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Abstract

The unique *point-rationalizable* solution of a game is the unique Nash equilibrium. However, this solution has the additional advantage that it can be justified by the epistemic assumption that it is Common Knowledge of the players that only best responses are chosen. Thus, games with a unique *point-rationalizable* solution allow for a plausible explanation of equilibrium play in *one-shot* strategic situations, and it is therefore desireable to identify such games. In order to derive sufficient and necessary conditions for unique *point-rationalizable* solutions this paper adopts and generalizes the *contraction-property* approach of Moulin (1984) and of Bernheim (1984). Uniqueness results obtained in this paper are derived under fairly general assumptions such as games with arbitrary metrizable strategy sets and are especially useful for complete and bounded, for compact, as well as for finite strategy sets. As a mathematical side result existence of a unique fixed point is proved under conditions that generalize a fixed point theorem due to Edelstein (1962).

Keywords: Uniqueness, Existence, Point-Rationalizability, Nash Equilibrium, Fixed Point Theorem, Cournot Competition

JEL Classification Numbers: C62, C72.

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1 Introduction

This paper explores mathematical conditions that are sufficient and necessary for the existence of unique *point-rationalizable* solutions of strategic games. *Point-rationalizability* (cf. Bernheim 1984, Moulin 1984, and Pearce 1984) belongs to the class of *iterative solution concepts* as an alternative to *equilibrium solution concepts* for the solution of strategic games. However, games with a unique *point-rationalizable* solution are especially attractive from the *equilibrium approach's* perspective as well: a unique *point-rationalizable* solution is not only the unique Nash equilibrium of the game but the epistemic interpretation of *point-rationalizability* provides also a plausible justification for equilibrium play even if this game is only played in *one-shot* strategic situations. Moulin (1984) and Bernheim (1984) present sufficient conditions for a unique *point-rationalizable* strategy that are based on contraction properties of the best response function. The findings of this paper extend Bernheim's and Moulin's uniqueness results with respect to contraction properties of the best response function and to the generality of considered strategy sets.

Equilibrium concepts presume that players' strategy choices are an equilibrium point in the sense of Nash (1950). Presuming that each player forms expectations (beliefs) about the play of her opponents a Nash equilibrium can be interpreted as a strategy profile such that each player's expectation is confirmed by the actual strategy choices of her opponents. When a game is repeated over and over some *learning mechanism* may be regarded as a justification for equilibrium play; however, for games that are just *one-shot* strategic situations (or that are not repeated very often) the question of how players shall be able to form correct expectations about their opponents' strategy choices may be difficult to answer.

Iterative concepts try to solve a game via elimination of sequentially *unreasonable* strategies. As a particular iterative solution concept *point-rationalizability* starts out with the assumption that a player will not choose a strategy which is not a best response to any strategy profile of her opponents. If this assumption results in an elimination of strategies the complexity of the problem is reduced. In the next step strategies are eliminated that are not best responses to some strategy profile that survived the first elimination round, and so forth. If this process converges to some nonempty set of strategies such that every strategy in this set is a best response to another strategy in this set, these remaining strategies are labeled as *point-rationalizable.* This process of *iterated elimination of strategies which are not best-responses* can be understood as a formal description of a player's internal process of reasoning under the epistemic assumption that it is *common knowledge of the players that only best responses are chosen* (cf. Pearce

1984, Tan and Werlang 1988, Guesnerie 2002). Consequently, under the assumption that each player engages exactly in this process of internal reasoning the set of *point-rationalizable* strategies describes a solution of the game that does neither require correct ex-ante beliefs nor any learning from previous play.

For games with a unique *point-rationalizable* solution the *point-rationalizable* strategy coincides with the unique Nash equilibrium of this game. As a consequence a good answer can be given for these particular games to the equilibrium approach's problem of how players might arrive in *one-shot* strategic situations at correct expectations about their opponents' strategy choices: The players just have to engage in the internal process of reasoning, as presumed by the *point-rationalizability* approach, and will then end up with correct expectations about their opponents' strategy choices.

Bernheim (proposition 5.5 in Bernheim 1984) derives a sufficiency condition for unique *point-rationalizable* strategies which states that a *point-rationalizable* strategy is unique if the best response function is a contraction mapping in the Euclidean metric with a sufficiently fast contraction whereby the speed of the contraction has to increase in the number of players, $\#I$, of a given game. In particular, the contraction speed of the best response function $f : S \rightarrow S$ is characterized by the following formula whereby the strategy set S is a compact subset of $\mathbf{R}^n$ and $d(s,t) = \|s-t\|_2$, $s, t \in S$, denotes the Euclidean metric

$$d(f(s), f(t)) < \frac{d(s,t)}{\sqrt{(\#I-1)}}$$

The proof of Theorem 4 in Moulin (1984) reveals that - independent of the number of players - a contraction of the best-response function in the supremum norm implies a unique *point-rationalizable* strategy if the individual strategy sets S_i, $i \in I$, are compact and convex subsets of $\mathbf{R}$.

