

Pacific Journal of Mathematics

SUBCONTINUITY FOR MULTIFUNCTIONS

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SUBCONTINUITY FOR MULTIFUNCTIONS

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The concept of subcontinuity is extended to multifunctions. This notion is then used to obtain a number of results on multifunctions with closed graphs and to develop criteria under which a multifunction is upper semicontinuous.

1. **Introduction.** In [1] R. V. Fuller introduced the concept of subcontinuous function and used it to obtain conditions implying continuity as well as some comparisons to compactness preserving functions and some results on functions with closed graphs. In [1] Fuller stated that he thought that his results would hold for multifunctions. The purpose of this paper is to show that such is the case. Indeed the definition of subcontinuity can be extended and conditions implying upper semi-continuity for multifunctions are derived, including a generalization of a result of Muenzenberger and Smithson [4].

By a *multifunction* we mean a correspondence $F: X \rightarrow Y$ on a set X into a set Y such that $F(x)$ is a nonempty subset of Y for each $x \in X$. If F is a multifunction, then the *graph of F* is the subset $\{(x, y): x \in X, y \in F(x)\}$ of $X \times Y$. We denote the graph of F by $G(F)$. Then a multifunction F has a *closed graph* if $G(F)$ is a closed subset of $X \times Y$. Whereas F is a *closed multifunction* if $F(A)$ is closed in Y for all closed sets $A \subset X$. Further, F is *upper semi-continuous* (u.s.c.) if and only if for each closed set $B \subset Y$, $F^{-1}(B) = \{x: F(x) \cap B \neq \emptyset\}$ is closed. This is equivalent to saying that F^{-1} (where $F^{-1}(y) = \{x: y \in F(x)\}$) is a closed multifunction on $F(X) = \bigcup \{F(x): x \in X\}$.

If $A \subset X$, then A^- denotes the closure of A . Other notation used is that of Kelley [3].

2. **Subcontinuous multifunctions.** Using Fuller's definition as a model we obtain the following definition.

DEFINITION. A multifunction $F: X \rightarrow Y$ is *subcontinuous* if and only if whenever $\{x_\alpha, \alpha \in D\}$ is a convergent net in X and $\{y_\alpha, \alpha \in D\}$ is a net in $F(X)$ with $y_\alpha \in F(x_\alpha)$ then $\{y_\alpha, \alpha \in D\}$ has a convergent subnet.

Next we say that F is *inversely subcontinuous* in case F^{-1} is subcontinuous. Note that since F and F^{-1} are both multifunctions we did not need a separate definition in terms of nets for inverse subcontinuity. Also, if F is single valued then the present definitions

are equivalent to Fuller's definitions. Finally, since the concepts of subcontinuity and inverse subcontinuity are dual, a result about one also has a dual result for the other. In most cases we shall give only the result for subcontinuous functions.

Immediate consequences of the definition of subcontinuous multifunction F are: If $K \subset X$ is compact and if $F(K)$ is closed, then $F(K)$ is compact. That is, in this case F preserves compact sets. Consequently a point closed (i.e. $F(x)$ closed for each $x \in X$) subcontinuous multifunction is point compact (i.e. $F(x)$ is compact for each $x \in X$).

THEOREM 2.1. *If $F: X \rightarrow Y$ is a subcontinuous multifunction on the space X into the completely regular space Y and if $K \subset X$ is compact, then $F(K)^-$ is compact.*

Proof. Suppose $K \subset X$ is compact and let $\{y_\alpha, \alpha \in D\}$ be a net in $F(K)$. Let \mathcal{B} be a base for the uniformity on Y and partial order \mathcal{B} by inclusion downward. Then give $D \times \mathcal{B}$ the product partial order. Then for each $a = (\alpha, B) \in D \times \mathcal{B}$ pick an element z_a in $B[y_\alpha] \cap F(K)$. Next let x_a be an element of K such that $z_a \in F(x_a)$. Now since K is compact some subnet $\{x_{a_n}\}$ of $\{x_a, a \in D \times \mathcal{B}\}$ converges and consequently some subnet of $\{z_{a_n}\}$ say $\{z_{a_m}\}$ converges, since F is subcontinuous, to z_0 . Now $a_m = (\alpha_m, B_m)$ and $z_{a_m} \in B_m[y_{\alpha_m}]$. Next let U be a neighborhood of z_0 and let B be a symmetric member of \mathcal{B} such that $B \circ B[z_0] \subset U$. There is an $a_{m'}$ such that $a_{m'} < a_m$ (i.e. $\alpha_{m'} < \alpha_m$ and $B_m \subset B_{m'}$) implies that $z_{a_{m'}} \in B[z_0]$ and since z_m is a subnet of z_a , $B_m \subset B$. Now $(z_0, z_{a_m}) \in B$ and $z_{a_m} \in B_m[y_{\alpha_m}]$ so $(y_{\alpha_m}, z_{a_m}) \in B_m \subset B$ and since B is symmetric $(z_0, y_{\alpha_m}) \in B \circ B$. Thus $y_{\alpha_m} \in B \circ B[z_0] \subset U$. Hence, a subnet of $\{y_\alpha, \alpha \in D\}$ converges.

