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MULTIVALUED MAPPINGS

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The present paper is a survey of the contemporary state of art in the theory of multivalued mappings. In it one considers different forms of continuity of multivalued mappings, one investigates differentiable and measurable multivalued mappings, one considers single-valued continuous approximations and sections of multivalued mappings, one studies fixed points of multivalued mappings and other questions of this theory. One gives references to the literature regarding applications to the theory of games, mathematical economics, the theory of differential inclusions and generalized dynamical systems. The paper contains an extensive bibliography.

INTRODUCTION

The theory of multivalued mappings is a branch of mathematics which has been developed intensively in the last years and lies at the junction of topology, theory of functions of a real variable and nonlinear functional analysis.

The concept of a multivalued mapping, assigning to the points of some set X a subset of another set Y, has arisen in a natural manner by refining the classical concept of a multivalued function. However, for a long time, in the above mentioned chapters of mathematics, one has studied systematically only the single-valued

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mappings and functions; moreover, as it is known, presently, without a special stipulation, the concepts of "mapping" and "function" mean single-valuedness. Of course, this gap can be compensated by that simple consideration that a multivalued mapping can be viewed as a single-valued mapping into the family (supplied with some structure) of subsets of Y, so that there is hardly a need for an independent theory of multivalued mappings. Nevertheless, the mentioned argument helps very little in the investigation of the specific problems which arise naturally in this theory. The gradual realization of these problems and the extension of their collection, the formation of the fundamental concepts, the development of the necessary machinery, all these have led to the formation of the theory of multivalued mappings, distinctly noticeable in the last decades. A large role in attracting attention to this theory has played the significant extension of the sphere of its application and methods, which in certain areas (especially in the theory of games, mathematical economics and in the theory of optimal control) have become generally accepted.

In the present survey we have undertaken an attempt to sketch the fundamental ideas of the theory of multivalued mappings (possibly with a complete bibliography).

In the first chapter we consider the elements of the analysis of multivalued mappings. Here we describe the various topologies in the space of closed subsets and we determine the forms of the continuity of multivalued mappings. We consider operations with multivalued mappings and we investigate the preservation of the continuity properties. Then, we touch the problem of the existence of continuous sections and of the approximations of multivalued mappings. We describe the concept of a differentiable multivalued mapping, we indicate the properties of measurable multivalued mappings and we give the definition of a multivalued integral.

The second chapter is devoted to the theory of fixed points of multivalued mappings. We consider fixed point principles of multivalued mappings, defined on continua and partially ordered sets, and we give some generalizations of the Banach principle of contraction mappings. A significant part of the chapter is devoted to the presentation of approximative and homological methods of the construction of the topological characteristics of multivalued mappings and to the investigation, on this basis, of various theorems on fixed points.

Unfortunately, the increasing volume of the manuscript has forced us to exclude from the survey the already written chapter on the applications of multivalued mappings. Instead, we present a supplement in which we give only references to the literature devoted to some of the fundamental directions of these applications. The authors propose to extend later this survey by elucidating in detail the problems of the applications.

At present, the various aspects of the theory of multivalued mappings have been very extensively developed and, therefore, the authors do not pretend in any measure the completeness of the survey. We note that many of these aspects (this refers especially to sections, measurable multivalued mappings, etc.) deserve undoubtedly a separate survey.

CHAPTER 1

THE ANALYSIS OF MULTIVALUED MAPPINGS

1.1. Space of Closed Subsets

Let X be a topological space. We denote by P(X) the collection of all nonempty subsets of the set X, by C(X) the set of all of its nonempty closed subsets and by K(X) the set of all of its nonempty compact subsets. We note that

$$C(X)\setminus C(X\setminus A)=\{F\in C(X)\mid F\cap A\neq\varnothing\}.$$

The set C(X) can be converted into a topological space by various methods. The most prevalent are the following constructions (see, for example, [140]).

1.1.1. Exponential Topology. Space 2^X. The concept of the exponential topology has been introduced and investigated in [140, 141, 938, 1211, etc.].

Let $A_0, A_1,\ldots, A_n\subset X$. We set $B(A_0, A_1,\ldots, A_n)=C(A_0)\cap[C(X)\setminus C(X\setminus A_1)]\cap\ldots\cap[C(X)\setminus C(X\setminus A_n)]$, i.e., the set F lies in $B(A_0, A_1,\ldots, A_n)$ if and only if $F\in C(X)$, $F\subset A_0$, $F\cap A_i\neq\varnothing$, $i=1,\ldots,n$.

It is easy to verify that the sets $B(G_0,\ldots, G_n)$, where $G_0,\ldots, G_n$ are open, form the basis of some topology on the set C(X). The set C(X), provided with this topology, is denoted by 2^X and is called the space of the closed subsets of X with the exponential topology.

1.1.2. THEOREM. The sets C(A) and $C(X)\setminus C(X\setminus A)$ are open (closed) in the space 2^X if and only if A is open (closed) in X.

We note that when the set G runs through all the open sets of the space X, the sets C(G) and $C(X)\setminus C(X\setminus G)$ form an open subbasis in the space 2^X.

1.1.3. Upper Semifinite Topology. Space $\varkappa X$. The concept of the upper semifinite topology has been investigated in [140, 240, 241, 938, etc.].

An open basis of this topology is formed by the sets C(G) when G runs through the collection of all nonempty open sets of the space X. The set C(X), provided with this topology, is denoted by $\varkappa X$. Thus, the topology $\varkappa X$ is weaker than 2^X. We also note that $\varkappa X$ is not a T_1-space with the exception of the trivial case when X consists of one point.

1.1.4. Lower Semifinite Topology. Space λX. The concept of the lower semifinite topology has been introduced by Michael [938]. An open subbasis of this topology is formed by the sets $C(X)\setminus C(X\setminus G)$, when G runs through the collection of all nonempty open sets of the space X. This is the weakest topology in which the sets C(K), where K is a closed set in X, are closed. The set C(X), provided with this topology, is denoted by λX. The space λX has a weaker topology than 2^X and it is not a T_1-space, also with the exception of the trivial case when X consists of one point.

1.1.5. Hausdorff Metric. Space $(2^X)_m$. Let (X, ρ) be a metric space. We denote by $C_0(X)$ the set of nonempty closed bounded subsets in X. As the distance $H(A_1, A_2)$ between $A_1, A_2 \in C_0(X)$ we take the largest of the numbers

$$\sup_{x\in A_1} \rho(x, A_2) \text{ and } \sup_{x\in A_2} \rho(x, A_1),$$

or, which is equivalent,

$$H(A_1, A_2)=\inf\{\varepsilon \mid \varepsilon\geqslant 0,\ A_1\subset U_\varepsilon(A_2),\ A_2\subset U_\varepsilon(A_1)\},$$

where $U_\varepsilon(A)$ is an ε-neighborhood of the set A.

The function H satisfies all the axioms of a metric on the set $C_0(X)$ and turns this set into a metric space which is denoted by $(2^X)_m$. The metric H is called the Hausdorff metric (or sometimes Pompeiu–Hausdorff), after Pompeiu and Hausdorff who have introduced and investigated it in [725, 1020].

There exists a theorem which establishes the connection between the topology of the space 2^X and the topology of the space $(2^X)_m$.

1.1.6. THEOREM [141]. Let X be a compact metric space. Then,

$$2^X \underset{\text{top}}{=} (2^X)_m,$$

i.e., the identity mapping $2^X\to(2^X)_m$ is a homeomorphism.

A more general fact is true.

1.1.7. THEOREM [141]. If $K(X)\subset 2^X$, while $(K(X))_m$ is the set K(X) with the metric H, then $K(X)\underset{\text{top}}{=}(K(X))_m$ for any metric space X.

1.1.8. Linear Operations on Sets. If X is a topological vector space, then in the set P(X) one can introduce in a natural manner the operations of addition and multiplication by a real number (the so-called Minkowski operations). These operations possess the following properties:

1) $A_1+A_2=A_2+A_1$;

2) $A_1+(A_2+A_3)=(A_1+A_2)+A_3$;

3) $A_1+\theta=A_1$, where θ is the zero of the space X;

4) $\lambda(A_1+A_2)=\lambda A_1+\lambda A_2$;

5) $\lambda(\mu A)=(\lambda\mu)A$;

6) $1\cdot A=A$.

For convex sets we also have the following property:

7) $(\lambda+\mu)A=\lambda A+\mu A$ if $\lambda, \mu\geqslant 0$.

If Y is a subset of a vector space X, then Pv(Y) denotes the collection of all nonempty convex subsets of Y. If X is a topological vector space, then Cv(X) is the collection of all nonempty closed convex subsets of X, while Kv(X) is the collection of all nonempty compact convex subsets of X.

1.1.9. Conductivity of Linear Operations. We consider the mapping $\alpha : K(X)\times K(X)\to K(X)$, generated by the addition of sets, and the mapping $\beta : \mathrm{R}\times K(X)\to K(X)$, generated by the multiplication of a set by a number.

1.1.10. THEOREM. If the set K(X) is endowed with the topology of the space $\varkappa$X, then the mappings α and β are continuous.

1.1.11. THEOREM. If the set K(X) is endowed with the topology of the space λX, then the mappings α and β are continuous.

1.1.12. THEOREM. If set K(X) is considered in the exponential topology, then the mappings α and β are continuous.

The validity of this theorem follows from Theorems 1.1.10 and 1.1.11 since the sets K(G) and K(X) $\setminus$ K (X$\setminus$G) form an open subbasis of this topology when G runs through all the open sets of the set X.

The space of subsets has been investigated from different points of view also in [190, 240, 241, 328, 342, 413, 417, 420, 439, 537, 648, 666, 729, 732, 931, 970, 1121, 1125, 1151, 1168, etc.].

1.2. Continuity of Multivalued Mappings

A multivalued mapping F of a set X into a set Y is a correspondence with associates to each point $x\in X$ a nonempty subset $F(x)\subseteq Y$, called the image of the point x, i.e., it is a single-valued mapping $F : F\to P(Y)$. From now on, we shall call every mapping $F : X\to P(Y)$ an m-mapping (from X into Y).

Since in the space of the subsets there exist various topologies, the classical concept of the continuity of a single-valued function splits into various concepts when applied to multivalued mappings. In 1931-1932, Kuratowski [848] and Bouligand [424] have introduced the concept of semicontinuous multivalued mappings.

Let X, Y be topological spaces.

1.2.1. Definition. An m-mapping $F : X\to P(Y)$ is said to be upper semicontinuous at the point $x\in X$, if for any open set $V\subset Y$ such that $F(x)\subset V$ there exists a neighborhood U(x) of the point x such that

$$F(U(x))\subset V.$$

An m-mapping $F : X\to P(Y)$ is said to be upper semicontinuous if it is upper semicontinuous at each point $x\in X$.

1.2.2. Definition. Let $D\subset Y$; by a small (full) preimage of D under the m-mapping $F : X\to P(Y)$ we mean the set $F_+^{-1}(D)\,(F_-^{-1}(D))$:

$$F_+^{-1}(D)=\{x\mid x\in X,\ F(x)\subset D\}$$
$$(F_-^{-1}(D)=\{x\mid x\in X,\ F(x)\cap D\neq\varnothing\}).$$

1.2.3. THEOREM. The following statements are equivalent:

(a) the m-mapping F is upper semicontinuous;

(b) for any open set $V\subset Y$ the set $F_+^{-1}(V)$ is open in X;

(c) for any closed set $W\subset Y$ the set $F_-^{-1}(W)$ is closed in X;

(d) if $D\subset Y$, then $F_-^{-1}(\bar{D})\supseteq F_-^{-1}(D)$.

1.2.4. THEOREM. An m-mapping $F : X\to C(Y)$ is upper semicontinuous if and only if F is continuous as a mapping from X into $\varkappa$Y.

1.2.5. Definition. An m-mapping $F : X\to P(Y)$ is said to be lower semicontinuous at the point $x\in X$, if for any open set $V\subset Y$ such that $F(x)\cap V\neq\varnothing$, there exists a neighborhood U(x) of the point x such that $F(x')\cap V\neq\varnothing$ for any $x'\in U(x)$.

An m-mapping $F : X\to P(Y)$ is said to be lower semicontinuous if it is lower semicontinuous at each point $x\in X$.

1.2.6. THEOREM. The following statements are equivalent:

(a) the m-mapping F is lower semicontinuous;

(b) for any open set $V \subset Y$ the set $F_{-}^{-1}(V)$ is open in X;

(c) for any closed set $W \subset Y$ the set $F_{+}^{-1}(W)$ is closed in X;

(d) if $D \subset Y$, then $F_{+}^{-1}(\bar{D}) \supseteq \overline{F_{+}^{-1}(D)}$;

(e) if $A \subset X$, then $F(\bar{A}) \subseteq \overline{F(A)}$.

1.2.7. THEOREM. An m-mapping $F: X \to C(Y)$ is lower semicontinuous if and only if it is continuous as a mapping from X into λY.

1.2.8. Definition. If an m-mapping $F: X \to P(Y)$ is both upper and lower semicontinuous, then it is said to be continuous.

1.2.9. THEOREM. An m-mapping $F: X \to C(Y)$ is continuous if and only if F is a continuous mapping from X into 2^Y.

Another important class is formed by the closed m-mappings.

1.2.10. Definition. An m-mapping $F: X \to C(Y)$ is said to be closed if its graph

$$\Gamma_F = \{(x, y) \mid (x, y) \in X \times Y,\ y \in F(x)\}$$

is a closed set in X × Y.

1.2.11. THEOREM. The following statements are equivalent:

(a) the m-mapping F is closed;

(b) for any pair $x \in X$, $y \in Y$ such that $y \notin F(x)$, there exists a neighborhood U(x) of the point x and a neighborhood V(y) of the point y such that $F(U(x)) \cap V(y) = \varnothing$;

(c) for any nets $\{x_\alpha\} \subset X$, $\{y_\alpha\} \subset Y$ such that $x_\alpha \to x$, $y_\alpha \in F(x_\alpha)$, $y_\alpha \to y$, we have $y \in F(x)$. In the case of metric spaces it is sufficient to consider sequences.

Between closed and upper semicontinuous m-mappings there exists a close connection.

1.2.12. THEOREM. If the m-mapping $F: X \to C(Y)$ is upper semicontinuous and the space Y is regular, then F is closed. If the m-mapping F has compact images: $F: X \to K(Y)$, then in the given statement the condition of the regularity of Y can be relaxed: it is sufficient to require that it be a Hausdorff space.

1.2.13. THEOREM. If $F: X \to K(Y)$ is a closed, locally compact m-mapping, then it is upper semicontinuous.

We mention the following properties of closed and upper semicontinuous m-mappings.

1.2.14. THEOREM. If the m-mapping $F: X \to C(Y)$ is closed and $A \in K(X)$, then $F(A) \in C(Y)$.

1.2.15. THEOREM. If the m-mapping $F: X \to K(Y)$ is upper semicontinuous and $A \in K(X)$, then $F(A) \in K(Y)$.

1.2.16. Mappings into a Metric Space. Let (Y, ρ) be a metric space.

1.2.17. THEOREM. For the upper (lower) semicontinuity of the m-mapping $F: X \to K(Y)$ it is necessary and sufficient that for any $\varepsilon > 0$ there should exist a neighborhood U(x) of the point x such that $F(x') \subset U_\varepsilon(F(x))$ ($F(x) \subset U_\varepsilon(F(x'))$) for all $x' \in U(x)$.

1.2.18. Definition. An m-mapping $F: X \to C_0(Y)$ is said to be continuous in the Hausdorff metric if F is continuous as a mapping into the metric space $(2^Y)_m$.

1.2.19. THEOREM. An m-mapping $F: X \to K(Y)$ is continuous if and only if it is continuous in the Hausdorff metric.

Assume now that the space Y is separable. Let $\{r_i\}_{i=1}^{\infty}$ be a countable, everywhere dense subset of Y. Every m-mapping $F: X \to P(Y)$ defines the functions $\{\varphi_i\}_{i=1}^{\infty}$, $\varphi_i: X \to \mathbf{R}$

$$\varphi_i(x) = \rho(r_i, F(x)).$$

1.2.20. THEOREM. For the upper semicontinuity of an m-mapping $F: X \to K(Y)$ it is necessary, and in the case when X is compact it is also sufficient, that all the functions φ_i be lower semicontinuous (in the single-valued sense).

1.2.21. THEOREM. For the lower semicontinuity of an m-mapping $F: X \to K(Y)$ it is necessary, and in the case when X is compact it is also sufficient, that all the functions φ_i be upper semicontinuous (in the single-valued sense).