This paper extends these existing uniqueness results in several respects. As a first result (Theorem 1) we identify mathematical conditions that are sufficient for a unique *point-rationalizable* solution in games with arbitrary metrizable strategy sets. For compact strategy sets we characterize (Theorem 2) uniqueness of the *point-rationalizable* solution by a sufficient and necessary condition. We define then the mathematical concept of *T-contractivity* (respectively, *T-contraction*) such that a best response function is *T-contractive* if and only if the distance between strategy profiles which obtain from a T-fold application of the best response function is smaller than the distance between its arguments. We show that *T-contractivity* (respectively, *T-contraction*) of the best response function is a sufficient uniqueness condition for compact (respectively, complete and bounded) strategy sets (Theorem 3, respectively, Theorem 5). Moreover, if the strategy set of a game is finite *T-contractivity* is a sufficient and necessary uniqueness condition (Theorem 4).

For games with differentiable individual best response functions and compact real-valued individual strategy sets we derive properties of the first-order partial derivatives of the individual best response functions that verify (Theorem 6) uniqueness of the *point-rationalizable* solution. Furthermore, we will apply these findings to an economic problem raised by Bernheim (1984): Bernheim observes that virtually every output-decision becomes *point-rationalizable* in a classical model of Cournot competition - possessing a unique Nash equilibrium - if there are at least three competitors. Our result demonstrates that Bernheim's pessimistic result does not necessarily apply when we admit marginal changes in a firm's presumed inverse demand function. In our model of Cournot competition between three firms *1-contractivity* is not satisfied, however, we can establish uniqueness of the point-rationalizable solution by showing *2-contractivity* of the best response function. Thus, our model of Cournot competition also demonstrates an applicational advantage that arises from the generalization of uniqueness conditions from simple *contractivity*, i.e., $T = 1$, to general *T-contractivity* with $T \geq 1$.

A result by Milgrom and Roberts (the second corollary at p. 1266 in Milgrom and Roberts 1990) implies an alternative uniqueness condition for *point-rationalizable* solutions: The *point-rationalizable* solution of a *supermodular* game is unique if and only if the Nash equilibrium is unique. Thus, for *supermodular games* the existence of a unique fixed point of the best response correspondence is sufficient for a unique *point-rationalizable* solution, which is not true for strategic games in general. Since the uniqueness conditions of this paper entail unique fixed points, they can be applied to *supermodular games* for establishing unique *point-rationalizable* solutions. In this context it may be of interest that we generalize a fixed point theorem due to Edelstein (1962) by showing that a *T-contractive* mapping on a compact set has a unique fixed point for any $T \geq 1$ and not only for $T = 1$ (cf. remark 2 in section 3).

Supermodular games (cf. Topkis 1979, Vives 1990, Milgrom and Roberts 1990) have to satisfy rather strong conditions: strategy sets are *complete lattices*, the utility functions are *supermodular* and they exhibit *increasing differences*. In contrast, our uniqueness conditions refer only to properties of the best response function whereas no assumptions with respect to utility functions are imposed. Our uniqueness conditions are therefore also applicable to non-*supermodular* games such as games with decreasing best response functions (e.g., Cournot competition with more than two firms, cf. Theorem 4.2. (iii) in Vives 1990). However, the unique *point-rationalizable* solution of a *supermodular game* has the advantage to coincide with the unique strategy that survives *iterated elimination of strongly dominated strategies*. In the concluding section 6 we explain why this coincidence is desirable and we mention possible extensions of this paper's uniqueness conditions to other iterated solution concepts than *point-rationalizability*.

The remainder of this paper is organized as follows. In section 2 we introduce basic definitions and observations. The main uniqueness results are presented in section 3, and in section 4 we derive further results under the assumption that the best response functions are differentiable on compact real-valued strategy sets. We apply in section 5 the findings of section 4 to demonstrate uniqueness of the *point-rationalizable* solution in a model of Cournot competition with three firms. Finally, section 6 concludes by relating this paper's uniqueness results to other iterative solution concepts.

2 Notation, Preliminaries

For a finite set of players, I, let $G = (S_i, f_i)_{i \in I}$ denote a game in *normal form* with S_i as individual strategy set of player i. Furthermore, $f_i : S_{-i} \to 2^{S_i}$ denotes the individual best response correspondence such that f_i maximizes player i's preference ordering over $S_i \times S_{-i}$. If all individual best response correspondences are single-valued we call $f : S \to S$ with $f(s) = \times_{i=1}^{I} f_i(s_{-i})$ the best response function of G and we write $s = f(t)$ instead of $s \in f(t)$.

Definition. *(*Bernheim 1984, Moulin 1984, Pearce 1984*)*
The set of point-rationalizable strategies of a game G is given by

$$P(G) = \bigcap_{k=0}^{\infty} \lambda^k(S)$$

such that

$$\lambda^k(S) = \bigcup_{s \in \lambda^{k-1}(S)} f(s)$$

and $\lambda^0(S) = S$.

Whenever $P(G)$ is a singleton, i.e., there exists a unique *point-rationalizable* strategy, we speak of a unique *point-rationalizable* solution of G. For a given best response function f fix now some $k \in \mathbf{N}$ and define inductively the function $f^k : S \to S$ by $f^k(s) = f\left(f^{k-1}(s)\right)$ with $f^0(s) = s$. The following result is easily verified:

Observation 1. *Given a game G with a best response function f. If $s = f^k(s)$ for some $k \geq 1$ then*

$$s, f(s), ..., f^{k-1}(s) \in P(G)$$

Thus, while a Nash equilibrium of G is by definition a fixed point of the best response function f, i.e., of f^k with $k = 1$, each fixed point of any function f^k with $k \geq 1$ is a *point-rationalizable* strategy of G.

