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**TWO SIMPLE PROOFS OF THE FEASIBILITY
OF THE LINEAR TRACING PROCEDURE**

By P. Jean-Jacques Herings

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Two Simple Proofs of the Feasibility of the Linear Tracing Procedure

P. Jean-Jacques Herings *

Abstract

Theories of equilibrium selection in non-cooperative games, as well as the notion of risk dominance, depend heavily on the so-called linear tracing procedure. The only proof for the feasibility of the linear tracing procedure is given in Schanuel, Simon, and Zame (1991). They show by means of heavy mathematical machinery that the so-called logarithmic tracing procedure selects a unique Nash equilibrium for every game. Using that result it can be shown by means of a straightforward limit argument that the linear tracing procedure is feasible. In this paper we give two direct, simple proofs of the feasibility of the linear tracing procedure. The first one utilizes a result that is related to Kakutani's fixed point theorem and that is an extension of Browder's fixed point theorem. The second proof shows that it is even possible to avoid the use of correspondences.

Keywords: Non-cooperative game theory, tracing procedure, equilibrium selection, Browder's fixed point theorem.

JEL codes: C72

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1 Introduction

The existence of multiple Nash equilibria is a common feature of many non-cooperative N -person games. Sometimes it is possible to reduce this multiplicity of equilibria using some refinement of the concept of Nash equilibrium. However, even when using some refinement of the Nash equilibrium concept, there exists a large class of games having many equilibria that cannot be ruled out.

The equilibrium selection theory as presented in Harsanyi and Selten (1988) has the nice feature that it selects a unique Nash equilibrium for every game. To a large extent the Harsanyi-Selten theory is based on the linear tracing procedure, a mathematical procedure introduced in Harsanyi (1975) that yields a unique Nash equilibrium for almost every game. To select also a unique equilibrium for the remaining measure zero set of games, Harsanyi and Selten use a construct called the logarithmic tracing procedure. The linear tracing procedure is used repeatedly in their equilibrium selection theory to find a unique solution of so-called basic games and to define risk-dominance relationships between Nash equilibria. These risk dominance relationships play also an important role in evolutionary game theory. The linear tracing procedure is also used in other theories of equilibrium selection that are usually closely related to the ideas of Harsanyi and Selten (1988) and that are applied to several interesting economic models, see for instance van Damme (1996), and van Damme and Hurkens (1996).

The linear tracing procedure models a process of convergent expectations by which rational players will come to adopt and expect each other to adopt on a particular Nash equilibrium as a solution for a given game. Before applying the tracing procedure, every player has a subjective probability distribution expressing his expectation about the strategy choices of the other players. This subjective probability distribution is called a prior. In the naive Bayesian approach all players would choose best replies to their priors and would in this way reach a strategy combination that does not constitute a Nash equilibrium in general. In the linear tracing procedure the information on the best replies is only gradually fed back into the expectations of the players. As the linear tracing procedure proceeds, both the priors and their best responses will gradually change until both converge to some Nash equilibrium of the game.

The linear tracing procedure is formally defined as the solution to a system of equations being a homotopy. If the set of solutions to this homotopy connects the prior to at least one Nash equilibrium, then the linear tracing procedure is said to be feasible. The only proof of feasibility of the linear tracing procedure is given in Schanuel, Simon, and Zame (1991). To show the feasibility of the linear tracing procedure, they show first in an ingenious way that the logarithmic tracing procedure connects the prior beliefs to exactly one Nash

equilibrium.¹ From this result, the feasibility of the linear tracing procedure follows by an easy limit argument. The proofs related to the logarithmic tracing procedure are very long and use heavy mathematical machinery from the field of algebraic geometry.

