

An Axiomatic Characterization of Nash Equilibrium

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We characterize Nash equilibrium by postulating coherent behavior across varying games. Nash equilibrium is the only solution concept that satisfies the following axioms: *(i)* strictly dominant actions are played with positive probability, *(ii)* if a strategy profile is played in two games, it is also played in every convex combination of these games, and *(iii)* players can shift probability arbitrarily between two indistinguishable actions, and deleting one of these actions has no effect. Our theorem implies that every equilibrium refinement violates at least one of these axioms. Moreover, every solution concept that approximately satisfies these axioms returns approximate Nash equilibria, even in natural subclasses of games, such as two-player zero-sum games, potential games, and graphical games.

Keywords: Game theory, axiomatic characterization, Nash equilibrium

1. Introduction

More than 70 years after the publication of Nash's (1951) original work, the concept of Nash equilibrium has been engraved in economic reasoning so deeply that it is rarely questioned. But what makes Nash equilibrium stand out from the plethora of solution concepts that have been proposed? The game theory literature has come up with various answers to this question based on different approaches.

In this paper, we take an axiomatic approach: we consider solution concepts for games in normal form with a fixed number of players and formulate conditions for solution concepts that capture coherent behavior across different games. The solution concepts we consider map every (finite) multi-player game to a non-empty set of (mixed) strategy profiles. Our first of three axioms requires that the labels of actions are irrelevant—only the payoffs matter. Call two actions of a player clones if, irrespective of the other players' actions, they give the same payoff to all players. In other words, clones are outcome-equivalent and only discernible by their labels.

Consequentialism. A player can shift probability arbitrarily between clones, and deleting a clone neither changes the probabilities assigned to the player's other actions nor the strategies of the other players.

If a solution concept satisfying consequentialism returns a strategy profile and we modify the game by cloning an action, then the solution concept has to return all strategy profiles in which the probabilities on the player's uncloned actions and the other players' strategies are unchanged.

The second axiom is motivated by situations where the players are uncertain which game will be played.

Consistency. Every strategy profile that is played in two given games with the same sets of actions for each player is also played when a coin toss decides which of the two games is played and the players choose their strategies before the coin toss.

Instead of modeling the randomization explicitly, we assume that a coin toss between two games is equivalent to the convex combination of these games.

Third, we stipulate a very weak notion of rationality.

Rationality. An action that dominates every other action of the same player in pure strategies is played with non-zero probability.

This notion of rationality is, for example, weaker than the condition demanding that actions that are dominated in pure strategies are never played.

Our main result characterizes Nash equilibrium as the unique solution concept that satisfies consequentialism, consistency, and rationality. In particular, players' behavior has to be consistent with expected utility maximization, which is not apparent from the axioms. Moreover, every refinement of Nash equilibrium violates at least one of the axioms.

The remainder of the paper is structured as follows. Existing axiomatic work on Nash equilibrium is discussed in Section 2. We define the model and introduce the required notation in Section 3. In Section 4, we formally define the three axioms and prove that every solution concept that satisfies these axioms has to return Nash equilibria. The converse statement, i.e., that any such solution concept has to return *all* Nash equilibria, is shown in the appendix. Section 5 concludes the paper by discussing consequences and variations of the main theorem.

2. Related Work

Which assumptions can be used to justify Nash equilibrium has been primarily studied in epistemic game theory. In this stream of research, the knowledge of individual players is modeled using Bayesian belief hierarchies, which consist of a game and a set of types for each player, with each type including the action played by this type and a probability distribution over types of the other players, called the belief of this type (Harsanyi, 1967). Rather than assuming that players actively randomize, the beliefs about the types of the other players are randomized. Players are rational if they maximize expected payoff given their types and beliefs. Aumann and Brandenburger (1995) have shown that for two-player games, the beliefs of every pair of types whose beliefs are mutually known and whose rationality is mutually known constitute a Nash equilibrium. This result extends to games with more than two players if the beliefs are commonly known and admit a common prior. Common knowledge assumptions in game theory have been criticized for not adequately modeling reality (see, e.g., Gintis, 2009). Barelli (2009), Hellman (2013), and Bach and Tsakas (2014) showed that the results of Aumann and Brandenburger (1995) still hold under somewhat weaker common knowledge assumptions.

Building on earlier work by Peleg and Tijs (1996), Norde et al. (1996) have charac-

terized Nash equilibrium via one-player rationality (only utility-maximizing strategies are returned in one-player games) and a consistency condition that is orthogonal to ours because it varies the set of *players*. Their condition requires that every strategy profile s returned for an n -player game is also returned for the $(n - k)$ -player game that results when k players invariably play their strategies in s . The two axioms immediately imply that only subsets of Nash equilibria can be returned. Their results have no implications for games with a fixed number of players. Other axiomatic work on Nash equilibrium includes a characterization of pure Nash equilibrium (Voornveld, 2019) and a characterization of Nash equilibrium for games with quasiconcave utility functions (Salonen, 1992).

The work most closely related to ours is due to Brandl and Brandt (2019), who have characterized *maximin strategies* in two-player zero-sum games by consequentialism, consistency, and rationality. The differences between their results and ours are as follows. Solution concepts as considered by Brandl and Brandt return a set of strategies for one player rather than a set of strategy *profiles*. Noting that Nash equilibria in zero-sum games consist of pairs of maximin strategies, their result translates as follows in the terminology of the present paper: *in zero-sum games*, every solution concept that satisfies consequentialism, consistency, and rationality returns an (exchangeable) *subset* of Nash equilibria.¹ Our main theorem, Theorem 1, is stronger since it *(i)* holds for any number of players, *(ii)* shows that *all* Nash equilibria have to be returned (and thus rules out equilibrium refinements), and *(iii)* is not restricted to games with rational-valued payoffs and rational-valued strategies (which are assumptions required for the proof of Brandl and Brandt). Moreover, we show that the containment in the set of Nash equilibria *(iv)* also holds for restricted classes of games (cf. Section 5).

3. The Model

Let U be an infinite universal set of actions and denote by $\mathcal{F}(U)$ the set of finite and nonempty subsets of U . A permutation of U is a bijection from U to itself that fixes

¹A set of strategy profiles is exchangeable if it is a Cartesian product of a set of strategies for each player.

all but finitely many elements, and for $A \in \mathcal{F}(U)$, Σ_A is the set of permutations of U that fix each element of $U \setminus A$. We denote by \mathbb{R}_+ and \mathbb{R}_{++} the set of non-negative and positive real numbers, respectively, and we use similar notation for \mathbb{Q} and \mathbb{Z} . If $p \in \mathbb{R}^U$, we write $\|p\| = \sum_{a \in U} |p(a)|$ for the ℓ_1 -norm of p whenever the sum on the right-hand-side is finite, and we write $\text{supp}(p) = \{a \in U : p(a) \neq 0\}$ for the support of p . Moreover, let

$$\Delta A = \{p \in \mathbb{R}_+^U : \text{supp}(p) \subseteq A \text{ and } \sum_{a \in A} p(a) = 1\}$$

be the set of probability distributions on U that are supported on A . We call ΔA the set of strategies for action set A .

