_0(x)$ for every $x \in U_0$,
4. $g_0^{-1}(\{0\}) \cap \Omega_0 = g^{-1}(\{0\}) \cap \Omega_0 \subset U_0$.

Proof. Let $\bar{h} \in \mathcal{HA}_T^\infty(\Omega_0)$ be a homotopy joining f_0 to g_0 . Take an open T -invariant subset U_0 of \mathbb{R}^n such that $\overline{U_0} \subset \Omega_0$ and $\bar{h}(x, t) \neq 0$ for every $(x, t) \in (\overline{\Omega_0} \setminus U_0) \times [0, 1]$. Consider an open T -invariant subset U of \mathbb{R}^n such that $\overline{U_0} \subset U \subset \overline{U} \subset \Omega_0$. Let $\eta : \mathbb{R}^n \rightarrow [0, 1]$ be



a smooth T -equivariant Urysohn function for the pair of sets U_0 and U , i.e. $\eta(x) = 1$ for every $x \in \overline{U}_0$ and $\eta(x) = 0$ for every $x \in \mathbb{R}^n \setminus U$. Let $h : \overline{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ be defined by

$$h(x, t) = \begin{cases} f(x) & \text{for } x \in \overline{\Omega} \setminus \overline{U}, \\ \bar{h}(x, t\eta(x)) & \text{for } x \in \Omega_0. \end{cases}$$

We check that $h \in \mathcal{HA}_T^\infty(\Omega)$ and $g(x) := h(x, 1)$, $x \in \overline{\Omega}$, satisfies the claim of our lemma.

Remark that $(\overline{\Omega} \setminus \overline{U}) \cap \Omega_0 = \Omega_0 \setminus \overline{U}$. If $x \in \Omega_0 \setminus \overline{U}$ then $\eta(x) = 0$, and hence $\bar{h}(x, t\eta(x)) = \bar{h}(x, 0) = f(x)$ for all $t \in [0, 1]$. In consequence, h is smooth and $h(x, 0) = f(x)$ for every $x \in \overline{\Omega}$. If $x \in \partial\Omega$ then $h(x, t) = f(x) \neq 0$ for all $t \in [0, 1]$. Moreover, for $x \in \Omega_0$ and $t \in [0, 1]$ we have $h(Tx, t) = \bar{h}(Tx, t\eta(Tx)) = \bar{h}(Tx, t\eta(x)) = T\bar{h}(x, t\eta(x)) = Th(x, t)$. Thus h is T -equivariant. Summarizing, $h \in \mathcal{HA}_T^\infty(\Omega)$ and it joins f to g .

Take $x \in \overline{\Omega} \setminus \Omega_0$. Since $\overline{\Omega} \setminus \Omega_0 \subset \overline{\Omega} \setminus U$, we get $g(x) = h(x, 1) = f(x)$.

If $x \in U_0$ then $\eta(x) = 1$ and $g(x) = h(x, 1) = \bar{h}(x, 1) = g_0(x)$.

Finally, fix $x \in \Omega_0$. If $x \in \Omega_0 \setminus \overline{U}$ then $g(x) = \bar{h}(x, 0) = f_0(x)$. If $x \in \overline{U}$ then $g(x) = \bar{h}(x, \eta(x))$. Since $\{x \in \overline{\Omega}_0 : \bar{h}(x, t) = 0 \text{ for any } t \in [0, 1]\} \subset U_0$, we have $g_0^{-1}(\{0\}) \cap \Omega_0 = g^{-1}(\{0\}) \cap \Omega_0 \subset U_0$, which completes the proof. ■

Let $K \subset \mathbb{R}^n$ be nonempty, compact and T -admissible. Set $k \in \mathbb{N}$. We call a family of open sets $\{U_i\}_{i=1}^k$ a (T, k) -simple covering of K if it satisfies the following conditions:

1. $U_i \cap TU_i = \emptyset$ for every $i \in \{1, 2, \dots, k\}$,
2. $K \subset \bigcup_{i=1}^k (U_i \cup TU_i)$.

We say that K is a (T, k) -simple set if it possesses a (T, k) -simple covering. If $K = \emptyset$, it is said to be $(T, 0)$ -simple.