We show that if one is only interested in the feasibility of the linear tracing procedure, then there is no need to invoke the logarithmic tracing procedure. Indeed, we will give two very short proofs of the feasibility of the linear tracing procedure that do not involve the logarithmic tracing procedure and that are based on theorems related to Brouwer's fixed point theorem and Kakutani's fixed point theorem, known as Browder's fixed point theorem and an extension of it given by Mas-Colell (1974). The second proof combines the idea of the first proof with the satisficing principle as introduced in Geanakoplos (1996). In this way it is even possible to avoid working with correspondences. These short proofs lead to more insight into the functioning of the linear tracing procedure and may be helpful for computational purposes.

2 Preliminaries

For $m \in \mathbb{N}$, let I_m denote the set of integers $\{1, \dots, m\}$, let $\mathbb{R}_+^m$ be the non-negative orthant of the m -dimensional Euclidean space, $\mathbb{R}_+^m = \{x \in \mathbb{R}^m \mid x_i \geq 0, \forall i \in I_m\}$, and let Δ^m denote the $(m - 1)$ -dimensional unit simplex, $\Delta^m = \{x \in \mathbb{R}_+^m \mid \sum_{i \in I_m} x_i = 1\}$.

Consider a non-cooperative N -person normal form game $\Gamma = (\Phi_1, \dots, \Phi_N, R_1, \dots, R_N)$. Each player $i \in I_N$ has M_i pure strategies that are numbered, so pure strategy $k \in I_{M_i}$ is denoted by (i, k) , and Φ_i denotes the set of pure strategies of player i . The total number of strategies is given by $M = \sum_{i \in I_N} M_i$. The set of all pure strategy combinations is given by $\Phi = \prod_{i \in I_N} \Phi_i$. The function $R_i : \Phi \rightarrow \mathbb{R}$ denotes the payoff function of a player i and it is extended in the standard way to the set of all mixed strategy combinations $\Delta = \prod_{i \in I_N} \Delta^{M_i}$. Here we identify all probability distributions on Φ_i with Δ^{M_i} , where for $s_i \in \Delta^{M_i}$ the probability assigned to pure strategy (i, k) is given by s_{ik} . Given a mixed strategy combination $s \in \Delta$ and a mixed strategy $\bar{s}_i \in \Delta_i$, we denote by $s \setminus \bar{s}_i$ the mixed strategy combination that results from replacing s_i by $\bar{s}_i$.

For the remainder of the paper, some game Γ is assumed to be given. A mixed strategy combination $s \in \Delta$ is said to be a Nash equilibrium of Γ if it is a best reply against itself. The set of Nash equilibria of a game Γ is denoted by $\text{NE}(\Gamma)$. Moreover, a subjective probability distribution $p \in \Delta$, called the prior, is given for the remainder of this paper. The prior describes the initial beliefs of all players about the strategies played by the other players. For every $t \in [0, 1]$, the linear tracing procedure generates a Nash equilibrium of

¹This is the result aimed at by Schanuel, Simon, and Zame (1991). The feasibility of the linear tracing procedure can be seen as a by-product of this result.

the game $\Gamma^t = (\Phi_1, \dots, \Phi_N, H_1^t, \dots, H_N^t)$, where the payoff function $H_i^t : \Delta \rightarrow \mathbb{R}$ of player i is defined by

$$H_i^t(s) = tR_i(s) + (1-t)R_i(p \setminus s_i).$$

The game Γ^0 corresponds to a trivial game, where all players believe that all their opponents play with probability 1 according to the prior beliefs. The game Γ^1 coincides with the game Γ . A best response against a strategy combination $s \in \Delta$ in the game Γ^t corresponds to a best response against the probability distribution $t[s] + (1-t)[p]$ in the game Γ . The latter probability distribution does not necessarily belong to Δ , since it is not necessarily an uncorrelated strategy combination.

