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# An Extension of the Sard-Smale Theorem to Domains with an Empty Interior

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## Abstract

A stumbling block in the modelling of competitive markets with commodity and price spaces of infinite dimensions, arises from having positive cones with an empty interior. This issue precludes the use of tools of differential analysis, ranging from the definition of a derivative, to the use of more sophisticated results needed to understand determinacy of equilibria and, more generally, the structure of the equilibrium set. To overcome these issues, this paper extends the Preimage Theorem and the Sard-Smale Theorem to maps between spaces that may have an empty interior.

**Keywords:** Determinacy; equilibrium manifold; positive cone.

**JEL Classification:** D5; D50; D51.

## Resumen

Un obstáculo en el modelado de mercados competitivos con espacios de bienes y precios en dimensiones infinitas, surge de tener conos positivos con interior vacío. Esto impide el uso de herramientas de análisis diferencial, desde la definición de una derivada, hasta el uso de resultados más sofisticados necesarios para entender determinación de equilibrios y, más generalmente, la estructura del conjunto de equilibrio. Con el objeto de sortear estos puntos, este documento extiende el Teorema de la Preimagen y el Teorema de Sard-Smale a mapeos entre espacios que pudiesen tener un interior vacío.

**Palabras Clave:** Determinación; conjunto de equilibrio; cono positivo.

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# 1 Introduction

Two closely related mathematical results, the Preimage Theorem and Sard's Theorem, are useful tools with many applications in economics, particularly within the theory of general economic equilibrium. The first of these, is stated as follows:

**Theorem. (*Preimage Theorem*)** *If  $y$  is a regular value of the map  $f : M \rightarrow N$  between differentiable manifolds  $M$  and  $N$ , then  $f^{-1}(y)$  is a sub-manifold of  $M$ .<sup>1</sup>*

The Preimage Theorem is usually applied to show results of the following nature:

*Consider the excess demand function  $Z : \Omega \times S \rightarrow X$  of a pure exchange economy, where  $\Omega$  is the set of parameters (e.g. initial endowments),  $S$  is the set of prices and  $X$  is the commodity space. Then, if 0 is a regular value of  $Z$ , we have that the equilibrium set,  $Z^{-1}(0)$ , is a manifold.*

The set  $\Gamma = Z^{-1}(0)$  is called the “equilibrium manifold” and the seminal paper of Balasko (1975) introduced this point of view of general equilibrium theory. The second result in this spirit is Sard's Theorem that states that almost all the values of a function are regular. Formally:

**Theorem. (*Sard's Theorem, 1942*)** *Let  $U$  be an open set of  $\mathbb{R}^p$  and  $f : U \rightarrow \mathbb{R}^q$  be a  $C^k$  map where  $k > \max(p - q, 0)$ . Then, the set of critical values in  $\mathbb{R}^q$  has measure zero.*

Sard's Theorem also has many applications, usually to show results similar to this:

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<sup>1</sup>Recall that for a map  $f : M \rightarrow N$ , a point  $x$  in  $M$  at which the derivative of  $f$  has rank less than  $n$  is called a *critical point* and its image a *critical value* of  $f$ . Other points  $y$  in  $N$ , that is, such that  $f$  has rank  $n$  at all points in  $f^{-1}(y)$ , are called *regular values* of  $f$ .

Consider the equilibrium manifold  $\Gamma \subset \Omega \times S$  and the projection map  $\pi : \Omega \times S \rightarrow \Omega$ , restricted to  $\Gamma$ , given by  $\pi(\omega, p) = \omega$ . Then, the regular values are almost all of  $\Omega$ . In other words, almost all equilibria are determinate.

Sard's Theorem turned out indeed to be the appropriate tool to study determinacy of equilibria since Debreu's (1970) seminal paper. These tools have been used in many other areas such as general equilibrium with incomplete financial markets where Chichilnisky and Heal (1996) have shown that the equilibrium set is a manifold, while determinacy of equilibria was shown by Magill and Shafer (1990).