Different types and tests for the continuity of the multivalued mappings have been studied by many authors (see [4, 7, 11, 14, 15, 19, 131, 132, 133, 153, 240, 241, 356, 377, 378, 381-389, 409, 413, 496, 498, 528, 536, 541, 578, 590, 592, 593, 605, 621, 645, 663, 705, 757, 795, 796, 811, 814, 849, 873, 875, 876, 934, 943, 958, 972, 1002, 1021, 1023, 1024, 1026, 1066, 1069, 1092, 1125, 1140, 1142, 1144, 1151, 1153, 1157]). We mention the surveys and monographs [19, 140, 141, 407, 408, 931, 1151]. The paper [408] contains, in particular, the original definitions of Kuratowski and Bouligand but it includes an incorrect statement regarding the equivalence of the concepts of closed and upper semicontinuous multivalued mappings.

1.3. Operations on Multivalued Mappings

In this section we consider various continuity properties of multivalued mappings which are the results of set-theoretic, topological or algebraic operations on multivalued mappings.

Operations on multivalued mappings and their properties have been investigated by Kuratowski [140, 141, 849] and by Berge [19, 407].

Let X, Y be topological spaces; let $\{F_j\}_{j\in J}$, $F_j: X \to P(Y)$ be a family of m-mappings.

1.3.1. THEOREM. (a) Assume that the m-mappings F_j are upper semicontinuous. If the index set J is finite, then the union of the m-mappings $\bigcup_{j\in J} F_j: X \to P(Y)$,

$$\Big(\bigcup_{j\in J} F_j\Big)(x) = \bigcup_{j\in J} F_j(x)$$

is upper semicontinuous.

(b) Assume that the m-mappings F_j are lower semicontinuous. Then the union $\bigcup_{j\in J} F_j$ is lower semicontinuous.

(c) Assume that the m-mappings $F_j: X \to C(Y)$ are closed. If the index set J is finite, then the union $\bigcup_{j\in J} F_j: X \to C(Y)$ is closed.

1.3.2. THEOREM. (a) Assume that the m-mappings $F_j: X \to C(Y)$ are upper semicontinuous. If the index set J is finite, the space Y is normal and

$$\bigcap_{j\in J} F_j(x) \neq \varnothing, \quad \forall x \in X,$$

then the intersection of the m-mappings

$$\bigcap_{j\in J} F_j: X \to C(Y),$$
$$\Big(\bigcap_{j\in J} F_j\Big)(x) = \bigcap_{j\in J} F_j(x)$$

is upper semicontinuous.

(b) Assume that the m-mappings $F_j: X \to C(Y)$ are closed and

$$\bigcap_{j\in J} F_j(x) \neq \varnothing, \quad \forall j \in J.$$

Then, the intersection $\bigcap_{j\in J} F_j$ is closed.

The following statement holds.

1.3.3. THEOREM. Assume that the m-mapping $F_0: X \to C(Y)$ is closed, the m-mapping $F_1: X \to K(Y)$ is upper semicontinuous and

$$F_0(x) \cap F_1(x) \neq \varnothing, \quad \forall x \in X.$$

Then, the intersection

$$F_0 \cap F_1: X \to K(Y)$$

is upper semicontinuous.

1.3.4. COROLLARY. Assume that the space Y is Hausdorff, the m-mappings $\{F_j\}_{j\in J}$, $F_j: X\to K(Y)$ are upper semicontinuous and

$$\bigcap_{j\in J} F_j(x)\neq\varnothing, \quad \forall x\in X.$$

Then, the intersection

$$\bigcap_{j\in J} F_j: X\to K(Y)$$

is upper semicontinuous.

If the m-mappings are lower semicontinuous, then the investigation of the continuity of their intersection becomes more complicated. Elementary examples show that in the general case such an intersection will not be lower semicontinuous (see [212]) (in this connection we mention the inaccuracy of statements in [19, 407]). In order to elucidate the conditions under which one can guarantee the lower semicontinuity of the intersection of m-mappings, the following concept will turn out to be useful (see [212, 958]).

1.3.5. Definition. An m-mapping $F: X\to P(Y)$ is said to be quasiopen at the point $x\in X$ if

$$\operatorname{int} F(x)\neq\varnothing$$

and if for any $y\in\operatorname{int} F(x)$ one can find a neighborhood $V(y)\subset Y$ and a neighborhood $U(x)\subset X$, such that

$$V(y)\subset F(x')$$

for all $x'\in U(x)$. If F is quasiopen at each point $x\in X$, then it will be called quasiopen.

1.3.6. THEOREM [958]. The following statements are equivalent:

(a) the m-mapping $F: X\to P(Y)$ is quasiopen;

(b) $\operatorname{int} F(x)\neq\varnothing$ for all $x\in X$ and the graph of the m-mapping $\operatorname{int} F: X\to P(Y)$,

$$(\operatorname{int} F)(x)=\operatorname{int} F(x)$$

is open in $X\times Y$.

The concept of a quasiopen m-mapping allows us to give the following criterion for lower semicontinuity.

1.3.7. THEOREM [212]. Let Y be a metric space. An m-mapping $F: X\to P(Y)$ is lower semicontinuous at the point $x\in X$ if and only if for any $\varepsilon>0$ the m-mapping $F_\varepsilon: X\to P(Y)$, $F_\varepsilon(x)=U_\varepsilon(F(x))$ is quasiopen at the point x.

1.3.8. THEOREM [212, 958]. Let Y be a finite-dimensional topological vector space. An m-mapping $F: X\to \mathrm{Cv}(Y)$ is quasiopen at the point $x\in X$ if and only if $\operatorname{int} F(x)\neq\varnothing$ and F is lower semicontinuous at the point x.

Now we formulate a condition for the lower semicontinuity of the intersection of multivalued mappings ([212, 958]):

1.3.9. THEOREM. Assume that the m-mapping $F_0: X\to P(Y)$ is lower semicontinuous at the point $x_0\in X$, the m-mapping $F_1: X\to P(Y)$ is quasiopen at x_0 and assume that

$$F_0(x)\cap F_1(x)\neq\varnothing.$$

for all $x\in X$ and

$$F_0(x_0)\cap F_1(x_0)\subset F_0(x_0)\cap\operatorname{int} F_1(x_0).$$

Then, the intersection $F_0\cap F_1$ is lower semicontinuous at the point x_0.

1.3.10. COROLLARY [212]. Let Y be a finite-dimensional topological vector space, assume that the m-mapping F_0, $F_1: X\to\mathrm{Cv}(Y)$ is lower semicontinuous and assume that

$$F_0(x)\cap F_1(x)\neq\varnothing$$

for all $x\in X$ and

1.3.11. $$F_0(x_0)\cap\operatorname{int} F_1(x_0)\neq\varnothing$$

for some $x_0\in X$. Then, the intersection

$$F_0 \cap F_1 : X \to \mathrm{Cv}(Y)$$

is lower semicontinuous at the point x_0.

We mention that the intersection of m-mappings is investigated in certain problems of mathematical economics and the condition 1.3.11 ensures a strong condition of Arrow–Debreu type (see, for example, [213]).

1.3.12. COROLLARY [212]. Let Y be a metric space, assume that the m-mappings F_0, $F_1 : X \to P(Y)$ are lower semicontinuous and that

$$F_0(x) \cap U_\varepsilon(F_1(x)) \neq \varnothing$$

for some $\varepsilon > 0$ at each point $x \in X$. Then, the m-mapping

$$F_0 \cap (F_1)_\varepsilon : X \to P(Y), \quad (F_0 \cap (F_1)_\varepsilon)(x) = F_0(x) \cap U_\varepsilon(F_1(x))$$

is lower semicontinuous.

We consider the continuity properties of the compositions of multivalued mappings.

Let X, Y, Z be topological spaces.

1.3.13. THEOREM. If the m-mappings $F_0 : X \to P(Y)$, $F_1 : Y \to P(Z)$ are upper (lower) semicontinuous, then their composition

$$F_1 \circ F_0 : X \to P(Z),$$
$$F_1 \circ F_0(x) = F_1(F_0(x))$$

is upper (lower) semicontinuous.

1.3.14. THEOREM. If the m-mapping $F_0 : X \to K(Y)$ is upper semicontinuous and the m-mapping $F_1 : Y \to C(Z)$ is closed, then their composition

$$F_1 \circ F_0 : X \to C(Z)$$

is closed.

Now we consider the operation of taking the Cartesian product of multivalued mappings.

1.3.15. THEOREM. (a) If the m-mappings $F_0 : X \to P(Y)$, $F_1 : X \to P(Z)$ are lower semicontinuous, then their Cartesian product

$$F_0 \times F_1 : X \to P(Y \times Z),$$
$$(F_0 \times F_1)(x) = F_0(x) \times F_1(x)$$

is lower semicontinuous.

(b) If the m-mappings $F_0 : X \to C(Y)$, $F_1 : X \to C(Z)$ are closed, then the m-mapping

$$F_0 \times F_1 : X \to C(Y \times Z)$$

is closed;

(c) if the m-mappings $F_0 : X \to K(Y)$, $F_1 : X \to K(Z)$ are upper semicontinuous, then the m-mapping

$$F_0 \times F_1 : X \to K(Y \times Z)$$

is upper semicontinuous.

We investigate algebraic and some other operations. Let X be a topological space and let Y be a topological vector space.

1.3.16. THEOREM. (a) If the m-mappings F_0, $F_1 : X \to P(Y)$ are lower semicontinuous, then their sum $F_0 + F_1 : X \to P(Y)$,

$$(F_0 + F_1)(x) = F_0(x) + F_1(x)$$

is lower semicontinuous.

(b) If the m-mappings F_0, $F_1 : X \to K(Y)$ are upper semicontinuous, then their sum $F_0 + F_1 : X \to K(Y)$ is upper semicontinuous.

1.3.17. THEOREM. (a) If the m-mapping $F: X \to P(Y)$ is lower semicontinuous and the function $f: X \to \mathbf{R}$ is continuous, then the product $f \cdot F: X \to P(Y)$,

$$(f \cdot F)(x) = f(x) \cdot F(x)$$

is lower semicontinuous.

(b) If the m-mapping $F: X \to K(Y)$ is upper semicontinuous and the function $f: X \to \mathbf{R}$ is continuous, then the product

$$f \cdot F: X \to K(Y)$$

is upper semicontinuous.

Let Y be a topological space.

1.3.18. THEOREM. An m-mapping $F: X \to P(Y)$ is lower semicontinuous if and only if the closure

$$\bar{F}: X \to C(Y), \quad \bar{F}(x) = \overline{F(x)},$$

is lower semicontinuous.

Let Y be a metric space.

1.3.19. THEOREM. If the m-mapping $F: X \to P(Y)$ is lower semicontinuous, then the m-mapping $F_\varepsilon: X \to P(Y)$,

$$F_\varepsilon(x) = U_\varepsilon(F(x))$$

is also lower semicontinuous.

Let Y be a normed space.

1.3.20. THEOREM. Let $F: X \to K(Y)$ be a compact, upper semicontinuous m-mapping. Then, for any $\varepsilon > 0$ the m-mapping $\bar{F}_\varepsilon: X \to C(Y)$,

$$\bar{F}_\varepsilon(x) = \overline{U_\varepsilon(F(x))},$$

is closed.

Let Y be a complete locally convex space.

1.3.21. THEOREM. If the m-mapping $F: X \to K(Y)$ is upper (lower) semicontinuous, then the convex closure $\overline{\mathrm{co}}\, F: X \to \mathrm{Kv}(Y)$,

$$\overline{\mathrm{co}}\, F(x) = \overline{\mathrm{co}}\,(F(x)),$$

is upper (lower) semicontinuous.

We conclude this section by a maximum theorem, sometimes called the continuity principle of optimal solutions, which plays an important role in the applications of the multivalued mappings to game theory and to mathematical economics.

1.3.22. THEOREM. Let X, Y be topological spaces, let $\Phi: X \to K(Y)$ be a continuous m-mapping and let $f: X \times Y \to \mathbf{R}$ be a continuous function. Then, the function $\varphi: X \to \mathbf{R}$,

$$\varphi(x) = \max_{\tilde{y} \in \Phi(x)} f(x, \tilde{y})$$

is continuous, while the m-mapping $F: X \to K(Y)$,

$$F(x) = \{y \mid y \in \Phi(x),\ f(x, y) = \varphi(x)\}$$

is upper semicontinuous.

Among other works devoted to the investigation of the various properties of the operations on m-mappings, we mention [17, 145, 146, 168, 259, 302, 303, 379, 380, 383, 384, 386, 387, 417, 590, 592, 614, 849, 876, 1033, 1078, 1156].

Various topological properties of m-mappings have been investigated in [5, 6, 16, 17, 19, 42, 50, 84, 123, 136, 139, 144, 153, 154, 158, 178, 185, 186, 240, 241, 248, 260, 262, 282, 287, 288, 314, 316, 341, 348, 355, 374, 434, 469, 486, 514, 515, 520, 533, 535, 546, 587, 596, 627, 638, 643, 644, 662, 665, 696, 719, 731, 732, 751, 752, 763, 768, 777, 785, 794, 797, 810, 812, 834, 854, 887, 898, 901, 912, 959, 960, 961, 973, 990, 997, 1022, 1033, 1034, 1068, 1073, 1075, 1076, 1098, 1101, 1125, 1134, 1146, 1151, 1154, 1156, 1159, 1162, 1163, 1164, 1165, 1174, 1198, 1213, 1216, 1217, 1235, 1238, 1239, 1240, 1243].

The homotopic properties of m-mappings have been investigated in [432, 693, 1061, 1062, 1063, 1171].

We mention that many topological properties of spaces can be expressed in terms of multivalued mappings (see, for example, [184, 187, 191, 242, 243, 284, 315, 418, 419, 525, 531, 583, 794, 886, 957, 971, 980, 1237, 1242]).

1.4. Continuous Sections of Multivalued Mappings

Let X, Y be topological spaces and let $F: X \to P(Y)$ be an m-mapping.

1.4.1. Definition. A continuous single-valued mapping $f: X \to Y$ be said to be a continuous section (selector, sample) of an m-mapping F if

$$f(x) \in F(x)$$

for any $x \in X$.

A classical theorem on the existence of a continuous section of an m-mapping is Michael's theorem [940]. Since we have not found a Russian translation of this significant result, having numerous applications, we give it in its entirety.

1.4.2. THEOREM. The following properties of a T_1 space X are equivalent:

a) X is paracompact;

b) if Y is a Banach space, then every lower semicontinuous m-mapping $F: X \to \mathrm{Cv}(Y)$ has a continuous section.

The proof of this theorem is based on the following statement.

1.4.3. LEMMA. Let X be a paracompact space, let Y be a normed space and let $F: X \to \mathrm{Pv}(Y)$ be a lower semicontinuous m-mapping. For any $\varepsilon > 0$ there exists a continuous single-valued mapping $f_\varepsilon: X \to Y$ such that

$$f_\varepsilon(x) \in U_\varepsilon(F(x))$$

for any $x \in X$.

Proof. Assume that

$$U_y = \{x \mid x \in X,\ y \in U_\varepsilon(F(x))\}$$

for any $y \in Y$. These sets are open by virtue of the lower semicontinuity of the m-mapping F. The system $\{U_y\}_{y \in Y}$ forms an open covering of the paracompact space X. Let $\{U_{y_j}\}_{j \in J}$ be a locally finite subcovering of this covering. We consider $\{\varphi_{y_j}\}_{j \in J}$, the partition of unity corresponding to the covering $\{U_{y_j}\}_{j \in J}$. We define a continuous mapping $f_\varepsilon: X \to Y$ in the following manner:

$$f_\varepsilon(x) = \sum_{j \in J} \varphi_{y_j}(x) \cdot y_j.$$

It is easy to verify that f_ε is the desired mapping.

1.4.4. Proof of Theorem 1.4.2. 1) First we prove that a) $\Rightarrow$ b). We construct an inductive sequence of continuous mappings

$$\{f_k\}_{k=1}^{\infty},\ f_k: X \to Y,$$

satisfying the conditions:

1.4.5. $\| f_{k+1}(x) - f_k(x) \| < 1/2^{k-1}$;

1.4.6. $f_k(x) \in U_{1/2^k}(F(x))$

for each $x \in X$. The existence of f_1, satisfying the condition 1.4.6, follows from Lemma 1.4.3. If $f_1, \ldots, f_k$ have been already constructed, then f_{k+1} is constructed in the following manner. By the induction hypothesis, we have

$$F_{k+1}(x) = F(x) \cap U_{2^{-k}}(f_k(x)) \neq \varnothing, \quad \forall x \in X.$$

From 1.3.12 it follows that the m-mapping $F_{k+1}: X \to \mathrm{Cv}(Y)$ is lower semicontinuous. Then, from Lemma 1.4.3 there follows the existence of a continuous mapping $f_{k+1}: X \to Y$ such that $f_{k+1}(x) \in U_{2^{-k-1}}(F_{k+1}(x))$ for each $x \in X$ But then, for each $x \in X$ we have

$$\| f_{k+1}(x) - f_k(x) \| < \frac{1}{2^k} + \frac{1}{2^{k+1}} < \frac{1}{2^{k-1}}$$

i.e., condition 1.4.5 holds, and $f_{k+1}(x) \in U_{2^{-k-1}}(F(x))$, i.e., condition 1.4.6 holds.