PROPOSITION 3.6. *Every nonempty compact T -invariant subset K of \mathbb{R}^n such that T acts freely on K is (T, k) -simple for a certain $k \in \mathbb{N}$.*

Proof. Since T acts freely on K , $K \cap \mathbb{R}^p = \emptyset$. Set $l = \text{dist}(K, \mathbb{R}^p)$. We have

$$K \subset \bigcup_{x \in K} B(x, l)$$

By compactness of K , there are $x_1, x_2, \dots, x_k \in K$ such that

$$K \subset \bigcup_{i=1}^k B(x_i, l).$$

Let $U_i = B(x_i, l)$ for $i = 1, 2, \dots, k$. It is evident that $U_i \cap TU_i = \emptyset$ and

$$K \subset \bigcup_{i=1}^k (U_i \cup TU_i). \quad \blacksquare$$

Let $\Omega \subset \mathbb{R}^n$ be an open bounded set. For every $f : \overline{\Omega} \rightarrow \mathbb{R}^n$ such that $f|_\Omega$ is C^r -smooth, where $r \geq 1$, and $f(x) \neq 0$ for all $x \in \partial\Omega$, set

$$R(f) = \{x \in f^{-1}(\{0\}) : Df(x) \in \text{GL}(\mathbb{R}^n)\}.$$



LEMMA 3.7. Assume that $\Omega \subset \mathbb{R}^n$ is T -admissible, T acts freely on $\overline{\Omega}$, which is (T, k) -simple for a certain $k \in \mathbb{N}$. Let $f \in \mathcal{A}_T^\infty(\Omega)$. Then there exists $g \in \mathcal{A}_T^\infty(\Omega)$ such that

- (i) $f \simeq g$ in $\mathcal{A}_T^\infty(\Omega)$,
- (ii) $g^{-1}(\{0\}) \setminus R(g)$ is $(T, k - 1)$ -simple.

Proof. Let $\{U_i\}_{i=1}^k$ be a (T, k) -simple covering of $\overline{\Omega}$. Set

$$K = \overline{\Omega} \setminus \bigcup_{i=2}^k (U_i \cup TU_i), \quad K_1 = K \cap U_1.$$

Let us remark that K is T -invariant, $K \subset (U_1 \cup TU_1)$, K and K_1 are compact. Thus K is $(T, 1)$ -simple and $K = K_1 \cup TK_1$.

From the Sard theorem it follows that there exists a regular value y_0 of $f|_{\Omega \cap U_1}$ such that $|y_0| < \inf\{|f(x)| : x \in \partial\Omega\}$. Since $f \circ T = T \circ f$, we have $Df(Tx) = T \circ Df(x) \circ T$ for every $x \in \Omega$. Hence Ty_0 is also a regular value of $f|_{\Omega \cap TU_1}$. Moreover, $|Ty_0| = |y_0|$.

Let $\eta : \mathbb{R}^n \rightarrow [0, 1]$ be a smooth function such that $\eta(x) = 1$ for all $x \in K_1$ and $\eta(x) = 0$ for all $x \in \mathbb{R}^n \setminus U_1$. Let $g : \overline{\Omega} \rightarrow \mathbb{R}^n$ be given by

$$g(x) = \begin{cases} f(x) - \eta(x)y_0 & \text{for } x \in U_1 \cap \overline{\Omega}, \\ f(x) - \eta(Tx)Ty_0 & \text{for } x \in TU_1 \cap \overline{\Omega}, \\ f(x) & \text{for } x \in \overline{\Omega} \setminus (U_1 \cup TU_1), \end{cases}$$

The map $g|_\Omega$ is easily seen to be smooth. Let

$$h(x, t) = f(x) + t(g(x) - f(x))$$

for all $(x, t) \in \overline{\Omega} \times [0, 1]$. Take $x \in \overline{\Omega}$. If $x \in U_1 \cap \overline{\Omega}$ then $g(Tx) = f(Tx) - \eta(T^2x)Ty_0 = Tf(x) - \eta(x)Ty_0 = T(f(x) - \eta(x)y_0) = Tg(x)$. If $x \in TU_1 \cap \overline{\Omega}$ then $g(Tx) = f(Tx) - \eta(Tx)y_0 = Tf(x) - \eta(Tx)y_0 = Tf(x) - T^2\eta(Tx)y_0 = T(f(x) - \eta(Tx)Ty_0) = Tg(x)$. Finally, if $x \in \overline{\Omega} \setminus (U_1 \cup TU_1)$ then $g(Tx) = f(Tx) = Tf(x) = Tg(x)$. Consequently, g is T -equivariant.

Since $|g(x) - f(x)| < |y_0|$ for all $x \in \overline{\Omega}$, we conclude that h is a homotopy joining f to g in $\mathcal{A}_T^\infty(\Omega)$.