The linear tracing procedure links a Nash equilibrium to the game Γ^0 , i.e. a mixed strategy combination consisting of best responses against the prior beliefs, to a Nash equilibrium of Γ^1 . Let $\mathcal{L}$ denote the set of all Nash equilibria related to the games Γ^t , $t \in [0, 1]$, so

$$\mathcal{L} = \{(t, s) \in [0, 1] \times \Delta \mid s \in \text{NE}(\Gamma^t)\}.$$

The linear tracing procedure is said to be feasible if there exists a continuous function $\gamma : [0, 1] \rightarrow \mathcal{L}$, i.e. a path, such that $\gamma(0) \in \mathcal{L} \cap (\{0\} \times \Delta)$ and $\gamma(1) \in \mathcal{L} \cap (\{1\} \times \Delta)$.

The set $\mathcal{L}^0 = \{(t, s) \in [0, 1] \times \Delta \mid t = 0, s \in \text{NE}(\Gamma^0)\}$ is obviously connected. In fact, it is a polytope. To show that the linear tracing procedure is feasible, it is sufficient to show that the component, that is a maximally connected subset, of $\mathcal{L}$ containing $\mathcal{L}^0$ intersects the set $\{1\} \times \Delta$. This component is denoted by $\mathcal{L}^c$. Indeed, since $\mathcal{L}$ is a set that can be described by a finite number of polynomial inequalities, all its components are path-connected, see Schanuel, Simon, and Zame (1991).

3 Two Proofs of Feasibility of the Linear Tracing Procedure

The key observation to give a simple proof of the feasibility of the linear tracing procedure is that one can use Browder's fixed point theorem as formulated in Browder (1960).

Theorem 3.1 (Browder's fixed point theorem)

Let S be a non-empty, compact, convex subset of $\mathbb{R}^m$ and let $f : [0, 1] \times S \rightarrow S$ be a continuous function. Then the set $F = \{(\lambda, x) \in [0, 1] \times S \mid x = f(\lambda, x)\}$ contains a connected set F^c such that $(\{0\} \times S) \cap F^c \neq \emptyset$ and $(\{1\} \times S) \cap F^c \neq \emptyset$.

Our second proof will avoid working with correspondences and uses only Theorem 3.1. For the first proof we need the following generalization of Theorem 3.1, which is a special case

of a result proved in Mas-Colell (1974).

Theorem 3.2 (Mas-Colell's fixed point theorem)

Let S be a non-empty, compact, convex subset of $\mathbb{R}^m$ and let $\varphi : [0, 1] \times S \rightarrow S$ be an upper hemi-continuous correspondence. Then the set $F = \{(\lambda, x) \in [0, 1] \times S \mid x \in \varphi(\lambda, x)\}$ contains a connected set F^c such that $(\{0\} \times S) \cap F^c \neq \emptyset$ and $(\{1\} \times S) \cap F^c \neq \emptyset$.

Theorem 3.3

Let $\Gamma = (\Phi_1, \dots, \Phi_N, R_1, \dots, R_N)$ be a non-cooperative N -person game and let $p \in \Delta$ be the prior. Then the linear tracing procedure is feasible.

Proof I

Let the correspondence $\beta_i : [0, 1] \times \Delta \rightarrow \Delta^{M_i}$ be defined by

$$\beta_i(t, s) = \{s_i^* \in \Delta^{M_i} \mid tR_i(s \setminus s_i^*) + (1-t)R_i(p \setminus s_i^*) \geq tR_i(s \setminus \bar{s}_i) + (1-t)R_i(p \setminus \bar{s}_i), \forall \bar{s}_i \in \Delta^{M_i}\}.$$

Since β_i is obtained by maximizing a continuous function in t and s over the compact set Δ^{M_i} it follows by the maximum theorem that β_i is upper hemi-continuous. The correspondence $\varphi : [0, 1] \times \Delta \rightarrow \Delta$ defined by $\varphi(t, s) = \prod_{i \in I_N} \beta_i(t, s)$, $\forall (t, s) \in [0, 1] \times \Delta$, satisfies the conditions of Mas-Colell's fixed point theorem and so there is a component F^c of $F = \{(t, s) \in [0, 1] \times \Delta \mid s \in \varphi(t, s)\}$ such that $(\{0\} \times \Delta) \cap F^c \neq \emptyset$ and $(\{1\} \times \Delta) \cap F^c \neq \emptyset$. Obviously, $F = \mathcal{L}$ and $F^c = \mathcal{L}^c$. The result now follows from the observation that $\mathcal{L}$ is defined by a finite number of polynomial inequalities, and therefore the components and path-components of $\mathcal{L}$ coincide, see for instance Schanuel, Simon, and Zame (1991).

