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EQUILIBRIA OF A TWO-PERSON NON-ZEROSUM

NOISY GAME OF TIMING

by

Carolyn Pitchik
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September 1979
Revised January 1981

Abstract: Necessary and sufficient conditions are obtained for the existence of an equilibrium point (as well as for the existence of a dominating equilibrium point) in a two-person non-zerosum game of timing.

*The first version of this paper was written in September 1979 while the author was a Ph.D. student at the University of Toronto. This research was supported by a Natural Sciences and Engineering Research Council Canada Scholarship. The author is very grateful to Anatol Rapoport and Marc Kilgour for encouragement, suggestions and support, to Martin Osborne and two referees for constructive criticisms and suggestions and to both the Institute for Advanced Studies at the Hebrew University of Jerusalem and Cowles Foundation for Research in Economics at Yale University for providing a stimulating working atmosphere. This research was also partially supported by the Office of Naval Research, Contract Number N00014-77-C-0518.
1. Introduction

Two toothpaste manufacturers are competing for a larger share of the dentifrice market. Each is in the process of developing a new and better toothpaste. The longer one company waits to introduce its new toothpaste, the better its chances are of successfully capturing a share of the market, if its product hits the stores first. (This is assuming that the toothpaste is being technologically improved as time goes on.) Alternatively, if a company waits too long to introduce its product, then it might be too late to successfully capture any of the market. (Everyone might already be quite happy brushing with the other company's toothpaste introduced just last week!) Essentially, the problem for each company is one of choosing a time at which to introduce their particular brand of toothpaste to the public.

Two researchers are working independently on a particular problem. When to publish one's results is a big question. By publishing one's results first, one has some advantage over the other. Alternatively, by waiting until later, one can capitalize on weaknesses in the other's results.

The above examples illustrate some characteristics of a 2-person noisy game of timing which may or may not be zero-sum. Mathematically, a 2-person noisy game of timing has the following structure. The player set is \( \{P_1, P_2\} \). The pure strategy set for \( P_1 \) consists of all choices of times of action in \([0,1]\), the closed unit interval. The strategy set for \( P_1 \) then consists of all cumulative distribution functions on the closed unit interval. Let the strategy set for \( P_1 \) be denoted by \( F \). Thus \( F \in F \) if \( F \) is a right-continuous, non-negative, non-decreasing
real-valued function defined on the real line \( \mathbb{R} \) such that \( F(t) = 0 \) for \( t < 0 \) and \( F(t) = 1 \) for \( t \geq 1 \). Let the degenerate distribution with a jump of 1 at a point \( T \in [0,1] \) be denoted by \( \delta_T \). Thus

\[
\delta_T(t) = \begin{cases} 
0 & \text{for } t < T \\
1 & \text{for } t \geq T
\end{cases}
\]

or, alternatively, we may write \( \delta_T(T) - \delta_T(T-) = 1 \).

The payoff to \( P_i \), if each \( P_k \) acts according to a pure strategy \( \delta_{t_k} \), \( t_k \in [0,1] \) for \( k = 1, 2 \), is denoted by \( K_i(\delta_{t_i}, \delta_{t_j}) \) and is equal to

\[
K_i(\delta_{t_i}, \delta_{t_j}) = \begin{cases} 
L_i(t_i) & \text{if } t_i < t_j \\
\phi_i(t_i) & \text{if } t_i = t_j \\
M_i(t_j) & \text{if } t_i > t_j
\end{cases}
\]

where \( L_i \), \( \phi_i \), and \( M_i \) are real-valued functions defined on \([0,1]\).

Thus \( P_i \) receives (i) \( L_i(t_i) \), if \( P_i \) acts first at time \( t_i \),
(ii) \( \phi_i(t_i) \), if both \( P_i \) and \( P_j \) act simultaneously at time \( t_i \),
or (iii) \( M_i(t_j) \), if \( P_j \) acts first at time \( t_j \). The above game is
zero-sum if \( K_1 + K_2 = 0 \) at all times.

If \( P_1 \) and \( P_2 \) choose mixed strategies \( F_1 \) and \( F_2 \) in \( F \), then
the payoff to \( P_i \), denoted by \( K_i(F_1, F_j) \), is equal to the Lebesgue-
Stieltjes integral of the kernel \( K_i(\delta_{t_i}, \delta_{t_j}) \) with respect to the measures
\( F_1 \) and \( F_2 \), i.e.

\[
K_i(F_1, F_j) = \int_{[0,1]} K_i(\delta_{t_i}, \delta_{t_j})dF_1(t) = \int_{[0,1]} \int_{[0,t]} \{ M_i(s)dF_j(s) + \phi_i(t)a_j(t) + L_i(t)(1 - F_j(t)) \}dF_1(t)
\]
where \( a_j(t) = F_j(t) - F_j(t-) \) is the \textit{size of the jump at} \( t \) of \( F_j \).

The above 2-person game of timing will be denoted by \((F, K_1, K_2)\).

A strategy pair \((F_1, F_2)\) is an equilibrium point (hereafter denoted by EP) of \((F, K_1, K_2)\) if and only if \( K_i(F_1, F_j) \geq K_i(F, F_j) \) for all \( F \in F, i = 1, 2, \{i,j\} = \{1,2\} \). An equivalent definition is that a strategy pair \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) if and only if \( K_i(F_1, F_j) \geq K_i(F, F_j) \) for all \( T \in [0,1] \). They are equivalent since \( F \in F \) is a right-continuous, non-negative, non-decreasing function on \([0,1]\) such that \( F(1) = 1 \).


Südžiūtė initiated the study of non-zero-sum silent games of timing in [1969]. In a silent game of timing, \( L_i, \phi_i \) and \( M_i \) are functions of both \( t_i \) and \( t_j \) (signifying that each player does not know if the other has acted or not). More recently, Kilgour, [1973], has obtained sufficient conditions for the existence of an EP in a 2-person non-zero-sum noisy game of timing (with differentiability conditions on the kernel which imply conditions (i), (ii) below).

This paper is concerned with obtaining necessary and sufficient conditions for the existence of an EP in the (not necessarily zero-sum) 2-person noisy game of timing in which \( P_i \)'s kernel satisfies the following for \( i = 1, 2 \):

Let \( a_i \) maximize \( \min(L_i(t), M_i(t)) \) in \([0,1]\).