Remark that $g^{-1}(\{0\}) \setminus R(g)$ is a compact set and $g^{-1}(\{0\}) \subset \bigcup_{i=2}^k (U_i \cup TU_i) \cup K$. Take $x \in K$. If $x \in K_1$ then $g(x) = f(x) - y_0$. If $x \in TK_1$ then $g(x) = f(x) - Ty_0$. From this $K \cap g^{-1}(\{0\}) \subset R(g)$, and so $g^{-1}(\{0\}) \setminus R(g) \subset \bigcup_{i=2}^k (U_i \cup TU_i)$ is $(T, k - 1)$ -simple. ■

LEMMA 3.8. Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set such that T acts freely on $\overline{\Omega}$. Assume that $f \in \mathcal{A}_T^\infty(\Omega)$ and $f^{-1}(\{0\}) \setminus R(f)$ is (T, k) -simple for a certain $k \in \mathbb{N}$. Then there exists a map $g \in \mathcal{A}_T^\infty(\Omega)$ such that

- (i) $f \simeq g$ in $\mathcal{A}_T^\infty(\Omega)$,
- (ii) $g^{-1}(\{0\}) \setminus R(g)$ is $(T, k - 1)$ -simple.

Proof. Since $f^{-1}(\{0\}) \setminus R(f)$ is (T, k) -simple, there is an open and T -invariant subset Ω_0 of Ω such that

- (a) $f^{-1}(\{0\}) \setminus R(f) \subset \Omega_0$,
- (b) $R(f) \subset \Omega \setminus \overline{\Omega}_0$,



(c) $\overline{\Omega}_0$ is (T, k) -simple.

Set $f_0 = f|_{\Omega_0}$. Combining (a) with (b), we see that $f_0 \in \mathcal{A}_T^\infty(\Omega_0)$. By Lemma 3.7 it follows that there is $g_0 \in \mathcal{A}_T^\infty(\Omega_0)$ such that $f_0 \simeq g_0$ in $\mathcal{A}_T^\infty(\Omega_0)$ and $g_0^{-1}(\{0\}) \setminus R(g_0)$ is $(T, k - 1)$ -simple. From Lemma 3.5 we have that there is $g \in \mathcal{A}_T^\infty(\Omega)$ such that $f \simeq g$ in $\mathcal{A}_T^\infty(\Omega)$ and $g^{-1}(\{0\}) \setminus R(g) = g_0^{-1}(\{0\}) \setminus R(g_0)$. Thus $g^{-1}(\{0\}) \setminus R(g)$ is $(T, k - 1)$ -simple. ■

Applying the mathematical induction, Lemma 3.8 and Conclusion 3.3, one can immediately prove the next theorem.

THEOREM 3.9. *Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set such that T acts freely on $\overline{\Omega}$. If $f \in \mathcal{A}_T(\Omega)$ then there exists a generic map $g \in \mathcal{A}_T^\infty(\Omega)$ such that $f \sim g$ in $\mathcal{A}_T(\Omega)$.*

CONCLUSION 3.10. *Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set such that T acts freely on $\overline{\Omega}$. If $f \in \mathcal{A}_T(\Omega)$ then $\deg(f, \Omega) \in 2\mathbb{Z}$.*

Here and subsequently, $\deg(f, \Omega)$ stands for the Brouwer degree of f on Ω .

Proof. Fix $f \in \mathcal{A}_T(\Omega)$. By Theorem 3.9 there is a generic map $g \in \mathcal{A}_T^\infty(\Omega)$ such that $f \sim g$ in $\mathcal{A}_T(\Omega)$. Hence $\deg(f, \Omega) = \deg(g, \Omega)$. Since $T \circ g = g \circ T$, we have $Dg(x) = T \circ Dg(Tx) \circ T$ for every $x \in \Omega$. From this

$$g^{-1}(\{0\}) \cap \Omega = \{x_1, x_2, \dots, x_m\} \cup \{Tx_1, Tx_2, \dots, Tx_m\}$$

and $\text{sign det } Dg(x_i) = \text{sign det } Dg(Tx_i)$ for $i = 1, 2, \dots, m$. In consequence,

$$\deg(g, \Omega) = \sum_{i=1}^m \text{sign det } Dg(x_i) + \sum_{i=1}^m \text{sign det } Dg(Tx_i) = 2 \sum_{i=1}^m \text{sign det } Dg(x_i),$$

which completes the proof. ■

4. T -equivariant normal maps. Let $\Omega \subset \mathbb{R}^n$ be T -admissible and let $\varepsilon > 0$. Define

$$\Omega(\varepsilon) = \{(u, v) \in \Omega : |v| < \varepsilon\}.$$

DEFINITION 4.1. Let $f = (f_1, f_2) \in \mathcal{A}_T(\Omega)$, where $f_1 : \overline{\Omega} \rightarrow \mathbb{R}^p$, and $f_2 : \overline{\Omega} \rightarrow \mathbb{R}^q$.