From condition 1.4.5 it follows that the sequence $\{f_k\}_{k=1}^{\infty}$ converges uniformly to a continuous function f for which, by virtue of the condition 1.4.6 and of the closedness of the images of the mapping F, we have $f(x) \in F(x)$ for each $x \in X$, i.e., f is the desired continuous section.

2) We show that b) ⇒ a). For this it is sufficient to establish that each open covering $\mathcal{U}$ of the space X admits a subordinate partition of unity. Let

$$Y = l_1(\mathcal{U}) = \left\{ y \mid y : \mathcal{U} \to \mathbf{R}, \sum_{U \in \mathcal{U}} |y(U)| < \infty \right\}.$$

Taking $\|y\| = \sum_{U \in \mathcal{U}} |y(U)|$, we convert Y into a Banach space. We consider

$$C = \left\{ y \mid y \in Y,\ y(U) \geqslant 0,\ \forall U \in \mathcal{U};\ \sum_{U \in \mathcal{U}} y(U) = 1 \right\}$$

a convex closed subspace of Y. For all x ∈ X, let

$$F(x) = C \cap \{ y \mid y \in Y,\ y(U) = 0\ \ \forall U \in \mathcal{U},\ x \notin U \}.$$

Clearly, $F(x) \in \mathrm{Cv}(Y)\ \forall x \in X$. We show that the m-mapping F is lower semicontinuous.

First of all we show that for any $y \in C$, $\varepsilon > 0$ there exists $y' \in C$ such that $\|y - y'\| < \varepsilon$ and $y'(U) > 0$ for at most a finite number of $U \in \mathcal{U}$. In order to find such a y' it is necessary to select $U_1, \ldots, U_n \in \mathcal{U}$, $y(U_i) > 0$, $1 \leqslant i \leqslant n$, where $y(U_1) + \cdots + y(U_n) = \delta > 1 - \varepsilon/2$, and then to determine $y' \in C$ from the relations

$$y'(U) = 0, \quad U \bar{\in} \{U_1, \ldots, U_n\};$$
$$y'(U_1) = y(U_1) + 1 - \delta;$$
$$y'(U_i) = y(U_i), \quad i = 2, \ldots, n.$$

It is easy to see that $\|y - y'\| < 2(1 - \delta) < \varepsilon$.

Assume now that $x \in X$, $y \in F(x)$ and there is given $\varepsilon > 0$. Assume that y' and $U_1, \ldots, U_n$ satisfy the above mentioned conditions. If $U = U_1 \cap \ldots \cap U_n$, then, due to $y(U_i) > 0$, $1 \leqslant i \leqslant n$, from the definition of F it follows that $y' \in F(x')$ for all $x' \in U$ and, thus, F is lower semicontinuous.

Assume now that $f : X \to Y$ is a continuous section of F. For each $U \in \mathcal{U}$ we define $f_U : X \to \mathbf{R}$ by the relation $f_U(x) = [f(x)](U)$. Then f_U is the desired partition of unity, which concludes the proof.

1.4.7. There exist examples (see [940]) which show that the conditions of the completeness of the space Y, of the closedness and convexity of the images of the m-mapping F, the condition of lower semicontinuity of the m-mapping F are necessary for the existence of a continuous section. At the same time it is easy to give examples of multivalued mappings with convex images, which are not lower semicontinuous but admit continuous sections. We give a new result in this direction, obtained by V. D. Gel'man.

Let X be a metric space and let Y be a convex, compact subspace of the Banach space E. Let $F : X \to \mathrm{Kv}(Y)$ be an m-mapping, $F_\varepsilon(x) = U_\varepsilon(F(x))$. For each point $x_0 \in X$ we define the set $L(F)(x_0)$ according to the following rule:

$$L(F)(x_0) = \bigcap_{\varepsilon > 0} \overline{\left(\bigcup_{\delta > 0} \left(\bigcap_{x \in U_\delta(x_0)} F_\varepsilon(x) \right) \right)}.$$

The set $L(F)(x_0)$ may be empty for some $x_0 \in X$.

1.4.8. LEMMA. For any point $x_0 \in X$ the set $L(F)(x_0)$ is a convex, closed subset of $F(x_0)$.

1.4.9. LEMMA. Assume that the m-mapping $\Psi : X \to \mathrm{Kv}(Y)$ is lower semicontinuous. If for any x ∈ X the inclusion $F(x) \supseteq \Psi(x)$ holds, then $L(F)(x) \supseteq \Psi(x)$ for any x ∈ X.

1.4.10. THEOREM. In order that an m-mapping $F_\varepsilon : X \to \mathrm{Pv}(Y)$ should have a continuous section for any $\varepsilon > 0$, it is necessary and sufficient that $L(F)(x) \neq \varnothing$ for any x ∈ X.

We mention that the nonemptiness of the sets L(F)(x) for any x ∈ X does not guarantee the presence of a continuous section for the m-mapping F.

1.4.11. Example. Let F be the m-mapping of the segment [−1, 1] into R^3, defined by the following conditions:

$$F(x)=\begin{cases}[(x,1,0);(x,-1,x)], & x>0,\ x\in\mathbf{Q};\\ [(x,1,0);(x,-1,-x)], & x>0,\ x\in[-1,1]\setminus\mathbf{Q};\\ [(0,1,0);(0,-1,0)], & x=0;\\ [(x,-1,0);(x,1,x)], & x<0,\ x\in\mathbf{Q};\\ [(x,-1,0);(x,1,-x)], & x<0,\ x\in[-1,1]\setminus\mathbf{Q}.\end{cases}$$

Obviously,

$$L(F)(x)=\begin{cases}\{(x,1,0)\}, & x>0;\\ [(0,1,0);(0,-1,0)], & x=0;\\ \{(x,-1,0)\}, & x<0,\end{cases}$$

i.e., $L(F)(x)\neq\varnothing$ for any x ∈ [−1, 1]. However, the m-mapping F does not have a continuous section.

We consider now the iterates of L:

$$L^0(F)=F,\quad L^n(F)=L(L^{n-1}(F)),\quad n\geqslant 1.$$

We continue this process for each transfinite number of the first type, while for a transfinite number of the second type we set

$$L^\alpha(F)(x)=\bigcap_{\beta<\alpha}L^\beta(F)(x).$$

We shall say that the sequence $\{L^\alpha(F)\}$ is stabilized at the step α_0 if

$$L^{\alpha_0}(F)(x)=L^{\alpha_0+1}(F)(x)$$

for any x ∈ X.

1.4.12. THEOREM. In order that an m-mapping $F:X\to \mathrm{Kv}(Y)$ should have a continuous section, it is necessary and sufficient that the sequence $\{L^\alpha(F)\}$ be stabilized at some (finite or countable) step α_0 and that $L^{\alpha_0}(F)(x)\neq\varnothing$ for any x ∈ X.

1.4.13. Remark. It presents interest to determine under which additional assumptions on F is the sequence $\{L^\alpha(F)\}$ stabilized in a finite number of steps.

We mention also the following interesting property of quasiopen m-mappings (see [212]).

1.4.14. Assume that X is a paracompact space, Y is a metric vector space, $F:X\to P(Y)$ is quasiopen and

$$\operatorname{int}F(x)\in \mathrm{Pv}(Y),\ \forall x\in X.$$

Then, F has a continuous section.

An extensive literature is devoted to the development of Michael's theorem as well as to other theorems on continuous sections (see, for example, [70, 155-158, 198-203, 289, 293, 299, 302, 303, 327, 329, 330, 331, 334, 335, 336, 346, 354, 356, 470, 471, 480, 487, 493, 528, 530, 562, 574, 585, 622, 625, 639, 649, 656, 677, 680, 724, 728, 739, 802, 851, 853, 888, 896, 897, 898, 899, 932, 939, 941, 942, 944, 945-947, 955, 969, 970, 979, 981, 992, 1009, 1057, 1104, 1105, 1110, 1125, 1161, 1168, 1169, 1194, 1227, 1245]).

We mention the survey [992] where one also gives some applications of the concept of section.

1.5. Continuous Approximations of Multivalued Mappings

It is easy to see that, in general, upper semicontinuous and closed m-mappings do not admit continuous sections. The path to their investigation by means of single-valued mappings is opened by single-valued approximations.

Let (X,ρ_X), (Y,ρ_Y) be metric spaces. The metric ρ in the product space X×Y is defined by the equality

$$\rho((x,y),(x',y'))=\max\{\rho_X(x,x'),\rho_Y(y,y')\}.$$

1.5.1. Definition. Let $F:X\to P(Y)$ be an m-mapping. A continuous mapping $f_\varepsilon:X\to Y$, where $\varepsilon > 0$, is said to be an ε-approximation of the m-mapping F if

$$\rho_*(\Gamma_{f_\varepsilon}, \Gamma_F)=\sup_{y\in\Gamma_{f_\varepsilon}} \rho(y, \Gamma_F)<\varepsilon,$$

where Γ_{f_ε}, Γ_F are the graphs of the mappings f_ε, F.

The problem of the existence of ε-approximations, raised by von Neumann [977] and important for applications, has been investigated by many authors (see, for example, [83, 488-492, 867, 983, 1112, 1113]).

One of the most general results is the following statement.

1.5.2. THEOREM [867]. Let X be a metric space and let Y be a metric LCS (locally convex space). Then, for any $\varepsilon > 0$, every upper semicontinuous m-mapping $F: X\to \mathrm{Cv}(Y)$ has an ε-approximation $f_\varepsilon: X\to Y$ such that

$$f_\varepsilon(X)\subset \mathrm{co}F(X).$$

We mention the following important property of ε-approximations.

1.5.3. THEOREM. Assume that the m-mapping $F:X\to C(Y)$ is upper semicontinuous and that $f_{\varepsilon_i}:X\to Y$ is a sequence of ε_i-approximations for F, $\varepsilon_i\to 0$. If $\{x_i\}_{i=1}^\infty\subset X$, $\lim_{i\to\infty} x_i=x_0$, and $\lim_{i\to\infty} f_{\varepsilon_i}(x_i)=y_0$, then $y_0\in F(x_0)$.

Theorems of existence of ε-approximations, for certain classes of upper semicontinuous m-mappings with nonconvex images, are contained in [39, 73, 82, 196].

The so-called acute-angled approximations are another suitable class of continuous single-valued approximations.

Let X be a paracompact topological space, let E be a Hausdorff LCS and let E* be its topological conjugate. By (l, y), where $l\in E^*$, $y\in E$, we denote the value $l(y)$.

1.5.4. THEOREM [212, 869, 870]. Assume that the m-mapping $F: X\to \mathrm{Cv}(E\setminus\theta)$ is upper semicontinuous. Then, there exists an acute-angled approximation for it, i.e., a continuous mapping $f: X\to E^*$ such that at each point $x \in X$, for all $y \in F(x)$ we have $(f(x), y) > 0$.

The proof of Theorems 1.5.2 and 1.5.4 can be found in the survey [37].

1.6. Differentiability of Multivalued Mappings

One of the most natural definitions of the differentiability of m-mappings is the definition of π-differentiability which occurs in [376].

If E is a topological vector space, then the set Kv(E) is a semilinear space (see 1.1.8). We consider

$$\mathrm{Kv}^2(E)=\mathrm{Kv}(E)\times \mathrm{Kv}(E)$$

and we introduce in this set an equivalence relation according to the following rule:

$$(A, B)\sim(C, D), \quad \text{if} \quad A+D=B+C.$$

The equivalence class of the element (A, B) will be denoted by $\langle A, B\rangle$. Let $\hat{E}=\mathrm{Kv}^2(E)/\sim$; we introduce in $\hat{E}$ linear operations according to the following rule:

$$\langle A, B\rangle + \langle C, D\rangle = \langle A+C, B+D\rangle;$$

$$\alpha\langle A, B\rangle = \begin{cases} \langle \alpha A, \alpha B\rangle & \text{if} \quad \alpha\geqslant 0; \\ \langle |\alpha| B, |\alpha| A\rangle & \text{if} \quad \alpha< 0. \end{cases}$$

It is easy to verify that the set $\hat{E}$, with the operations defined in this manner, is a vector space.

Let $\pi: \mathrm{Kv}(E)\to\hat{E}$ be the mapping defined by:

$$\pi(A)=\langle A, \theta\rangle, \ A\in\mathrm{Kv}(E),$$

where θ is the zero of the space E. Obviously, this mapping is semilinear, i.e.,

$$\pi(\alpha A+\beta B)=\alpha\pi(A)+\beta\pi(B), \ \alpha, \beta\geqslant 0.$$

If E is a normed space, then in Kv(E) there is defined the Hausdorff metric H, which generates in $\hat{E}$ a norm according to the following rule:

$$\|\langle A, B\rangle\| = H(A, B).$$

Then

$$\|\langle A, B\rangle - \langle C, D\rangle\| = H(A+D, B+C).$$

It is easy to see that the mapping π is an isometry, i.e.,

$$H(A; B) = \|\pi(A) - \pi(B)\|,$$

for any $A, B \in \mathrm{Kv}(E)$.

1.6.1. THEOREM. If E is a linear normed space, then there exist a linear normed space $\hat{E}$ and an isometry

$$\pi : \mathrm{Kv}(E) \to \hat{E},$$

satisfying the universality condition; i.e., if E_1 is a linear space and $\varphi : \mathrm{Kv}(E) \to E_1$ is a semilinear mapping, then there exists a linear operator $\hat{\varphi} : \hat{E} \to E_1$ such that the diagram

$$\begin{array}{ccc} \mathrm{Kv}(E) & \xrightarrow{\pi} & \hat{E} \\ & {\scriptstyle\varphi}\searrow \quad \swarrow{\scriptstyle\hat{\varphi}} & \\ & E_1 & \end{array}$$

is commutative.

Let L, E be linear normed spaces, let U be an open subset in L and let $F : U \to \mathrm{Kv}(E)$ be an m-mapping.

1.6.2. Definition. An m-mapping F is said to be π-differentiable at the point $x_0 \in U$ if the mapping $\pi \circ F : U \to \hat{E}$ is differentiable at this point. If an m-mapping F is π-differentiable at each $x \in U$, then F is said to be π-differentiable on U.

Thus, F is π-differentiable at the point $x_0 \in U$ if there exists a continuous linear mapping $dF_{x_0} : L \to \hat{E}$ such that

$$\pi \circ F(x) - \pi \circ F(x_0) - dF_{x_0}(x - x_0) = o(\|x - x_0\|).$$

The following properties of π-differentiable m-mappings are obvious.

1.6.3. If an m-mapping F is π-differentiable at the point $x_0 \in U$, then F is continuous at this point.

1.6.4. If F is π-differentiable at the point x_0, then the differential dF_{x_0} is defined in a unique manner.

We consider some examples of π-differentiable m-mappings.

1.6.5. Let $r : U \to E$ be a differentiable mapping and let $A \in \mathrm{Kv}(E)$; then, the m-mapping $F(x) = r(x) + A$ is a π-differentiable m-mapping and

$$dF_{x_0}(\Delta x) = \langle r'(x_0)\Delta x, \theta \rangle.$$

1.6.6. If $g : U \to \mathbf{R}$ is a smooth function of a fixed sign [i.e., $g(x) \geq 0$ or $g(x) \leq 0$ for any $x \in U$] and $A \in \mathrm{Kv}(E)$, then the m-mapping $F(x) = g(x)A$ is π-differentiable and

$$dF_{x_0}(\Delta x) = g'_{x_0}(\Delta x)\langle A, \theta \rangle.$$

1.6.7. THEOREM. Let U be an open subset of $\mathbf{R}^m$ and assume that the mappings $f, \varphi : U \to \mathbf{R}$ satisfy the inequality $f(x) \leqslant \varphi(x)$, $x \in U$. The m-mapping $F : U \to \mathrm{Kv}(\mathbf{R})$ defined by $F(x) = [f(x); \varphi(x)]$ is π-differentiable at the point x_0 if and only if the functions f and φ are differentiable at this point.

From the results of [1168] there follows the following statement.

1.6.8. THEOREM. Let U be an open subset of $\mathbf{R}^m$ and let $F : U \to \mathrm{Kv}(\mathbf{R}^n)$ be a π-differentiable m-mapping; then, for any point $x_0 \in U$ and any point $y_0 \in F(x_0)$ there exists a differentiable mapping $f : U \to \mathbf{R}^n$ such that $f(x) \in F(x)$ for any $x \in U$ and $f(x_0) = y_0$.

Thus, through each point of the graph Γ_F of a π-differentiable m-mapping there passes a differentiable section. We note that another theorem on the existence of a differentiable section is proved in [302, 303].

B. D. Gel'man has proved a theorem which shows that there are sufficiently many π-differentiable m-mappings:

1.6.9. THEOREM. Let L be a linear normed space and let U be an open subset of L. Let $\Phi: U \to \mathrm{Kv}(\mathbf{R}^n)$ be an upper semicontinuous m-mapping; then, for any number $\varepsilon > 0$ there exists a π-differentiable m-mapping $F: U \to \mathrm{Kv}(\mathbf{R}^n)$, such that

(1) $F(x) \supset \Phi(x)$, for any $x \in U$;

(2) $\Gamma_F \subset U_\varepsilon(\Gamma_\Phi)$, where $U_\varepsilon(\Gamma_\Phi)$ is the ε-neighborhood of the set Γ_Φ in the space $U \times \mathbf{R}^n$.