(i) \( L_i, \phi_i \) and \( M_i \) are continuous real-valued functions on \([0,1]\) such that \( L_i \) is a strictly increasing function while \( M_i \) is a strictly decreasing function.
(ii) either \( \lim_{t \to a_i} \frac{[L_i(t) - L_i(a_i)]}{[L_i(t) - M_i(t)]} \) exists and is strictly positive (hereafter, this condition will be known as Condition I), or \( a_i = 0 \) and either \( L_i(0) > M_i(0) \) (which implies that \( \lim_{t \to a_i} \frac{[L_i(t) - L_i(a_i)]}{[L_i(t) - M_i(t)]} = 0 \)) or \( L_i(0) = M_i(0) \) and \( \exists \epsilon > 0 \) such that \( L_i \) is differentiable in \( (0, \epsilon) \) and \( \frac{L_i'(t)}{[L_i(t) - M_i(t)]} \) is bounded for \( t \in (0, \epsilon) \) (hereafter, this condition will be known as Condition II).

Condition I is used solely in the "only if" part of Lemma 7A while Condition II is used solely in the "only if" part of Lemma 7B.

The first main result of this paper, Theorem 8, gives necessary and sufficient conditions for the existence of an EP in a game \( (F, K_1, K_2) \) which satisfies conditions (i) and (ii) above. (Hereafter, \( (F, K_1, K_2) \) will denote a game of timing \( (F, K_1, K_2) \) described in the Introduction which satisfies conditions (i) and (ii) above.)

A strategy pair \( (F_1, F_2) \) is a dominating EP of \( (F, K_1, K_2) \) if and only if \( (F_1, F_2) \) is an EP such that \( K_i(F_1, F_2) \geq K_i(G_1, G_2) \) for \( i = 1, 2 \), \( \{i, j\} = \{1, 2\} \) for any EP \( (G_1, G_2) \) of \( (F, K_1, K_2) \), i.e., a dominating EP is an EP at which the payoff to each player is larger than or equal to the payoff received at any other EP. A second result of this paper, Theorem 10, gives necessary and sufficient conditions for the existence of a dominating EP in \( (F, K_1, K_2) \) satisfying, in addition to (i), (ii) above, (iii) below:

(iii) \( L_i(0) \leq M_i(0) \) for \( i = 1, 2 \).
2. Preliminary Notation and Definitions

Alternate proofs of Lemmas 2, 3 and 4 in Section 3 and of the "if" part of Lemma 7 in Section 4 can be found in [Kilgour, 1973] and [Kilgour, 1979]. For completeness, the author offers these proofs (some of which use Lemma 1 very efficiently). In order to begin, the following notation and definitions will be needed.

Let $\text{Supp}(F)$ denote the support of $F \in F$, i.e., $\text{Supp}(F)$ is the complement of the set of all points which have a neighborhood on which $F$ is constant.

Let $J_i$ denote the set of jump points of $F_i \in F$, i.e.,

$$J_i = \{ t \in \text{Supp}(F_i) : F_i(t) - F_i(t-) > 0 \}.$$

Recall that $a_i(t)$ denotes the size of the jump at a jump point of $F_i$, i.e., $a_i(t) = F_i(t) - F_i(t-)$ for $t \in J_i$. If $t \notin J_i$, then $a_i(t) = 0$.

3. Preliminary Lemmas

This section gives shape to the supports of strategy pairs which are possible EP's of $(F, K_1, K_2)$. The first simple yet useful lemma (see the proofs of Lemmas 3, 4, 5 and 6) is an elaboration of Lemma 2.2.1 in [Karlin, 1959]. Basically, Lemma 1 states that, if $(F_1, F_2)$ is an EP of $(F, K_1, K_2)$ and $T \in \text{Supp}(F_1)$, then, either $T$ contributes to $K_1(F_1, F_2)$ as much as the whole $\text{Supp}(F_1)$ does or there exist points $S_n \in \text{Supp}(F_1), S_n \neq T, S_n$ converging to $T$ that do the job. Let $\exists$ denote "there exist"; $\forall," for each"; and let $\chi_U$ denote, for $U \subset [0,1]$, the function defined by

$$\chi_U(t) = \begin{cases} 
0 & \text{if } t \notin U \\
1 & \text{if } t \in U 
\end{cases}.$$
Given a strategy $F_i \in F$ we define a new function: $H_i : [0,1] \times F \to \mathbb{R}$ as follows

$$H_i(T, F_j) = \int_{[0,T]} M_i(t) dF_j(t) + \alpha_j(T) \phi_i(T) \chi_{(0,1)}(\alpha_i(T)) + L_i(T)(1 - F_j(T)).$$

Note the difference between this function $H_i$ and the restriction of the payoff function $K_i$ of Player $i$, $K_i : [0,1] \times F \to \mathbb{R}$ defined previously as

$$K_i(\epsilon_T, F_j) = \int_{[0,T]} M_i(t) dF_j(t) + \alpha_j(T) \phi_i(T) + L_i(T)(1 - F_j(T)).$$

These functions may differ whenever the first variable $T$ belongs to $CJ_i \cap J_j$ (where $C$ denotes the complement of $J_i$ in $[0,1]$) since, in that case, $\phi_i(T)$ does not appear in the computation of $H_i(T, F_j)$ but does appear in the computation of $K_i(\epsilon_T, F_j)$.

The following facts are almost immediate

(A) $H_i(T, F_j) = K_i(\epsilon_T, F_j)$ whenever $T \in J_i \cup C J_j$.

Since $\int_U K_i(\epsilon_T, F_j) dF_i(T) = \int_U \left( \int_{[0,T]} M_i(t) dF_j(t) + \alpha_j(T) \phi_i(T) \right) dF_i(T) = \int_U \left( \int_{[0,T]} M_i(t) dF_j(t) + \alpha_j(T) \phi_i(T) \chi_{(0,1)}(\alpha_i(T)) \right) dF_i(T) + L_i(T)(1 - F_j(T)))dF_i(T)$, it is true that

(B) $\int_U K_i(\epsilon_T, F_j) dF_i(T) = \int_U H_i(T, F_j) dF_i(T)$ for any closed set $U \subseteq [0,1]$.

Suppose that $(F_1, F_2)$ is an EP of $(F, K_1, K_2)$. If ever $K_i(F_1, F_j) < H_i(T, F_j)$ on a set $U$ of positive $F_i$ measure, then one
could define a new distribution \( G_1 \) (by translating \( F_1 \) and multiplying by a normalizing constant) on a closed set \( V \) of positive \( F_1 \) measure such that \( K_i(G_1, F_2) = (by \ (B)) \int_V H_i(T, F_j) dG_1(T) > K_i(F_1, F_j) \). This would contradict the hypothesis that \( (F_1, F_2) \) is an EP of \( (F, K_1, K_2) \).