In spite of these general results and vast applications, many models of competitive markets have an infinite number of commodities which naturally lead to consumption and price spaces of infinite dimensions.<sup>2</sup> At a first glance, it would seem appropriate to use Smale's generalisation of the Submanifold and Sard's Theorem to infinite dimensions, as follows:

**Theorem. (*Smale Theorem, 1965*)** *If  $f : M \rightarrow V$  is a  $C^s$  Fredholm map between differentiable manifolds locally like Banach spaces with  $s > \max(\text{index } f, 0)$ , then*

1. *For almost all  $y \in V$ ,  $f^{-1}(y)$  is a submanifold of  $M$ ;*
2. *The regular values of  $f$  are almost all of  $V$ .*

The statement and proof of Smale's Theorem is local, and requires for  $M$  and  $V$  to have a nonempty interior. However, there are many instances in economic modelling that require a domain with an empty interior. For example, many models of competitive markets use a consumption space in the positive cone of an  $\ell_p$  or  $L_p$  space, for  $1 \leq p \leq \infty$ .<sup>3</sup> Unfortunately, the only spaces among  $L_p$  and  $\ell_p$  space whose positive cone have a nonempty interior

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<sup>2</sup>Smale (1965) contains most mathematical definitions that will be used throughout this paper.

<sup>3</sup>Recall the following definitions. Let  $p$  be a real number  $1 \leq p < \infty$ . The space  $\ell_p$  consists of all sequence of scalars  $\{x_1, x_2, \dots\}$  for which  $\sum_{i=1}^{\infty} \|x_i\|^p < \infty$ . The norm of an element  $x = \{x_i\}$  in  $\ell_p$  is defined as  $\|x\|_p = (\sum_{i=1}^{\infty} \|x_i\|^p)^{1/p}$ . The space  $\ell_{\infty}$  consists of bounded sequences. The norm of an element  $x = \{x_i\}$  in  $\ell_{\infty}$  is defined as  $\|x\|_{\infty} = \sup_i \|x_i\|$ . The  $L_p$  spaces are defined analogously. For  $p \geq 1$ , the space  $L[a, b]$  consists of

are  $L_\infty$  and  $\ell_\infty$ . To complicate things, prices are elements of the positive cone of the dual space of the commodity space.<sup>4</sup> Recall that the dual space of  $\ell_p$  ( $L_p$ , respectively),  $1 \leq p < \infty$ , is the space  $\ell_q$  ( $L_q$ , respectively) where  $1/p + 1/q = 1$ . In other words, even if the commodity space had a positive cone with a nonempty interior, the positive cone of the dual space -that is, the price space- will have an empty interior, and vice versa. The dual spaces of  $L_\infty$  and  $\ell_\infty$  are subtler, but this problem still holds.<sup>5</sup> There are plenty of examples in different directions, but to name a few consider the following list:

- Duffie and Huang (1985) model financial markets through the space  $L_2$ ;
- Bewley (1972) uses the space  $L_\infty$  to model infinite variations in any of the characteristics describing commodities. These Characteristics could be physical properties, location, the time of delivery, or the state of the world (in the probabilistic sense) at the time of delivery;
- The infinite horizon model which requires the set  $\ell_\infty$  as modelled in Kehoe and Levine (1985) and Balasko (1997a,b,c);

The purpose of this paper is precisely to extend Sard's and Smale's Theorems to maps between subsets of Banach manifolds which may have an empty interior. To this end, we will prove in the next sections the following result.

**Theorem. (*Main theorem*)** *Let  $f : M \rightarrow V$  be a  $C^r$  star Fredholm map between star Banach manifolds, with  $r > \max(\text{index } f, 0)$ . Suppose that  $M$  and  $V$  are connected and have a countable basis. Furthermore, suppose that  $f$  is locally proper and that it has at least one regular value. Then, the regular values of  $f$  are almost all of  $V$ .*

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those real-valued functions  $x$  on the interval  $[a, b]$  for which  $\|x(t)\|$  is Lebesgue integrable. The norm on this space is defined as  $\|x\|_p = \left( \int_a^b \|x(t)\|^p \right)^{1/p}$ . The space  $L_\infty[a, b]$  consists of all Lebesgue measurable functions on  $[a, b]$  which are bounded, except possibly on a set of measure zero. The norm is defined by  $\|x\|_\infty = \text{ess sup} \|x(t)\|$ .

<sup>4</sup>If  $X$  is a normed linear vector space. The space of all bounded linear functionals on  $X$  is called the *normed dual* of  $X$  and is denoted by  $X^*$ . The norm of an element  $f \in X^*$  is  $\|f\| = \sup_{\|x\|=1} \|f(x)\|$ .