Observation 2. *If there exists unique point-rationalizable strategy s^* of a game G then s^* is also the unique Nash equilibrium of G.*

Proof: If s^* is a *point-rationalizable* strategy then $s^* \in \lambda^k(S)$ for all $k \in \mathbf{N}$. Moreover, there must exist some strategy $s \in \lambda^k(S)$ for all $k \in \mathbf{N}$ such that $s^* \in f(s)$, which implies $s \in P(G)$, i.e., s is also a *point-rationalizable* strategy. Because there exists by assumption a unique *point-rationalizable* strategy we must have $s^* = s$ and therefore $s^* \in f(s^*)$, i.e., s^* is a Nash equilibrium. By Observation 1 this Nash equilibrium is unique.□

3 Main Results

Throughout this section we presume that the strategy set S can be described as a subset of a metric space (X, d) for some given metric $d : X \times X \to \mathbf{R}_+ \cup +\infty$. Before we proceed recall that the *diameter* of some subset A of the metric space (X, d) is defined by

$$diam(A) = \sup\{d(s,t) : s, t \in A\}$$

Theorem 1. *Given a game G such that*
(A1) There exists a continuous best response function f.
(A2) S is a nonempty subset of some metric space (X, d).
Then there exists a unique point-rationalizable strategy s^* of G if
(i) $\lim_{k\to\infty} f^k(s) = s^*$ for some $s \in S$, and
(ii) $\lim_{k\to\infty} diam(\lambda^k(S)) = 0$.

Proof: Continuity of f on $S \subset (X, d)$ and condition (i) imply

$$\lim_{k\to\infty} f^{k+1}(s) = \lim_{k\to\infty} f\left(f^k(s)\right) = f(s^*)$$

Moreover

$$\lim_{k\to\infty} f^{k+1}(s) = \lim_{k\to\infty} f^k(s) = s^*$$

and therefore

$$s^* = f(s^*)$$

Thus, $P(G)$ is nonempty by Observation 2 since s^* is a fixed point of f.

Suppose now on the contrary that $s^*, t^* \in P(G)$ with $s^* \neq t^*$, i.e., $diam(P(G)) > 0$. Since $P(G) \subset \lambda^k(S)$ for all $k \in \mathbf{N}$ we obtain

$$\lim_{k\to\infty} diam\left(\lambda^k(S)\right) \geq diam(P(G)) > 0$$

A contradiction to condition (ii).□

Theorem 2. *Given a game G such that*

(A1) There exists a continuous best response function f.

(A2') S is a nonempty and compact subset of some metric space (X, d).

Then there exists a unique point-rationalizable strategy of G if and only if

$$\lim_{k\to\infty} d\left(f^k(t), f^k(s)\right) = 0$$

for all $s, t \in S$.

Proof: Observe at first that each set $\lambda^k(S)$, $k \geq 0$, is compact and nonempty because continuity of f inherits compactness and nonemptiness. Since $\lambda^k(S) \subset \lambda^{k-1}(S)$ for all $k \in \mathbf{N}$, $P(G)$ is compact and nonempty as an infinite intersection of compact and nonempty nested sets, (cf. Theorem 2.36 and the corollary in Rudin 1976, p.38). Moreover,

$$\begin{aligned} diam(P(G)) &= \max_{s,t\in P(G)} d(s,t) \\ &= d(s^*, t^*) \end{aligned}$$

for some $s^*, t^* \in P(G)$. By continuity of d there exist $s, t \in S$ with $\lim_{k\to\infty} f^k(s) = s^*$ and $\lim_{k\to\infty} f^k(t) = t^*$ such that

$$\lim_{k\to\infty} d\left(f^k(s), f^k(t)\right) = d(s^*, t^*)$$

The assumption $\lim_{k\to\infty} d\left(f^k(s), f^k(t)\right) = 0$ implies then $diam(P(G)) = 0$, i.e., $P(G)$ is singlevalued. The only-if part is obvious.□

Definition. *Fix some $T \in \mathbf{N}$.*

The best response function f is said to be T-contractive if f^T is contractive, i.e., $d\left(f^T(s), f^T(t)\right) < d(s,t)$ for all $s, t \in S$ with $s \neq t$.

The best response function f is said to be a T-contraction if f^T is a contraction, i.e., there exists some $c \in (0,1)$ such that $d\left(f^T(s), f^T(t)\right) \leq c * d(s,t)$ for all $s, t \in S$

.

Theorem 3. *Given a game G such that*

(A1) There exists a continuous best response function f.

(A2') S is a nonempty and compact subset of some metric space (X, d).

Then there exists a unique point-rationalizable strategy of G if the best response function f is T-contractive.