Thus, it is true that

\[(C) \quad \text{If } (F_1, F_2) \text{ is an EP of } (F, K_1, K_2), \text{ then } K_i(F_1, F_j) \geq H_i(T, F_j) \text{ almost everywhere with respect to } F_i.
\]

By facts (B) and (C), it is true that \( K_i(F_1, F_j) = \int_{[0,1]} H_i(T, F_j) dF_1(T) \) and \( K_i(F_1, F_j) \geq H_i(T, F_j) \) almost everywhere with respect to \( F_i \) whenever \( (F_1, F_2) \) is an EP of \( (F, K_1, K_2) \). Thus,

\[(D) \quad K_i(F_1, F_j) = H_i(T, F_j) \text{ almost everywhere with respect to } F_i \text{ whenever } (F_1, F_2) \text{ is an EP of } (F, K_1, K_2).
\]

\( \text{Supp } (F_1) \) is a closed set in \( [0,1] \) whose only possible isolated points must be jumps of the distribution \( F_1 \). Thus,

\[(E) \quad \text{If } T \in \text{Supp}(F_1) \text{ and } T \notin J_4, \text{ then } \exists \text{ a sequence } \{T_n\} \subset \text{Supp}(F_1) \cap (T-\epsilon, T) \text{ for some } \epsilon > 0 \text{ (and/or } \exists \text{ a sequence } \{T_n\} \subset \text{Supp}(F_1) \cap (T, T+\epsilon) \text{ for some } \epsilon > 0 \text{) such that } T_n \text{ converges to } T \text{ (to be denoted by } T_n \rightarrow T). \]

Finally, Lemma 1 can be stated as follows:
Lemma 1. Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\). If \(T \in \text{Supp}(F_i)\) for some \(i = 1\) or \(2\), then

1. If \(T \in J_1\), then \(K_i(F_1, F_j) = K_j(F_1, F_j) = H_i(T, F_j)\).

2. If \(\exists\) a sequence \(\{S_n\} \subset \text{Supp}(F_i) \cap (T - \epsilon_1, T)\) for some \(\epsilon_1 > 0\) such that \(S_n \to T\), then \(\exists\) \(\{T_n\} \subset \text{Supp}(F_i) \cap (T - \epsilon_1, T)\) such that \(T_n \to T\) and such that \(K_i(F_1, F_j) = H_i(T_n, F_j)\) \(\forall n\).

3. If \(\exists\) a sequence \(\{S_n\} \subset \text{Supp}(F_i) \cap (T, T + \epsilon_2)\) for some \(\epsilon_2 > 0\) such that \(S_n \to T\), then \(\exists\) \(\{T_n\} \subset \text{Supp}(F_i) \cap (T, T + \epsilon_2)\) such that \(T_n \to T\) and such that \(K_i(F_1, F_j) = H_i(T_n, F_j)\) \(\forall n\).

Proof. Let \((F_1, F_2)\) be an EP of \((F, K_1, K_2)\) and let \(T \in \text{Supp}(F_i)\) for some \(i = 1\) or \(2\).

(1) is true by facts (A) and (D) since \(\{T\}\) is a set of positive \(F_i\) measure if \(T \in J_1\).

Suppose that \(\exists\) \(\{S_n\} \subset \text{Supp}(F_i) \cap V\) where \(V = (T - \epsilon_1, T)\) or \(V = (T, T + \epsilon_2)\) for some \(\epsilon_1, \epsilon_2 > 0\). Let \(V_m = (T - (\epsilon_1/m), T)\) or let \(V_m = (T, T + (\epsilon_2/m))\) depending on whether \(V = (T - \epsilon_1, T)\) or \(V = (T, T + \epsilon_2)\) respectively. For each \(m\), \(\exists n\) such that \(S_n \in V_m\), so that \(\int_{V_m} dF_i(t) > 0\) (since \(S_n \in \text{Supp}(F_i)\)). Thus \(\exists\) \(T_m \in V_m\) such that \(H_i(T_m, F_j) = K_i(F_1, F_j)\) by (D), i.e., \(\exists\) \(\{T_m\} \subset \text{Supp}(F_i) \cap V\) such that \(T_m \to T\) and \(K_i(F_1, F_j) = H_i(T_m, F_j)\) \(\forall m\).

Since the limit of a constant sequence exists, \(\lim_{m \to \infty} H_i(T_m, F_j)\) \((\{T_m\} \subset \text{Supp}(F_i) \cap V\) as in (2) or (3) of Lemma 1) exists and is equal to
\[ K_i(F_i, F_j) = \lim_{m \to \infty} H_i(T_m, F_j) = \int_{[0, T)} M_i(t) dF_j(t) + \alpha_j(T) \chi_{(T_m)}(T_m) + M_1(T) \chi_{(T, T + \epsilon_2)}(T_m) + L_i(T)(1 - F_j(T)) \]

by the Lebesgue Dominated Convergence Theorem and the fact that \( \sum_{m=1}^{\infty} \alpha_j(T) \chi_{(T_m)}(T_m) \) exists implies that \( \alpha_j(T_m) \to 0 \) which implies that \( \alpha_j(T_m) \phi_i(T_m) \chi_{[0,1]}( \alpha_i(T_m) ) \to 0 \) as \( T_m \to T \) since \( \phi_i \) is bounded.

Thus, one can conclude that, if \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) and \( T \in \text{Supp}(F_i) \), \( i = 1 \) or \( 2 \), then (i) if \( T \in J_1 \setminus J_2 \) and \( \exists \) sequence \( \{S_n\} \) satisfying (2) in Lemma 1, then \( \phi_i(T) = L_i(T) \), (ii) if \( T \in J_1 \setminus J_2 \) and \( \exists \) sequence \( \{S_n\} \) satisfying (3) in Lemma 1, then \( \phi_i(T) = M_i(T) \) and (iii) if \( T \in J_j \) and \( \exists \) sequences satisfying both (2) and (3) in Lemma 1, then \( L_i(T) = M_i(T) \).

Lemma 2: The pure timing strategy pair \((F_1, F_2)\) with \( F_k = \delta_{T_k} \) for \( k = 1, 2 \), is an EP of \((F, K_1, K_2)\) if and only if \( T_1 = T_2 = T \) and for \( i = 1, 2 \)

\[
\phi_i(T) \geq \begin{cases} 
L_i(1) & \text{if } T = 1 \\
\max\{L_i(T), M_i(T)\} & \text{if } 0 < T < 1 \\
M_i(0) & \text{if } T = 0 
\end{cases}
\]

Proof: If \( T_i < T_j \), then by the definition of an EP, \( L_i(T_i) = K_i(F_i, F_j) \) must be strictly larger than \( K_i(\delta_{t}, F_j) = L_i(t) \) for each \( t \in (T_i, T_j) \); but, this contradicts the assumption that \( L_i \) is an increasing function. Thus \( T_1 = T_2 = T \). By the definition of an EP,
\[ \phi_i(T) = K_i(F_i, F_j) \geq K_i(\delta_i, F_j) = \begin{cases} L_i(t) & \text{if } t < T \\ \phi_i(T) & \text{if } t = T \\ M_i(T) & \text{if } t > T \end{cases} \]

for all \( t \in [0,1] \). The Lemma now follows from the continuity and monotonicity of \( L_i \).