1. A map f is said to be ε -normal if there exists $\varepsilon > 0$ such that

$$f(u, v) = (f_1(u, 0), v)$$

for all $(u, v) \in \Omega(\varepsilon)$.

2. A map f is called normal if there exists $\varepsilon > 0$ such that f is ε -normal.

We will denote by $\mathcal{NA}_T(\Omega)$ the family of all normal maps from $\overline{\Omega}$ into \mathbb{R}^n .

DEFINITION 4.2. Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set.

1. A homotopy $h \in \mathcal{HA}_T(\Omega)$ is called normal if there exists $\varepsilon > 0$ such that $h_t : \overline{\Omega} \rightarrow \mathbb{R}^n$ is ε -normal for every $t \in [0, 1]$.
2. We say that f is homotopic to g in $\mathcal{NA}_T(\Omega)$ and write $f \approx g$ in $\mathcal{NA}_T(\Omega)$ if there exists a normal homotopy joining f to g .

We will denote by $\mathcal{HNA}_T(\Omega)$ the family of all normal homotopies from $\overline{\Omega} \times [0, 1]$ into \mathbb{R}^n . The homotopy class of $f \in \mathcal{NA}_T(\Omega)$ under \approx will be denoted by $[[f]]$. Finally, the set of all homotopy classes of the relation \approx will be denoted by $\mathcal{NA}_T[\Omega]$.



The construction of the degree for maps in $\mathcal{A}_T(\Omega)$, which will be described in the next section, is based on the following theorem.

THEOREM 4.1. *The map $\tau : \mathcal{N}\mathcal{A}_T[\Omega] \rightarrow \mathcal{A}_T[\Omega]$, $[[f]] \mapsto [f]$ is a bijection.*

Proof.

Step 1. We show that τ is a surjection.

Fix $f = (f_1, f_2) \in \mathcal{A}_T(\Omega)$. We show that there is $g \in \mathcal{N}\mathcal{A}_T(\Omega)$ such that $f \sim g$ in $\mathcal{A}_T(\Omega)$. Set $d = \inf\{|f(x)| : x \in \partial\Omega\}$. Since f is T -equivariant, $f_2(u, 0) = 0$ for every $(u, 0) \in \overline{\Omega}$. By the continuity of f , there is $0 < \varepsilon \leq d/12$ such that if $x, y \in \overline{\Omega}$ and $|x - y| < 2\varepsilon$ then $|f_i(x) - f_i(y)| < d/6$ for $i = 1, 2$.

Let $\eta : \mathbb{R} \rightarrow [0, 1]$ be a smooth function such that $\eta(t) = 1$ for every $|t| \leq \varepsilon$ and $\eta(t) = 0$ for every $|t| \geq 2\varepsilon$. Let $h : \overline{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ be defined by

$$h(u, v, t) = (1 - t\eta(|v|))f(u, v) + t\eta(|v|)(f_1(u, 0), v).$$

Then

$$\begin{aligned} h(T(u, v), t) &= h(u, -v, t) = (1 - t\eta(|v|))f(u, -v) + t\eta(|v|)(f_1(u, 0), -v) \\ &= (1 - t\eta(|v|))Tf(u, v) + t\eta(|v|)T(f_1(u, 0), v) = Th(u, v, t), \end{aligned}$$

for every $(u, v) \in \overline{\Omega}$ and $t \in [0, 1]$.

Take $(u, v) \in \partial\Omega$ and $t \in [0, 1]$. If $|v| \geq 2\varepsilon$ then $h(u, v, t) = f(u, v) \neq 0$. If $|v| < 2\varepsilon$ then

$$\begin{aligned} |h(u, v, t)| &= |f(u, v) - t\eta(|v|)(f_1(u, v) - f_1(u, 0), f_2(u, v) - v)| \\ &\geq |f(u, v)| - t\eta(|v|)|f_1(u, v) - f_1(u, 0)| - t\eta(|v|)|f_2(u, v) - v| \\ &\geq |f(u, v)| - |f_1(u, v) - f_1(u, 0)| - |f_2(u, v) - v| \\ &\geq |f(u, v)| - (|f_1(u, v) - f_1(u, 0)| + |f_2(u, v)| + |v|) \\ &> d - 3\frac{d}{6} = \frac{d}{2} > 0. \end{aligned}$$

In consequence, $h \in \mathcal{H}\mathcal{A}_T(\Omega)$. Set $g := h_1$. If $|v| \leq \varepsilon$ then $g(u, v) = h(u, v, 1) = (f_1(u, 0), v)$. Thus g is normal.