Let $N = \{1, \dots, n\}$ be the set of players. For action sets $A_1, \dots, A_n \in \mathcal{F}(U)$, we write $A = A_1 \times \dots \times A_n$ for the corresponding set of action profiles. A game on A is a function $G: A \rightarrow \mathbb{R}^n$. For $i \in N$ and $a \in A$, $G_i(a)$ is the payoff of player i for the action profile a . We call $\Delta A_1 \times \dots \times \Delta A_n$ the set of (strategy) profiles on A . The players' payoffs for a strategy profile are the corresponding expected payoffs. Thus, a strategy profile p is a Nash equilibrium of G if

$$G_i(p_i, p_{-i}) \geq G_i(q_i, p_{-i}) \text{ for all } q_i \in \Delta A_i \text{ and } i \in N.$$

For two games G and G' on $A = A_1 \times \dots \times A_n$ and $A' = A'_1 \times \dots \times A'_n$, we say that G is a blow-up of G' or that G' is a blow-down of G if G can be obtained from G' by replacing actions with multiple payoff-equivalent actions and renaming actions. That is, there are surjective functions $\phi_i: A_i \rightarrow A'_i$, $i \in N$, such that with $\phi = (\phi_1, \dots, \phi_n)$, $G = G' \circ \phi$. Actions in $\phi_i^{-1}(a'_i)$ for $a'_i \in A'_i$ are called clones of a'_i . So G is obtained from G' by replacing each action a'_i by $|\phi_i^{-1}(a'_i)|$ clones of it.² A strategy $p_i \in \Delta A_i$ induces a strategy on A'_i via the pushforward along ϕ_i : $(\phi_i)_*(p_i) = p_i \circ \phi_i^{-1}$. Then, a strategy profile p on A induces the strategy profile $\phi_*(p) = ((\phi_1)_*(p_1), \dots, (\phi_n)_*(p_n))$ on A' .

²Kohlberg and Mertens (1986) have considered a more permissive notion of “blowing down” in the context of Nash equilibrium refinements for extensive-form games. Their notion of a reduced form of a normal-form game allows deleting any action that is a convex combination of other actions.

A solution concept f maps every game G to a set of strategy profiles $f(G)$ on the actions of G . If $f(G) \neq \emptyset$ for all G , f is a *total* solution concept. An example of a solution concept is *NASH*, which returns all strategy profiles that constitute Nash equilibria. Nash (1951) has shown that every game admits at least one Nash equilibrium, and so *NASH* is total. A non-example of a solution concept is correlated equilibrium since correlated strategy profiles (i.e., distributions over action profiles) are not strategy profiles according to our definition.

4. Characterization of Nash Equilibrium

This section defines our axioms and states the characterization of Nash equilibrium along with the more illuminating part of its proof. The remainder of the proof and all other proofs are given in the Appendix.

Consequentialism requires that if G is a blow-up of G' , a strategy profile is returned in G if and only if its pushforward is returned in G' . Equivalently, it asserts that (i) cloning an action does not change the probabilities of other actions and the strategies of the other players, and (ii) the probability on the cloned action can be distributed arbitrarily among its clones.

Definition 1 (Consequentialism). A solution concept f satisfies consequentialism if for all games G and G' such that G is a blow-up of G' with surjection $\phi = (\phi_1, \dots, \phi_n)$,

$$f(G) = \phi_*^{-1}(f(G')).$$

Consequentialism is a common desideratum in decision theory. It corresponds to the conjunction of Chernoff's (1954) *Postulate 6* (cloning of a player's actions) and *Postulate 9* (cloning of Nature's states, i.e., of opponent's actions). The latter also appears as *column duplication* (Milnor, 1954) and *deletion of repetitious states* (Arrow and Hurwicz, 1972; Maskin, 1979). In the context of social choice theory, a related condition called *independence of clones* was introduced by Tideman (1987) (see also Zavist and Tideman, 1989; Brandl et al., 2016).

Suppose $G = G'$ and ϕ_i permutes the actions of each player i . Then consequentialism reduces to equivariance, that is, relabeling the actions of a player results in the

same relabeling of her strategies. Formally, a solution concept f satisfies *equivariance* if for all games G on A and all $\pi = (\pi_1, \dots, \pi_n)$ where π_i is a permutation of A_i ,³

$$f(G \circ \pi) = f(G) \circ \pi.$$

We will frequently apply equivariance to strategy profiles where each player's strategy is the uniform distribution on some subset of her actions, and the permutations map each action to an action with the same probability, thus giving a new game for which the same strategy profile is returned.

Consistency requires that if a strategy profile is returned in two games with the same action sets, it is also returned in any convex combination of these games. An inductive argument shows that this is equivalent to the extension of the axiom to convex combinations of any finite number of games. We will frequently use this fact in our proofs.

Definition 2 (Consistency). A solution concept f satisfies consistency if for any two games G, G' on A and any $\lambda \in [0, 1]$,

$$f(G) \cap f(G') \subseteq f(\lambda G + (1 - \lambda)G').$$

We are not aware of game-theoretic work using this consistency axiom other than that by Brandl et al. (2016). Chernoff considers combinations of decision-theoretic situations obtained by taking unions of action sets. His *Postulate 9* states that any action that is chosen in two situations should also be chosen in such a combination. In our context, this translates to a consistency condition on the support of strategies and varying sets of actions. Closer analogs of consistency, involving convex combinations of distributions over states (i.e., strategies of Nature), have been considered as decision-theoretic axioms (see, e.g., Chernoff, 1954; Milnor, 1954; Gilboa and Schmeidler, 2003). Shapley's (1953) characterization of the Shapley value involves an additivity axiom (which he calls *law of aggregation*) that is similar in spirit to consistency. Lastly, analogs of consistency feature prominently in several axiomatic

³For a strategy $p_i \in \Delta(A_i)$, $p_i \circ \pi_i$ is the strategy with $(p_i \circ \pi_i)(a_i) = p_i(\pi(a_i))$. For a strategy profile $p = (p_1, \dots, p_n)$, $p \circ \pi = (p_1 \circ \pi_1, \dots, p_n \circ \pi_n)$, and this operation extends to sets of strategy profiles pointwise.

characterizations in social choice theory, where it relates the choices for different sets of voters to each other (see, e.g., Smith, 1973; Young, 1975; Young and Levenglick, 1978; Myerson, 1995; Brandl et al., 2016; Lackner and Skowron, 2021).

For a game G on A and two actions $a_i, a'_i \in A_i$, we say that a_i *dominates* a'_i if $G_i(a_i, a_{-i}) > G_i(a'_i, a_{-i})$ for all $a_{-i} \in A_{-i}$; a_i is *dominant* if it dominates every other action in A_i . Clearly, dominant actions are unique whenever they exist. Rationality requires that a dominant action has to be played with non-zero probability.