Proof. For each $x \in U$ we fix $\delta = \delta(x)$, $0 < \delta < \varepsilon$ so that $\Phi(U_{\delta(x)}(x)) \subset U_{\frac{\varepsilon}{2}}(\Phi(x))$; such a δ always exists by virtue of the upper semicontinuity of the m-mapping Φ.

For $\eta(x) = \frac{1}{4}\delta(x)$ we consider the covering $\{U_{\eta(x)}(x)\}_{x \in U}$ of the space U and we extract from it a locally finite subcovering $\{U_{\eta(x_j)}(x_j)\}_{j \in I}$. Let $\{\varphi_j\}_{j \in I}$ be a smooth partition of unity, constructed over this covering. We define a mapping $F: U \to \mathrm{Kv}(\mathbf{R}^n)$ by the relation:

$$F(x) = \sum_{j \in I} \varphi_j(x) \cdot \overline{U_{\frac{\varepsilon}{2}}(\Phi(x_j))}.$$

The mapping F is the desired one. Indeed, since the covering $\{U_{\eta(x_j)}(x_j)\}_{j \in I}$ is locally finite, it follows that for any point $x_0 \in U$ there exists an open neighborhood $V(x_0) \subset U$ such that only a finite number of functions φ_j are different from zero at the points of this neighborhood. Let these functions be $\varphi_{j_1}, \varphi_{j_2}, \ldots, \varphi_{j_k}$; then

$$F(x_0) = \sum_{i=1}^{k} \varphi_{j_i}(x_0) \overline{U_{\frac{\varepsilon}{2}}(\Phi(x_{j_i}))}.$$

Since $\sum_{i=1}^{k} \varphi_{j_i}(x_0) = 1$ and $x_0 \in U_{\eta(x_{j_i})}(x_{j_i})$, we have $\Phi(x_0) \subset U_{\frac{\varepsilon}{2}}(\Phi(x_{j_i}))$ and, consequently, $\Phi(x_0) \subset F(x_0)$.

The m-mapping F is π-differentiable at the point $x_0 \in U$ since in the neighborhood $V(x_0)$ we have

$$F(x) = \sum_{i=1}^{k} F_i(x),$$

where $F_i(x) = \varphi_{j_i}(x) \cdot \overline{U_{\frac{\varepsilon}{2}}(\Phi(x_{j_i}))}$ and $F_i(x)$ is π-differentiable (see 1.6.6). It is easy to verify that the condition (2) of this theorem also holds.

We note that the original definition of π-differentiability [376] has been given for the case when E is a reflexive Banach space and the m-mapping F acts in the collection of nonempty, closed, bounded subsets of E.

Other definitions of differentiability of m-mappings and some applications have been considered in [206, 298, 359, 376, 431, 438, 563, 566, 736, 761, 868, 922, 935, 1168, 1179, etc.].

We mention, however, that the theory of the differentiation of m-mappings is not sufficiently developed and has not found yet wide applicability in the theory of multivalued mappings and in their applications.

1.7. Measurable Multivalued Mappings. The Integral. A. F. Filippov's Lemma. The Superposition Operator

1.7.1. Measurable Multivalued Mappings. Apparently, the concept of a measurable multivalued mapping, generalizing the classical concept of a measurable mapping, has been introduced for the first time in [1010]. Subsequently, the properties of measurable multivalued mappings have been investigated in an entire cycle of works (see, for example, [120-122, 358, 367, 368, 462, 472, 474-479, 482, 485, 526, 552, 556, 557, 567, 570, 575, 661, 736, 742, 749, 750, 753, 755, 760, 761, 767, 769, 774, 779, 780, 876, 880, 934, 982, 1010, 1071, 1072, 1074, 1087, 1088, 1099, 1100, 1196, 1197, 1200, 1201, 1203-1206, 1234, 1251, etc.]).

We indicate certain fundamental properties of measurable multivalued mappings, without aspiring to a maximal generality. A detailed analysis of the properties of such mappings and some of their applications to convex analysis and to variational problems can be found in [3, 120, 121, 122, 475, 477, 485, 556, 557, 742, 755, 760, 761, 779, 1071, 1201].

Let $\Delta \subseteq \mathbf{R}$ be a measurable subset; let R be endowed with the Lebesgue measure μ.

1.7.2. Definition. An m-mapping $F:\Delta\to K(\mathbf{R}^n)$ is said to be measurable if for any open set $V\subseteq\mathbf{R}^n$ the set $F_+^{-1}(V)$ is measurable.

An equivalent condition is the measurability of $F_-^{-1}(W)$ for any closed set $W\subseteq\mathbf{R}^n$.

1.7.3. THEOREM. The measurability of an m-mapping $F:\Delta\to K(\mathbf{R}^n)$ is equivalent to the measurability of the set $F_+^{-1}(W)\,[F_-^{-1}(V)]$ for any closed set $W\subseteq\mathbf{R}^n$ [open set $V\subseteq\mathbf{R}^n$].

Obviously, an upper or a lower semicontinuous m-mapping is measurable.

1.7.4. Definition. A single-valued mapping $f:\Delta\to\mathbf{R}^n$ is said to be a measurable section of the m-mapping $F:\Delta\to K(\mathbf{R}^n)$, if f is measurable and $f(t)\in F(t)$ for almost all $t\in\Delta$.

The following theorem describes the fundamental properties of measurable m-mappings.

1.7.5. THEOREM. For an m-mapping $F:\Delta\to K(\mathbf{R}^n)$ the following statements are equivalent:

a) F is measurable;

b) for any point $x\in\mathbf{R}^n$ with rational coordinates, the function $\varphi_x:\Delta\to\mathbf{R}$, $\varphi_x(t)=\rho(x,F(t))$ is measurable (ρ is the metric in $\mathbf{R}^n$).

c) there exists a countable set $\{f_m\}_{m=1}^{\infty}$ of measurable sections of F such that

$$\left(\overline{\bigcup_{m=1}^{\infty} f_m(t)}\right)=F(t) \qquad \text{for almost all} \qquad t\in\Delta;$$

d) for any $\delta>0$ there exists a closed set $\Delta_\delta\subset\Delta$ such that $\mu(\Delta\setminus\Delta_\delta)\leqslant\delta$ and $F|_{\Delta_\delta}$ is continuous (the analogue of Luzin's C-property).

The proof of this theorem and bibliographic indications can be found, for example, in [120-122, 475, 779].

Measurable sections of m-mappings have been investigated in [3, 102, 150-152, 299, 332, 333, 339, 368, 372, 373, 392, 404, 475, 479, 482, 485, 493, 516, 554, 572, 575, 581, 589, 615, 649, 655, 661, 681, 682, 739, 746, 747, 773, 774, 792, 804, 817, 850-853, 856, 880, 890, 896, 897, 899, 900, 992, 1065, 1067, 1074, 1096-1097, 1102, 1103, 1160, 1169, 1201, 1219].

Applying Theorem 1.7.5 to the operations on m-mappings, we obtain the following statement.

1.7.6. COROLLARY.

a) If the m-mappings

$$\{F_j\}_{j=1}^{\infty},\quad F_j:\Delta\to K(\mathbf{R}^n)$$

are measurable and if

$$\bigcap_{j=1}^{\infty} F_j(t)\neq\varnothing$$

for each $t\in\Delta$, then the intersection

$$\bigcap_{j=1}^{\infty} F_j:\Delta\to K(\mathbf{R}^n)$$

is measurable;

b) if the m-mappings $F_0, F_1:\Delta\to K(\mathbf{R}^n)$ are measurable, then their Cartesian product

$$F_0\times F_1:\Delta\to K(\mathbf{R}^n\times\mathbf{R}^n)$$

and their sum

$$F_0+F_1:\Delta\to K(\mathbf{R}^n)$$

are measurable;

c) if the m-mapping $F:\Delta\to K(\mathbf{R}^n)$ is measurable and $f:\Delta\to\mathbf{R}$ is a measurable function, then their product

$$f\cdot F:\Delta\to K(\mathbf{R}^n)$$

is measurable;

d) if the m-mapping $F:\Delta\to K(\mathbf{R}^n)$ is measurable, then the convex closure $\overline{\mathrm{co}}\,F:\Delta\to K(\mathbf{R}^n)$ is measurable.

1.7.7. COROLLARY. If the m-mappings F_0, $F_1:\Delta\to K(\mathbf{R}^n)$ are measurable, then the functions

$$\rho_*:\Delta\to\mathbf{R},\quad \rho_*(t)=\rho_*(F_0(t), F_1(t));$$
$$H_*:\Delta\to\mathbf{R},\quad H_*(t)=H(F_0(t), F_1(t))$$

(where ρ_* is the deviation and H is the Hausdorff metric) are measurable.

We mention also the following fact.

1.7.8. THEOREM. If the m-mappings

$$\{F_j\}_{j=1}^{\infty},\quad F_j:\Delta\to K(\mathbf{R}^n)$$

are measurable and there exists an m-mapping

$$\Phi:\Delta\to K(\mathbf{R}^n)$$

such that

$$\bigcup_{j=1}^{\infty}F_j(t)\subset\Phi(t)$$

for all $t\in\Delta$, then the m-mapping

$$\overline{\bigcup_{j=1}^{\infty}F_j}:\Delta\to K(\mathbf{R}^n),\quad \overline{\bigcup_{j=1}^{\infty}F_j}(t)=\overline{\bigcup_{j=1}^{\infty}F_j(t)}$$

is measurable.

1.7.9. Integral of a Multivalued Function. By the integral of a multivalued mapping $F:\Delta\to P(\mathbf{R}^n)$ we mean the set of all integrals of the summable sections of F. In other words,

$$\int_{\Delta}F(t)\,dt=\left\{y\mid y=\int_{\Delta}f(t)\,dt,\ f\in L_1(\Delta),\ f(t)\in F(t)\quad\forall t\in\Delta\right\}.$$

Clearly, for the existence of the integral $\int_{\Delta}F(t)dt$ it is sufficient that the m-mapping $F:\Delta\to K(\mathbf{R}^n)$ be measurable and be majorized by some summable function $z:\Delta\to\mathbf{R}$, i.e.,

$$\|F(t)\|=\sup\{\|f\|\mid f\in F(t)\}<z(t)$$

for almost all $t\in\Delta$.

One of the fundamental properties of the multivalued integral is described by the following statement, basically equivalent to the well-known theorem of A. A. Lyapunov on vector measures.

1.7.10. THEOREM. The integral $\int_{\Delta}F(t)dt$ is a convex set. If $F:\Delta\to K(\mathbf{R}^n)$ is measurable and is majorized by a summable function, then

$$\int_{\Delta}F(t)\,dt=\int_{\Delta}\overline{\mathrm{co}}\,F(t)\,dt.$$

The proof of this statement can be found in [122].

The integral of a multivalued mapping and its applications have been investigated in [162, 237, 291, 357, 367, 438, 462, 485, 529, 553, 556, 557, 570, 715, 736, 760, 761, 876, 924, 948, 985, 1196, 1199, 1200, 1201, 1218, 1220, 1234, etc.].

1.7.11. Carathéodory Conditions and A. F. Filippov's Lemma. Everywhere in the sequel we shall assume that the set $\Delta\subset\mathbf{R}$ is compact. Let E be a Banach space.

1.7.12. Definition. We say that an m-mapping $F:\Delta\times E\to K(\mathbf{R}^n)$ satisfies the Carathéodory conditions if:

a) for all fixed $x\in E$ the m-mapping $F(\cdot,x):\Delta\to K(\mathbf{R}^n)$ is measurable;

b) for almost all fixed $t\in\Delta$ the m-mapping $F(t,\cdot):E\to K(\mathbf{R}^n)$ is upper semicontinuous.

An m-mapping F satisfies the strong Carathéodory conditions if it satisfies the condition a) and the condition

b') for almost all fixed $t \in \Delta$ the m-mapping $F(t, \cdot) : E \to K(\mathbf{R}^n)$ is continuous.

Both of these definitions are natural generalizations of the Carathéodory conditions for single-valued functions.

We give some properties of m-mappings which satisfy the Carathéodory conditions.

1.7.13. THEOREM [818]. Assume that the m-mapping $F : \Delta \times \mathbf{R}^m \to K(\mathbf{R}^n)$ satisfies the strong Carathéodory conditions. Then, for any $\delta > 0$ there exists a compact set $\Delta_\delta \subset \Delta$ such that

$$\mu(\Delta \setminus \Delta_\delta) < \delta \text{ and } F|_{\Delta_\delta \times \mathbf{R}^m}$$

is continuous.

We mention that a similar statement for m-mappings which satisfy the (simple) Carathéodory conditions does not hold (see a counterexample in [210]).

The following statement is a generalization of a result which is important for the theory of controlled systems, proved in its initial form by A. F. Filippov [306]. Subsequently, this statement, known as "A. F. Filippov's lemma on implicit functions," has been generalized in a series of works (see [188, 189, 472, 475, 589, 613, 743, 767, 769, 778]).

1.7.14. THEOREM. Assume that the m-mapping $F : \Delta \times \mathbf{R}^m \to K(\mathbf{R}^n)$ satisfies the strong Carathéodory conditions and let $U : \Delta \to K(\mathbf{R}^m)$ be a measurable m-mapping. Assume that $g : \Delta \to \mathbf{R}^n$ is a measurable mapping such that $g(t) \in F(t, U(t))$ for almost all $t \in \Delta$. Then, there exists a measurable section $u : \Delta \to \mathbf{R}^m$ of the m-mapping U such that $g(t) \in F(t, u(t))$.

1.7.15. Superposition Operator. Every m-mapping $F : \Delta \times E \to K(\mathbf{R}^n)$ defines an operator which associates to an m-mapping $Q : \Delta \to P(E)$ the m-mapping $\Phi : \Delta \to P(\mathbf{R}^n)$ according to the rule

$$\Phi(t) = F(t, Q(t)).$$

This operator is called the superposition operator. We describe some of its properties.

1.7.16. THEOREM [816]. If the m-mapping $F : \Delta \times \mathbf{R}^m \to K(\mathbf{R}^n)$ satisfies the strong Carathéodory conditions, then F is superpositionally measurable; i.e., for any measurable m-mapping $Q : \Delta \to K(\mathbf{R}^n)$ the m-mapping Φ,

$$\Phi(t) = F(t, Q(t))$$

is measurable.

We mention that the property of superpositional measruability of an m-mapping F is lost when passing from the strong Carathéodory conditions to the usual ones (see [210]).

Nevertheless, it turns out that also in the case of the usual Carathéodory conditions, an m-mapping Φ possesses definite "good" properties. Namely, we have the following statement.

1.7.17. THEOREM [473]. Let E be a Banach space and assume that $F : \Delta \times E \to K(\mathbf{R}^n)$ satisfies the Carathéodory conditions. Let $q : \Delta \to E$ be a measurable mapping. Then, there exists a measurable m-mapping $S : \Delta \to K(\mathbf{R}^n)$ such that

$$S(t) \subset F(t, q(t))$$

for almost all $t \in \Delta$.

CHAPTER 2

FIXED POINTS OF MULTIVALUED MAPPINGS

Let $X \subseteq Y$, and let $F : X \to P(Y)$ be an m-mapping. A point $x \in X$ such that $x \in F(x)$ is said to be a fixed point of F. The set of all fixed points of F is denoted by Fix F.

The problems on the fixed points of m-mappings, important for applications, have been investigated by many authors, starting with von Neumann [977], Kakutani [801], Wallace [1221], Eilenberg–Montgomery [610], etc. In this chapter we present a survey of the fundamental directions in the theory of the fixed points of m-mappings.

2.1. Fixed Points of Multivalued Mappings on Continua and on Partially Ordered Sets

We recall some definitions. A compact, connected Hausdorff space is called a continuum. A Peano continuum is a Hausdorff space which is the continuous image of the segment [0, 1]. A dendrite is a Peano continuum which does not contain any closed Jordan curves. A continuum in which each pair of distinct points is separated by a third one is called a tree.

The following theorems are classical results on the fixed points of m-mappings on trees.

2.1.1. THEOREM (Wallace [1221]). Each upper semicontinuous continuum-valued m-mapping of a tree into itself has a fixed point.

Capel and Strother [468] have proved this theorem making use of the lattice order on a tree and of the theorem on continuous sections.

2.1.2. THEOREM (Plunkett [1019]). A Peano continuum X has a fixed point for any continuous m-mapping $F:X \to C(X)$ if and only if X is a dendrite.

2.1.3. THEOREM (Smithson [1150]). Every lower semicontinuous m-mapping of a tree into itself, with connected images, has a fixed point.