Step 2. We show that τ is an injection.

Take $f = (f_1, f_2) \in \mathcal{N}\mathcal{A}_T(\Omega)$ and $g = (g_1, g_2) \in \mathcal{N}\mathcal{A}_T(\Omega)$ such that $f \sim g$ in $\mathcal{A}_T(\Omega)$. We prove that $f \approx g$ in $\mathcal{N}\mathcal{A}_T(\Omega)$. Let $h = (h_I, h_{II}) \in \mathcal{A}_T(\Omega)$ be a homotopy joining f to g in $\mathcal{A}_T(\Omega)$. Set $d = \inf\{|h(x, t)| : x \in \partial\Omega \wedge t \in [0, 1]\}$. Since h is T -equivariant, we get $h_{II}(u, 0, t) = 0$ for every $(u, 0) \in \overline{\Omega}$ and $t \in [0, 1]$. Take $0 < \varepsilon \leq d/12$ such that f, g are 2ε -normal, and if $x, y \in \overline{\Omega}$ and $|x - y| < 2\varepsilon$ then $|h(x, t) - h(y, t)| < d/6$. Let $\eta : \mathbb{R} \rightarrow [0, 1]$ be a smooth function such that $\eta(t) = 1$ for every $|t| \leq \varepsilon$ and $\eta(t) = 0$ for every $|t| \geq 2\varepsilon$. Let $\hat{h} : \overline{\Omega} \times [0, 1] \rightarrow \mathbb{R}^n$ be given by

$$\hat{h}(u, v, t) = (1 - \eta(|v|))h(u, v, t) + \eta(|v|)(h_I(u, 0, t), v).$$

We check at once that \hat{h} is a normal homotopy joining f to g . ■

5. T -equivariant degree. In this section we introduce the degree of T -equivariant maps in \mathbb{R}^n , called the T -equivariant degree. First we define this degree for T -equivariant normal maps, and next for all T -admissible ones.

Let $\Omega \subset \mathbb{R}^n$ be a T -admissible set and let $f = (f_1, f_2) \in \mathcal{NA}_T(\Omega)$, where $f_1 : \overline{\Omega} \rightarrow \mathbb{R}^p$, $f_2 : \overline{\Omega} \rightarrow \mathbb{R}^q$. Set $\Omega_0 = \Omega \cap \mathbb{R}^p$. Assume that $\Omega_0 \neq \emptyset$. The map $g_0 : \overline{\Omega}_0 \rightarrow \mathbb{R}^p$ is given by $g_0(u) = f_1(u, 0)$. Since $f(u, v) \neq 0$ for all $(u, v) \in \partial\Omega$ and $f_2(u, 0) = 0$ for all $(u, 0) \in \overline{\Omega}$, we conclude that $g_0(u, v) \neq 0$ for all $(u, v) \in \partial\Omega_0$. Define

$$d_0 = \begin{cases} \deg(g_0, \Omega_0) & \text{if } \Omega_0 \neq \emptyset, \\ 0 & \text{if } \Omega_0 = \emptyset. \end{cases}$$

Since f is normal, there is $\varepsilon > 0$ such that $f(x) \neq 0$ for all $x \in \partial\Omega(\varepsilon)$. Set $\Omega_1 = \Omega \setminus \overline{\Omega(\varepsilon)}$. Let us remark that T acts freely on $\overline{\Omega}_1$. Define

$$g_1(x) = f(x),$$

where $x \in \overline{\Omega}_1$. It is evident that $g_1 \in \mathcal{A}_T(\Omega_1)$. By Conclusion 3.10 there exists an integer d_1 such that $\deg(g_1, \Omega_1) = 2d_1$. The T -equivariant degree of f on Ω is given as follows:

$$\deg_T(f, \Omega) = (d_0, d_1) \in \mathbb{Z} \oplus \mathbb{Z}.$$

Let us denote by \mathcal{N} the set of all pairs (f, Ω) such that $f \in \mathcal{NA}_T(\Omega)$ and $\Omega \subset \mathbb{R}^n$ is T -admissible.