Definition 3 (Rationality). A solution concept f satisfies rationality if for all games G , all $i \in N$, and all dominant $a_i \in A_i$,

$$(p_1, \dots, p_n) \in f(G) \text{ implies } p_i(a_i) > 0.$$

Note that rationality is not concerned with *mixed* strategies and thus does not rely on *expected* payoffs. Moreover, it does not need any assumptions about other players. The strengthening of rationality requiring that dominated action receive probability 0 is equivalent to Milnor's (1954) *strong domination*, Maskin's (1979) *Property (5)*, and weaker than Chernoff's (1954) *Postulate 2*.

It turns out that Nash equilibrium is the only total solution concept that satisfies the three axioms defined above.

Theorem 1. *Let f be a total solution concept that satisfies consequentialism, consistency, and rationality. Then, $f = \text{NASH}$.*

The proof of Theorem 1 uses a lemma that illustrates how one can manipulate games using the above axioms. It shows that solution concepts satisfying consequentialism and consistency behave as one would hope under the analog of row and column operations familiar from linear algebra. More precisely, it shows that when adding a linear combination of some actions (with positive rational-valued coefficients) to another action, then a solution concept satisfying consequentialism and consistency shifts probability from the former actions to the latter in proportion to the coefficients (see Figure 1). A linear combination of actions here means a linear combination of the corresponding payoffs for all players. A similar conclusion applies to adding new actions that are linear combinations of existing ones.

$$\begin{array}{ccc}
& G & \hat{G} \\
& \begin{array}{ccc} 1/3 & 1/3 & 1/3 \end{array} & \begin{array}{ccc} 1/3 & 1/3 & 1/3 \end{array} \\
\begin{array}{c} 0 \\ 1/3 \\ 1/3 \\ 1/3 \end{array} & \left(\begin{array}{ccc} 1, 0 & 1, 1 & 1, 0 \\ 0, 1 & 2, 0 & 0, 1 \\ 1, 1 & 1, 0 & 0, 0 \\ 1, 0 & 0, 0 & 1, 1 \end{array} \right) & \begin{array}{c} 0 \\ 1/6 \\ 1/6 \\ 2/3 \end{array} & \left(\begin{array}{ccc} 1, 0 & 1, 1 & 1, 0 \\ 0, 1 & 2, 0 & 0, 1 \\ 1, 1 & 1, 0 & 0, 0 \\ \frac{3}{4}, \frac{1}{2} & \frac{3}{4}, 0 & \frac{1}{4}, \frac{3}{4} \end{array} \right)
\end{array}$$

Figure 1: Example for an application of Lemma 1. Here, one half of the second and third action of the first player are added to the fourth action. That is, \hat{a}_1 is the fourth action, $k_1 = (0, 1, 1, 2)$, $\kappa_1 = 1/6$, and $x_1 = (0, 1/6, 1/6, 1/3)$; \hat{a}_2 is arbitrary, say, the first action of player 2, $k_2 = (1, 0, 0)$, $\kappa_2 = 1$, and $x_2 = (1, 0, 0)$.

Lemma 1. *Let f be a solution concept satisfying consequentialism and consistency, G be a game on A , and $p \in f(G)$. Let $\hat{a} = (\hat{a}_1, \dots, \hat{a}_n) \in U^N$, $k = (k_1, \dots, k_n) \in \mathbb{Z}_+^{U \times N}$, and $\kappa = (\kappa_1, \dots, \kappa_n) \in \mathbb{R}_+^N$ such that for all $i \in N$, $k_i \neq (0, 0, \dots) \in \mathbb{Z}_+^U$, $k_i(\hat{a}_i) > 0$ if $\hat{a}_i \in A_i$, $\text{supp}(k_i) \subseteq A_i$, $x_i := \kappa_i k_i \leq p_i$, and $x_i(\hat{a}_i) = p_i(\hat{a}_i)$. Then, there is a game \hat{G} on \hat{A} with $\hat{A}_i = A_i \cup \{\hat{a}_i\}$ so that the following holds.*

1. $\hat{p} \in f(\hat{G})$, where $\hat{p}_i = p_i - x_i + \|x_i\|e_{\hat{a}_i}$.⁴
2. For all $I \subseteq N$ and $a \in A$, $\hat{G}(\hat{a}_I, a_{-I}) = G\left(\left(\frac{k_i}{\|k_i\|}\right)_{i \in I}, a_{-I}\right)$.

Condition 1 states that \hat{p}_i is obtained from p_i by shifting probability $x_i(a_i)$ from a_i to \hat{a}_i for all $a_i \neq \hat{a}_i$. Since $x_i \leq p_i$, \hat{p}_i is a lottery, and since x_i is a scalar multiple of an integer-valued vector, the ratios between the shifted probabilities are rational numbers, which is crucial for the proof technique. Condition 2 ensures that playing \hat{a}_i in \hat{G} is payoff-equivalent to playing $\frac{k_i}{\|k_i\|}$ in G . We remark that for each $i \in N$, one of three cases occurs:

- (i) $\hat{a}_i \in A_i$ and $p_i(\hat{a}_i) > 0$: then, $k_i(\hat{a}_i) > 0$ and $\kappa_i > 0$, and so \hat{a}_i is replaced by a linear combination of actions in A_i , each with positive probability in p_i , and non-zero weight on \hat{a}_i , and probability $x_i(a_i)$ is shifted from a_i to \hat{a}_i for all $a_i \neq \hat{a}_i$.

⁴By $e_{\hat{a}_i}$, we denote the standard unit vector in \mathbb{R}^U with a 1 in position \hat{a}_i .

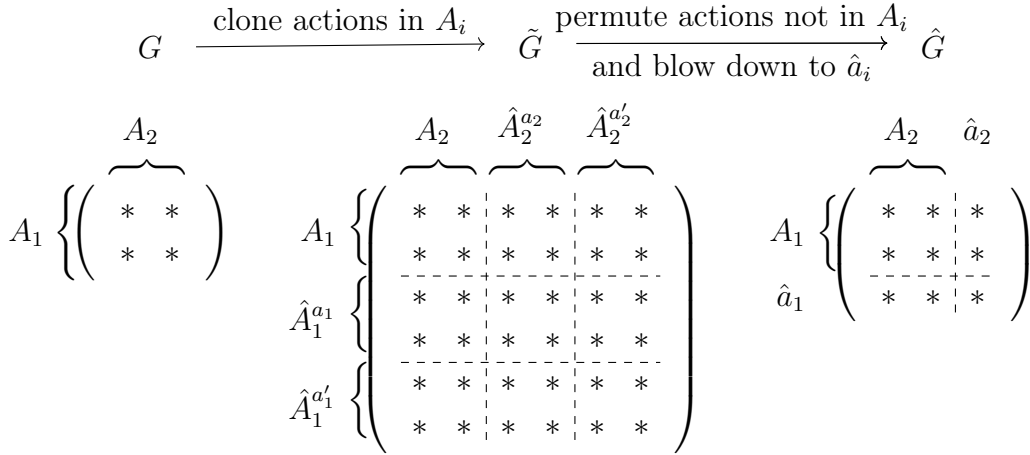


Figure 2: Schematic depiction of the games G , \tilde{G} , and \hat{G} constructed in the proof of Lemma 1 (with $n = 2$, $|A_i| = 2$, $k_i = (2, 2)$, and $\hat{a}_i \notin A_i$ for $i = 1, 2$). \tilde{G} is obtained from G by adding $k_i(a_i)$ clones of every action a_i of player i . Then, an intermediate game \hat{G} is constructed from \tilde{G} by permuting the actions outside of A_i and summing over the resulting games. The actions outside of A_i are now clones obtained from a convex combination (with weights k_i) of actions in A_i . Removing all but one of these clones gives \hat{G} .