Proof: Proceed as in the proof of Theorem 2 and observe that there exist $s, t \in S$ with $\lim_{k\to\infty} f^k(s) = s^*$ and $\lim_{k\to\infty} f^k(t) = t^*$ such that

$$\begin{aligned} \lim_{k\to\infty} d\left(f^k(s), f^k(t)\right) &= d(s^*, t^*) \\ d(s^*, t^*) &= diam\,(P(G)) \end{aligned}$$

Continuity of f implies continuity of f^T and we have therefore

$$\lim_{k\to\infty} d\left(f^T\left(f^k(s)\right), f^T\left(f^k(t)\right)\right) = d\left(f^T(s^*), f^T(t^*)\right)$$

Since $f^T(s^*), f^T(t^*) \in P(G)$ we obtain

$$d(f(s^*), f(t^*)) \leq diam\,(P(G)) = d(s^*, t^*)$$

which is a contradiction to *T-contractivity* whenever $d(s^*, t^*) \neq 0$. Thus, $P(G)$ must be singlevalued.□

Theorem 4. *Given a game G such that*

(A1') There exists a best response function f.

(A2") S is nonempty and finite.

Then there exists a unique point-rationalizable strategy of G if and only if

$$f^m(s) = f^m(t)$$

for all $s, t \in S$ whereby $m = \#S$.

Proof: Delegated to the appendix.

Theorem 5. *Given a game G such that*

(A1) *There exists a continuous best response function f.*

(A2"') *S is a nonempty, bounded, and complete subset of some metric space (X, d).*

Then there exists a unique point-rationalizable strategy of G if the best response function f is a T-contraction.

Proof: Delegated to the appendix.

Remark 1. At first glance the assumption of a best response function, i.e., a single-valued best response correspondence, appears as a severe restriction for the application of the obtained uniqueness results. However, these uniqueness results extend immediately to any game with a multi-valued best response correspondence such that this best response correspondence reduces after finitely many elimination-rounds (according to the definition of *point-rationalizability*) to a best response function for the remaining strategies.

Remark 2. In the proof of Theorem 5 (see appendix) we assure existence of *point-rationalizable* strategies by a fixed point theorem due to Bonsall (cf. Theorem 1.3 in Bonsall 1962) which is basically an extension of the famous Banach fixed point theorem from *1-contractions* to *T-contractions*. In contrast, the proofs of Theorem 1-4 include, respectively imply, their own fixed point theorems. For example, Theorem 3, combined with Observation 2, establishes the existence of a unique fixed point for *T-contractive* functions on compact sets. This result generalizes a fixed point theorem of Edelstein (cf. Remark 3.1. in Edelstein 1962, and Theorem 1.6 in Bonsall 1962) who proves the existence of a unique fixed point for *1-contractive* functions on compact sets.

4 Differentiable Best Response Functions

In this section we exploit the fact that for continuously differentiable individual best response functions *T-contraction* of f can be verified by conditions imposed on the partial derivatives of f^T.

Theorem 6. *Given a game G such that*
(A1") Each S_i is a nonempty, compact, and convex subset of $\mathbf{R}$.
(A2"") Each individual best response function f_i is continuously differentiable.
Then there exists a unique point-rationalizable strategy of G
(i) if for each player i

$$\sum_{j \in I} \left| \frac{\partial f_i^T}{\partial s_j}(s) \right| < 1 \tag{1}$$

for all $s \in S$, for some $T \geq 1$, or *(ii) if for each player j*

$$\sum_{i \in I} \left| \frac{\partial f_i^T}{\partial s_j}(s) \right| < 1 \tag{2}$$

for all $s \in S$*, for some* $T \geq 1$*.*

Proof: Delegated to the appendix.

Remark 1. The uniqueness conditions (i) and (ii) of Theorem 6 represent special applications of the mean-value inequality for functions $f^T : \mathbf{R}^n \to \mathbf{R}^n$, i.e.,

$$\left\| f^T(s) - f^T(t) \right\| \leq \left| Df^T(r) \right|_M * \|s - t\|$$

whereby $Df^T(r) = \left(\frac{\partial f_i^T}{\partial s_j}(r) \right)_{i=1,\ldots,I; j=1,\ldots I}$ denotes the matrix of first-order partial derivatives and $r \in S$ maximizes some matrix-norm $|\cdot|_M$ over the elements in

$$\{\lambda s + (1 - \lambda) t \mid \lambda \in [0, 1]\}$$

which is compatible with the norm $\|\cdot\|$. For example, condition (1) implies *T-contraction* of f in the *supremum norm* $\|\cdot\|_\infty$ because the *absolute row-sum norm* of a matrix is compatible with the *supremum norm* $\|\cdot\|_\infty$. Analogously, the condition (2) is implied by the fact that the *absolute column-sum norm* of a matrix is compatible with the *absolute value norm* $\|\cdot\|_1$. Consequently, whenever there is a compatible matrix-norm $|\cdot|_M$ for some norm $\|\cdot\|$ (with $S \subset (X, d)$ and $d(s, t) = \|s - t\|$) such that $\left| Df^T(r) \right|_M < 1$ for some $T \geq 1$, then uniqueness of the *point-rationalizable* solution is established. As another example for a *compatible matrix-norm* observe that the *spectrum norm* of a matrix, given by

$$\left| Df^T(r) \right|_M = \max Eigenvalue \left(Df^T(r) * \left(Df^T(r) \right)^{trans} \right)$$

is compatible with the Euclidean norm $\|\cdot\|_2$. Thus, whenever the maximal singular value of $Df^T(r)$ is strictly smaller than 1 for all $r \in S$ the *point-rationalizable* solution must be unique.