<sup>5</sup>The dual space of  $L_\infty$  can be identified with bounded signed finitely additive measures that are absolutely continuous with respect to the measure. There are relatively consistent extensions of Zermelo-Franekel set theory in which the dual of  $\ell_\infty$  is  $\ell_1$ .

## 2 Analytical preliminaries

Let  $B$  be a Banach space, and let  $B_+$  denote the positive cone of  $B$  which may have an empty interior. Notice that  $B_+$  is a convex subset of  $B$ . The results of this paper can be generalized to any convex subset, not just the positive cone, but we restrict the analysis to this set because of an interest in economic applications.

**Definition 1. ( $\alpha$ -admissible directions)** We say that  $h \in B$  is an  $\alpha$ -admissible direction for  $x \in B_+$  if and only if there exist  $\alpha > 0$  such that  $x + \alpha \frac{h}{\|h\|} \in B_+$ . The set of  $\alpha$ -admissible directions at  $x$  will be denoted by  $\mathcal{A}_\alpha(x)$ .

Note that since  $B_+$  is a convex subset of  $B$  then, if  $y$  and  $x$  are points in  $B_+$ , it must be that  $h = (y - x)$  is  $\alpha$ -admissible for  $x$ . To see this, consider  $z = \alpha'y + (1 - \alpha')x$ ,  $0 \leq \alpha' \leq 1$ . Then  $z \in B_+$  and  $z = x + \alpha'(y - x)$ ,  $\forall 0 \leq \alpha'$ . Let  $\alpha = \frac{\alpha'}{\|h\|}$ . Similarly, it follows that if  $h$  is  $\alpha$ -admissible, it is also  $\beta$ -admissible for all  $0 < \beta \leq \alpha$ . Note then that for  $\alpha \geq \beta > 0$ , we have  $\mathcal{A}_\alpha(x) \subseteq \mathcal{A}_\beta(x)$ .

**Definition 2. (Star-differentiable functions)** Let  $u : B_+ \rightarrow \mathbb{R}$  be a real function defined on  $B_+$ . We say that  $u$  is star-differentiable at  $x \in B_+$  if the Gâteaux derivative of  $u$  at  $x$  exists for all  $h \in \mathcal{A}_\alpha$ .

Definition 2, in other words, states that  $u$  is star-differentiable at  $x$  if and only if there exists a map  $L_x \in L(B_+, \mathbb{R})$  such that

$$\lim_{\alpha \rightarrow 0} \frac{u(x + \alpha h) - u(x)}{\alpha} = \frac{d}{d\alpha} \Big|_{\alpha=0} u(x + \alpha h) = L_x h$$

for all  $h \in \mathcal{A}_\alpha(x)$ ; that is, if  $u(x + \alpha h) - u(x) = \alpha L_x h + o(\alpha h)$ .

**Definition 3. (Star-neighborhoods)** Let  $x \in B_+$ . We define a star-neighborhood of  $x$  by

$$V_x^*(\alpha) = \left\{ y \in B_+ : y = x + \beta \frac{h}{\|h\|}, \forall h \in \mathcal{A}_\alpha(x), \text{ where } 0 \leq \beta \leq \alpha \right\}.$$

We will say that  $O$  is a star-open subset of  $B_+$  if for each  $x \in O$  there exist  $V_x^*(\alpha) \subset O$ .

One can check that star-neighborhoods form a base of a topology, called the *star-topology*.

**Remark 1.** From now on to represent admissible directions we consider vectors  $h$  such that  $\|h\| = 1$ .

**Definition 4. (Star-charts)** Let  $\Gamma$  be a Hausdorff topological space. A star-chart on  $\Gamma$  is a pair  $(U^*, \phi^*)$  where the set  $U^*$  is an open set in  $\Gamma$  and  $\phi : V^* \rightarrow U^*$  is a homeomorphism from the star-neighborhood  $V^* \subset B^+$  onto  $U^*$ . We call  $\phi$  a parametrization. In such case, we say that the parametrization is of class  $C^k$  if the function  $\phi$  is  $k$  times star-differentiable.

**Definition 5. (Star-manifold)** Let  $\Gamma$  be a Hausdorff topological space. We say that  $\Gamma$  is a  $C^k$  star-manifold if for every  $p \in \Gamma$ , there exists an open star-neighborhood of  $B_+$ , denoted  $V_a^*(\alpha)$ , and a  $C^k$  parametrization,  $\phi : V_a(\alpha) \rightarrow V_p$ , where  $V_p \subset \Gamma$  is an open neighborhood of  $p$ .