(ii) $\hat{a}_i \in A_i$ and $p_i(\hat{a}_i) = 0$: then, $k_i(\hat{a}_i) > 0$ and $\kappa_i = 0$, and \hat{a}_i is replaced by a linear combination of actions in A_i with non-zero weight on \hat{a}_i , and $\hat{p}_i = p_i$.

(iii) $\hat{a}_i \in U \setminus A_i$ (and thus $p_i(\hat{a}_i) = 0$): then, $k_i(\hat{a}_i) = 0$ and $\kappa_i \geq 0$, and \hat{a}_i is replaced by a linear combination of actions in A_i , and $\hat{p}_i = p_i$ if (and only if) $\kappa_i = 0$.

Figure 2 illustrates the proof of Lemma 1 in Case (iii).

Proof. The first step constructs from G a game \tilde{G} by adding $k_i(a_i)$ clones of every action (with an exception for \hat{a}_i). For all $i \in N$ and $a_i \in A_i$, let $\hat{A}_i^{a_i} \subseteq U$ so that $|\hat{A}_i^{a_i}| = k_i(a_i)$ if $a_i \neq \hat{a}_i$, $|\hat{A}_i^{\hat{a}_i}| = k_i(\hat{a}_i) - 1$ if $\hat{a}_i \in A_i$, and $\hat{A}_i^{\hat{a}_i} = \emptyset$ if $\hat{a}_i \in U \setminus A_i$, and all $\hat{A}_i^{a_i}$ are disjoint and disjoint from $A_i^- := A_i \setminus \{\hat{a}_i\}$. Let $\tilde{A}_i = A_i \cup (\bigcup_{a_i \in A_i} \hat{A}_i^{a_i})$ and $\phi_i: \tilde{A}_i \rightarrow A_i$ so that $\phi_i^{-1}(a_i) = \{a_i\} \cup \hat{A}_i^{a_i}$. Let \tilde{G} be a game on $\tilde{A} = \tilde{A}_1 \times \cdots \times \tilde{A}_n$ so that \tilde{G} is a blow-up of G with surjection $\phi = (\phi_1, \dots, \phi_n)$. Hence, \tilde{G} is a game with $k_i(a_i) + 1$ clones of each action $a_i \in A_i$ if $a_i \neq \hat{a}_i$ and $k_i(\hat{a}_i)$ clones of \hat{a}_i . Consequentialism implies that $\tilde{p} \in \phi_*^{-1}(p) \subseteq f(\tilde{G})$, where $\tilde{p}_i = p_i - x_i + \|x_i\| \sum_{a_i \in \tilde{A}_i \setminus A_i^-} \frac{e_{a_i}}{|\tilde{A}_i \setminus A_i^-|}$, which is a lottery since $x_i \leq p_i$. In words, \tilde{p}_i is obtained from p_i by subtracting probability x_i from a_i and distributing it uniformly over the added clones of a_i , and a_i itself

if $a_i = \hat{a}_i \in A_i$. The number of clones has been chosen so that this amounts to subtracting x_i and adding the uniform lottery on $\tilde{A}_i \setminus A_i^-$ —the added clones and \hat{a}_i if $\hat{a}_i \in A_i$ —times $\|x_i\|$.

The second step constructs from \tilde{G} as game \bar{G} by permuting all actions in $\tilde{A}_i \setminus A_i^-$ in all possible ways and averaging over those permutations of \tilde{G} . Recall that for all $i \in N$, $\Sigma_{\tilde{A}_i \setminus A_i^-} \subseteq \Sigma_{\tilde{A}_i}$ is the set of all permutations of \tilde{A}_i that fix each element of A_i^- , and let $\Sigma = \Sigma_{\tilde{A}_1 \setminus A_1^-} \times \cdots \times \Sigma_{\tilde{A}_n \setminus A_n^-}$. Let

$$\bar{G} = \frac{1}{|\Sigma|} \sum_{\pi \in \Sigma} \tilde{G} \circ \pi.$$

By definition, \bar{G} is invariant under permutations of the actions in $\tilde{A}_i \setminus A_i^-$, and so all actions in $\tilde{A}_i \setminus A_i^-$ are clones of each other. Since \tilde{p}_i assigns the same probability to all actions in $\tilde{A}_i \setminus A_i^-$ and f is equivariant (since it satisfies consequentialism), $\tilde{p} \in f(\tilde{G} \circ \pi)$ for all $\pi \in \Sigma$. Consistency then implies that $\tilde{p} \in f(\bar{G})$. Every action in $\tilde{A}_i \setminus A_i^-$ is by construction the convex combination of actions in A_i with coefficients k_i . Thus, for all $I \subseteq N$, $a \in A$, and $\tilde{a} \in (\tilde{A}_1 \setminus A_1^-) \times \cdots \times (\tilde{A}_n \setminus A_n^-)$,

$$\bar{G}(\tilde{a}_I, a_{-I}) = G \left(\left(\frac{k_i}{\|k_i\|} \right)_{i \in I}, a_{-I} \right).$$

Hence, playing $\tilde{a}_i \in \tilde{A}_i \setminus A_i^-$ in \bar{G} is payoff-equivalent to playing $\frac{k_i}{\|k_i\|}$ in G .