Remark 2. The uniqueness conditions (i) and (ii) of Theorem 6 are most easily verified for *1-contraction.* For $T = 1$ inequality (1) becomes

$$\sum_{j \neq i} \left| \frac{\partial f_i}{\partial s_j}(s) \right| < 1$$

for all i and all $s \in S$, and inequality (2) becomes

$$\sum_{i \neq j} \left| \frac{\partial f_i}{\partial s_j}(s) \right| < 1$$

for all j and all $s \in S$. The former of these two contraction-conditions is already implied by Theorem 4 in Moulin (1984): Moulin shows in the proof of his Theorem 4 that an equivalent formulation of this contraction-condition (in terms of second-order partial derivatives of the utility functions) guarantees a unique *point-rationalizable* strategy.

5 An Economic Example: Cournot Competition with Three Firms

A Cournot duopoly with linear inverse demand functions possesses a unique Nash equilibrium as well as a unique *point-rationalizable* strategy. However, as Bernheim (1984) observes, any output between zero and the Monopoly-output is *point-rationalizable* when we consider Cournot oligopolies with three (or more) firms despite the fact that the Nash equilibrium remains unique regardless of the number of competitors. Basu (1992) extends Bernheim's result to a large class of symmetric Cournot oligopolies by showing that a wide range of output decisions becomes *point-rationalizable* if sufficiently many firms belong to the oligopoly. Therefore, since Cournot oligopolies are the standard models in industrial organization theory for the description of output competition among firms, it is quite disappointing that *point-rationalizability* performs here rather poorly as a predictive solution concept by admitting virtually any output decision.

For the remainder of this section we focus on Bernheim's result regarding Cournot competition with three firms and demonstrate that uniqueness of the *point-rationalizable* output decision can already be established under the assumption of marginal deviations from the original model description of Cournot competition. Moreover, our model provides an example for the usefulness of *T-contractivity*, $T \geq 1$, compared to mere *1-contractivity*: the best response function will be *2-contractive* but not *1-contractive* in the *supremum* or in the *absolute value norm.*

Consider a Cournot oligopoly of three firms such that the utility function of firm $i \in \{1, 2, 3\}$ is given by

$$U_i(s) = (P_i(s_i) - c)\, s_i \tag{3}$$

with $s_i \in [0, 1]$ as output, $c \in (0, 1)$ as marginal cost, and P_i as inverse demand function of firm i. Moreover, presume the following inverse demand functions

$$\begin{aligned} P_1(s) &= P_2(s) = \max\{0, 1 - s_1 - s_2 - s_3\} \\ P_3(s) &= \max\{0, 1 - s_1 - (1 - \varepsilon)\, s_2 - s_3\} \end{aligned}$$

for some given $\varepsilon \in [0,1]$. As individual best response functions we obtain then

$$\begin{aligned} f_1(s_{-1}) &= \max\{0, 0.5(1 - s_2 - s_3 - c)\} \\ f_2(s_{-2}) &= \max\{0, 0.5(1 - s_1 - s_3 - c)\} \\ f_3(s_{-3}) &= \max\{0, 0.5(1 - s_1 - (1-\varepsilon)s_2 - c)\} \end{aligned}$$

For $\varepsilon = 0$ the standard Cournot oligopoly with linear inverse demand functions obtains for which Bernheim observes that any output decision between zero and the monopoly output, i.e., any individual strategy in the interval $\left[0, \frac{1-c}{2}\right]$, is *point rationalizable*. For example, the monopoly output is a firm's best response to zero outputs of the other firms whereas such a zero output can be vice versa justified as a firm's best response to monopoly outputs of the other firms, thereby closing the circle of *point rationalizable* reasoning.

Assume now that $\varepsilon > 0$. The output decision of firm 2 has then less impact on the demand for firm 3's product than in the original model of Cournot competition with linear inverse demand functions. Thus, we interpret ε here as a measures for the degree by which firm 2's product is not any longer a perfect substitute for firm 3's product on the market of firm 3.

Because the individual best response functions f_i are not differentiable everywhere - they have a *kink* at strategies s_{-i} where the interior and the boundary solutions of the utility maximization problem coincide - we can not immediately apply Theorem 6 to f. Consider therefore the functions $h_i : \mathbf{R} \to \mathbf{R}$, $i \in \{1,2,3\}$

$$\begin{aligned} h_1(s_{-1}) &= 0.5(1 - s_2 - s_3 - c) \\ h_2(s_{-2}) &= 0.5(1 - s_1 - s_3 - c) \\ h_3(s_{-3}) &= 0.5(1 - s_1 - (1-\varepsilon)s_2 - c) \end{aligned}$$

resulting from an unrestricted maximization of (3) over $\mathbf{R}$, and observe that *T-contractivity* of the unbounded maximizers $h = \times_{i \in I} h_i$ entails *T-contractivity* of the bounded maximizers f. Hence, we can establish *T-contractivity* of f by showing that h satisfies condition (i) or condition (ii) of Theorem 6.