THEOREM 5.1. *The map $\deg_T : \mathcal{N} \rightarrow \mathbb{Z} \oplus \mathbb{Z}$, $(f, \Omega) \mapsto \deg_T(f, \Omega)$, possesses the following properties:*

1. *Homotopy invariance:*
If $h \in \mathcal{HNA}_T(\Omega)$ then $\deg_T(h_t, \Omega) = \deg_T(h_0, \Omega)$ for every $t \in (0, 1]$.
2. *Excision:*
Assume that $\Omega_0 \subset \Omega$ is T -invariant and $f^{-1}(\{0\}) \cap \Omega \subset \Omega_0$. Then

$$\deg_T(f, \Omega) = \deg_T(f|_{\Omega_0}, \Omega_0).$$

3. *Additivity:*
Assume that Ω_1, Ω_2 are disjoint open T -invariant subsets of Ω such that $f^{-1}(\{0\}) \cap \Omega \subset \Omega_1 \cup \Omega_2$. Then

$$\deg_T(f, \Omega) = \deg_T(f|_{\Omega_1}, \Omega_1) + \deg_T(f|_{\Omega_2}, \Omega_2).$$

4. *Existence:*
If $\deg_T(f, \Omega) \neq 0$ then there exists a point $x \in \Omega$ such that $f(x) = 0$.

We call $\deg_T : \mathcal{N} \rightarrow \mathbb{Z} \oplus \mathbb{Z}$ the T -equivariant degree of normal maps. Its properties follow directly from the definition. It is worth pointing out that if $f \in \mathcal{NA}_T(\Omega)$ then there is the following dependence between $\deg(f, \Omega)$ and $\deg_T(f, \Omega)$:

$$\deg(f, \Omega) = d_0 + 2d_1, \quad d_0 = \deg(f, \Omega(\varepsilon)).$$

Let \mathcal{E} denote the family of all pairs (f, Ω) such that $f \in \mathcal{A}_T(\Omega)$ and Ω is T -admissible. Applying Theorem 4.1 one can extend the T -equivariant degree over \mathcal{E} . Consider $f \in \mathcal{A}_T(\Omega)$. There exists $g \in \mathcal{NA}_T(\Omega)$ such that $[g] = [f]$. Set

$$\text{Deg}_T(f, \Omega) = \deg_T(g, \Omega).$$



From Theorem 4.1 it follows that the above formula does not depend on the choice of g .

DEFINITION 5.1. The map $\text{Deg}_T : \mathcal{E} \rightarrow \mathbb{Z} \oplus \mathbb{Z}, (f, \Omega) \mapsto \text{Deg}_T(f, \Omega)$, is called the *T-equivariant degree*.

The next theorem is a natural consequence of Definition 5.1 and Theorem 5.1.

THEOREM 5.2. *The T-equivariant degree possesses the following properties:*

1. If $h \in \mathcal{HA}_T(\Omega)$ then $\text{Deg}_T(h_t, \Omega) = \text{Deg}_T(h_0, \Omega)$ for every $t \in (0, 1]$.
2. Assume that $\Omega_0 \subset \Omega$ is T -invariant and $f^{-1}(\{0\}) \cap \Omega \subset \Omega_0$. Then

$$\text{Deg}_T(f, \Omega) = \text{Deg}_T(f|_{\Omega_0}, \Omega_0).$$

3. Assume that Ω_1 and Ω_2 are disjoint open T -invariant subsets of Ω such that $f^{-1}(\{0\}) \cap \Omega \subset \Omega_1 \cup \Omega_2$. Then

$$\text{Deg}_T(f, \Omega) = \text{Deg}_T(f|_{\Omega_1}, \Omega_1) + \text{Deg}_T(f|_{\Omega_2}, \Omega_2).$$

4. If $\text{Deg}_T(f, \Omega) \neq 0$ then there exists a point $x \in \Omega$ such that $f(x) = 0$.

6. T-homotopies versus gradient T-homotopies. In this section we prove the Parusiński theorem in T -invariant case.

From now on, we assume that $\mathbb{R}^n = \mathbb{R}^p \oplus \mathbb{R}^q$ and $p \geq 2$. Let B^n denote the open unit ball, S^{n-1} the unit sphere, and D^n the unit disc in \mathbb{R}^n centered at 0. We have $D^n = B^n \cup S^{n-1}$. It is trivial that these sets are T -invariant. Set $D^p = D^n \cap \mathbb{R}^p$, $B^p = B^n \cap \mathbb{R}^p$ and $S^{p-1} = S^{n-1} \cap \mathbb{R}^p$.