Many investigations have been devoted to the study of various fixed point principles for multivalued mappings on continua (see, for example, [393, 394, 401, 499, 690, 894, 895, 903, 904, 964-966, 975, 976, 1019, 1080, 1107, 1109, 1111, 1139, 1141, 1143, 1145, 1149, 1221-1225]; we also mention the surveys [970, 1151, 1208, 1226]).

In a series of papers one investigates the fixed points of multivalued mappings which preserve the order on partially ordered sets. We give the following theorem of Smithson [1148].

2.1.4. THEOREM. Let $(X, \geq)$ be a partially ordered set such that each nonempty chain in X has a least upper bound. Assume that the m-mapping $F: X \to P(X)$ satisfies the conditions:

1) if $x_1, x_2 \in X$; $x_1 < x_2$ and $y_1 \in F(x_1)$, then there exists $y_2 \in F(x_2)$ such that $y_1 < y_2$;

2) there exist $e \in X$ and $y \in F(e)$ such that $e < y$;

3) let $C \subset X$ be a chain and assume that F has a monotone section f on C. If $x_0 = \sup C$, then there exists $y_0 \in F(x_0)$ such that $f(x) < y_0$ for all $x \in C$.

Then, $\mathrm{Fix} F \neq \varnothing$.

For other results in this direction see [964, 966, 1151, 1152, 1226].

2.2. Fixed Points of m-Mappings of Metric Spaces

In this section we consider theorems on fixed points of m-mappings, which are formulated in metric terms without introducing additional structures. A large number of papers are devoted to this question since practically every theorem on fixed points of single-valued contractive mappings has a multivalued analogue. A natural generalization of the Banach principle is the following statement.

2.2.1. THEOREM [967]. Let (X, d) be a complete metric space, let Cb(X) be the collection of nonempty, closed, bounded subsets of X and let $F:X \to Cb(X)$ be an m-mapping such that

$$H(F(x), F(y)) \leqslant q d(x, y)$$

for any $x, y \in X$ and for a fixed q, $0 \leqslant q < 1$. Then, $\mathrm{Fix} F \neq \varnothing$.

The proof of this theorem consists in the fact that, starting with an arbitrary point $x_0 \in X$, one constructs a sequence $\{x_i\}_{i=0}^{\infty}$ such that

a) $x_i \in F(x_{i-1})$, $i = 1, 2, \dots$;

b) $d(x_i, x_{i+1}) \leqslant q' d(x_i, x_{i-1})$, $i \geqslant 1$, $q < q' < 1$.

This sequence is a Cauchy sequence and $x_i \to \xi \in X$. Clearly, ξ is a fixed point of the m-mapping F.

For multivalued mappings one has a local variant of Banach's theorem.

2.2.2. Definition. A metric space (X, d) is said to be ε-connected if for any points $x, y \in X$ there exists a sequence $x_0 = x, x_1, \dots, x_n = y$, such that $d(x_i, x_{i+1}) < \varepsilon$, $i = 0, 1, \dots, n-1$.

2.2.3. THEOREM [967]. Let (X, d) be a complete ε-connected metric space and let $F: X \to \mathrm{Cb}(X)$ be an m-mapping such that

$$H(F(x),\ F(y)) < qd(x,\ y)$$

for $d(x, y) < \varepsilon$ and for a fixed q, $0 \le q < 1$. Then, $\operatorname{Fix} F \neq \varnothing$.

In [540], the principle of contraction mappings is generalized to multivalued mappings whose images are nonempty, closed subsets of a metric space.

One has obtained a series of theorems on the fixed points of m-mappings in convex metric spaces. Thus, for example, the following statement holds.

2.2.4. THEOREM [362]. Let (X, d) be a complete, convex metric space, let M be a nonempty, closed set in (X, d) and let $F: M \to C(M)$ be an m-mapping such that:

a) $H(F(x), F(y)) < qd(x, y)$; $x, y \in M$, $0 < q < 1$;

b) $F(x) \subset M$ for all $x \in \partial M$.

Then, there exists a fixed point of the m-mapping F.

In [631, 646, 647, 915, etc.] one investigates the topological structure of the set of fixed points of contraction mappings.

In [369, 776, 825, 839, 840, 1025, 1126] one investigates the common fixed points of multivalued mappings.

We mention the following interesting fixed point principle.

If (X, d) is a metric space and $F: X \to K(X)$ is an upper semicontinuous m-mapping, then there is defined the mapping $\hat{F}: K(X) \to K(X)$, where $\hat{F}(A) = F(A)$. If F is a q-contractive (contractive) m-mapping, then also $\hat{F}$ is q-contractive (contractive).

2.2.5. THEOREM [647]. Let (X, d) be a metric space and assume that $F: X \to K(X)$ satisfies the conditions:

a) $H(F(x), F(y)) < d(x, y)$, $\forall x, y \in X$, $x \neq y$;

b) there exists $A \in K(X)$ such that some subsequence of the sequence $\{\hat{F}^n(A)\}_{n=1}^{\infty}$ converges in (K(X), H). Then, $\operatorname{Fix} F \neq \varnothing$.

Various generalizations of the principle of contraction mappings are contained in [345, 347, 361, 362, 370, 371, 422, 500, 505, 531, 539, 540, 576, 586, 588, 597, 600, 601, 632, 654, 658, 698, 700, 701, 745, 770, 772, 775, 841, 902, 905, 913, 925, 927, 967, 968, 1040-1043, 1046, 1048, 1050, 1051, 1053, 1089, 1094, 1106, 1118, 1120, 1128, 1129, 1147, 1183]; see also the papers on nonexpanding m-mappings: [423, 599, 845, 862, 881, 882, 883, 884, 914, 918, 926, 933, 1049, 1155]. We also mention the surveys [112, 598, 968].

2.3. Approximative Methods

2.3.1. Rotation of Completely Continuous Multivalued Vector Fields. Let E be a Hausdorff locally convex space (LCS); let $X \subseteq E$. Every m-mapping $F: X \to P(E)$ defines an m-mapping $\Phi: X \to P(E)$, $\Phi(x) = x - F(x)$, called the multivalued vector field (briefly: m.v.-field) corresponding to F. Denoting by $i: X \to E$ the imbedding mapping, we shall write $\Phi = i - E$. If $G: X \times L \to P(E)$ is a family of m-mappings, then $\Psi: X \times L \to P(E)$, $\Psi(x, \lambda) = x - F(x, \lambda)$ is called a family of m.v.-fields. A point $x \in X$ such that $0 \in \Phi(x)$ is called a singular point of the m.v.-field Φ. Clearly, the singular points of a m.v.-field $\Phi = i - F$ are fiexed points of F and the converse is also true. If $\operatorname{Fix} F = \varnothing$, then $\Phi = i - F$ is nondegenerate, i.e., $\Phi: X \to P(E \setminus 0)$. The family $\Psi: X \times L \to P(E \setminus 0)$ is also called nondegenerate.

If the m-mapping $F: X \to P(E)$ is upper semicontinuous and compact, i.e., F(X) is relatively compact in E, then both F and its corresponding m.v.-field $\Phi = i - F$ are said to be completely continuous.

The collection of all completely continuous m.v.-fields $\Phi = i - F: X \to \mathrm{Kv}(E)$ will be denoted by $\mathscr{C}(X)$. The collection of m.v.-fields $\Phi \in \mathscr{C}(X)$, nondegenerate on $X_1 \subseteq X$, is denoted by $\mathscr{C}(X,\ X_1)$. The collection $\mathscr{C}(X, X)$ will be denoted by $\mathscr{C}_0(X)$.

If L is a topological space, then there is a natural definition (replacing X by $X \times L$) for the complete continuity of a family of m-mappings $G: X \times L \to \mathrm{Kv}(E)$ and the corresponding family of m.v.-fields $\Psi = i - G$.

2.3.2. Definition. The m.v.-fields $\Phi_0, \Phi_1 \in \mathscr{C}(X, X_1)$ are said to be homotopic $(\Phi_0 \sim \Phi_1)$, if there exists a completely continuous family of m.v.-fields (deformation)

$$\Psi : X \times [0, 1] \to \mathrm{Kv}(E)$$

such that

$$0 \notin \Psi(X_1 \times [0, 1] \text{ and } \Psi(\cdot, 0) = \Phi_0, \ \Psi(\cdot, 1) = \Phi_1.$$

In particular, Φ_0, $\Phi_1 \in \mathscr{C}_0(X)$ are said to be homotopic if they can be connected by a nondegenerate deformation on X.

The set of all m.v.-fields, homotopic to the m.v.-field $\Phi \in \mathscr{C}(X, X_1)$ (or $\mathscr{C}_0(X)$) in the corresponding class, is called the homotopy class of Φ and is denoted by $[\Phi]_{X_1}$, $[\Phi]$ respectively. Assume, further, that $T \subseteq E$ is a convex, closed set and $X \subseteq T$ is closed. We shall say that T is invariant for the m.v.-field $\Phi = i - F \in \mathscr{C}(X)$ if $F(X) \subseteq T$. In the classes $\mathscr{C}(X, X_1)$, $\mathscr{C}_0(X)$ we separate the subclasses $\mathscr{C}^T(X, X_1)$, $\mathscr{C}_0{}^T(X)$ of all those m.v.-fields for which T is invariant. For $\Phi \in \mathscr{C}^T(X, X_1)$, $\mathscr{C}_0{}^T(X)$ we denote by $[\Phi]^T{}_{X_1}$, $[\Phi]^T$ its homotopy class in $\mathscr{C}^T(X, X_1)$ or $\mathscr{C}_0{}^T(X)$, respectively.

Let $U \subset E$ be open. The closure and the boundary of the set $U_T = U \cap T$ in the relative topology of the space T will be denoted by $\overline{U}_T$ and ∂U_T.

For a m.v.-field $\Phi = i - F \in \mathscr{C}_0^T(\partial U_T)$ one defines an integer-valued characteristic – the rotation

$$\gamma_T(\Phi, \partial U_T)$$

relative to T, possessing the following fundamental properties (see [29, 31, 33, 37, 40]).

2.3.3. If $F(x) \equiv x_0$ for all $x \in \partial U_T$, then

$$\gamma_T(i - F, \partial U_T) = \begin{cases} 1, & x_0 \in U_T, \\ 0, & x_0 \overline{\in} U_T. \end{cases}$$

2.3.4. Homotopy Invariance. If Φ_0,

$$\Phi_1 \in \mathscr{C}_0^T(\partial U_T), \quad \Phi_0 \underset{T}{\sim} \Phi_1,$$

i.e., $\Phi_1 \in [\Phi_0]^T$, then

$$\gamma_T(\Phi_0, \partial U_T) = \gamma_T(\Phi_1, \partial U_T).$$

2.3.5. The quantity $\gamma_T(\Phi, \partial U_T)$ does not depend on the continuation of Φ to U_T.

2.3.6. Additive Dependence on the Domain. Let $\{U_{jT}\}_{j \in J}$ be a family of disjoint subsets of U_T, open in T, and let $\Phi \in \mathscr{C}^T(\overline{U}_T, \overline{U}_T \setminus \bigcup_{j \in J} U_{jT})$. Then the rotations $\gamma_T(\Phi, \partial U_{jT})$ are different from zero only for a finite number of indices j and

$$\gamma_T(\Phi, \partial U_T) = \sum_{j \in J} \gamma_T(\Phi, \partial U_{jT}).$$

2.3.7. Principle of Mapping Restrictions. Let T_1 be a convex, closed subset of E, $T_1 \subseteq T$. If $F(\partial U_T) \subset T_1$, then

$$\gamma_T(\Phi, \partial U_T) = \gamma_{T_1}(\Phi, \partial U_{T_1}).$$

The application of the concept of relative rotation of m.v.-fields to the investigation of fixed points is related to the following property:

2.3.8. If $\Phi = i - F \in \mathscr{C}^T(\overline{U}_T, \partial U_T)$ and

$$\gamma_T(\Phi, \partial U_T) \neq 0,$$

then $\varnothing \neq \mathrm{Fix}\, F \subset U_T$.

We describe briefly the scheme of the construction of the indicated characteristic (see [37, 40]).

We start with the "absolute" case, i.e., we set T = E. We consider in the finite-dimensional space E_n the m.v.-field $\Phi \in \mathscr{C}_0(X)$, where $X \subseteq E_n$ is closed.

2.3.9. Definition. A completely continuous single-valued vector field $\varphi : X \to E_n \setminus 0$ is called a single-valued homotopic approximation (s.h.-approximation) of the m.v.-field $\Phi \in \mathscr{C}_0(X)$, if $\varphi \in [\Phi]$.

2.3.10. THEOREM. Every m.v.-field $\Phi \in \mathscr{C}_0(X)$ has a s.h.-approximation.

Indeed, such an approximation φ can be taken to be an acute-angled approximation (by identifying $E_n^* = E_n$) or an ε-approximation for a sufficiently small $\varepsilon > 0$.

2.3.11. Definition. By the rotation $\gamma(\Phi, \partial U)$ of a m.v.-field $\Phi \in \mathscr{C}_0(\partial U)$ we mean the rotation $\gamma(\varphi, \partial U)$ of any of its s.h.-approximations.

Assume now that E is infinite dimensional; let $X \subseteq E$ be closed.

2.3.12. Definition. An m.v.-field $\Phi_{E'} = i - F_{E'}: X \to \mathrm{Kv}(E \setminus 0)$ is said to be a finite-dimensional homotopic approximation (f.h.-approximation) of the m.v.-field $\Phi \in \mathscr{C}_0(X)$, if $\Phi_{E'} \in [\Phi]$ and $F_{E'}(X) \subset E'$, where E' is a finite-dimensional subspace of E. Let $U \subset E$ be an open subset, let $\Phi \in \mathscr{C}_0(\partial U)$ and let $\Phi_{E'}$ be an arbitrary f.h.-approximation of Φ.

2.3.13. Definition. By the rotation $\gamma(\Phi, \partial U)$ we mean the rotation in the space E' of the restriction of $\Phi_{E'}$ to $\partial U'$, where $U' = U \cap E'$:

$$\gamma(\Phi, \partial U) \underset{\mathrm{def}}{=} \gamma(\Phi_{E'}, \partial U').$$

We turn now to the general case of relative rotation. Let $\Phi = i - F \in \mathscr{C}_0^T(\partial U_T)$. Assume that V is an absolutely convex neighborhood of zero.

2.3.14. Definition. A completely continuous m-mapping $F_V: \partial U \to \mathrm{Kv}(T)$ is said to be V-close to F on T if $F_V(x) \subset F(x) + V$ for all $x \in \partial U_T$.

2.3.15. THEOREM. For any absolutely convex neighborhood V, the m-mapping F has a V-close m-mapping F_V.

It is easy to see that the set $\Phi(\partial U_T)$ is closed. Assume then that V is an absolutely convex neighborhood of zero such that $V \cap \Phi(\partial U^T) = \varnothing$.

2.3.16. Definition. By the relative rotation $\gamma_T(\Phi, \partial U_T)$ of the m.v.-field $\Phi = i - F$ we mean the rotation of any V-close m.v.-field $\Phi_V = i - F_V$:

$$\gamma_T(\Phi, \partial U_T) = \gamma(\Phi_V, \partial U).$$

2.3.17. Homotopy Properties of Noncompact Multivalued Vector Fields. Presently, the investigation of the problems, related to the solvability of inclusions with multivalued operators, has been realized in a significant degree also for the case of noncompact operators. We describe the theory of rotations for the class of fundamentally contractible multivalued vector fields, including the condensing and the limit-compact fields. This will be preceded by the investigation of the homotopy properties of such fields.

Let E be a Hausdorff LCS, let $X \subseteq E$ and let L be a compact topological space.

2.3.18. Definition (see [104, 207]). A convex closed set $T \subseteq E$ is said to be fundamental for the m-mapping $F: X \to K(E)$ (or for its corresponding m.v.-field $\Phi = i - F$) if:

1) $F(X \cap T) \subseteq T$;

2) from $x_0 \in \overline{\mathrm{co}}\,(F(x_0) \cup T)$ there follows that $x_0 \in T$.

We emphasize that the definition does not exclude the case $T = \varnothing$ or $X \cap T = \varnothing$. We also mention that every fundamental set of the m-mapping F contains Fix F.

A convex closed set $T \subseteq E$ is said to be fundamental for the family of m.v.-fields $\Psi = i - G: X \times L \to K(E)$ if it is fundamental for each m.v.-field $\Psi(\cdot, \lambda)$, $\lambda \in L$ from the given family.

Examples of fundamental sets are the entire space E and the set $\overline{\mathrm{co}}\, F(X)$.

We describe now the considered class of m-mappings (see [37, 40, 137, 212, 215]).

2.3.19. Definition. If an upper semicontinuous m-mapping $F: X \to K(E)$ has a fundamental (possibly empty) set T such that the restriction of F to $X \cap T$ is compact, then F and its corresponding m.v.-field Φ = i − F are called fundamentally contractible (on T).