Note that h is not *1-contractive* according to the conditions (i) and (ii) of Theorem 6; however, we can show *2-contraction* in the supremum norm (h^T satisfying condition (i) for $T = 2$) as well as in the absolute value norm (h^T satisfying condition (ii) for $T = 2$). To see this verify at first that the functions h_i^2, $i \in \{1,2,3\}$, are given by

$$\begin{aligned} h_1^2(s) &= 0.25(2s_1 + (1-\varepsilon)s_2 + s_3 + 2c) \\ h_2^2(s) &= 0.25(s_1 + (2-\varepsilon)s_2 + s_3 + 2c) \\ h_3^2(s) &= 0.25(\varepsilon + (1-\varepsilon)s_1 + s_2 + (2-\varepsilon)s_3 + 2c) \end{aligned}$$

It is now easy to see that, e.g., condition (ii) is satisfied since

$$\sum_{j\in I}\left|\frac{\partial h_i^2}{\partial s_j}(s)\right| \leq 1-0.25\varepsilon$$

for all i and all $s \in S$. We can therefore conclude that there exists a unique *point-rationalizable* output decision in our model of Cournot competition with three firms whenever $\varepsilon > 0$. Moreover, firm i's unique *point-rationalizable* strategy is given by its Nash equilibrium strategy

$$s_i^* = \frac{1-c}{4}$$

$i \in \{1,2,3\}$.

Remark. Recall the definition of the function h^T and observe that a partial derivative evaluated at s, $\frac{\partial h_i^T}{\partial s_j}(s)$, can be computed via successive applications of the chain-rule as follows:

$$\begin{aligned}
\frac{\partial h_i^1}{\partial s_j}(s) &= \frac{\partial h_i}{\partial s_j}(s) \\
\frac{\partial h_i^T}{\partial s_j}(s) &= \sum_{k\neq i}\frac{\partial h_i}{\partial s_k}\frac{\partial h_k^{T-1}}{\partial s_j}(s)
\end{aligned}$$

Thus, instead of first determining the entire function h_1^2 in order to derive the partial derivatives $\frac{\partial h_1^2}{\partial s_1}$, $\frac{\partial h_1^2}{\partial s_2}$, and $\frac{\partial h_1^2}{\partial s_3}$, we could have obtained these partial derivatives more easily by the following computations:

$$\begin{aligned}
\frac{\partial h_1^2}{\partial s_1}(s) &= \frac{\partial h_1}{\partial s_2}\frac{\partial h_2}{\partial s_1}(s)+\frac{\partial h_1}{\partial s_3}\frac{\partial h_3}{\partial s_1}(s) = 0.25+0.25 = 0.5 \\
\frac{\partial h_1^2}{\partial s_2}(s) &= \frac{\partial h_1}{\partial s_2}\frac{\partial h_2}{\partial s_2}(s)+\frac{\partial h_1}{\partial s_3}\frac{\partial h_3}{\partial s_2}(s) = 0+0.25\,(1-\varepsilon) = 0.25\,(1-\varepsilon) \\
\frac{\partial h_1^2}{\partial s_3}(s) &= \frac{\partial h_1}{\partial s_2}\frac{\partial h_2}{\partial s_3}(s)+\frac{\partial h_1}{\partial s_3}\frac{\partial h_3}{\partial s_3}(s) = 0.25+0 = 0.25
\end{aligned}$$

6 Concluding Remarks

In this paper we have studied uniqueness conditions for the specific iterative solution concept of *point-rationalizability*. Different iterative solution concepts differ in their definition of *unreasonable* strategies. On the one hand, *rationalizability concepts* have in common that any strategy which is not a best response to some *belief* is regarded as *unreasonable*. However, there are different definitions of relevant *beliefs*: Besides the assumption of degenerated *point-beliefs* by *point-rationalizability* we can encounter, e.g., *independent* versus *arbitrarily correlated additive beliefs* (cf. Bernheim 1984, Pearce 1984), or *non-additive beliefs* (Ghirardato and Le Breton 1997). On the other hand, *dominance solution concepts* regard a strategy as *unreasonable* if it is dominated by another strategy. Here different definitions of *domination* - e.g., weakly versus strongly dominated, or/and dominated with respect to mixed versus pure strategies (cf. Moulin 1984, Börgers 1993) - give rise to different *dominance solution concepts.*

The uniqueness conditions of this paper with regard to *point-rationalizability* do not necessarily imply uniqueness for weaker iterative solution concepts like, e.g., *correlated rationalizability* (cf. Bernheim 1984, Pearce 1984) or *iterated elimination of strongly dominated strategies.* In contrast to these weaker iterative solution concepts *point-rationalizability* may eliminate strategies that appear intuitively reasonable. Consider the following payoff-matrix of a two-player game

B

A

	beat	*bite*
allow	$2 $0	-$1Mill $1
assist	$1 $1	$1 $0
avoid	-$1Mill $0	$2 $1

To *assist* is not a best choice against any point-belief of A: if A believed that B *beats* then A would *allow*, and if A believed that B *bites* then A would *avoid.* Moreover, when we go through further iterative steps of the *point-rationalizability* concept we arrive at *(avoid, bite)* as the unique *point-rationalizable* solution of the game. However, in this example all strategies survive *iterated elimination of strongly dominated strategies* and they are even *correlated rationalizable:* Suppose A conceived *beat* and *bite* as equally likely. Then it may be reasonable for A to *assist* because she could avoid by this choice the subjectively perceived 0.5 chance of losing 1Mill. which may in turn justify B's decision to *beat...*

Despite these interpretational flaws there are three reasons why this paper's uniqueness results are interesting.