Next we characterize compact preserving multifunctions in terms of subcontinuity.

THEOREM 2.2. *Let $F: X \rightarrow Y$ be a multifunction. Then F is compact preserving if and only if $F|K \rightarrow F(K)$ is subcontinuous for each compact set $K \subset X$.*

Proof. Suppose F is compact preserving and let $K \subset X$ be compact. Then $F(K)$ is compact and consequently $F|K \rightarrow F(K)$ is subcontinuous.

Next let $K \subset X$ be compact and suppose $F|K \rightarrow F(K)$ is subcontinuous. But then each set in $F(K)$ must have a convergent subnet and thus $F(K)$ is compact. Hence, F is compact preserving.

3. Closed graphs and upper semicontinuity. A number of

examples exist which show that a function with a closed graph need not be continuous. However, it is easy to show that a function with a closed graph into a compact space is continuous (see remark below). By using subcontinuity we can get a significant generalization of this.

THEOREM 3.1. *Let $F: X \rightarrow Y$ be a subcontinuous multifunction which has a closed graph. Then F is upper semicontinuous.*

Proof. Let $A \subset Y$ be closed and let $x_0 \in F^{-1}(A)^-$. Further, let $\{x_\alpha, \alpha \in D\}$ be a net in $F^{-1}(A)$ which converges to x_0 . Let $\{y_\alpha, \alpha \in D\}$ be net in A such that $y_\alpha \in F(x_\alpha)$ for each α . Then, since F is subcontinuous, there is a convergent subnet $y_{\alpha_n} \rightarrow y_0 \in A$. If $y_0 \notin F(x_0)$, then $(x_0, y_0) \notin G(F)$ and since $G(F)$ is closed, there exist open sets $U \subset X, V \subset Y$, such that $(x_0, y_0) \in U \times V \subset X \times Y \setminus G(F)$. But $x_\alpha \rightarrow x_0$ and $y_{\alpha_n} \rightarrow y_0$. Thus there is an α_n such that $x_{\alpha_n} \in U$ and $y_{\alpha_n} \in V$ which is a contradiction. Thus $y_0 \in F(x_0)$ and $x_0 \in F^{-1}(A)$. Hence, F is u.s.c.

We can deduce another result from the proof of Theorem 3.1. This result strengthens known results on upper semicontinuous point closed multifunctions.

PROPOSITION 3.2. *Let $F: X \rightarrow Y$ be a subcontinuous multifunction with a closed graph. Let $x_\alpha \rightarrow x_0$ and let $\{y_\alpha\}$ be a net such that $y_\alpha \in F(x_\alpha)$ for each α . If $y_\alpha \rightarrow y_0$, then $y_0 \in F(x_0)$.*

If we assume that Y is regular in Theorem 3.1, then the converse is also true.

THEOREM 3.3. *If $F: X \rightarrow Y$ is a point closed upper semicontinuous multifunction into a regular space, then F has a closed graph.*

Proof. Suppose $(x, y) \notin G(F)$. Then $y \notin F(x)$. Thus there are disjoint open sets $U, V \subset Y$ such that $F(x) \subset U$ and $y \in V$. Further, there is an open set $W \subset X$ with $x \in W$ such that $F(W) \subset U$ (W exists because F is u.s.c.). Thus $(x, y) \in W \times V$ and $W \times V \cap G(F) = \emptyset$. Hence, $G(f)$ is closed.

REMARK. In [1] Fuller had a result for single valued functions which is analogous to Theorem 3.3. In this result Fuller assumed that Y was Hausdorff. But in the case of multifunctions we need to assume that Y is regular.