Lemma 3 (for an alternate proof, see [Kilgour, 1973], [Kilgour, 1979]) indicates that, if \( (F_1, F_2) \) is an EP of \( (F, K_1, K_2) \), then the supports of \( F_1 \) and \( F_2 \) are identical until the probability of at least one player's having acted is one. A precise statement of this idea requires the following definitions.

Let \( \epsilon(F) = \max\{t \in [0,1] : t \in \text{Supp}(F)\} \). Thus \( \epsilon(F) \) is the earliest time of certain action corresponding to \( F \).

Let \( \text{Supp}(F,G) = \text{Supp}(F) \cap \text{Supp}(G) \), i.e., \( \text{Supp}(F,G) \) denotes the common support of \( F \) and \( G \).

**Lemma 3:** If \( (F_1, F_2) \) is an EP of \( (F, K_1, K_2) \) such that \( \epsilon(F_1) \leq \epsilon(F_j) \), then \( \text{Supp}(F_1) = \text{Supp}(F_j) \cap [0, \epsilon(F_i)] \).

**Proof:** Suppose that there exists a point \( T \in \text{Supp}(F_i) \) such that \( T \notin \text{Supp}(F_j) \). Since \( \text{Supp}(F_j) \) is closed and \( \epsilon(F_1) \leq \epsilon(F_j) \), there must exist points \( t_1 < t_2 \) such that \( T \in [t_1, t_2] \), \([t_1, t_2] \cap \text{Supp}(F_j) = \emptyset\), and \( F_j(t_2) < 1 \). By Lemma 1 and facts (A) and (E) there exists \( S \in [t_1, t_2] \) such that
\[ K_i(F_1, F_j) = K_i(\delta_{t_2}, F_j) = \]
\[ = \int_{[0,S]} M_i(t) dF_j(t) + \int_{(S,t_2]} L_i(s) dF_j(t) + \int_{(t_2,1]} L_i(s) dF_j(t) \]
\[ < \int_{[0,S]} M_i(t) dF_j(t) + \int_{(S,t_2]} M_i(t) dF_j(t) + \int_{(t_2,1]} L_i(t) dF_j(t) \]
\[ = K_i(\delta_{t_2}, F_j), \]

since \( F_j(t_2) - F_j(S) = 0 \), \( F_j(t_2) < 1 \), and \( L_i(S) < L_i(t_2) \). This contradicts the hypothesis that \((F_1, F_2)\) is an EP. \( \square \)

Thus, \( \text{Supp}(F_1, F_2) = \text{Supp}(F_1) \) whenever \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) and \( e(F_1) \leq e(F_j) \). Hereafter, the term initial support of \( F_1 \) and \( F_2 \) naturally describes, and is synonymous with, the common support of \( F_1 \) and \( F_2 \) whenever \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\). This result contrasts with one of Šudžiūtė's results in [1969] which states that if \((F_1, F_2)\) is an EP of a silent non-zero sum game of timing, then \( \text{Supp}(F_1) \cap (0,1) = \text{Supp}(F_2) \cap (0,1) \). Lemmas 7A and 7B show that this is certainly not true for our noisy game of timing, \((F, K_1, K_2)\).

**Lemma 4** (for an alternate proof, see [Kilgour, 1973], [Kilgour, 1979]) gives us more information about the possible behavior of an EP of \((F, K_1, K_2)\). Recall that \( a_i \) maximizes \( \min(L_i(t), M_i(t)) \) for \( t \in [0,1] \).

**Lemma 4**: Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) such that \( T \in \text{Supp}(F_1, F_2) \). If \( T < e(F_j) \), \( a_i \) for \( i \neq j \), then \( T \) is a common jump of the EP \((F_1, F_2)\), i.e., \( T \in J_1 \cap J_2 \).
Proof: Suppose, to the contrary, that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) such that \(\exists T \in \text{Supp}(F_1, F_2)\) satisfying (i) \(T < e(F_j)\), \(a_i\), for \(i \neq j\) and (ii) \(T \not\in J_1 \cap J_2\). Since \(T < e(F_j)\), \(a_i\), \(\exists \epsilon > 0\) such that \(\exists \epsilon_1 > \epsilon\) such that \(T + \epsilon_1 \not\in J_j\) and \(T + \epsilon_1 < e(F_j)\), \(a_i\) and such that \(\exists\) a sequence \(\{T_n\} \subset (T-\epsilon, T+\epsilon)\) satisfying the conclusions in (2) or (2) of Lemma 1 (such a sequence exists by Lemma 3 and fact (E)) so that

\[
K_i(F_1, F_j) = \lim_{n \to \infty} H_i(T_n, F_j) = \int_{[0,T)} M_i(t) dF_j(t) + a_j(T) \chi_{[0,T)}(T_n) \chi_{(T,T+\epsilon)}(T_n) \right.
\]

\[
+ L_i(T) \chi_{(T-\epsilon, T)}(T_n) + L_i(T)(1 - F_j(T)) \right.
\]

\[
< \int_{[0,T)} M_i(t) dF_j(t) + \int_{[T,T+\epsilon_1)} M_i(t) dF_j(t) \right.
\]

\[
+ \int_{(T+\epsilon_1, 1]} L_i(T+\epsilon_1) dF_j(t) \right.
\]

\[
= K_i(\delta_{T+\epsilon_1}, F_j) ,
\]

since \(T + \epsilon_1 < e(F_j)\), \(a_i\), and \(T + \epsilon_1 \not\in J_j\) i.e., since \(F_j(T+\epsilon_1) < 1\).

\(L_i(T) < L_i(T+\epsilon_1), M_i(t)\), for \(t, T < a_i\) and \(a_j(T+\epsilon_1) = 0\). This contradicts the definition of EP.