The third step constructs from \bar{G} a game \hat{G} by deleting all actions in $\tilde{A}_i \setminus A_i^-$ —which are all clones of each other—except for \hat{a}_i . For all $i \in N$, let $\hat{\phi}_i: \tilde{A}_i \rightarrow \hat{A}_i$ so that $\hat{\phi}_i$ is the identity A_i^- and $\hat{\phi}_i^{-1}(\hat{a}_i) = \tilde{A}_i \setminus A_i^-$. Let \hat{G} be a blow-down of \bar{G} with surjection $\hat{\phi} = (\hat{\phi}_1, \dots, \hat{\phi}_n)$. Note that $\hat{p} = \hat{\phi}_*(\tilde{p})$. Consequentialism thus gives $\hat{p} \in f(\hat{G})$. Moreover, for all $I \subseteq N$ and $a \in A$,

$$\hat{G}(\hat{a}_I, a_{-I}) = \bar{G}(\hat{a}_I, a_{-I}) = G \left(\left(\frac{k_i}{\|k_i\|} \right)_{i \in I}, a_{-I} \right).$$

□

We show that every solution concept satisfying consequentialism, consistency, and rationality returns a *subset* of Nash equilibria by contraposition: we assume that a

non-equilibrium profile is returned in some game G and derive a violation of rationality in two steps, each using Lemma 1. First, we construct from G a game \bar{G} where a non-equilibrium profile is returned, and every player plays some distinguished action with probability close to 1 with the distinguished action of one player, say j , not being a best response. Using consequentialism, we may furthermore assume that j plays some best response with probability zero. The second step is to replace each non-distinguished action of each player, except for j 's probability-zero best response, by a convex combination of itself and the distinguished action of that player with large weight on the latter. In the resulting game \hat{G} , j 's probability-zero best response dominates all of j 's other actions, violating rationality. Notably, totality of the solution concept is not used in proving the containment in *NASH*. The proof that *all* Nash equilibria are returned crucially uses the containment in *NASH* and totality. It appears in the appendix and shows that every game with equilibrium p can be written as a convex combination of games in which p is the *unique* equilibrium, possibly after removing clones. This statement requires an elaborate proof and may be of independent interest.

Proof of Theorem 1. We prove that $f \subseteq \text{NASH}$. The proof of $\text{NASH} \subseteq f$ is given in the Appendix.

Let G be a game on A and $p \in f(G)$. We assume that the payoffs in G are normalized so that for every player i , the maximum and the minimum of G_i differ by at most 1. This assumption simplifies the expressions for some bounds below but is inessential. Assume for contradiction that $p \notin \text{NASH}(G)$. Then, there is a player $j \in N$ for whom p_j is not a best response. That is, $G_j(a_j^*, p_{-j}) - G_j(p) > \varepsilon$ for some $a_j^* \in A_j$ and $\varepsilon > 0$. We may assume that $\frac{3n}{\varepsilon} \in \mathbb{N}$.

The first step is to replace G by a game \bar{G} , where every player i has an additional action that is payoff-equivalent to playing approximately p_i . Let $\bar{a} \in (U \setminus A_1) \times \cdots \times (U \setminus A_n)$, $k \in (\mathbb{Z}_+^U \setminus \{0\})^N$, and $\kappa \in \mathbb{R}_+^N$ so that for all $i \in N$, $\text{supp}(k_i) \subseteq A_i$, $\kappa_i > 0$, and for $x_i = \kappa_i k_i$, $\|x_i\| \geq 1 - \frac{\varepsilon^2}{6n}$ and $x_i \leq p_i$. By Lemma 1, which applies by the conditions imposed on k_i and x_i , there is a game \bar{G} on \bar{A} with $\bar{A}_i = A_i \cup \{\bar{a}_i\}$ so that

1. $\bar{p} \in f(\bar{G})$, where $\bar{p}_i = p_i - x_i + \|x_i\|e_{\bar{a}_i}$, and
2. for all $I \subseteq N$ and $a \in A$, $\bar{G}(\bar{a}_I, a_{-I}) = G\left(\left(\frac{k_i}{\|k_i\|}\right)_{i \in I}, a_{-I}\right)$.

In particular, $\bar{p}_j(\bar{a}_j) \geq 1 - \frac{\varepsilon^2}{6n}$ and, using the normalization of G and the fact that

$$\left\| p_i - \frac{k_i}{\|k_i\|} \right\| = \left\| p_i - \frac{x_i}{\|x_i\|} \right\| \leq \|p_i - x_i\| + \left\| x_i - \frac{x_i}{\|x_i\|} \right\| \leq \frac{\varepsilon^2}{3n},$$

we have

$$\begin{aligned} \bar{G}_j(a_j^*, \bar{a}_{-j}) - \bar{G}_j(\bar{a}) &= G_j \left(a_j^*, \left(\frac{k_i}{\|k_i\|} \right)_{i \neq j} \right) - G_j \left(\left(\frac{k_i}{\|k_i\|} \right)_{i \in N} \right) \\ &\geq G_j(a_j^*, p_{-j}) - G_j(p) - \sum_{i \in N} \left\| p_i - \frac{k_i}{\|k_i\|} \right\| > \frac{2\varepsilon}{3}. \end{aligned}$$

Using that f satisfies consequentialism, we may add clones of actions, and so we may assume without loss of generality that $\bar{p}_j(a_j^*) = 0$ and that there is $B \in \mathcal{F}(U)$ so that $\bar{A}_j = B \cup \{a_j^*, \bar{a}_j\}$, and for all $i \neq j$, $\bar{A}_i = B \cup \{\bar{a}_i\}$.

The second step is to modify \bar{G} so that a_j^* dominates every action in $B \cup \{\bar{a}_j\}$ by replacing every action in B of every player $i \in N$ by a convex combination of itself and \bar{a}_i with a sufficiently large weight on \bar{a}_i . For every $b \in B$, let $k^b \in (\mathbb{Z}_+^U \setminus \{0\})^N$ and $\kappa^b \in \mathbb{R}_+^N$ so that for all $i \in N$ and $x_i^b := \kappa_i^b k_i^b$, $k_i^b = e_b + \frac{3n}{\varepsilon} e_{\bar{a}_i}$ and $x_i^b(b) = \bar{p}_i(b)$. Note that for all $i \in N$,

$$\sum_{b \in B} x_i^b(\bar{a}_i) = \frac{3n}{\varepsilon} \sum_{b \in B} x_i^b(b) = \frac{3n}{\varepsilon} \sum_{b \in B} \bar{p}_i(b) \leq \frac{3n}{\varepsilon} \frac{\varepsilon^2}{6n} = \frac{\varepsilon}{2},$$

and hence, $\sum_{b \in B} x_i^b \leq \bar{p}_i$. Sequential application of Lemma 1 to \bar{G} , one for each $b \in B$ with $\hat{a} = (b, \dots, b)$, gives a game \hat{G} on \bar{A} so that

1. $\hat{p} \in f(\hat{G})$, where $\hat{p}_i = \bar{p}_i - \frac{3n}{\varepsilon}(1 - \|x_i\|)e_{\bar{a}_i} + \frac{3n}{\varepsilon} \sum_{b \in B} (p_i(b) - x_i(b))e_b$ for all $i \in N$, and
2. for all $I \subseteq N$ and $a \in A$, $\hat{G}(a_I, \bar{a}_{-I}) = \bar{G} \left(\left(\frac{k_i^{a_i}}{\|k_i^{a_i}\|} \right)_{i \in I}, \bar{a}_{-I} \right)$.