As we have seen a multifunction with a closed graph is in a sense almost u.s.c. In this regard there is an exercise in Kelley [3] which asserts that for such a function $F(K)$ is closed and $F^{-1}(K')$ is

closed whenever K, K' are compact (a proof of this appears in [4]). Next we develop some conditions under which a multifunction has a closed graph. For this we need the following definition.

DEFINITION. A multifunction $F: X \rightarrow Y$ is called *locally closed* if and only if for each $p \in X$ and for each neighborhood U of p there is a neighborhood V of p such that $V \subset U$ and $F(V)$ is closed.

A closed function or multifunction on a regular space is locally closed. But a locally closed function need not be closed.

THEOREM 3.4. *If $F: X \rightarrow Y$ is locally closed and if $F^{-1}(y)$ is closed for each $y \in Y$, then F has a closed graph.*

Proof. If $y \notin F(x)$, then $x \notin F^{-1}(y)$ and so there is a neighborhood U of x such that $U \cap F^{-1}(y) = \emptyset$ and $F(U)$ is closed. Then there is an open set V with $y \in V$ such that $F(U) \cap V = \emptyset$. Then $U \times V$ is a neighborhood of (x, y) which misses $G(F)$. Hence, F has a closed graph.

COROLLARY 3.5. *If $F: X \rightarrow Y$ is a closed multifunction on a regular space X and if $F^{-1}(y)$ is closed for each $y \in Y$, then F has a closed graph.*

REMARK. Corollary 3.5 is a restatement of Theorem 3.3.

Since a closed multifunction on a regular space is locally closed, and since a multifunction with compact range is subcontinuous; Theorems 3.1 and 3.4 given the following result from [5] which was a generalization of a result of Halfar [2].

COROLLARY 3.6. *If $F: X \rightarrow Y$ is a closed multifunction on a regular space X into a compact space Y for which $F^{-1}(y)$ is closed for all $y \in Y$, then F is upper semicontinuous.*

Another immediate consequence of the definition of locally closed is that a locally closed multifunction with closed point inverses is point closed.

By putting together some of the above we can prove.

THEOREM 3.7. *If X is a regular, locally compact space, and if F is a multifunction on F , then the following are equivalent.*

- (i) F has a closed graph
- (ii) If $K \subset X$ is compact, then $F(K)$ and $F^{-1}(y)$ are closed for each $y \in Y$.

(iii) F is locally closed and $F^{-1}(y)$ is closed for each $y \in Y$.

Proof. That (iii) implies (i) is Theorem 3.4 and (i) implies (ii) was proved in [4]. Finally, since X is regular and locally compact, X has a compact bases for each point and hence, (ii) implies (iii).

4. Compact preserving multifunctions and k_3 -spaces. In [1] Fuller defines what he calls a k_3 -space. This definition is only slightly different from the definition of a k -space as given by Kelley [3]. In fact when the space is Hausdorff they are identical. We shall use the definition given by Fuller.

DEFINITION. A topological space X is a k_3 -space provided that a set is open in X if and only if its intersection with each compact subset of X is relatively open.

Our next theorem gives an extension of the main result in [4].

THEOREM 4.1. Let $F: X \rightarrow Y$ be a multifunction on a k_3 -space. If F is compact preserving and if F has a closed graph, then F is upper semicontinuous.

Proof. Let $A \subset Y$. If $F^{-1}(A)$ is not closed, then there is a compact set $K \subset X$ such that $K \cap (X \setminus F^{-1}(A))$ is not open in K . Now $F(K)$ is compact and thus $A \cap F(K)$ is compact. Hence, $F^{-1}(A \cap F(K)) = C$ is closed. Next we show that $F^{-1}(A) \cap K = C \cap K$. For this

$$\begin{aligned} C \cap K &= F^{-1}(A \cap F(K)) \cap K = F^{-1}(A) \cap F^{-1}(F(K)) \cap K \\ &= F^{-1}(A) \cap K. \end{aligned}$$

Thus $F^{-1}(A) \cap K$ is relatively closed and so $(X \setminus F^{-1}(A)) \cap K$ is open in K . Thus $F^{-1}(A)$ is closed.

Next we prove another result for k_3 -spaces which is a variation on one of Fuller's results.