An upper semicontinuous m-mapping $G: X \times L \to K(E)$ such that every m-mapping $G(\cdot, \lambda)$, $\lambda \in L$, is fundamentally contractible on T and the restriction of G to $(X \cap T) \times L$ is compact is called a family of fundamentally contractible m-mappings (on T).

It is clear that a completely continuous m-mapping $F: X \to K(E)$ is fundamentally contractible (on $\overline{\mathrm{co}}F(X)$). Other examples are limit-compact and condensing m-mappings (see [37, 207, 1004, 1005]).

We give some necessary definitions.

For an m-mapping $F: X \to K(E)$ we construct a transfinite sequence $\{D_\alpha\}$ of sets in the following manner:

a) $D_0 = \overline{\mathrm{co}}\, F(X)$;

b) $D_\alpha = \overline{\mathrm{co}}\, F(X \cap D_{\alpha-1})$, if $\alpha - 1$ exists;

c) $D_\alpha = \bigcap_{\beta<\alpha} D_\beta$, if $\alpha - 1$ does not exist.

The sequence $\{D_\alpha\}$ stabilizes; i.e., there exists an ordinal number δ such that $D_\alpha = D_\delta$ for $\alpha \geqslant \delta$ (the proof does not differ from that in the single-valued case; see [265]). The limit set D_δ is called the limit domain of the values of the m-mapping F and is denoted by D_∞.

2.3.20. Definition. An upper semicontinuous m-mapping $F: X \to K(E)$ is said to be limit-compact if its restriction to the set $X \cap D_\infty$ is compact.

We recall (see, for example, [265]) that a mapping $\chi: 2^E \to A$, where A is a partially ordered set and 2^E is the collection of all subsets of E, is called a measure of noncompactness in E if

$$\chi(\overline{\mathrm{co}}\Omega) = \chi(\Omega)$$

for any $\Omega \in 2^E$. A measure of noncompactness χ is said to be monotone if $\Omega_0, \Omega_1 \in 2^E$, $\Omega_0 \subseteq \Omega_1$ imply that $\chi(\Omega_0) \leqslant \chi(\Omega_1)$. A measure of noncompactness χ is said to be nonsingular if $\chi(\{a\} \cup \Omega) = \chi(\Omega)$ for any $a \in E$, $\Omega \in 2^E$. A measure of noncompactness $\chi: 2^E \to A$ is said to be real if $A = [0, \infty)$. A real measure of noncompactness is said to be

a) proper if $\chi(\Omega) = 0$ is equivalent to the relative compactness of Ω;

b) semiadditive if $\chi(\Omega_0 \cup \Omega_1) = \max\{\chi(\Omega_0), \chi(\Omega_1)\}$ for any $\Omega_0, \Omega_1 \in 2^E$.

Extended examples of measures of noncompactness in normed spaces are the Kuratowski measure of noncompactness: $\alpha(\Omega) = \inf\{d \mid d > 0$, Ω admits a partition into a finite number of sets whose diameters are less than d$\}$ and the Hausdorff measure of noncompactness: $\varkappa(\Omega) = \inf\{\varepsilon \mid \varepsilon > 0$, Ω has in E a finite ε-net$\}$.

2.3.21. Definition. An upper semicontinuous m-mapping $F: X \to K(E)$ or a family of upper semicontinuous m-mappings $G: X \times L \to K(E)$ is said to be condensing relative to a measure χ of noncompactness (or χ-condensing) if we have, respectively,

$$\chi(F(\Omega)) \not\geqslant \chi(\Omega),$$
$$\chi(G(\Omega \times L)) \not\geqslant \chi(\Omega)$$

for any $\Omega \subset X$ that is not relatively compact.

A limit-compact m-mapping is fundamentally contractible since all the sets D_α are fundamental. An m-mapping which is condensing relative to a monotone measure of noncompactness is limit-compact (see [265]).

2.3.22. Definition. A fundamental set T of an m-mapping $F: X \to K(E)$ for which $X \cap T \neq \varnothing$ and the restriction $F|_{X \cap T}$ is compact is called essential.

2.3.23. Definition. If an m-mapping $F: X \to K(E)$ has an essential fundamental set T, then F and also its corresponding m.v.-field $\Phi = i - F$ are called completely fundamentally contractible (on T).

2.3.24. LEMMA. If $X \subseteq E$ is closed and the m-mapping $F: X \to K(E)$ is condensing relative to a monotone nonsingular measure χ of noncompactness, then F is completely fundamentally contractible.

Let (X, X_1), $X_1 \subseteq X$ be a pair of subsets of E. Everywhere in the sequel we assume that X_1 is closed. We denote by $\mathscr{M}(X, X_1)$, $\mathscr{M}_B(X, X_1)$, $\mathscr{D}_\chi(X, X_1)$ the sets of all m.v.-fields $\Phi: X \to Kv(E)$, $0 \,\overline{\in}\, \Phi(X_1)$ that are, respectively, fundamentally contractible, completely fundamentally contractible, and χ-condensing. If $X_1 = X$, then we shall write $\mathscr{M}(X)$, $\mathscr{M}_B(X)$, $\mathscr{D}_\chi(X)$, respectively, while if we consider families of m.v.-fields, then we also mention the set L of values of the parameters ($\mathscr{M}(X, X_1; L$, etc.).

Next, the collections of m.v.-fields that are fundamentally contractible on a fixed fundamental set T are denoted by $\mathscr{M}^T$, $\mathscr{M}_B{}^T$ and T is assumed to be essential if we consider the class $\mathscr{M}_B{}^T$.

2.3.25. Definition. The m.v.-fields Φ_0, $\Phi_1 \in \mathcal{M}^T(X, X_1)\,[\mathcal{M}_B^T(X, X_1)]$ are said to be homotopic relative to a fundamental set T, in symbols

$$\Phi_0 \underset{T}{\sim} \Phi_1,$$

if there exists a family $\Psi \in \mathcal{M}^T(X, X_1; [0, 1])$ [respectively, $\Psi \in \mathcal{M}_B^T(X, X_1; [0, 1])$] such that $\Psi(\cdot, 0) = \Phi_0$, $\Psi(\cdot, 1) = \Phi_1$. The family Ψ is called a deformation, joining Φ_0 and Φ_1.

The relative homotopy classes of the m.v.-field $\Phi \in \mathcal{M}^T[\mathcal{M}_B^T]$ are denoted by $[\Phi]^T$, $[\Phi]_B^T$ respectively.

2.3.26. Definition. The m.v.-fields Φ_0, $\Phi_1 \in \mathcal{M}(X, X_1)\,[\mathcal{M}_B(X, X_1)]$ are said to be homotopic, in symbols $\Phi_0 \underset{\mathcal{M}}{\sim} \Phi_1$ $\left[\Phi_0 \underset{\mathcal{M}_B}{\sim} \Phi_1\right]$, if there exist sequences of m.v.-fields $Q_i \in \mathcal{M}(X, X_1)\,[\mathcal{M}_B(X, X_1)]$, $0 \leqslant i \leqslant n$ and of essential fundamental sets T_i, $0 \leqslant i \leqslant n-1$, such that:

1) $Q_0 = \Phi_0$, $Q_n = \Phi_1$;

2) $Q_i \underset{T_i}{\sim} Q_{i+1}$, $0 \leqslant i \leqslant n-1$.

We denote the corresponding homotopy class of the field $\Phi \in \mathcal{M}$ $[\mathcal{M}_B]$ by $[\Phi]$ $[[\Phi]_B]$.

Examples of fundamentally contractible homotopies are the homotopies of condensing and completely continuous m.v.-fields. Assume that X is closed. The m.v.-fields $\Phi_0, \Phi_1 \in \mathcal{D}_\chi(X, X_1)$ are said to be homotopic (relative to a measure χ of noncompactness), in symbols

$$\Phi_0 \underset{\chi}{\sim} \Phi_1,$$

if there exists a family $\Psi \in \mathcal{D}_\chi(X, X_1; [0, 1])$ such that $\Psi(\cdot, 0) = \Phi_0$, $\Psi(\cdot, 1) = \Phi_1$. The homotopy class of $\Phi \in \mathcal{D}_\chi(X, X_1)$ relative to χ is denoted by $[\Phi]_\chi$.

Now we formulate the following fundamental theorem.

2.3.27. THEOREM. If $\Phi = i - F \in \mathcal{M}_B(X, X_1; L)$, then for any neighborhood V of zero and for any essential fundamental set T of the family Φ there exists a family $\Psi = i - G \in \mathcal{M}_B{}^T(X, X_1; L \times [0, 1])$ such that

1) $G(x, \lambda, \tau) \subset F(x, \lambda) + V$ for all $(x, \lambda, \tau) \in (X \cap T) \times L \times [0, 1]$;

2) $\Psi(x, \lambda, \tau) = (1-\tau)\Phi(x, \lambda) + \tau\tilde{\Psi}(x, \lambda)$, where $\tilde{\Psi} \in \mathscr{C}(X, X_1; L)$;

3) $G(X \times L \times \{1\}) \subset T \cap E'$, where $E' \subset E$ is a finite-dimensional subspace.

We formulate an analogue of Theorem 2.3.27 for condensing m-mappings.

2.3.28. THEOREM. Let $\Phi \in D_\chi(X, X_1; L)$, where (X, X_1) is a pair of closed subsets and χ is a proper semiadditive monotone and nonsingular measure of noncompactness. Then there exists a family $\Psi \in D_\chi(X, X_1; L \times [0, 1])$ such that $\Psi(\cdot, \cdot, 0) = \Phi$, $\Psi(\cdot, \cdot, 1) \in \mathscr{C}(X, X_1; L)$ and the field $\Psi(\cdot, \cdot, 1)$ is finite-dimensional.

The construction of the deformations of a completely fundamentally contractible m.v.-field and of a completely continuous one allows us to prove easily the following statement.

2.3.29. LEMMA. Let $\Phi \in \mathcal{M}_B^{T_0}(X, X_1) \cap \mathcal{M}_B^{T_1}(X, X_1)$, where X_1 is closed and $T_0 \cap T_1 \cap X \neq \varnothing$. Then there exists a m.v.-field $\tilde{\Phi} \in \mathscr{C}(X, X_1)$, such that $\tilde{\Phi} \in [\Phi]_B^{T_0} \cap [\Phi]_B^{T_1}$.

Our purpose now is to describe the relation between the homotopy classes of completely fundamentally contractible and completely continuous m.v.-fields. Namely, we give the conditions under which there exists a bijective correspondence between these classes.

2.3.30. Definition. An m.v.-field $\Phi \in \mathcal{M}_B(X, X_1)$ is said to be 1(2)-fundamentally contractible if Φ possesses an essential fundamental set containing any previously given point $x_0 \in X$ (respectively, pair of points x_0, $x_1 \in X$).

We denote the set of 1(2)-fundamentally contractible m.v.-fields by $\mathcal{M}_B^1(X, X_1)$ [respectively, $\mathcal{M}_B^2(X, X_1)$]. Clearly, $\mathcal{M}_B^2(X, X_1) \subset \mathcal{M}_B^1(X, X_1)$.

If χ is a monotone nonsingular measure of noncompactness, then

$$\mathcal{D}_\chi(X, X_1) \subset \mathcal{M}_B^2(X, X_1).$$

The definition of the homotopy of the m.v.-fields

$$\Phi_0, \ \Phi_1 \in \mathcal{M}_B^1(X, X_1)\,[\mathcal{M}_B^2(X, X_1)]$$

in the corresponding sets differs from Definition 2.3.26 only in one respect: we shall assume that the m.v.-fields Q_i, $0 \leqslant i \leqslant n$, connecting Φ_0 and Φ_1, also belong to $\mathcal{M}_B^1(X, X_1)$ ($\mathcal{M}_B^2(X, X_1)$, respectively). The homotopy classes of the m.v.-field Φ in $\mathcal{M}_B^1(X, X_1)$ [$\mathcal{M}_B^2(X, X_2)$] will be denoted by $[\Phi]_B^1$, $[\Phi]_B^2$ respectively.

2.3.31. LEMMA. Let $\tilde{\Phi}_0$, $\tilde{\Phi}_1 \in \mathscr{C}(X, X_1) \subset \mathcal{M}_B^2(X, X_1)$ and $\tilde{\Phi}_0 \underset{\mathcal{M}_B^2}{\sim} \tilde{\Phi}_1$. Then $\tilde{\Phi}_0 \sim \tilde{\Phi}_1$.

From Lemma 2.3.31 there follows the following principle of bijective correspondence, generalizing the bijection principle of Yu. I. Sapronov for single-valued condensing mappings (see [266]).

2.3.32. THEOREM. The mapping $[\Phi]_B^2 \to [\tilde{\Phi}]$, where $\Phi \in \mathcal{M}_B^2(X, X_1)$, $\tilde{\Phi} \in \mathscr{C}(X, X_1)$, $\tilde{\Phi} \in [\Phi]_B^2$, $[\tilde{\Phi}]$ is the homotopy class of $\tilde{\Phi}$ in $\mathscr{C}(X, X_1)$, is a bijective correspondence between the sets of homotopy classes in $\mathcal{M}_B^2(X, X_1)$ and $\mathscr{C}(X, X_1)$.

From Theorem 2.3.28 there follows a variant of the principle of bijective correspondence for condensing m.v.-fields:

2.3.33. THEOREM. The mapping $[\Phi]_\chi \to [\tilde{\Phi}]$, where $\Phi \in \mathscr{D}_\chi(X, X_1)$, χ is a proper semiadditive monotone and nonsingular measure of noncompactness, $\tilde{\Phi} \in \mathscr{C}(X, X_1)$, $\tilde{\Phi} \in [\Phi]_\chi$, $[\tilde{\Phi}]$ being the homotopy class of $\tilde{\Phi}$ in $\mathscr{C}(X, X_1)$, is a bijective correspondence between the sets of homotopy classes in $\mathscr{D}_\chi(X, X_1)$ and $\mathscr{C}(X, X_1)$.

2.3.34. Rotation of Fundamentally Contractible Multivalued Vector Fields. The concept of the rotation of a fundamentally contractible m.v.-field, described in the present subsection, is based on the theory of the rotations of completely continuous multivalued vector fields with convex images (see 2.3.1).

Let $\Phi = i - F \in \mathcal{M}(\bar{U}, \partial U)$.

2.3.35. Definition. If $\Phi \bar{\in} \mathcal{M}_B(\bar{U}, \partial U)$, then

$$\gamma(\Phi, \bar{U}) \underset{\text{def}}{=} 0.$$

If $\Phi \in \mathcal{M}_B(\bar{U}, \partial U)$, then

$$\gamma(\Phi, \bar{U}) = \gamma(\tilde{\Phi}, \partial U),$$

where $\tilde{\Phi} \in \mathscr{C}(\bar{U}, \partial U)$ is an arbitrary compact homotopic approximation of Φ.

The validity of this definition is justified by the following statement.

2.3.36. LEMMA [40]. If $\Phi \in \mathcal{M}_B(\bar{U}, \partial U)$, then $\gamma(\Phi, \bar{U}) = \gamma_T(\Phi, \partial U_T)$, where T is an arbitrary essential fundamental set of Φ.

Lemma 2.3.36 opens the path to an equivalent definition of the rotation of fundamentally contractible m.v.-fields in terms of the relative rotation. In the majority of cases, this definition is more convenient for the computation of the rotation of concrete m.v.-fields.

2.3.37. Definition. Let $\Phi \in \mathcal{M}(\bar{U}, \partial U)$. If $\Phi \bar{\in} \mathcal{M}_B(\bar{U}, \partial U)$, then

$$\gamma(\Phi, \bar{U}) \underset{\text{def}}{=} 0.$$

If $\Phi \in \mathcal{M}_B(\bar{U}, \partial U)$, then

$$\gamma(\Phi, \bar{U}) = \gamma_T(\Phi, \partial U_T),$$

where T is an arbitrary essential fundamental set of the m.v.-field Φ (see [37, 40, 207, 215]).

Now we describe the principal properties of the rotation we have introduced.

2.3.38. Homotopy Invariance. If Φ_0, $\Phi_1 \in \mathcal{M}(\bar{U}, \partial U)$ and $\Phi_0 \underset{\mathcal{M}}{\sim} \Phi_1$, then

$$\gamma(\Phi_0, \bar{U}) = \gamma(\Phi_1, \bar{U}).$$

Property 2.3.38 admits a partial converse, the following analogue of Hopf's classification theorem.

2.3.39. Let U be an absolutely convex open subset of the metrizable LCS E such that intersection of U with any finite-dimensional subspace E' is bounded in E'. If for the m.v.-fields Φ_0, $\Phi_1 \in \mathcal{M}_B(\bar{U}, \partial U)$ we have $\gamma(\Phi_0, \bar{U}) = \gamma(\Phi_1, \bar{U})$, then $\Phi_0 \underset{\mathcal{M}_B}{\sim} \Phi_1$.

If, under the assumptions of 2.3.39, the m.v.-fields Φ_0, Φ_1 are condensing, then it would be interesting to find out in which case will they be homotopic in the class of condensing m.v.-fields. Taking into account Theorem 2.3.28 and also the fact that every completely continuous homotopy is condensing relative to a proper measure of noncompactness, we obtain the following statement.