Note that $\hat{p}_j(a_j^*) = \bar{p}_j(a_j^*) = 0$ by assumption. By the second statement, player j playing a_j^* in \hat{G} is payoff equivalent to playing a_j^* in \bar{G} , and for all $i \in N$ and $b \in B \cup \{\bar{a}_i\}$, player i playing a_i in \hat{G} is payoff equivalent to playing a_i with probability $\frac{1}{1+3n/\varepsilon}$ and \bar{a}_i with probability $\frac{3n/\varepsilon}{1+3n/\varepsilon}$ in \bar{G} . Thus, using again the normalization of G ,

we have for all $a \in \bar{A}$ with $a_j \neq a_j^*$,

$$|\hat{G}_j(a_j^*, a_{-j}) - \bar{G}_j(a_j^*, \bar{a}_{-j})| \leq \frac{n}{1 + 3n/\varepsilon} < \frac{\varepsilon}{3} \quad \text{and} \quad |\hat{G}_j(a) - \bar{G}_j(\bar{a})| \leq \frac{\varepsilon}{3}.$$

It follows that for all $a \in \bar{A}$ with $a_j \neq a_j^*$,

$$\hat{G}_j(a_j^*, a_{-j}) - \hat{G}_j(a) \geq \bar{G}_j(a_j^*, \bar{a}_{-j}) - \bar{G}_j(\bar{a}) - \frac{2\varepsilon}{3} > 0.$$

That is, a_j^* dominates every other action of j in \hat{G} , and so is dominant. Since \hat{p}_j assigns probability 0 to a_j^* , this contradicts rationality. \square

5. Discussion

We conclude by discussing consequences and variations of our characterization of Nash equilibrium, as well as the independence of the axioms.

Rationalizability and admissibility A player's strategy is rationalizable if it is a best response to some belief about the other players' strategies, assuming that everyone's rationality is common knowledge (Bernheim, 1984; Pearce, 1984). Every Nash equilibrium strategy is rationalizable; thus, rationalizability is consistent with our axioms. However, the solution concept returning all rationalizable strategy profiles—profiles in which every player plays a rationalizable strategy—violates consistency. In the first two games below, every strategy of either player is rationalizable.⁵ In the first game, the second action of the row player is rationalizable by a belief with high probability on the column player's first action, whereas in the second game, the second action of the row player is rationalizable by a belief with high probability on the column player's second action. The third game is the uniform convex combination of the first two. In that game, the second action of the row player is strictly dominated and thus not rationalizable, which shows the violation of consistency. These consistency failures arise because the strategy profile is not common knowledge: a player

⁵In two-player games, an action is rationalizable if and only if it survives the iterated elimination of strictly dominated strategies (Bernheim, 1984; Pearce, 1984). Since no strategy is strictly dominated in either game, every strategy is rationalizable in both games.

may rationalize a strategy with a belief that differs from the other players' strategies. However, note that common knowledge of the strategy profile and the rationality of all players already entail that the strategy profile is a Nash equilibrium.

$$\frac{1}{2} \begin{pmatrix} 0,0 & 4,0 \\ 2,0 & 0,0 \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 4,0 & 0,0 \\ 0,0 & 2,0 \end{pmatrix} = \begin{pmatrix} 2,0 & 2,0 \\ 1,0 & 1,0 \end{pmatrix}$$

A strategy is admissible if it is not weakly dominated or, equivalently, if it is a best response to some belief about the other players' strategies with full support. While each of our axioms individually is compatible with admissibility,⁶ their conjunction is not since not all Nash equilibria are admissible. The example for rationalizability above also shows that the solution concept returning all admissible strategy profiles violates consistency.

Equilibrium refinements One consequence of Theorem 1 is that every refinement of Nash equilibrium violates at least one of the axioms (including totality). We discuss some examples. Since rationality is preserved under taking subsets, every refinement satisfies rationality. *Quasi-strict equilibrium* (Harsanyi, 1973) satisfies consistency, and, for two players, is total (Norde, 1999). However, it violates consequentialism (even for two players) since it does not allow for the possibility that clones of equilibrium actions are played with probability 0. A trivial example is a game where all players' utility functions are constant for all action profiles. Then, every *full support* strategy profile is a quasi-strict equilibrium, whereas consequentialism requires that every strategy profile is returned. For three or more players, quasi-strict equilibria may not exist.

Trembling-hand perfect equilibrium (Selten, 1975) is total and satisfies consequentialism; thus, it is not consistent. In the first two games below, the strategy profile with probability 1 on the bottom-right action profile is a trembling-hand perfect equilibrium. To see this, recall that in two-player games, an equilibrium is trembling-hand

⁶The solution concept returning all admissible strategy profiles satisfies consequentialism and rationality. The solution concept returning all strategy profiles in which every player best responds to uniformly randomizing opponents satisfies consistency (see also the discussion of the independence of the axioms below), and each such strategy profile is admissible by the stated equivalence.

perfect if and only if it is admissible (see, e.g., van Damme, 1991). The third game is the uniform convex combination of the first two. In that game, the row player's second action is weakly dominated; thus, the same equilibrium is not trembling-hand perfect, which shows a consistency violation. The reason is the same as for the consistency violation discussed in the previous paragraph: in the first game, the second action of the row player is justified by trembles with much more probability on the column player's first action, whereas in the second game, the second action of the row player is justified by trembles with much more probability on the column player's second action.

$$\frac{1}{2} \begin{pmatrix} 0,0 & 4,0 & 2,0 \\ 2,0 & 0,0 & \mathbf{2,0} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 4,0 & 0,0 & 2,0 \\ 0,0 & 2,0 & \mathbf{2,0} \end{pmatrix} = \begin{pmatrix} 2,0 & 2,0 & 2,0 \\ 1,0 & 1,0 & \mathbf{2,0} \end{pmatrix}$$

Lastly, *strong equilibrium* (Aumann, 1959) and *coalition-proof equilibrium* (Bernheim et al., 1987) also satisfy consequentialism but violate consistency. To see this, consider the example below. In the first two games, the strategy profile with probability 1 on the bottom-right action profile is a strong (and thereby also coalition-proof) equilibrium. In the third game, which is a convex combination of the first two, the bottom-right action profile is not coalition-proof (and thereby not strong).

$$\frac{1}{2} \begin{pmatrix} 4,0 & 0,0 \\ 0,0 & \mathbf{1,1} \end{pmatrix} + \frac{1}{2} \begin{pmatrix} 0,4 & 0,0 \\ 0,0 & \mathbf{1,1} \end{pmatrix} = \begin{pmatrix} 2,2 & 0,0 \\ 0,0 & \mathbf{1,1} \end{pmatrix}$$

Moreover, strong equilibrium and coalition-proof equilibrium are not total even when there only two players.

Independence of axioms All properties in Theorem 1 are required to derive the conclusion. For each of the four axioms (including totality), there is a solution concept different from *NASH* that satisfies the three remaining axioms.

- (i) *Consequentialism*: return all strategy profiles in which every player randomizes only over actions that are best responses against uniformly randomizing opponents; satisfies totality, consistency, and rationality but violates consequentialism.