To highlight the structure of  $\Gamma$  as a star-manifold, we will use the notation  $\Gamma^*$ . We wish to remark in Definition 5 that, since we consider  $\Gamma \subset B$  where  $B$  is a Banach space, then the open set in question can be considered to be  $V_p^* = V_p \cap \Gamma$  where  $V_p$  is an open neighborhood of  $p$  in the topology of the norm.

**Definition 6. (Star-atlas)** A  $C^k$  star-atlas is a collection of star charts  $(V_{p_i} \cup M, \phi_i)$ ,  $i \in I$ , that satisfies the following properties:

- (i) The collection  $V_{p_i} \cup M$ ,  $i \in I$ , covers  $\Gamma$ .
- (ii) Any two charts are compatible.
- (iii) The map  $\phi : V_{a_i}(\alpha) \rightarrow V_{p_i}$  is  $C^k$  star-differentiable.



(iv) The set  $\phi_i^{-1}(V_{p_i} \cup M)$  is a star-open subset of  $B_+$ .

**Definition 7. (Star-submanifolds)** Let  $\Gamma^*$  a  $C^k$  Banach manifold,  $k \geq 0$ . A subset  $S$  of  $\Gamma^*$  is called a star-submanifold of  $\Gamma^*$  if and only if for each point  $x \in S$  there exists an admissible chart in  $\Gamma^*$  such that

(i)  $\phi_i^{-1}(S \cap V_{p_i}) \subset V_{a_i}^*(\alpha)$ .

(ii) The admissible directions  $\mathcal{A}_a$  contain a closed subset  $\mathcal{B}_a$  which splits  $\mathcal{A}_a$ .

(iii) The star-chart image  $\phi^{-1}(V_p \cap S)$  is a star-open set  $V^* = V_a^*(\alpha) \cap \mathcal{B}_a$ .

**Definition 8. (Tangent spaces)** Let  $M^*$  be a star manifold. The tangent set at  $p \in M^*$  is the subset  $T_p M^*$  that can be described in the following way. Let  $\phi : V_a^*(\alpha) \rightarrow V_p$  with  $p = \phi(a)$ . We write  $T_p M^* = \phi'(a)(\mathcal{A}_\alpha(a))$ . That is,  $y \in T_p M^*$  if and only if  $y = \phi'(a)h$ ,  $h \in \mathcal{A}_\alpha(x)$ .

**Definition 9. (Submersions)** Let  $f : D(f) \rightarrow Y$  be a mapping between  $B_+ = D(f)$  and the Banach space  $Y$ . Then,  $f$  is called a submersion at the point  $x$  if and only if

1.  $f$  is a  $C^1$  mapping on a star-neighborhood  $V^*(x)$  of  $x$ ;
2.  $f'(x) : B \rightarrow Y$  is surjective; and,
3. the null space  $N(f'(x))$  splits  $B$ .

We also say  $f$  is a submersion on the set  $M$  if it is a submersion at each  $x \in M$ .

**Definition 10. (Regular points and regular values)** Let  $f : D(f) \rightarrow Y$  be a mapping between  $B_+ = D(f)$  and the Banach space  $Y$ . Then, the point  $x \in D(f)$  is called a regular point of  $f$  if and only if  $f$  is a submersion at  $x$ . The point  $y \in Y$  is called a regular value if and only if  $f^{-1}$  is empty or it consists solely of regular points. Otherwise  $y$  is called a singular value, i.e.  $f^{-1}(y)$  contains at least one singular point.

### 3 Results

**Theorem 1. (*The preimage theorem*)** *Let  $f : M^* \rightarrow N$  a  $C^k$  mapping from a star-manifold  $M^*$  to a Banach space  $N$ . If  $y$  is a regular value of  $f$ , then  $S = f^{-1}(y)$  is a star-submanifold of  $M^*$*