An immediate corollary to Lemma 4 is the following: Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) such that \(T \in \text{Supp}(F_1, F_2)\) and \(T < e(F_i)\) for some \(i\). If \(T\) is not a common jump, then \(T > a_j\) for \(j \neq i\).
4. Key Lemmas and First Main Theorem

The following lemma provides the key to both theorems. Lemma 5 tells us that the existence of an EP \((F_1, F_2)\) of \((F, K_1, K_2)\) with a common jump implies the existence of a pure EP of \((F, K_1, K_2)\). (If, in addition, \(L_i(0) \leq M_i(0)\) for \(i = 1, 2\), then it also implies the existence of a pure EP of \((F, K_1, K_2)\) which dominates \((F_1, F_2)\).) The reason this information provides the key is that Section 3 already tells us a lot about the initial support of an EP of \((F, K_1, K_2)\) which does not have a common jump. Section 3 also gives us necessary and sufficient conditions for the existence of a pure EP of \((F, K_1, K_2)\). Thus, after Lemma 5, it only remains to find necessary and sufficient conditions for the existence of an EP of \((F, K_1, K_2)\) without any common jumps.

**Lemma 5:** Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\). If \(T \in J_1 \cap J_2\), then \((\delta_T, \delta_T)\) is an EP of \((F, K_1, K_2)\).

Suppose further that \(L_i(0) \leq M_i(0)\) for \(i = 1, 2\). If \(\exists T \in J_1 \cap J_2\), then \(\exists\) a pure EP of \((F, K_1, K_2)\) which dominates \((F_1, F_2)\).

**Proof:** Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\) such that \(T \in J_1 \cap J_2\). For any sequence \(\{S_n\} \subset [0,T)\) if \(T > 0\) and any sequence \(\{S_n\} \subset (T,1]\) if \(T < 1\), if \(S_n\) converges to \(T\), then

\[
K_i(\delta_{S_n}, F_j) = \int_{[0,S_n]} M_i(t)dF(t) + a_j(S_n)\phi_i(S_n) + \int_{(S_n,1]} L_i(S_n)dF_i(t).
\]

But, by the Lebesgue Convergence Theorem and the fact that \(a_j(S_n) \to 0\),
\[
\lim_{n \to \infty} K_i(\delta_n, F_j) = \int_{[0,T]} M_i(t) dF_j(t) + M_i(T) \alpha_j(T) \chi_{[T,1]}(S_n) + L_i(T) \alpha_j(T) \chi_{(0,T]}(S_n) + \int_{(T,1]} L_i(t) dF_j(t)
\]

\[
\geq \int_{[0,T]} M_i(t) dF_j(t) + \phi_i(T) u_j(T) + \int_{(T,1]} L_i(t) dF_j(t)
\]

\[
= K_i(F_i, F_j) \quad \text{(by Lemma 1)}
\]

if either \( \phi_i(T) < M_i(T) \) for \( T < 1 \) (choose \( \{S_n\} \subset (T,1) \)) or \( \phi_i(T) < L_i(T) \) for \( T > 0 \) (choose \( \{S_n\} \subset [0,T) \)) since \( \alpha_j(T) > 0 \).

This would contradict the hypothesis that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\).

Thus \( \phi_i(T) \geq M_i(T) \) if \( T < 1 \) and \( \phi_i(T) \geq L_i(T) \) if \( T > 0 \), i.e.,

\( (\delta_T, \delta_T) \) is an EP of \((F, K_1, K_2)\) (by Lemma 2).

Further suppose that \( L_i(0) \preceq M_i(0) \) for \( i = 1, 2 \) and that \( \exists \) a common jump of \((F_1, F_2)\).

Let \( T = \inf \{S \in J_1 \cap J_2\} \). \( (\delta_S, \delta_S) \) is an EP \( \forall s \in J_1 \cap J_2 \) (by above). Thus \( (\delta_T, \delta_T) \) is an EP of \((F, K_1, K_2)\) by the continuity of \( L_i \), \( \phi_i \) and \( M_i \). It remains to show that \( (\delta_T, \delta_T) \) dominates \((F_1, F_2)\).

If \( T = 0 \), then \( \phi_i(0) \geq M_i(0) \geq L_i(0) \) (by above and by assumption respectively) implies that

\[
K_i(\delta_0, \delta_0) = \phi_i(0) \geq \begin{cases}
\alpha_j(0) \phi_i(0) + (1 - \alpha_j(0)) L_i(0) = H_i(T, F_j) \\
\alpha_j(0) M_i(0) + (1 - \alpha_j(0)) L_i(0) = H_i(T, F_j)
\end{cases}
\]

if \( T \in J_1 \cap J_2 \)

\[
= K_i(F_i, F_j) \quad \text{(by Lemma 1)}.
\]
If \( 0 < T \leq 1 \), then \( \phi_i(T) \geq L_i(T) \) since \((\delta_T, \delta_T)\) is an EP.

Thus, by Lemma 1,

\[
K_i(F_i, F_j) = \begin{cases} 
H_i(T, F_j) & \text{if } T \not\in J_1 \cap J_2 \\
\lim_{n \to \infty} H_i(T_n, F_j) & \text{if } T_n \not\in J_1 \cap J_2, \; T_n \to T
\end{cases}
\]

\[
\frac{\int_{[0,T]} M_i(t) dF_j(t) + \phi_i(T) \alpha_j(T) + L_i(T)(1-F_j(T))}{[0,T]} = \frac{\int_{[0,T]} M_j(t) dF_j(t) + M_i(T) \alpha_j(T) + L_i(T)(1-F_j(T))}{[0,T]} \leq \phi_i(T) = K_i(\delta_T, \delta_T)
\]

since \( \int_{[0,T]} M_i(t) dF_j(t) \) is non-zero only if \( T \) does not begin the support of \( F_j \); in which case \( \phi_i(T) \geq L_i(T) > M_i(t) \) for all \( t \in \text{Supp}(F_j) \cap [0,T] \) (by Lemma 4, since \( T \) is the earliest possible common jump).

Thus, \((\delta_T, \delta_T)\) is an EP of \((F, K_1, K_2)\) which dominates \((F_1, F_2)\).

And so, \((F, K_1, K_2)\) has an EP with a common jump if and only if \((F, K_1, K_2)\) has a pure EP (see Lemma 5) if and only if \( \phi_i, \; i = 1, 2 \) are both large for some \( T \in [0,1] \) (large in the sense of Lemma 2).

Another consequence of Lemma 5 is that, if \( L_i(0) < M_i(0) \) for \( i = 1, 2 \), then it is only necessary to search among pure EP's of \((F, K_1, K_2)\) and EP's of \((F, K_1, K_2)\) without any common jumps for the existence of a dominating EP of \((F, K_1, K_2)\).

Lemma 2 already gives us necessary and sufficient conditions for the existence of a pure EP of \((F, K_1, K_2)\). It remains to find necessary and sufficient conditions for the existence of an EP of \((F, K_1, K_2)\) with no jumps in common. Lemmas 6, 7A and 7B provide us with exactly this
The next lemma rules out the possibility of an EP among a certain class of strategy pairs with no common jumps.