THEOREM 4.2. Let $F: X \rightarrow Y$ be a multifunction on a Hausdorff k_3 -space X into a Hausdorff space Y . If F is compact preserving and if $F^{-1}(y)$ is closed for all $y \in Y$, then F is upper semicontinuous.

Proof. Let $A \subset Y$ be closed, then in order to show that $F^{-1}(A)$ is closed it is sufficient to show that $F^{-1}(A) \cap K$ is closed for each compact set $K \subset X$. For this note that $F^{-1}(A) \cap K = (F|K)^{-1}(A)$, and thus it will suffice to show that $F|K$ is u.s.c. Now since K is compact T_2 , it is regular and since $F|K$ is closed ($F|K$ is compact

preserving and Y is T_2), F is locally closed with $F^{-1}(y)$ closed for each y . Then $F|K$ has a closed graph by Theorem 3.4 and thus Theorem 4.1 shows that $F|K$ is u.s.c. Hence, $F^{-1}(A) \cap K$ is closed and the theorem follows.

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Received April, 1 1975 and in revised form July 15, 1975.

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AMERICAN MATHEMATICAL SOCIETY
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Printed in Japan by International Academic Printing Co., Ltd., Tokyo, Japan

Pacific Journal of Mathematics

Vol. 61, No. 1

November, 1975

Jiří Adámek, V. Koubek and Věra Trnková, <i>Sums of Boolean spaces represent every group</i>	1
Richard Neal Ball, <i>Full convex l-subgroups and the existence of a^*-closures of lattice ordered groups</i>	7
Joseph Becker, <i>Normal hypersurfaces</i>	17
Gerald A. Beer, <i>Starshaped sets and the Hausdorff metric</i>	21
Dennis Dale Berkey and Alan Cecil Lazer, <i>Linear differential systems with measurable coefficients</i>	29
Harald Boehme, <i>Glättungen von Abbildungen 3-dimensionaler Mannigfaltigkeiten</i>	45
Stephen LaVern Campbell, <i>Linear operators for which T^*T and $T + T^*$ commute</i>	53
H. P. Dikshit and Arun Kumar, <i>Absolute summability of Fourier series with factors</i>	59
Andrew George Earnest and John Sollion Hsia, <i>Spinor norms of local integral rotations. II</i>	71
Erik Maurice Ellentuck, <i>Semigroups, Horn sentences and isolic structures</i>	87
Ingrid Fotino, <i>Generalized convolution ring of arithmetic functions</i>	103
Michael Randy Gabel, <i>Lower bounds on the stable range of polynomial rings</i>	117
Fergus John Gaines, <i>Kato-Taussky-Wielandt commutator relations and characteristic curves</i>	121
Theodore William Gamelin, <i>The polynomial hulls of certain subsets of C^2</i>	129
R. J. Gazik and Darrell Conley Kent, <i>Coarse uniform convergence spaces</i>	143
Paul R. Goodey, <i>A note on starshaped sets</i>	151
Eloise A. Hamann, <i>On power-invariance</i>	153
M. Jayachandran and M. Rajagopalan, <i>Scattered compactification for $N \cup \{P\}$</i>	161
V. Karunakaran, <i>Certain classes of regular univalent functions</i>	173
John Cronan Kieffer, <i>A ratio limit theorem for a strongly subadditive set function in a locally compact amenable group</i>	183
Siu Kwong Lo and Harald G. Niederreiter, <i>Banach-Buck measure, density, and uniform distribution in rings of algebraic integers</i>	191
Harold W. Martin, <i>Contractibility of topological spaces onto metric spaces</i>	209
Harold W. Martin, <i>Local connectedness in developable spaces</i>	219
A. Meir and John W. Moon, <i>Relations between packing and covering numbers of a tree</i>	225
Hiroshi Mori, <i>Notes on stable currents</i>	235
Donald J. Newman and I. J. Schoenberg, <i>Splines and the logarithmic function</i>	241
M. Ann Piech, <i>Locality of the number of particles operator</i>	259
Fred Richman, <i>The constructive theory of KT-modules</i>	263
Gerard Sierksma, <i>Carathéodory and Helly-numbers of convex-product-structures</i>	275
Raymond Earl Smithson, <i>Subcontinuity for multifunctions</i>	283
Gary Roy Spoor, <i>Differentiability conditions and bounds on singular points</i>	289
Rosario Strano, <i>Azumaya algebras over Hensel rings</i>	295