- (ii) *Consistency*: return all strategy profiles in which every player randomizes only over actions that maximize this player's highest possible payoff; satisfies totality, consequentialism, and rationality but violates consistency.
- (iii) *Rationality*: return all strategy profiles that maximize the sum of all players' payoffs; satisfies totality, consequentialism, and consistency but violates rationality.
- (iv) *Totality*: return all strategy profiles whose pushforwards are pure Nash equilibria in a blowdown of the original game; satisfies consequentialism, rationality, and consistency but violates totality.

The first three examples are neither contained in nor contain *NASH*. The last one is necessarily a refinement of *NASH* since totality is not needed for the inclusion $f \subseteq \text{NASH}$ in Theorem 1. Further examples that *are* refinements or coarsenings of *NASH* are not hard to find. Quasi-strict equilibrium (for two players) violates consequentialism but satisfies consistency and rationality as discussed above. Trembling-hand perfect equilibrium is not consistent but satisfies the other two axioms. The trivial solution concept returning all strategy profiles in all games violates rationality but satisfies the remaining two axioms. Note that rationality is so weak that even for *one*-player games, all three axioms are required for the characterization.

Restricted classes of games Examining the proof of the inclusion $f \subseteq \text{NASH}$, one can see that it remains valid for any class of games that is closed under blowing-up, blowing-down, and taking convex combinations. More precisely, it holds for any class of games \mathcal{G} with the following properties.

- (i) If G is a blow-up of G' , then $G \in \mathcal{G}$ if and only if $G' \in \mathcal{G}$.
- (ii) If $G_1, \dots, G_k \in \mathcal{G}$ are games on the same action profiles and $\lambda \in \mathbb{R}_+^k$ with $\sum_j \lambda_j = 1$, then $\lambda_1 G_1 + \dots + \lambda_k G_k \in \mathcal{G}$.

Various well-known classes of games satisfy these properties, for example, (strategically) zero-sum games, graphical games, and potential games. A game is symmetric if all players have the same set of actions, and permuting the actions in any action

profile results in the same permutation of the players' payoffs. Symmetric games are not closed with respect to blow-ups. For example, cloning or permuting actions of only one player makes a symmetric game asymmetric. It is unclear how to extend the current proof approach to symmetric games. The following symmetric two-player game illustrates this.

$$\begin{array}{c}
 0 \quad 1/2 \quad 1/2 \\
 0 \left(\begin{array}{ccc} 3,3 & 2,2 & 2,2 \\ 2,2 & 3,3 & 0,0 \\ 2,2 & 0,0 & 3,3 \end{array} \right) \\
 1/2 \\
 1/2
 \end{array}$$

The indicated strategy profile is not a Nash equilibrium. However, all symmetric games that are blow-ups of this game and convex combinations thereof have the same payoffs on the diagonal. Hence, clones of the second and third action of either player are not dominated in any of these games, so no contradictions to rationality occur. This issue does not arise for symmetric *zero-sum* games (see Brandl and Brandt, 2019, Remark 3).

For our proof of the converse inclusion, $NASH \subseteq f$, a class of games needs to have enough games with a unique equilibrium. Suppressing technicalities, it is required that for every game $G \in \mathcal{G}$ and every equilibrium p of G , G can be written as a convex combination of games in \mathcal{G} that have p as the unique equilibrium. We have not examined which classes of games, other than the class of all games, have this property.

Closures of solution concepts One can “repair” any given solution concept by iteratively adding strategy profiles whenever there is a failure of consequentialism or consistency. For instance, if a profile is returned in two games but not in some convex combination thereof, it is added to the set of returned profiles for the convex combination to eliminate this failure of consistency. One can equivalently define the closure of a solution concept f as the smallest solution concept containing f and satisfying consequentialism and consistency.⁷ By Theorem 1, the closure of a total

⁷This closure is well-defined since consequentialism and consistency are preserved under arbitrary intersections of solution concepts.

refinement of Nash equilibrium is Nash equilibrium, and the closure of total non-refinements violates rationality.

Robustness of the characterization In many areas of mathematics, it is common to aim for robust versions of results.⁸ In this spirit, we note that the inclusion $f \subseteq \text{NASH}$ in Theorem 1 is robust with respect to small violations of the axioms: every solution concept that approximately satisfies the three axioms is approximately Nash equilibrium. This can be made precise by formulating quantitatively relaxed versions of the axioms and replacing Nash equilibrium by ε -equilibrium. The details are worked out in the extended version of this paper (Brandl and Brandt, 2023).

Correlated equilibrium Our framework excludes correlated equilibrium since a strategy profile consists of a strategy for each player rather than a distribution over action profiles. It is an intriguing question whether our results extend to solution concepts returning correlated strategy profiles, but there are several obstacles to obtaining such a result. First, the axioms must be defined for correlated solution concepts, which leads to subtle issues in the case of consequentialism. Second, new proof techniques will be required since our arguments crucially exploit that the players' strategies are independent. Third, Nash equilibrium will satisfy many reasonable extensions of the axioms to correlated solution concepts, and thus, a unique characterization of correlated equilibrium without further axioms may not be feasible.

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⁸A classic example is isoperimetric stability. In Euclidean space, a ball is characterized as the unique volume-maximizing shape among all well-behaved shapes with the same surface area. Isoperimetric stability strengthens this assertion by showing that any shape that is close to volume maximizing has to resemble a sphere.

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APPENDIX

As a shorthand, we say that a solution concept is *nice* if it satisfies consequentialism, consistency, and rationality. This appendix contains the proof of the missing direction of Theorem 1, that is, $NASH \subseteq f$ for any nice solution concept f . The main idea of the proof is simple: for every game G and every equilibrium p of G , show that G can be written as a convex combination of games for which p is the unique equilibrium. Since $f \subseteq NASH$ and f is total, we know that f has to return unique equilibria. Consistency thus gives $p \in f(G)$.

The difficult part is to find a suitable representation of G as a convex combination. A first observation is that it suffices to prove that $NASH \subseteq f$ holds for games where the payoff functions of all players but one are 0. More formally, we say that G is a player i payoff game if for all $j \neq i$, $G_j \equiv 0$. Then, the following holds.

Lemma 2 (Reduction to player i payoff games). *Let G be a game and $p \in NASH(G)$. For $i \in N$, let G^i be the game with $G_i^i = G_i$ and $G_j^i \equiv 0$ for all $j \neq i$. Then, $p \in NASH(G^i)$.*

Proof. First, p_i is a best response to p_{-i} in G^i since it is a best response in G and $G_i^i = G_i$. Second, for all $j \neq i$, p_j (and any other strategy for that matter) is a best response to p_{-j} in G^i since $G_j^i \equiv 0$. Hence, $p \in NASH(G)$. \square

So if we can show that for every player i payoff game G , $NASH(G) \subseteq f(G)$, we can use Lemma 2 and consistency to conclude that the same conclusion holds for all games. While this reduction is convenient, it is not as powerful as it may seem since player i payoff games have a unique equilibrium only if all players other than i have only a single action. Thus, even when decomposing player i payoff games into games with a unique equilibrium, one needs to consider games with non-zero payoffs for all players.