**Lemma 6:** Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\). If \(J_1 \cap J_2 = \emptyset\), then \(\text{Supp}(F_1, F_2) = \{e(F_j)\}\) where \(e(F_j) \leq e(F_i)\) \(i \neq j\).

**Proof:** By Lemma 3, \(\text{Supp}(F_1, F_2) = \text{Supp}(F_j)\). Suppose that \(\text{Supp}(F_j)\) contains more than one point, i.e., let \(T\) begin \(\text{Supp}(F_1, F_2)\) and suppose that \(T < e(F_j) \leq e(F_i)\), \(\{i,j\} = \{1,2\}\).

Since \(T \in \text{Supp}(F_1, F_2)\) is not a common jump, \(\exists\) a sequence \(\{S_n\} \subset \text{Supp}(F_1, F_2) \cap (T, T + \epsilon)\) for some \(\epsilon > 0\) such that \(S_n \to T\) (by fact (E) and Lemma 3). Thus, by Lemma 1, \(\exists\) a sequence \(\{T_n\}\) satisfying the conclusion in (3) of Lemma 1. Thus \(K_k(F_k, F_x) = \lim_{n \to \infty} H_k(T_n, F_x)\)

\[ = M_k(T)T_k(T) + L_k(T)(1 - F_x(T))\] for \(k = 1, 2\), \(\{k, x\} = \{1, 2\}\).

Similarly, since \(e(F_j) \in \text{Supp}(F_1, F_2)\) is not a common jump, \(\exists\) a sequence \(\{T'_n\}\) satisfying the conclusion in (2) of Lemma 1. Let \(\epsilon\) be such that \(a_\epsilon(e(F_j)) = 0\). Thus \(K_k(F_k, F_x) = \lim_{n \to \infty} H_k(T'_n, F_x) = \int_{[0, e(F_j)]} M_k(t) dF_x(t)\)

But then a contradiction results since

\[K_k(F_k, F_x) = M_k(T)T_k(T) + L_k(T)(1 - F_x(T))\]

\[\geq \int_{[T, e(F_j)]} M_k(t) dF_x(t) = K_k(F_k, F_x)\]

since \(T \geq a_\epsilon\) (by Lemma 4), \(F_x(T) < 1\) and \(M_k\) is strictly decreasing.
Among the strategy pairs without any common jumps, the only remaining candidates for an EP are those for which the initial support, $\text{Supp}(F_1, F_2)$ is a singleton set $\{T\}$ such that $T \notin J_1 \cap J_2$. The next lemma stipulates exactly under what conditions this type of EP can occur.

Let $Q$ be the set of strategy pairs of $(F, K_1, K_2)$ without any jumps in common but with $\text{Supp}(F_1, F_2) = \text{Supp}(F_1) = \{T\}$ where $e(F_i) \leq e(F_j)$, i.e.,

$$Q = \{(F_1, F_2) \in F \times F : \text{Supp}(F_1, F_2) = \text{Supp}(F_1) = \{T\}$$
where $e(F_i) \leq e(F_j), F_j(T) = 0, a_i(T) = 1 \}$.

Note that, in the above, $T < 1$.

For the proof of the "if" part of Lemma 7A, see [Kilgour, 1973], [Kilgour, 1979].

Recall that Condition I states that $\lim_{t \to a_1} [L(t) - L(a_1)]/[L(t) - M(t)]$ exists and is strictly positive.

**Lemma 7A:** $\exists (F_1, F_2) \in Q$ such that $(F_1, F_2)$ is an EP of $(F, K_1, K_2)$ (satisfying Condition I) if and only if $\exists T \in [0,1)$ such that $a_1 < T \leq a_j$ and $M_j(T) > \phi_j(T)$.

**Proof:** "if" Suppose that $\exists T \in [0,1)$ such that $L_1(T) > N_1(T)$, $M_j(T) > L_j(T)$, $\phi_j(T)$. Let $F_1(T) - F_1(T-1) = 1$. Let $F_j$ be any absolutely continuous distribution such that $F_j(T) = 0$ and

$$F_j(t) > \frac{L_1(t) - L_1(T)}{L_1(t) - M_1(T)} \text{ in } (T,1)$$
(such an \( F_j \) exists since \( L_i(t) > M_1(T) \) for \( t \in [T,1] \)). Then

\[
K_j(F_j, F_i) = M_j(T) = \begin{cases} 
L_j(t) & \text{if } t < T \\
\phi_j(T) & \text{if } t = T \\
M_j(T) & \text{if } t > T 
\end{cases}
\]

\[
= K_j(\delta_t, F_j) \quad \forall t \in [0,1],
\]

i.e., \( F_j \) is a best response for \( F_j \) against \( F_i \).

Also \( K_i(F_i, F_j) = L_i(T) > M_1(T)F_j(t) + L_i(t)(1 - F_j(t)) \) (by assumption) \( \geq \int_{[T,t]} M_i(s) dF_j(s) + L_i(t)(1 - F_j(t)) = K_i(\delta_t, F_j) \forall t \in [T,1] \)

since \( M_i \) is decreasing and \( K_i(F_i, F_j) = L_i(T) > L_i(t) = K_i(\delta_t, F_j) \forall t \in [0,T] \), i.e., \( F_i \) is a best response for \( F_i \) against \( F_j \).

Thus, \( (F_1, F_2) \in \mathcal{Q} \) is an EP of \( (F, K_1, K_2) \).

"only if" Suppose that \( (F_1, F_2) \in \mathcal{Q} \) is an EP of \( (F, K_1, K_2) \).

By definition of EP,

\[
M_j(T) = K_j(F_i, F_j) \geq K_j(\delta_t, F_i) = \begin{cases} 
L_j(t) & \text{if } t < T \\
\phi_j(T) & \text{if } t = T \\
M_j(T) & \text{if } t > T 
\end{cases}
\]

Also, \( T \in \text{Supp}(F_1, F_2) \), \( T \) not a common jump, \( T < e(F_j) \) implies that \( T > a_1 \) (by Lemma 4). Thus \( a_1 < T < a_j \) and \( M_j(T) > \phi_j(T) \).

It remains to show that \( T \) must be strictly larger than \( a_1 \).