Among many generalizations of the Brouwer degree there is the stable equivariant degree. It was considered by several authors (see [2, 4, 17] and the references given there). The stable equivariant degree of the T -equivariant continuous map $f : S^{n-1} \rightarrow S^{n-1}$ is the element $d_T(f) \in \mathbb{Z} \oplus \mathbb{Z}$ given by

$$d_T(f) = (\text{deg}(f, S^{p-1}), \text{deg}(f, S^{n-1})).$$

Let $[S^{n-1}, S^{n-1}]_T$ denote the set of all T -equivariant homotopy classes of T -equivariant continuous self-maps of S^{n-1} . Let $[f]_T$ stands for the T -equivariant homotopy class of $f : S^{n-1} \rightarrow S^{n-1}$. D. Ferrario proved that the stable equivariant degree d_T classifies T -equivariant continuous self-maps of S^{n-1} (see Theorem 7.1 in [4]). This means that the map

$$[S^{n-1}, S^{n-1}]_T \ni [f]_T \longmapsto d_T(f) \in \mathbb{Z} \oplus \mathbb{Z}$$

is an injection.

PROPOSITION 6.1. *Suppose that $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a T-equivariant continuous map such that $f(S^{n-1}) \subset \mathbb{R}^n \setminus \{0\}$. Then there exist a T-equivariant continuous map $\hat{f} : \mathbb{R}^n \rightarrow \mathbb{R}^n$ and a T-equivariant homotopy $h : \mathbb{R}^n \times [0, 1] \rightarrow \mathbb{R}^n$ such that*

- $h_0 = f, h_1 = \hat{f}$,
- $\hat{f}(S^{n-1}) \subset S^{n-1}$,
- $\hat{f}(D^n) \subset D^n$,
- $h(S^{n-1} \times [0, 1]) \subset \mathbb{R}^n \setminus \{0\}$.



Proof. We check at once that $\hat{f} : \mathbb{R}^n \rightarrow \mathbb{R}^n$ given by

$$\hat{f}(x) = \begin{cases} |x| \left| f\left(\frac{x}{|x|}\right) \right|^{-1} f\left(\frac{x}{|x|}\right) & \text{for } x \neq 0, \\ 0 & \text{for } x = 0 \end{cases}$$

and $h(x, t) = t\hat{f}(x) + (1 - t)f(x)$ satisfy all the claims. ■

Fix $f \in \mathcal{A}_T(B^n)$. Clearly, f can be extended to a T -equivariant continuous map over \mathbb{R}^n . Moreover, two different extensions of f are linear homotopic and the linear homotopy joining these extensions has no zeroes on $S^{n-1} \times [0, 1]$. Therefore we identify f with its extension. Let \hat{f} be a map as in Proposition 6.1. Then $\text{Deg}_T(f, B^n) = \text{Deg}_T(\hat{f}, B^n)$. Remark that there is one-to-one correspondence between $\text{Deg}_T(f, B^n) = (d_0, d_1)$ and $d_T(\hat{f}) = (\text{deg}(\hat{f}, S^{p-1}), \text{deg}(\hat{f}, S^{n-1}))$. Namely,

$$d_0 = \text{deg}(\hat{f}, S^{p-1}), \quad d_1 = \frac{1}{2}(\text{deg}(\hat{f}, S^{n-1}) - \text{deg}(\hat{f}, S^{p-1})).$$

Therefore the map

$$\mathcal{A}_T[B^n] \ni [f] \longmapsto d_T(\hat{f}) \in \mathbb{Z} \oplus \mathbb{Z}$$

is an injection.

CONCLUSION 6.2. *The T -equivariant degree $\text{Deg}_T(f, B^n)$ classifies T -admissible maps from D^n into \mathbb{R}^n .*

Another generalization of the Brouwer degree is the T -equivariant degree for gradient T -equivariant maps from \mathbb{R}^n into \mathbb{R}^n . This degree was considered in [7, 5, 1].

Assume that $f : \mathbb{R}^n \rightarrow \mathbb{R}^n$ is a T -equivariant continuous map. We say that f is ∇_T -admissible if $f(S^{n-1}) \subset \mathbb{R}^n \setminus \{0\}$ and there exists a T -equivariant C^1 function $\varphi : \mathbb{R}^n \rightarrow \mathbb{R}$ such that $f = \nabla\varphi$. We will denote by $\nabla\mathcal{A}_T(B^n)$ the set of all ∇_T -admissible maps. In the same spirit we introduce the notion of ∇_T -admissible homotopy. Let $h : \mathbb{R}^n \times [0, 1] \rightarrow \mathbb{R}^n$ be a T -equivariant homotopy. We say that h is ∇_T -admissible if $h(S^{n-1} \times [0, 1]) \subset \mathbb{R}^n \setminus \{0\}$ and there exists a T -equivariant C^1 function $\chi : \mathbb{R}^n \times [0, 1] \rightarrow \mathbb{R}$ such that $h(x, t) = \nabla_x \chi(x, t)$ for all $x \in \mathbb{R}^n$ and $t \in [0, 1]$.

f is homotopic to g in $\nabla\mathcal{A}_T(B^n)$, if there is a ∇_T -admissible homotopy h joining f to g . The ∇_T -admissible homotopy class of $f \in \nabla\mathcal{A}_T(B^n)$ will be denoted by $[f]_\nabla$. The set of all ∇_T -admissible homotopy classes in $\nabla\mathcal{A}_T(B^n)$ will be denoted by $\nabla\mathcal{A}_T[B^n]$.