First, a unique *point-rationalizable* strategy is also the unique Nash equilibrium of the game. Thus, even when we are rather interested in equilibrium solutions, and not in iterative solutions, we can use the results of this paper to establish existence and uniqueness of Nash equilibria.

Second, as already argued in the introduction, *point-rationalizability* offers a possible explanation of how players can coordinate themselves towards equilibrium play in *one-shot* strategic situations. We think that such an explanation of equilibrium play, even if sometimes flawed, is still favorable to the mere assumption that players won't be disappointed by the actual course of play in the solution of a game.

Finally, there exist several results in the literature that identify conditions under which different iterative solution concepts are equivalent. For example, the *nice games* of Moulin (1984), i.e., games with strictly quasiconcave utility functions and convex real-valued individual strategy sets, guarantee equivalence of the *point-rationalizable* solution and of the dominance solution that results from *iterated elimination of strongly dominated strategies*. Since the *iterated elimination of strongly dominated strategies* is the weakest iterative solution concept we can think of the unique *point rationalizable* solution of a *nice game* is the unique solution of this game according to any perceivable iterative solution concept. Milgrom and Roberts (1990) show that increasing utility differences and supermodular utility functions, as assumed in so-called *supermodular games*, imply (basically) equivalence of all iterative solution concepts if the *point rationalizable* solution is unique. Furthermore, Zimper (2003) generalizes Milgrom and Roberts' result to decreasing utility differences. Thus, for games satisfying those equivalence conditions this paper's uniqueness conditions for *point-rationalizability* imply a unique solution with regard to every iterative solution concept. Moreover, because the equivalence conditions in Milgrom and Roberts (1990) and in Zimper (2003) include uniqueness of the *point-rationalizable* solution, this paper's uniqueness results contribute directly to equivalence results for iterative solution concepts.

7 Appendix: More Proofs

Proof of Theorem 4: Let d be the discrete metric, i.e., $d(s,t) = 0$ for $s = t$ and $d(s,t) = 1$ else. Obviously, if $f^m(s) = f^m(t)$ for all $s,t \in S$ then $d(f^m(s), f^m(t)) < d(s,t)$ for all $s \neq t$ since $d(f^m(s), f^m(t)) = 0$. Hence, f is *m-contractive* and there exists a unique *point-rationalizable* solution by Theorem 3. It remains to show that *m-contractivity* is also necessary for uniqueness. Consider the finite sequence

$$s, f(s), f^2(s), ..., f^m(s)$$

of $m+1$ elements and observe that this sequence must contain $f^k(s)$ and $f^h(s)$, with $k < h$, such that $f^k(s) = f^h(s)$. If $f^{m-1}(s) \neq f^m(s)$ there can not exist a unique *point-rationalizable* solution because of $f^k(s), f^{k+1}(s), ..., f^{h-1}(s), f^h(s) \in P(G)$ (cf. Observation 1). Consequently, a unique *point-rationalizable* solution requires $f^{m-1}(s) = f^m(s)$ and $f^{m-1}(t) = f^m(t)$ for any $s,t \in S$. Suppose now there exists a unique *point-rationalizable* solution and assume $f^m(s) \neq f^m(t)$ for some $s, t \in S$. But since $f^{m-1}(s) = f^m(s)$ and $f^{m-1}(t) = f^m(t)$ Observation 1 implies $f^m(s), f^m(t) \in P(G)$. Thus, the condition $f^m(s) = f^m(t)$ is necessary for uniqueness.□

Proof of Theorem 5: If S is complete then continuity and *T-contraction* of the best response function imply the existence of a (unique) fixed point $s^* = f(s^*)$ (cf. Theorem 1.3 in Bonsall 1962), i.e., $P(G)$ is nonempty. Furthermore, since S is bounded and $\lambda^k(S) \subset \lambda^{k-1}(S)$ for $k \in \mathbf{N}$, there exists for each set $\lambda^k(S)$ a finite diameter $diam\left(\lambda^k(S)\right)$. Due to $diam\left(\lambda^k(S)\right) \geq d\left(s^k, t^k\right)$ for all $s^k, t^k \in \lambda^k(S)$, *T-contraction* implies $d\left(s^{k+T}, t^{k+T}\right) \leq c * diam\left(\lambda^k(S)\right)$ for all $s^{k+T}, t^{k+T} \in \lambda^{k+T}(S)$. Observe now that

if there is some $s^{k+T}, t^{k+T} \in \lambda^{k+T}(S)$ with $d\left(s^{k+T}, t^{k+T}\right) = c * diam\left(\lambda^k(S)\right)$ then $diam\left(\lambda^{k+T}(S)\right) = c * diam\left(\lambda^k(S)\right)$, and

if $d\left(s^{k+T}, t^{k+T}\right) < c * diam\left(\lambda^k(S)\right)$ for all $s^{k+T}, t^{k+T} \in \lambda^{k+T}(S)$ then

$$diam\left(\lambda^{k+T}(S)\right) \leq c * diam\left(\lambda^k(S)\right)$$

Consequently

$$diam\left(\lambda^{k+T}(S)\right) \leq c * diam\left(\lambda^k(S)\right)$$

for $k \geq 0$ and we obtain under the assumption $c < 1$ the desired uniqueness result

$$\lim_{k\to\infty} diam\left(\lambda^k(S)\right) = \lim_{n\to\infty} diam\left(\lambda^{n*T}(S)\right) \leq \lim_{n\to\infty} c^n * diam(S) = 0$$