Suppose, to the contrary, that \( L_i(T) = M_1(T) \). Then

\[
L_i(T) = K_i(F_i, F_j) \geq K_i(\delta_t, F_j) = \int_{[T,t]} M_i(s) dF_j(s) + F_j(t)(1 - L_i(t))
\]

\[
\geq M_i(t)F_j(t) + F_j(t)(1 - L_i(t)),
\]
for all but at most a countable set of \( t \in J_j \), implies that

\[
F_j(t) \geq \frac{L_1(t) - L_1(T)}{L_1(t) - M_j(t)}
\]

which implies that

\[
\lim_{t \to T^+} F_j(t) > \lim_{t \to a_j^-} \frac{L_1(t) - L_1(T)}{L_1(t) - M_j(t)} > 0
\]

which contradicts the hypothesis that \( F_j(T) = 0 \) since \( F_j \) must be right-continuous. \( \square \)

The counterpart of Lemma 7A uses Condition II. Recall that Condition II states that \( a_1 = 0 \) and either \( L_1(0) > M_j(0) \) or \( L_1(0) = M_j(0) \)

and \( \exists \varepsilon > 0 \) such that \( L_1 \) is differentiable in \((0, \varepsilon]\) and

\[
L_1'(t)/[L_1(t) - M_j(t)] \text{ is bounded for } t \in (0, \varepsilon].
\]

**Lemma 7B:** \( \exists (F_1, F_2) \in Q \) such that \( (F_1, F_2) \) is an EP of \((F, K_1, K_2)\)

(satisfying Condition II) if and only if \( \exists T \in [0, 1) \) such that

\[
a_1 < T < a_j \text{ and } M_j(T) \geq \phi_j(T).
\]

**Proof:** "only if" \( M_j(T) \geq L_j(T), \phi_j(T), \) as in Lemma 7A. Also \( T < e(F_j) \)

implies that \( T \geq a_1 \) (by Lemma 4). Thus \( a_1 \leq T \leq a_j \) and \( M_j(T) \geq \phi_j(T) \).

"if" if either \( 0 < T < a_j \) and \( M_j(T) \geq \phi_j(T) \) or \( T = 0 \) and

\( L_1(0) > M_1(0), M_j(0) \geq \phi_j(0) \), then \((\delta_T, F_j) \in Q\) as in the "if" part of Lemma 7A will be an EP of \((F, K_1, K_2)\).

It remains to show that if \( T = a_1 = 0 \) and \( M_j(T) > \phi_j(T) \) then

\( \exists F_j \in F \) such that \((\delta_T, F_j) \in Q\) is an EP of \((F, K_1, K_2)\).

Choose \( F_j \in F \) as follows. Let \( F_j \) be any absolutely continuous distribution such that \( F_j(0) = 0 \), \( F_j(\varepsilon) = 1 \) and such that

\[
F_j'(t) > \frac{L_1'(t)}{L_1(t) - M_j(t)} \text{ in } (0, \varepsilon].
\]

\( K_j(F_j, \delta_j) > K_j(F, \delta_0) \) for all \( F \in F \) by assumptions on \( M_j \). It remains to show that \( \delta_0 \) is best for \( P_1 \) against \( F_j \).

\[
K_1(\delta, F_j) = \int_{[0, t]} M_1(s) dF_j(s) + L_1(t) (1 - F_j(t)).
\]
The derivative of $K_1(\delta_t, F_j)$ with respect to $t$ is

$$M_i(t)F'_j(t) + L'_j(t)(1 - F_j(t)) - L'_j(t)F'_j(t) < 0 \text{ by assumption on } F'_j(t)$$

for all $t \in (0, \epsilon]$. But $K_1(\delta_0, F_j) = L_j(0)$. Thus $K_1(\delta_t, F_j) < K_1(\delta_0, F_j)$ for all $t \in (0, \epsilon]$. Also $K_1(\delta_t, F_j) = \int_{[0, e(F_j)]} M_i(s)dF_j(s) < L_j(0)$ for all $t \in (\epsilon, 1]$. Thus, $\delta_0$ is best for $P_1$ against $F_j$. Therefore $(\delta_0, F_j) \in \mathcal{Q}$ is an EP of $(F, K_1, K_2)$.\[\square\]

And so, by Lemmas 6, 7A and 7B, the only candidates for an EP of $(F, K_1, K_2)$ without any common jumps are those strategy pairs whose initial common support is a singleton set \{T\} such that $T \in [0, 1)$, $M_j(T) \geq \phi_j(T)$ and $a_i < T \leq a_j$ if Condition I holds ($a_i = 0 < T \leq a_j$ if Condition II holds).

We are now ready to state necessary and sufficient conditions for the existence of an EP of $(F, K_1, K_2)$.

**Theorem 8:** The game of timing, $(F, K_1, K_2)$, has an EP if and only if there exists a point $T \in [0, 1]$ such that

- either (i) $T = 0$ and $\phi_i(0) > M_i(0)$ for $i = 1, 2$
- or (ii) $0 < T < 1$ and $\phi_i(T) \geq \max\{L_i(T), M_i(T)\}$ for $i = 1, 2$
- or (iii) $T = 1$ and $\phi_i(1) > L_i(1)$ for $i = 1, 2$
- or (iv) $a_i < T \leq a_j$ and $M_j(T) \geq \phi_j(T)$ for $i \neq j$
- or (v) $0 = a_i = T < a_j$, $M_j(T) \geq \phi_j(T)$ for $i \neq j$ and Condition II holds (i.e., either $L_i(0) > M_i(0)$ or the derivative of $L_i$ exists in some interval $(0, \epsilon)$ for $\epsilon > 0$ and $L_i'(t)/(L_i(t) - M_i(t))$ is bounded in $(0, \epsilon)$).
Proof: "if" If (i), (ii) or (iii) is true, then \((\delta_T, \delta_T)\) is an EP of \((F, K_1, K_2)\) by Lemma 2. If (iv) is true, then \(\exists (F_1, F_2) \in \mathcal{Q}\) which is an EP of \((F, K_1, K_2)\) by the "if" parts of Lemmas 7A and 7B.

If (v) is true, then \(\exists (F_1, F_2) \in \mathcal{Q}\) which is an EP of \((F, K_1, K_2)\) by the "if" part of Lemma 7B.

"only if" Suppose that \((F_1, F_2)\) is an EP of \((F, K_1, K_2)\). If there exists a point \(T \in J_1 \cap J_2\), then \((\delta_T, \delta_T)\) is an EP (by Lemma 5) which implies, by Lemma 2, that one of (i), (ii) or (iii) is true. If \(J_1 \cap J_2 = \emptyset\), then (iv) or (v) is true by Lemmas 6, 7A and 7B.