*Proof.* It suffices to study the local problem. Let  $V_a^*(\epsilon)$  be a star-neighborhood of  $a \in B_+$  and consider the  $C^k$  star-differentiable map  $\phi : B_+ \rightarrow M^*$  such that  $\phi(a) = p$ . Without loss of generality, let  $f(p) = 0$ . Let  $h \in \mathcal{A}_\epsilon(a)$  and let  $V_p$  be a neighborhood of  $p$ . Then  $V_p \cap M^* = \phi(V_a^*(\epsilon))$ . Thus,  $\phi(a + \alpha h) \in V_p \cap M^*$ . From the local submersion theorem if  $f$  is a submersion, there exists a parametrization  $\phi$  such that,  $\phi(a) = p$ ,  $\phi'(a) = I$ . From Definition 5, for all  $p' \in V_p \cap M^*$ , there exists  $h$  and  $\alpha$  such that  $h \in \mathcal{A}_a(\alpha)$ . Since  $\ker f'(p)$  splits  $B$ , there exists a projection  $P : B \rightarrow N$ . Let  $P^\perp = I - P$  and  $N^\perp = P^\perp$ . Thus, we obtain that  $B = N \oplus N^\perp$  and that  $f'(p) : N^\perp \rightarrow Y$  is bijective. Denote its inverse by  $A : Y \rightarrow N^\perp$ . So let

$$a = P(p) + Af(p) \text{ and } a + \alpha h = [P(p') + Af(p')],$$

$$\phi^{-1}(x) = Px + Af(x)$$

where  $A = f'(p)^{-1}$ .

Multiplying both sides of this equation we obtain:  $f'(p)\phi(x) = f(x)$ . So, from the local submersion theorem, given that  $f(\phi(a)) = 0$ , the equality

$$f(\phi(a + \alpha h)) = f'(\phi(a))(\alpha h) + y,$$

implies that, the solution of the equation  $f(z) = y$  in a star-neighborhood  $V_p^*$  of  $p$ , corresponds to the solution of the equation  $f'(\phi(a))h = 0$ . Therefore,  $S$  is the set  $h \in \mathcal{A}_a$  such that  $f'(\phi(a))h = 0$  for some  $h \in \mathcal{A}_a(a)$ . Hence,  $S$  is a star-submanifold of  $M^*$ . □

**Definition 11. (*Star Fredholm maps*)** *A star Fredholm operator is a star continuous linear map  $L : E_1 \rightarrow E_2$  such that*

- (i)  $\dim \ker L < \infty$ ;
- (ii) *range  $L$  is closed*;

(iii)  $\dim \operatorname{coker} L < \infty$ .

The index of  $L$  is A star Fredholm map is a star continuous map between star-manifolds such that at each point in the domain, its star Gateaux derivative is a star Fredholm operator. The index of a star Fredholm map is the index of its linearization.

**Definition 12. (Locally star proper maps)** A star Fredholm map  $F : M \rightarrow V$  is said to be locally star-proper if for every  $x \in M$  there is a star-neighborhood  $U$  of  $x$  such that  $f$  restricted to  $U$  is proper.

**Theorem 2. (Main theorem)** Let  $f : M \rightarrow V$  be a  $C^r$  star Fredholm map between star Banach manifolds, with  $r > \max(\operatorname{index} f, 0)$ . Suppose that  $M$  and  $V$  are connected and have a countable basis. Furthermore, suppose that  $f$  is locally proper and that it has at least one regular value. Then, the regular values of  $f$  are almost all of  $V$ .

*Proof.* The proof follows closely [14]. The theorem is proved locally, since we assume  $M$  has a countable base and first category. Thus, let  $U$  be a star neighborhood of  $x_0 \in M$ . In this case,  $U$  is a subset of some Banach space  $E$ . Then,  $A = Df(x_0) : E \rightarrow E'$  for some Banach space  $E'$ . Since  $A$  is a star Fredholm operator, we can write  $x_0 = (p_0, q_0) \in E_1 \times \ker A = E$ . Thus, the Gateaux-star derivative  $D_1 f(p, q) : E_1 \rightarrow E$  maps  $E_1$  injectively onto a closed subspace of  $E$  for all  $(p, q)$  sufficiently close to  $(p_0, q_0)$ . From the generalized implicit function theorem of [1], we know there is a star-neighborhood  $U_1 \times U_2 \subset E_1 \times \ker A$  of  $(p_0, q_0)$  such that  $D_2$  is compact and if  $q \in U_2$ ,  $f$  restricted to  $U_1 \times q$  is a homeomorphism onto its image. Since  $f$  is locally proper by assumption, the critical points of  $f$  (which by assumption there is at least one) are closed.

□

## 4 Conclusions

This paper provided a generalised Sard Theorem and Preimage Theorem which are mathematical tools widely used in economic theory to study the structure of the equilibrium set. Through our approach, this tool can be used

in situations where the spaces involved might have a positive cone with an empty interior.

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