The T -equivariant degree of $f \in \nabla\mathcal{A}_T(B^n)$ is the element $\nabla_T \text{deg}(f, B^n) \in \mathbb{Z} \oplus \mathbb{Z}$. From the construction made by Gęba in [5] (see formula 3.5, Theorems 3.2 and 3.3), it follows that

$$\nabla_T \text{deg}(f, B^n) = \text{Deg}_T(f, B^n).$$

Dancer, Gęba and Rybicki proved that this degree classifies ∇_T -admissible maps. More precisely, the map

$$\nabla\mathcal{A}_T[B^n] \ni [f]_\nabla \longmapsto \nabla_T \text{deg}(f, B^n) \in \mathbb{Z} \oplus \mathbb{Z}$$

is a bijection (see Corollary 4.1 and Remark 4.1 in [1]).

CONCLUSION 6.3. *The T -equivariant degree $\text{Deg}_T(f, B^n)$ classifies ∇_T -admissible maps.*



From Conclusions 6.2 and 6.3 we get a nice theorem.

THEOREM 6.4. *Assume that $f, g \in \nabla \mathcal{A}_T(B^n)$. If f is homotopic to g in $\mathcal{A}_T(B^n)$ then f is homotopic to g in $\nabla \mathcal{A}_T(B^n)$.*

Acknowledgments. We wish to express our sincere thanks to K. Gęba and M. Izydorek for their useful hints and comments.

References

- [1] E. N. Dancer, K. Gęba, S. M. Rybicki, *Classification of homotopy classes of equivariant gradient maps*, Fund. Math. 185 (2005), 1–18.
- [2] T. tom Dieck, *Transformation Groups*, Walter de Gruyter, Berlin 1987.
- [3] J. Dugundji, A. Granas, *Fixed Point Theory*, Vol. I, Monografie Matematyczne 61, PWN, Warszawa 1982.
- [4] D. L. Ferrario, *On the equivariant Hopf theorem*, Topology 42 (2003), 447–465.
- [5] K. Gęba, *Degree for gradient equivariant maps and equivariant Conley index*, in: Topological Nonlinear Analysis II (Frascati 1995), Progr. Nonlinear Differential Equations Appl. 27, Birkhäuser, Boston 1997, 247–272.
- [6] K. Gęba, W. Krawcewicz, J. Wu, *An equivariant degree with applications to symmetric bifurcation problems. I. Construction of the degree*, Proc. London Math. Soc. (3) 69 (1994), 377–398.
- [7] K. Gęba, I. Massabó, A. Vignoli, *On the Euler characteristic of equivariant gradient vector fields*, Boll. Un. Mat. Ital. A (7) 4 (1990), 243–251.
- [8] A. Granas, J. Dugundji, *Fixed Point Theory*, Springer Monogr. Math., Springer, New York 2003.
- [9] J. Ize, *Equivariant degree*, in: Handbook of Topological Fixed Point Theory, Springer, Dordrecht 2005, 301–337.
- [10] J. Ize, I. Massabó, A. Vignoli, *Degree theory for equivariant maps I*, Trans. Amer. Math. Soc. 315 (1989), 443–510.
- [11] W. Krawcewicz, J. Wu, *Theory of Degrees with Applications to Bifurcation and Differential Equations*, Wiley, New York 1997.
- [12] J. W. Milnor, *Topology from the Differentiable Viewpoint*, The Univ. Press of Virginia, Charlottesville 1965.
- [13] L. Nirenberg, *Topics in Nonlinear Functional Analysis*, Lecture Notes, 1973–1974, Courant Institute of Mathematical Sciences, New York University, New York 1974.
- [14] A. Parusiński, *Gradient homotopies of gradient vector fields*, Studia Math. 96 (1990), 73–80.
- [15] G. Peschke, *Degree of certain equivariant maps into a representation sphere*, Topology Appl. 59 (1994), 137–156.
- [16] M. Spivak, *Calculus on Manifolds*, PWN, Warsaw 1977 (in Polish).
- [17] H. Ulrich, *Fixed Point Theory of Parametrized Equivariant Maps*, Lecture Notes in Math. 1343, Springer, Berlin 1988.