5. Dominance Theorem

Let us assume that, in this section, the game of timing, \((F, K_1, K_2)\) under consideration also satisfies condition (iii) in the Introduction, i.e., in addition to the continuity and monotonicity conditions, the kernel also satisfies the condition that \(L_i(0) \leq M_i(0)\) for \(i = 1, 2\).

Thus far, this condition was assumed only in the second part of Lemma 5 which established that, if \(L_i(0) \leq M_i(0)\) for \(i = 1, 2\), then the existence of a common jump in an EP \((F_1, F_2)\) of \((F, K_1, K_2)\) implies the existence of a pure EP \((\delta_T, \delta_T)\) of \((F, K_1, K_2)\) which dominates \((F_1, F_2)\). [If \(L_i(0) > M_i(0)\) for some \(i\), then this is not necessarily true, i.e., there may then exist an EP \((F_1, F_2)\) with a jump in common even though no pure EP dominates \((F_1, F_2)\).]

Theorem 10, in this section, will provide necessary and sufficient conditions for the existence of a dominating EP in \((F, K_1, K_2)\). Before we proceed, we need some additional notation. Let

\[Q = \{S \in [0,1] : \exists \text{ EP } (F_1, F_2) \in \mathcal{Q} \text{ with } \text{Supp}(F_1, F_2) = \{S\}\}.\]
Thus, if Condition I holds, then

\[ Q = \{ S \in (0,1) : a_i < S \leq a_j, \ M_j(S) \geq \phi_j(S) \} ; \]

while, if Condition II holds, then

\[ Q = \{ S \in [0,1) : a_i = 0 < S \leq a_j, \ M_j(S) \geq \phi_j(S) \} . \]

Let

\[ P = \{ S \in [0,1] : (\delta_S, \delta_S) \text{ is an EP of } (F, K_1, K_2) \} . \]

Now, Theorem 8 can be restated as follows: An EP of \((F, K_1, K_2)\) exists if and only if \(P \cup Q \neq \emptyset\). The next lemma states that, if \(\exists \text{ EP } \in Q \) which is a dominating EP of \((F, K_1, K_2)\), then \(Q\) is a singleton set.

**Lemma 9:** Suppose that \(Q\) contains more than one point. If \((F_1, F_2) \in Q\) is an EP of \((F, K_1, K_2)\), then \((F_1, F_2)\) is not a dominant EP of \((F, K_1, K_2)\).

**Proof:** Let \(\text{Supp}(F_1, F_2) = \{ T \}\) for some \(T \in Q\). The payoffs to \(P_i\) and \(P_j\) are \(L_i(T)\) and \(M_j(T)\) respectively, for \(i \neq j\) (see Lemmas 7A, 7B). There exists a point \(S \neq T\), \(S \in Q\) such that either both

\[ L_i(T) < L_i(S) \text{ and } M_j(T) > M_j(S) \]

or both \(L_i(T) > L_i(S)\) and \(M_j(T) < M_j(S)\).

This is due to the monotonicity of \(L_i\) and \(M_j\) and to the assumption that \(Q\) contains more than one point. By Lemmas 7A, 7B there exists an EP \((of \quad (F, K_1, K_2))\) \((G_1, G_2) \in Q\) such that \(K_i(G_1, G_2) = L_i(S)\) and \(K_j(G_1, G_2) = M_j(S)\). The EP \((F_1, F_2)\) does not dominate the EP \((G_1, G_2)\). \[\square\]
We are now prepared to state the conditions necessary and sufficient for the existence of a dominating EP of \((F, K_1, K_2)\).

Theorem 10: A dominating EP of \((F, K_1, K_2)\) exists if and only if

either (i) \(\exists p \in P\) such that \(\phi_i(p) \geq \phi_i(T)\) \(\forall T \in P\), \(i = 1, 2\) and \(\phi_i(p) \geq L_i(T), \phi_j(p) \geq M_j(T)\) for all \(T \in Q\), \(i \neq j\) (in which case, \((\delta_p, \delta_p)\) is a dominating EP of \((F, K_1, K_2)\))

or (ii) \(Q = \{q\}\) and \(L_i(q) \geq \phi_i(T), M_j(q) \geq \phi_j(T)\) \(\forall T \in P\), \(i \neq j\) (in which case \(\exists (F_1, F_2) \in Q\) which is a dominating EP of \((F, K_1, K_2)\)).

Proof: "if" Suppose (i) or (ii) is true. Let \((F_1, F_2)\) be the EP of \((F, K_1, K_2)\) with respective payoffs to \(P_i, P_j\), \(i \neq j\), equal to \(\phi_i(p), \phi_j(p)\) if (i) is true (equal to \(L_i(q), M_j(q)\) if (ii) is true). Let \((G_1, G_2)\) be any EP of \((F, K_1, K_2)\). If there exists a common jump in \(\text{Supp}(G_1, G_2)\) then, by Lemma 5, there exists a pure EP of \((F, K_1, K_2)\) which dominates \((G_1, G_2)\). But, by assumption, \((F_1, F_2)\) dominates all pure EP's of \((F, K_1, K_2)\). Thus \((F_1, F_2)\) dominates \((G_1, G_2)\). If there does not exist a common jump in \(\text{Supp}(G_1, G_2)\) then, by Lemmas 7A and 7B, the payoffs to \(P_i\) and \(P_j\) from \((G_1, G_2)\) are \(L_i(T), M_j(T)\) respectively, for some \(T \in Q\). Thus \((F_1, F_2)\) dominates \((G_1, G_2)\).

"only if" Suppose that \((F_1, F_2)\) is a dominating EP of \((F, K_1, K_2)\)

(1) If \(\exists p \in J_1 \cap J_2\), ((2) if \(J_1 \cap J_2 = \emptyset\)) then \(K_i(F_1, F_j) = \phi_i(p)\) for \(i = 1, 2\) by Lemma 5; since, otherwise, \(K_i(F_1, F_j) < \phi_i(p)\) for \(i = 1, 2\) for a pure EP \((\delta_p, \delta_p)\) contradicts the dominancy of \((F_1, F_2)\)

(then \(K_i(F_1, F_j) = L_i(q)\) and \(K_j(F_1, F_i) = M_j(q)\) for \(\{q\} = Q\) by Lemmas 6, 7A, 7B and 9). Thus (1) if \(\exists p \in J_1 \cap J_2\) ((2) if \(J_1 \cap J_2 = \emptyset\).
then (1)((1ω)) must be true since \( \forall T \in P \exists \text{EP payoffs of } \Phi_i(T) \)
for \( P_i \) for \( i = 1, 2 \) and \( \forall T \in Q \exists \text{EP payoffs of } L_i(T), M_j(T) \)
for \( P_i, P_j \) respectively, \( i \neq j \), by Theorem 8.
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