□

Proof of Theorem 6:

Part (i). Let $g_i(\lambda) = f_i^T(\lambda(s-t)+t)$, and observe that $g_i(\lambda)$ is continuously differentiable on $[0,1]$. The mean-value inequality for real-valued functions with a real-valued domain implies

$$|g_i(1) - g_i(0)| \leq \left|\frac{\partial g_i}{\partial \lambda}(\lambda^*)\right| * |1-0| \tag{4}$$

for some λ^* such that $\lambda^* = \arg\max_{[0,1]} \left|\frac{\partial g_i}{\partial \lambda}(\lambda)\right|$. By an application of the chain-rule:

$$\begin{aligned}
\frac{\partial g_i}{\partial \lambda}(\lambda^*) &= \sum_{j\in I} \frac{\partial f_i^T}{\partial s_j}(\lambda^*(s_j - t_j) + t_j) * (s_j - t_j) \\
\left|\frac{\partial g_i}{\partial \lambda}(\lambda^*)\right| &\leq \left|\sum_{j\in I} \frac{\partial f_i^T}{\partial s_j}(\lambda^*(s_j - t_j) + t_j)\right| * \|s-t\|_\infty
\end{aligned}$$

Substituting for the terms in inequality (4):

$$\left|f_i^T(s) - f_i^T(t)\right| \leq \left|\sum_{j \in I} \frac{\partial f_i^T}{\partial s_j}(r)\right| * \|s-t\|_\infty$$

with $r = \lambda^*(s-t)+t$. Since this is true by assumption for all $i \in I$ we obtain for the *supremum norm*

$$\left\|f^T(s) - f^T(t)\right\|_\infty \leq \left|\sum_{j \in I} \frac{\partial f_i^T}{\partial s_j}(r)\right| * \|s-t\|_\infty$$

Consequently, condition (i) of Theorem 6 implies *T-contraction* of f in the *supremum norm.*

Note that we have here *T-contraction*, and not only *T-contractivity*, because $\sum_{j \in I}\left|\frac{\partial f_i^T}{\partial s_j}(s)\right|$ is a continuous function such that it obtains a maximum on the compact set S. Consequently, if $\sum_{j \in I}\left|\frac{\partial f_i^T}{\partial s_j}(s)\right| < 1$ for all i and all $s \in S$ then there exists some $c < 1$ such that $\sum_{j \in I}\left|\frac{\partial f_i^T}{\partial s_j}(s)\right| \leq c$ for all i.

Part (ii) Let again $g_i(\lambda) = f_i^T(\lambda(s-t)+t)$, and observe that the mean-value inequality implies

$$|g_i(1) - g_i(0)| \leq \left|\frac{\partial g_i}{\partial \lambda}\left(\lambda^i\right)\right| * |1-0|$$

for some $\lambda^i = \arg\max_{[0,1]}\left|\frac{\partial g_i}{\partial \lambda}(\lambda)\right|$. By the chain-rule and substitution

$$\left|f_i^T(s) - f_i^T(t)\right| \leq \left|\sum_{j \in I} \frac{\partial f_i^T}{\partial s_j}\left(r^i\right) * (s_j - t_j)\right| \tag{5}$$

with $r^i = \lambda^i s + \left(1-\lambda^i\right)t$. Summing up over all i and rearranging

$$\begin{aligned}
\sum_{i \in I}\left|f_i^T(s) - f_i^T(t)\right| &\leq \sum_{i \in I}\left|\sum_{j \in I}\left(\frac{\partial f_i^T}{\partial s_j}\left(r^i\right)\right) * (s_j - t_j)\right| \\
\sum_{i \in I}\left|f_i^T(s) - f_i^T(t)\right| &\leq \max_{j \in I}\left\{\left|\sum_{i \in I}\left(\frac{\partial f_i^T}{\partial s_j}\left(r^i\right)\right)\right|\right\} * \sum_{j \in I}|s_j - t_j| \\
\left\|f^T(s) - f^T(t)\right\|_1 &< \|s-t\|_1
\end{aligned}$$

Where the last step follows from the assumption $\sum_{i \in I}\left(\frac{\partial f_i^T}{\partial s_j}\left(r^i\right)\right) < 1$ for all j and all $r^i \in \{\lambda s + (1-\lambda)t \mid \lambda \in [0,1]\}$. Consequently, $d\left(f^T(s), f^T(t)\right) < d(s,t)$ with d induced by the *absolute value norm.* Thus, condition (ii) of Theorem 6 implies *T-contraction* in the *absolute value norm.*□

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