2.3.40. Let U be as in 2.3.39. Let $\Phi_0, \Phi_1 \in \mathcal{D}_\chi(\bar{U}, \partial U)$, where χ is a proper semiadditive monotone and nonsingular measure of noncompactness and assume that $\gamma(\Phi_0, \bar{U}) = \gamma(\Phi_1, \bar{U})$. Then $\Phi_0 \underset{\chi}{\sim} \Phi_1$.

2.3.41. Additive Dependence on the Domain. Let $\{U_j\}_{j \in J}$ be a family of open disjoint subsets of U and let $\Phi \in \mathcal{M}(\bar{U}, \bar{U} \setminus \bigcup_{j \in J} U_j)$. Then the rotations $\gamma(\Phi, \bar{U}_j)$ are different from zero only for a finite number of indices j ∈ J and $\gamma(\Phi, \bar{U}) = \sum_{j \in J} \gamma(\Phi, \bar{U}_j)$.

Now from the property 2.3.8 and Definition 2.3.37 there follows the following important

2.3.42. Fixed Point Principle. If $\Phi = i - F \in \mathcal{M}_B(\bar{U}, \partial U)$ and $\gamma(\Phi, \bar{U}) \neq 0$, then $\varnothing \neq \mathrm{Fix}\, F \subset U$.

In conclusion, we consider the problem of the dependence of the rotation of a fundamentally contractible m.v.-field on the values taken by it inside the domain. Since for the proof of the validity of the definition of rotation (Lemma 2.3.36) one makes use of information on the m.v.-field defined on the entire domain $\bar{U}$, in general the rotation of a fundamentally contractible (as well as limit-compact or condensing) m.v.-field is defined on $\bar{U}$. It turns out that the 2-fundamentally contractible m.v.-fields form the class for which the rotation can be correctly defined from the values taken only on the boundary ∂U of the domain.

Indeed, if $\Phi \in \mathcal{M}_B^2(\partial U)$ and $\tilde{\Phi} \in \mathcal{C}(\partial U)$, $\tilde{\Phi} \in [\Phi]_B^2$ is a compact homotopic approximation of Φ, then, by virtue of Theorem 2.3.32 on the bijection of the homotopy classes, the rotation $\gamma(\Phi, \partial U)$ can be correctly defined as $\gamma(\tilde{\Phi}, \partial U)$. In the case when $\Phi \in \mathcal{M}_B^2(\bar{U}, \partial U)$, this definition of the rotation coincides with the one given before. This means, in particular, that for a 2-fundamentally contractible m.v.-field $\Phi \in \mathcal{M}_B^2(\bar{U}, \partial U)$, the rotation $\gamma(\Phi, \bar{U})$ does not depend on the behavior of the m.v.-field Φ on U.

This fact, applied to condensing m.v.-fields, means that for a m.v.-field, condensing relative to a monotone nonsingular measure of noncompactness, the rotation can be defined on the boundary of the domain and does not depend on the continuation to its inside. We mention, however, that the fact that the rotation $\gamma(\Phi, \bar{U})$ is independent of the continuation can be established also for an m.v.-field Φ, condensing relative to a monotone semiadditive measure of noncompactness. The proof of this fact, taking into account that the linear deformation of χ-condensing m.v.-fields will be a χ-condensing family, does not differ from the single-valued case (see [265]).

2.3.43. Theorems on Fixed Points. The theory of rotations developed in the previous section allows us to give a simple and geometrically intuitive proof of a series of fixed point principles for noncompact m-mappings.

Everywhere in the sequel U is an open subset of the Hausdorff LCS E. First we consider the following generalization of Rothe's theorem.

2.3.44. THEOREM. Let U be convex, assume that the m-mapping $F: \bar{U} \to \mathrm{Kv}(E)$ is completely fundamentally contractible and let

$$F(x) \cap \bar{U} \neq \varnothing$$

for all $x \in \partial U$. Then $\mathrm{Fix}\, F \neq \varnothing$; if $\mathrm{Fix}\, F \cap \partial U = \varnothing$, then $\gamma(i - F, \bar{U}) = 1$.

Bordering on Theorem 2.3.44 is the following statement which generalizes the classical theorem of Kakutani [801]-Glicksberg [660]-Ky Fan [623] as well as a series of fixed point principles for condensing and limit-compact single-valued mappings (see, for example, [265, 544, 744, 1005]).

2.3.45. THEOREM. If M is a convex closed subset of E and if the m-mapping $F: M \to \mathrm{Kv}(M)$ is completely fundamentally contractible, then $\mathrm{Fix}\, F \neq \varnothing$.

2.3.46. THEOREM. Let the 1-fundamentally contractible m-mapping $F: \bar{U} \to \mathrm{Kv}(E)$ be such that for the corresponding m.v.-field $\Phi = i - F$ one has at each point $x \in \partial U$:

$$\Phi(x) \cap L_x^a = \varnothing,$$

where $a \in U$, $L_x^a = \{z \mid z \in E,\ z = \mu(x - a),\ \mu < 0\}$. Then $\mathrm{Fix}\, F \neq \varnothing$. If $\mathrm{Fix}\, F \cap \partial U = \varnothing$, then $\gamma(\Phi, \bar{U}) = 1$.

2.3.47. COROLLARY (Generalization of Schaefer's Theorem). Let 0 ∈ U and assume that the 1-fundamentally contractible m-mapping $F: \bar{U} \to \mathrm{Kv}(E)$ is such that at each point $x \in \partial U$ we have $F(x) \cap \lambda x = \varnothing$ for all $\lambda > 1$. Then $\mathrm{Fix}\, F \neq \varnothing$. If $\mathrm{Fix}\, F \cap \partial U = \varnothing$, then $\gamma(i - F, \bar{U}) = 1$.

2.3.48. COROLLARY. Let 0 ∈ U, U is convex and assume that the 1-fundamentally contractible m-mapping $F: \bar{U} \to \mathrm{Kv}(E)$ is directed inside ∂U, i.e., $F(x) \subset I_{\bar{U}}(x) = \{y \mid y \in E,\ x + \lambda(y - x) \in \bar{U}$ for some $\lambda > 0\}$. Then $\mathrm{Fix}\, F \neq \varnothing$. If $\mathrm{Fix}\, F \cap \partial U = \varnothing$, then $\gamma(i - F, \bar{U}) = 1$.

Now we formulate the odd field theorem for fundamentally contractible m.v.-fields.

2.3.49. THEOREM. Let U be a symmetric neighborhood of zero and assume that the m-mapping $F:\bar{U}\to \mathrm{Kv}(E)$ is completely fundamentally contractible and possesses an essential fundamental set which is symmetric relative to zero. Assume that for the m.v.-field $\Phi = i - F$ one has

$$\Phi(x)\cap\mu\Phi(-x)=\varnothing$$

for all $x\in\partial U$ and $0\le\mu\le 1$. Then $\gamma(\Phi,\bar{U})\equiv 1 \pmod 2$ and, consequently, $\varnothing\ne \mathrm{Fix}\, F\subset U$.

A consequence of Theorem 2.3.49 is the odd field theorem for condensing m-mappings.

2.3.50. THEOREM. Assume that U is symmetric relative to zero and assume that the m-mapping $F:\bar{U}\to\mathrm{Kv}(E)$ is χ-condensing, where χ is a semiadditive montone measure of noncompactness, invariant relative to reflections in the origin (i.e., $\chi(-\Omega)=\chi(\Omega)$). Assume that the m.v.-field $\Phi = i - F$ satisfies the condition

$$\Phi(x)\cap\mu\Phi(-x)=\varnothing$$

for all $x\in\partial U$ and $0\le\mu\le 1$. Then $\gamma(\Phi,\bar{U})\equiv 1 \pmod 2$ and, consequently, $\varnothing\ne \mathrm{Fix}\, F\subset U$.

2.3.51. THEOREM (Generalization of Browder's Theorem). Let U_0, U_1, U be open subsets of E; $\bar{U}_0\subset U_1\subset\bar{U}_1\subset U$; U_0 and U are convex. Let $\Phi=i-F\in\mathcal{M}^1_B(U,\partial U_1)$ and assume that for some integer $m\ge 1$ the following conditions hold:

1) $\bigcup_{1\le j\le m-1}\overline{F^j(\bar{U}_1)}\subset U$;

2) $\bigcup_{1\le j\le m-1}\overline{F^j(\bar{U}_0)}\subset U_1$;

3) $\overline{F^m(\bar{U}_1)}\subset U_0$.

Then $\gamma(\Phi,\bar{U}_1)=1$ and, consequently, $\varnothing\ne\mathrm{Fix}\,F\subset U_0$.

Theorem 2.3.51 generalizes the results established in the single-valued case by Browder and Yu. G. Borisovich [30, 441].

We also mention that the theorems of this subsection generalize the fixed point theorems for condensing, limit-compact and fundamentally contractible m-mappings, considered in [207, 212, 215, 1005].

The complete proofs of the statements of this subsection can be found in [37, 40]. In the survey [37] one can also find detailed bibliographic indications regarding the development of approximative methods in the theory of fixed points of m-mappings. Therefore, we restrict ourselves to Table 1 which illustrates the process of the construction of the topological degree (rotation) for m.v.-fields with convex images.

Lately, one has developed the theory of the degree of Fredholm operators perturbed by a condensing m-mapping (see, for example, [32, 34, 94, 185]).

2.4. Homological Methods in the Theory of Fixed Points

2.4.1. The Topological Characteristic of Multivalued Mappings. First we make some preliminary remarks. Let X, Y be arbitrary sets, let $F:X\to P(Y)$ be an m-mapping and let $\Gamma_F\subset X\times Y$ be the graph of F. We consider the mappings $t:\Gamma_F\to X$, $r:\Gamma_F\to Y$, which are the restrictions to Γ_F of the natural projections $\mathrm{Pr}_X:X\times Y\to X$, $\mathrm{Pr}_Y:X\times Y\to Y$. Obviously, for any $x\in X$ we have the equality $F(x)=r\circ t^{-1}(x)$.

Thus, every m-mapping $F:X\to P(Y)$ defines a quintuple (X, Y, Γ_F, t, r) of objects. The converse is also true: if a quintuple (X, Y, Z, f, g) is given, where X, Y, and Z are arbitrary sets and $f: Z\to X$, $g:Z\to Y$ are mappings, where f is surjective, then the equality $F(x)=g\circ f^{-1}(x)$ defines an m-mapping $F:X\to P(Y)$. It is easy to see that one and the same m-mapping can be defined by different quintuplets.

The quintuple (X, Y, Γ_F, t, r) is called a canonical representation of the m-mapping F.

Assume now that Y is a vector space, $X\subseteq Y$, and $F:X\to P(Y)$ is an m-mapping. We consider the m.v.-field $\Phi = i - F$. Obviously, the field Φ is defined by the quintuple $(X, Y, \Gamma_F, t, t-r)$; we call this representation canonical for the m.v.-field Φ.

Let U be a domain in the finite-dimensional Euclidean space E^{n+1}. We consider the m-mapping

$$F:\bar{U}\to P(E^{n+1}),\quad \mathrm{Fix}\,F\cap L=\varnothing,$$

TABLE 1. Topological Degree of m-Mappings with Convex Images

Space / Class of mappings	Banach	Frechet space	Hausdorff LCS
Completely continuous	Granas [683, 684]; Borisovich, Gel'man, Mukhamadiev, Obukhovskii [35, 36]; Cellina, Lasota [495]; Hukuhara [759]		Izrailevich [116]; Ma [891]
Condensing		Obukhovskii [207]	
Limit-compact	Webb [1232]; Vanderbauwhede [1207]	Petryshyn, Fitzpatrick [1004, 1005]	
Fundamentally contractible		Obukhovskii [212]; Obukhovskii, Gorokhov [215]	Borisovich, Obukhovskii [37, 40]

where L = ∂U. Let $\Gamma_{\bar{U}}(F)$ and $\Gamma_L(F)$ be the graphs of the m-mapping F over $\bar{U}$ and L, respectively.

We consider the m.v.-field

$$\Phi = i - F: \bar{U} \to P(E^{n+1}).$$

Since the m.v.-field Φ does not have singular points on L, it follows that there is defined the mapping of pairs

$$t - r: (\Gamma_{\bar{U}}(F),\ \Gamma_L(F)) \to (E^{n+1},\ E^{n+1} \setminus \theta),$$

which induces a homomorphism $(t-r)^*$ of the Aleksandrov–Cech cohomology groups of these spaces. We consider the composition ϰ of the homomorphisms:

2.4.2.
$$H^n(E^{n+1} \setminus \theta, G) \xrightarrow{(t-r)_n^*} H^n(\Gamma_L(F), G) \xrightarrow{\delta} H^{n+1}(\Gamma_{\bar{U}}(F), \Gamma_L(F), G),$$

where δ is the connecting homomorphism of the exact sequence of the pair $(\Gamma_{\bar{U}}(F), \Gamma_L(F))$, and G is the coefficient group.

2.4.3. Definition. The topological characteristic of the m.v.-field Φ on the domain $\bar{U}$ is the homomorphism

$$\varkappa = \delta \circ (t - r)_n^*.$$

We say that the topological characteristic of an m.v.-field is equal to zero (different from zero) if ϰ is the zero (a nonzero) homomorphism. It is convenient to introduce the notation $\varkappa = \varkappa(\Phi, \bar{U})$.

2.4.4. THEOREM. If $\varkappa(\Phi, \bar{U}) \neq 0$, then $\varnothing \neq \mathrm{Fix} F \subset U$.

We give the formulation of certain theorems regarding the computation of the topological characteristic.

2.4.5. Definition. We say that the m.v.-field Φ = i − F does not have opposite orientation on L to that of the continuous single-valued field φ = i − f if

$$\varphi(x) \cap (-\lambda \Phi(x)) = \varnothing,$$

for any $x \in L$, $\lambda \geqslant 0$.

2.4.6. THEOREM (An Analogue of the Poincaré–Bohl Theorem). Assume that the m.v.-field Φ is nondegenerate and does not have opposite orientation on L to that of the continuous vector field φ = i − f. Then $\varkappa(\Phi, \bar{U}) = \delta \circ t_n^* \circ \varphi_n^*$,

$$H^n(E^{n+1} \setminus \theta, G) \xrightarrow{\varphi_n^*} H^n(L, G) \xrightarrow{t_n^*} H^n(\Gamma_L(F), G) \xrightarrow{\delta} H^{n+1}(\Gamma_{\bar{U}}(F), \Gamma_L(F), G).$$

From this theorem we obtain as a corollary a simple statement which is important in the theory of fixed points.

Let B be the closed unit ball in E^{n+1}, $S = \partial B$.

2.4.7. THEOREM [75]. Let $F: B \to P(E^{n+1})$ be an m-mapping without fixed points on S and let $F(S) \subset B$. In order that $\varkappa(\Phi, B) \neq 0$ it is necessary and sufficient that the composition $\delta \circ t_n^*$ of the homomorphisms

$$H^n(S, G) \xrightarrow{t_n^*} H^n(\Gamma_S(F), G) \xrightarrow{\delta} H^{n+1}(\Gamma_B(F), \Gamma_S(F), G)$$

should not be zero.

We also have the following analogue of the odd field theorem.

2.4.8. THEOREM. Assume that the m-mapping $F: B \to P(E^{n+1})$ is defined by the canonical quintuple $(B, E^{n+1}, \Gamma_B(F), t, r)$, and the homomorphism $\delta \circ t_n^*$

$$H^n(S, \mathbf{Z}_2) \xrightarrow{t^*} H^n(\Gamma_S(F), \mathbf{Z}_2) \xrightarrow{\delta} H^{n+1}(\Gamma_B(F), \Gamma_S(F), \mathbf{Z}_2)$$

is not zero.

Suppose that there exists an upper semicontinuous m.v.-field $\Psi: S \to K(E^{n+1} \setminus \theta)$, satisfying the following conditions:

1) there exists a quintuple $(S, E^{n+1} \setminus \theta, Z, f, g)$ defining the field Ψ, and $f: Z \to S$ is a Vietoris mapping, i.e., the set $f^{-1}(x)$ is acyclic for any $x \in S$;

2) $(i - F)(x) \subseteq \Psi(x)$ for any $x \in S$;

3) $\Psi(x) \cap \lambda \Psi(-x) = \varnothing$ for any $x \in S$; $\lambda \geqslant 0$.

Then $\varkappa(i - F, B) \neq 0$.

As we can see, in Theorems 2.4.7 and 2.4.8 there occurs the condition of the nontriviality of the homorphism $\delta \circ t_n^*$.

A sufficient condition for this, by virtue of the Vietoris–Begle–Sklyarenko theorem (see [271, 399, 1212]), is that t be an n-Vietoris mapping (see 2.4.10 below).

Another condition is given by the following statement.