Q.E.D.

Combining the idea of the first proof with the approach used in Geanakoplos (1996), it is even possible to use Browder's fixed point theorem only and to avoid the use of correspondences. Geanakoplos's idea is to replace the maximizing principle used in the definition of β_i by the so-called satisficing principle. The satisficing principle means that instead of using the best response correspondence β_i it is sufficient to use a function that assigns to t and a mixed strategy combination s a mixed strategy that gives a player if possible a higher payoff than s_i , but not necessarily a maximal payoff.

Proof II

Let the function $\sigma_i : [0, 1] \times \Delta \rightarrow \Delta^{M_i}$ be defined by

$$\sigma_i(t, s) = \arg \max_{\bar{s}_i \in \Delta^{M_i}} tR_i(s \setminus \bar{s}_i) + (1-t)R_i(p \setminus \bar{s}_i) - \|\bar{s}_i - s_i\|^2,$$

where $\|\cdot\|$ denotes the Euclidean norm. Obviously, σ_i is a continuous function since the penalty $-\|\bar{s}_i - s_i\|^2$ is strictly concave in $\bar{s}_i$. The function $f : [0, 1] \times \Delta \rightarrow \Delta$ defined by

$f(t, s) = (\sigma_1(t, s), \dots, \sigma_N(t, s))$, $\forall (t, s) \in [0, 1] \times \Delta$, satisfies the conditions of Browder's fixed point theorem and so there is a component F^c of $F = \{(t, s) \in [0, 1] \times \Delta \mid s = f(t, s)\}$ such that $(\{0\} \times \Delta) \cap F^c \neq \emptyset$ and $(\{1\} \times \Delta) \cap F^c \neq \emptyset$. Using exactly the same arguments as Geanakoplos (1996) it follows that $F = \mathcal{L}$ and $F^c = \mathcal{L}^c$. Indeed, let $(\bar{t}, \bar{s}) \in F^c$ and suppose for some $s_i \in \Delta^{M_i}$, $H_i^t(\bar{s} \setminus s_i) - H_i^t(\bar{s}) = h > 0$. Linearity of H_i^t in s_i implies that, for $0 < \varepsilon < 1$, $H_i^t(\bar{s} \setminus \varepsilon s_i + (1 - \varepsilon)\bar{s}_i) - H_i^t(\bar{s}) = \varepsilon h > 0$ while $\|(\varepsilon s_i + (1 - \varepsilon)\bar{s}_i) - \bar{s}_i\|^2 = \varepsilon^2 \|s_i - \bar{s}_i\|^2 < \varepsilon h$, for small enough ε . This contradicts the definition of σ_i . Now the result follows again from the observation that $\mathcal{L}$ is defined by a finite number of polynomial inequalities, and therefore the components and path-components of $\mathcal{L}$ coincide. Q.E.D.

Proof II implies that all major existence theorems in cooperative game theory, non-cooperative game theory, and general equilibrium theory can be shown without using correspondences and by means of constructions whose fixed points are the points of interest. The latter property is useful for computational purposes. Besides Brouwer's fixed point theorem, or results related to it like Browder's fixed point theorem, no heavy mathematical tools are needed. For the existence of core elements in an N -person cooperative non-transferable utility game such a construction is given in Herings (1996). For the existence of pure strategy Nash equilibria in non-cooperative N -person games with compact convex strategy sets² and the existence of Walrasian equilibria in an Arrow-Debreu economy under assumptions similar to those of Debreu (1959), see Geanakoplos (1996). Finally, for the feasibility of the linear tracing procedure in non-cooperative N -person games, one can use the construction of the second proof.

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