2.4.9. THEOREM. Let X be a compact metric space and let $F: B \to K(X)$ be an upper semicontinuous m-mapping. If there exists a sequence of numbers $\{\varepsilon_i\}_{i=1}^{\infty}$ such that $\varepsilon_i > 0$, $\lim_{i \to \infty} \varepsilon_i = 0$, and if for any ε_i the m-mapping F admits a single-valued ε_i-approximation f_i, then the composition $\delta \circ t_n^*$ of homomorphisms

$$H^n(S, G) \xrightarrow{t_n^*} H^n(\Gamma_S(F), G) \xrightarrow{\delta} H^{n+1}(\Gamma_B(F), \Gamma_S(F), G)$$

is nonzero for any nontrivial group G.

In conclusion we formulate some theorems on the fixed points of m-mappings F.

Let X, Y be metric spaces and let $f: Y \to X$ be a continuous mapping. We consider the set $M_k(f) \subset X$ of points at which the preimages fail to be k-acyclic, i.e.,

$$M_0(f) = \{x \mid x \in X,\ H^0(f^{-1}(x), G) \neq G\},$$
$$M_k(f) = \{x \mid x \in X,\ H^k(f^{-1}(x), G) \neq 0\}, \quad k > 0.$$

2.4.10. Definition [674]. A mapping $f: Y \to X$ is called an n-Vietoris mapping, $n \geq 1$ (relative to the coefficient group G) if the following conditions hold:

(1) f is proper and surjective;

(2) $\mathrm{rd}_X(M_k(f)) \leqslant n - k - 2$,

where rd_X denotes the relative dimension in X.

2.4.11. THEOREM (An Analogue of Rothe's Theorem). Assume that the m-mapping $F: B \to K(E^{n+1})$ satisfies the conditions:

1) $F(S) \subset B$;

2) there exists a quintuple (B, E^{n+1}, Z, f, g) such that f is an n-Vietoris mapping and

$$g \circ f^{-1}(x) \subset F(x) \quad \text{for all} \quad x \in B.$$

Then, $\mathrm{Fix} F \neq \varnothing$.

2.4.12. THEOREM. Let $F: B \to K(E^{n+1})$ be an upper semicontinuous m-mapping such that $F(S) \subset B$. If there exists a sequence of positive numbers $\{\varepsilon_i\}_{i=1}^{\infty}$, $\lim_{i\to\infty} \varepsilon_i = 0$, such that for any ε_i the m-mapping F admits a single-valued ε_i-approximation, then $\mathrm{Fix} F \neq \varnothing$.

2.4.13. THEOREM. Assume that the upper semicontinuous m-mapping $F: B \to K(E^{n+1})$ satisfies the following conditions:

1) there exists a quintuple (B, E^{n+1}, Z, f, g) such that f is an n-Vietoris mapping and

$$g \circ f^{-1}(x) \subset F(x) \quad \text{for any} \quad x \in B;$$

2) for each point $x \in S$ there exists a linear functional ξ_x, defined on E^{n+1}, separating the sets $x - F(x)$ and $-x - F(-x)$.

Then $\mathrm{Fix} F \neq \varnothing$.

2.4.14. THEOREM. Assume that $F: B \to K(E^{n+1})$ is an upper semicontinuous m-mapping, satisfying the following conditions:

1) for each point $x \in S$ there exists a linear functional ξ_x, defined on E^{n+1}, separating the sets $x - F(x)$ and $-x - F(-x)$;

2) there exists a sequence of positive numbers

$$\{\varepsilon_i\}_{i=1}^{\infty}, \quad \lim_{i\to\infty} \varepsilon_i = 0,$$

such that for any ε_i the m-mapping F admits an ε_i-approximation f_i on B.

Then $\mathrm{Fix} F \neq \varnothing$.

The topological characteristic of an m.v.-field has been introduced and investigated in [37, 74, 75]. This concept is generalized to the case of completely continuous m.v.-fields in infinite dimensional spaces (see [37, 76]).

We describe briefly the connection between the concept of topological characteristic and certain theories of the topological degree, which have been developed by a series of authors.

Let X, Y be metric spaces; let $F: X \to K(Y)$ be an m-mapping. We consider the sets of nonacyclic images of F:

$$M_0(F) = \{x \mid x \in X,\ H^0(F(x), \mathbf{Z}) \neq \mathbf{Z}\},$$
$$M_k(F) = \{x \mid x \in X,\ H^k(F(x), \mathbf{Z}) 0 \neq\}, \quad k \geqslant 1.$$

2.4.15. Definition. An upper semicontinuous m-mapping $F: X \to K(Y)$ is said to be n-acyclic ($n \geq 1$) if $\mathrm{rd}_X M_k(F) \leqslant n-k-2$ for all $k \geq 0$.

If F is 1-acyclic, then the image F(x) of each point $x \in X$ is acyclic. Such m-mappings are called acyclic.

Let B be the closed unit ball in E^{n+1}, let $S = \partial B$ and let $F: B \to K(E^{n+1})$ be an n-acyclic m-mapping.

2.4.16. LEMMA. The diagram

$$\begin{array}{ccccc}
H^n(B) & \xrightarrow{i_n'^*} & H^n(S) & \xrightarrow{\delta'} & H^{n+1}(B, S) \\
\downarrow{\scriptstyle i_n^*} & & \downarrow{\scriptstyle \tilde{i}_n^*} & & \downarrow{\scriptstyle \tilde{i}_n^*} \\
H^n(\Gamma_B(F)) & \xrightarrow{i_n^*} & H^n(\Gamma_S(F)) & \xrightarrow{\delta} & H^{n+1}(\Gamma_B(F), \Gamma_S(F))
\end{array}$$

is commutative and all its vertical arrows are isomorphisms.

The last statement follows from the Vietoris–Begle–Sklyarenko theorem.

If $\mathrm{Fix} F \cap S = \varnothing$, then there is defined the mapping

$$(t-r):\Gamma_S(F)\to E^{n+1}\setminus\theta.$$

We consider the composition $\hat{\varkappa}$ of the homomorphisms in the sequence

$$H^n(E^{n+1}/\theta)\xrightarrow{(t-r)^*_n}H^n(\Gamma_S(F))\xrightarrow{(t^*_n)^{-1}}H^n(S).$$

In $H^n(E^{n+1}\setminus\theta)$ and $H^n(S)$ we choose identical orientations (i.e., generators z_1, z_2 of the groups $H^n(E^{n+1}\setminus\theta)$ and $H^n(S)$ such that the homomorphism induced by the imbedding of S in $E^{n+1}\setminus\theta$ carries z_1 into z_2). Then $\hat{\varkappa}(z_1)=k\cdot z_2$, where $k\in\mathbf{Z}$.

2.4.17. Definition. The rotation of an n-acyclic m.v.-field $\Phi=i-F$ on S is the number $\gamma(\Phi,S)=k$.

The Kronecker index mod 2 for acyclic m.v.-fields in a finite-dimensional space has been constructed by Granas and Jaworowski [686]. This paper has been preceded by Jaworowski's paper [787] in which properties of a homomorphism generated by an m-mapping have been investigated.

In [38] these methods have been developed for m-mappings whose images under the retractions of $E^{n+1}\setminus\theta$ to S turn into acyclic sets and one has defined the rotation of the corresponding m.v.-fields on the boundary of a simply connected domain.

The rotation (toplogical degree) of n-acyclic m.v.-fields has been defined and used in [427, 669]. This rotation possesses many usual properties: it is preserved under homotopies in the class of n-acyclic m.v.-fields, it is the algebraic number of the singular points, etc.

We describe the relation between the topological characteristic and the rotation of n-acyclic m.v.-fields.

2.4.18. THEOREM (see [37]). Let $\Phi=i-F:B\to K(E^{n+1})$ be an n-acyclic m.v.-field, not degenerated on S; let z_1 be a generating element of the group $H^n(E^{n+1}\setminus\theta)$. Then there exists a generating element $z_3\in H^{n+1}(\Gamma_B(F),\ \Gamma_S(F))$ such that $\varkappa(z_1)=\gamma(\Phi,S)\cdot z_3$.

We consider a wider class of m.v.-fields.

2.4.19. Definition. An m-mapping F:X → K(Y) is said to be generalized n-acyclic if there exists a quintuple (X, Y, Z, f, g) such that the following conditions hold:

1) f:Z → X is an n-Vietoris mapping, $n\geq 1$;

2) $g(f^{-1}(x))\subseteq F(x)$ for all $x\in X$.

The rotation of a generalized n-acyclic (n-admissible) m.v.-field is defined as a certain set $\Gamma(\Phi,S)$ of integers (see [459, 674]). Many theorems on the rotation of n-acyclic m.v.-fields are generalized in a natural manner to this concept (see same references).

2.4.20. THEOREM (see [37]). If $\Gamma(\Phi,S)\neq\{0\}$, then the homomorphism $\varkappa$ is nonzero.

2.4.21. In the infinite dimensional case, the definition of an n-acyclic m.v.-field can be modified somewhat, obtaining a more convenient form.

2.4.22. Definition. An upper semicontinuous m-mapping $F:X\to K(Y)$ is said to be almost acyclic if:

1) $M_k(F)=\varnothing$ for all $k\geqslant k_0\geqslant 0$;

2) $\max\limits_{0\leqslant k\leqslant k_0}\mathrm{rd}_X M_k(F)<\infty$.

The rotation (degree) of almost acyclic m.v.-fields has been constructed by Bourgin [429, 430]. Also this concept is connected with the topological characteristic: it is different from zero simultaneously with the rotation (see [37]).

The rotation of almost acyclic m.v.-fields covers, in particular, also the class of compact acyclic m.v.-fields (for such fields the degree in an infinite dimensional space has been constructed by Williams [1241] and Furi–Martelli [652]).

The relative rotation of almost acyclic m.v.-fields in LCS has been constructed and investigated in [216].

The extension of the degree theory to the case of compact generalized n-acyclic m.v.-fields in Banach spaces and LCS has been done in [458, 460, 606].

TABLE 2. Topological Degree of m-Mappings with Nonconvex Images

Class of mappings \ Space	Finite-dimensional space	Banach space	LCS: completely continuous mappings	LCS: fundamentally contractible mappings
Acyclic	Granas–Jaworowski [686]; Borisovich–Gel'man–Obukhovskii [38]	Furi–Martelli [652]	Williams [1241]	
Almost acyclic	Górniewicz [669]; Bourgin [427]	Bourgin [429, 430]	Obukhovskii–Fleidervish [216]	Obukhovskii [214]
Generalized almost acyclic	Bryszewski–Górniewicz [459, 674]	Bryszewski–Górniewicz [458, 460]	Dzedzej [606]	
Arbitrary	Gel'man [74]	Gel'man [76]		

The construction of the degree for fundamentally contractible (see Sec. 2.3) almost acyclic m.v.-fields has been communicated by Obukhovskii [214] (the detailed publication is in print).

The development of the theory of rotations for m.v.-fields with nonconvex images is illustrated in Table 2. For more detailed bibliographical indications and proofs, see the survey [37].

2.4.23. Lefschetz Number of m-Mappings. Let X be a compact metric ANR space and let $F:X\to K(X)$ be an acyclic m-mapping.

The m-mapping F defines a canonical quintuple (X, X, Γ_F, t, r), where t is a 1-Vietoris mapping and, consequently, it induces an isomorphism $t_{*n}: H_n(\Gamma_F, G)\to H_n(X, G)$ of the cohomology groups for any $n \geq 0$.

Eilenberg and Montgomery [610] have defined the Lefschetz number of the m-mapping F in the following manner:

$$\lambda(F)=\sum_{n=0}^{\infty}(-1)^n \operatorname{tr}(r_{*n}\circ t_{*n}^{-1})$$

and they have proved the following statement.

2.4.24. THEOREM. If $\lambda(F)\neq 0$, then $\mathrm{Fix}F\neq\varnothing$.

Subsequently, the Eilenberg–Montgomery theorem has been generalized and developed in various directions (see [39, 80, 272, 273, 276, 277, 279, 400, 461, 630, 641, 642, 650, 653, 667, 668, 670, 671, 673, 674, 676, 788, 843, 844, 993, 996, 1027-1031, 1132, 1137, 1208, etc.]; for more detailed information see [37]).

We indicate briefly one of the generalizations of this theorem, due to Gorniewicz and Granas [676]. First we give the definition of the generalized Lefschetz number, due to Leray.

Let E be a vector space over the field **Q** of rational numbers and let $\zeta:E\to E$ be an endomorphism. We set $N(\zeta)=\bigcup_{n=1}^{\infty}\operatorname{Ker}\zeta^n$, $\tilde{E}=E/N(\zeta)$ and we define the induced endomorphism $\tilde{\zeta}:\tilde{E}\to\tilde{E}$. If $\dim\tilde{E}<\infty$, then we define the generalized trace

$$\operatorname{Tr}(\zeta)=\operatorname{tr}(\tilde{\zeta}).$$

Let $E=\{E_n\}$ be a graded vector space and let $\zeta=\{\zeta_n\}:E\to E$ be a zero-degree endomorphism.

2.4.25. Definition. The endomorphism ζ is said to be a Leray endomorphism if the quotient space $\tilde{E}=\{\tilde{E}_n\}$ is of finite type, i.e., $\dim\tilde{E}_n<\infty$ for all n and $\tilde{E}_n=0$ for all but finitely many n. For such endomorphisms we can define the (generalized) Lefschetz number

$$\Lambda(\zeta)=\sum_{n=0}^{\infty}(-1)^n \operatorname{Tr}(\zeta_n).$$

2.4.26. THEOREM. Let X be an ANR space and let $F:X\to K(X)$ be a compact acyclic m-mapping. Then

(a) $F_*=\{r_*\circ t_*^{-1}\}:H_*(X, Q)\to H_*(X, Q)$

is a Leray endomorphism (the Aleksandrov–Cech homology with compact supports);

(b) if $\Lambda(F_*)\neq 0$, then $\operatorname{Fix}F\neq\varnothing$.

2.4.27. At the conclusion of this chapter we mention that various theorems on fixed points of m-mappings have been obtained also in [85, 161, 171, 172, 180, 204, 245, 349, 363, 366, 402, 403, 504, 538, 542, 543, 550, 578, 579, 602, 616-618, 628, 650, 658, 699, 701, 702, 716, 717, 721, 722, 762, 774, 791, 795, 805, 833, 861, 874, 877, 878, 885, 917, 929, 962, 988, 989, 1058, 1093, 1151, 1170, 1172, 1190, 1236].

In the direction connected with the approximate determination of the fixed points, we mention [58, 170, 239, 261, 264, 297, 353, 500, 603, 604, 607, 608, 664, 758, 846, 860, 937, 1056, 1158, 1191].

SUPPLEMENT

Literature on the Applications of Multivalued Mappings

As already mentioned in the introduction, we give only undifferentiated guiding information on the literature regarding the applications; we intend to present these questions in detail in the second part of the present survey.

1. Applications to game theory and mathematical economics: [16, 19, 128, 142, 205, 213, 217, 218, 238, 249, 263, 286, 324, 326, 375, 623, 660, 697, 798, 803, 977, 1073, 1181, 1193, 1210].

2. Applications to the theory of differential and integral inclusions, to the theory of optimal control and to the theory of differential equations: [1, 2, 10, 12-15, 18, 20-29, 50-55, 57, 59, 61, 62, 64-69, 71, 72, 77-79, 86-88, 90-99, 124-127, 130, 134, 138, 142, 143, 147-149, 160, 163-167, 169, 173-177, 179, 181-183, 189, 192, 193, 195, 197, 209, 210, 212, 219-223, 225-236, 249-258, 269, 270, 285, 290, 292-296, 299, 304-313, 317-319, 324, 326, 337, 344, 351, 352, 354, 364, 390, 391, 395-397, 410-412, 414, 415, 433, 435, 437, 455-457, 463, 465-467, 473, 481, 483, 484, 491, 497, 498, 501-503, 507-513, 520, 547-549, 555, 558-561, 564, 568, 584, 591, 595, 612, 640, 657, 659, 687-689, 726, 727, 733-739, 740, 754, 781-784, 798-800, 805, 806, 809, 813, 815-821, 823, 824, 835-838, 842, 847, 857-859, 863-866, 871, 906-911, 916, 936, 974, 984, 986, 995, 998, 1000, 1001, 1007, 1008, 1011-1018, 1032, 1035-1039, 1044, 1045, 1060, 1079, 1083, 1090, 1115, 1122-1124, 1127, 1166, 1167, 1179-1181, 1187, 1188, 1202, 1209, 1214, 1215, 1228-1231, 1234, 1240, 1246-1250, 1252-1254].

3. Applications to the theory of generalized dynamical systems: [1, 8, 9, 37, 39, 43-47, 82, 97, 111, 113-115, 196, 211, 212, 267, 268, 320-323, 325, 340, 343, 365, 398, 517, 714, 793, 827-829, 889, 999, 1082-1086, 1175-1178, 1192, 1193].

4. Other applications: [137, 300, 301, 440, 519, 577, 665, 794, 830-832, 956, 1073, 1116].

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