A. Reduction to Deterministic Slice-Stochastic Tensors

The next step is a further reduction showing that it is sufficient to consider the case when G_i is a *slice-stochastic tensor*. To motivate this notion, recall that the well-known Birkhoff-von Neumann theorem states that every bistochastic matrix can be written as a convex combination of permutation matrices (Birkhoff, 1946; von Neumann, 1953).⁹ There are different ways one might try to generalize this statement to higher-order tensors. For example, one might say that a tensor $T: A_1 \times \cdots \times A_n \rightarrow \mathbb{R}_+$ is n -stochastic if for all $i \in N$ and $a_{-i} \in A_{-i}$, $\sum_{a_i \in A_i} T(a_i, a_{-i}) = 1$ (which is to say that every “tube” of T sums to 1). However, with this definition, for $n \geq 3$, it is not true that every n -stochastic tensor can be written as a convex combination of n -stochastic tensors taking values in $\{0, 1\}$ (see Cui et al., 2014). We thus opt for a different generalization of bistochastic matrices.

Definition 4 (Slice-stochastic tensors). Let $A \in \mathcal{F}(U)^n$ with $|A_1| = \cdots = |A_n|$. A tensor $T: A \rightarrow \mathbb{R}$ is *slice-stochastic for $i \in N$* if

- (i) for all $a_{-i} \in A_{-i}$, $\sum_{a_i \in A_i} T(a_i, a_{-i}) = 1$,
- (ii) for all $a_i \in A_i$, $\sum_{a_{-i} \in A_{-i}} T(a_i, a_{-i}) = m^{n-2}$, and
- (iii) for all $a \in A$, $0 \leq T(a) \leq 1$.

We say that T is a *deterministic slice-stochastic tensor* if it is slice-stochastic and takes values in $\{0, 1\}$.

For $n = 2$, T is a bistochastic matrix if and only if it is slice-stochastic for some $i = 1, 2$. Note that if T is slice-stochastic for i , then

$$\sum_{a \in A} T(a) = \sum_{a_{-i} \in A_{-i}} 1 = \sum_{a_i \in A_i} m^{n-2} = m^{n-1}.$$

We omit writing “for i ” when i is clear from the context.

⁹A matrix $M \in \mathbb{R}_+^{m \times m}$ is bistochastic if the row sums and column sums are 1.

It turns out that the Birkhoff-von Neumann theorem does extend to slice-stochastic tensors of any order. That is, every slice-stochastic tensor is a convex combination of deterministic slice-stochastic tensors. This will allow us to reduce the problem $NASH \subseteq f$ to payoff functions of the latter type.

Lemma 3 (Birkhoff-von Neumann theorem for slice-stochastic tensors). *Let $A \in \mathcal{F}(U)^n$ with $|A_1| = \dots = |A_n|$. Let $T: A \rightarrow \mathbb{R}$ be a slice-stochastic tensor for $i \in N$. Then, there are tensors $T^1, \dots, T^K: A \rightarrow \{0, 1\}$ that are slice-stochastic for i and $(\lambda^1, \dots, \lambda^K) \in \Delta([K])$ so that*

$$T = \sum_{k \in [K]} \lambda^k T^k.$$

Proof. Viewing T as an element of \mathbb{R}^A , T is slice-stochastic for i if it is a solution to the linear feasibility program

$$Mx \leq v,$$

where the matrix M and the vector v are given by the constraints of type (i), (ii), and (iii). Thus, M has $2|A_{-i}| + 2|A_i| + 2|A| = 2(m^{n-1} + m + m^n)$ rows (2 for each constraint of each of the three types) and $|A| = m^n$ columns; the number of rows of v is the same as for M . Note that M is of the form $M = (\tilde{M}^\top, -\tilde{M}^\top)^\top$ for some matrix \tilde{M} , since each constraint gives two rows in M where one is the negative of the other. (For $n = 3$ and $m = 2$, the matrix \tilde{M} is depicted in Figure 3.)

We want to show that the polytope defined by $Mx \leq v$ has integral vertices. Since v is integral (in fact, $\{-1, 0, 1\}$), it suffices to show that M is totally unimodular.¹⁰ But M is totally unimodular if and only if \tilde{M} is totally unimodular. Now \tilde{M} is totally unimodular if for every subset R of rows of \tilde{M} , there is an assignment $\sigma: R \rightarrow \{-1, 1\}$ of signs to the rows in R so that for all $a \in A$,

$$\sum_{r \in R} \sigma(r) \tilde{M}_{r,a} \in \{-1, 0, 1\}. \tag{1}$$

A proof of this result appears, for example, in the book by Schrijver (1998).

¹⁰ M is totally unimodular if every square submatrix of M has determinant $-1, 0$, or 1 .

$$\begin{array}{l}
\text{type (i)} \\
\text{type (ii)} \\
\text{type (iii)}
\end{array}
\left\{ \begin{array}{cccccc}
1 & 1 & & & & \\
& & 1 & 1 & & \\
& & & & 1 & 1 \\
& & & & & & 1 & 1 \\
\hline
1 & & 1 & & 1 & & & 1 \\
& 1 & & 1 & & 1 & & 1 \\
\hline
& & & & I_8 & & &
\end{array} \right\}$$

Figure 3: The matrix \tilde{M} in the proof of Lemma 3 for $n = 3$ and $m = 2$. I_8 denotes the identity matrix with $8 = m^n$ rows and columns. Each of the four pairs of columns separated by dashed lines corresponds to some $a_{-i} \in A_{-i}$. One can check that \tilde{M} is totally unimodular by verifying the equivalent condition (1).

This condition is easy to check in the present case. Let R be a subset of rows of \tilde{M} . It is easy to see that we may assume that R does not contain rows corresponding to constraints of type (iii) since those rows only contain of single 1 or -1 and can thus always be signed so as to not introduce violations of (1). We then define σ as follows.

- For each $r \in R$ corresponding to a constraint of type (i) for $a_{-i} \in A_{-i}$, let $\sigma(r) = 1$.
- For each $r \in R$ corresponding to a constraint of type (ii) for $a_i \in A_i$, let $\sigma(r) = -1$.

Then, for each column index $a \in A$, there is a most one 1 and at most one -1 in the sum in (1), which concludes the proof. \square

To show that considering games where every player's payoff function is slice-stochastic games is sufficient, we examine how certain changes to the payoff functions influence the set of equilibria. For $\alpha \in \mathbb{R}_{++}^N$ and $\beta \in \mathbb{R}^N$, we write $\alpha G + \beta$ for the game with payoff function $(\alpha G + \beta)_i = \alpha_i G_i + \beta_i$ for all $i \in N$. Moreover, we say that $T: A \rightarrow \mathbb{R}$ is *constant* for $i \in N$ if for all $a_{-i} \in A_{-i}$, $T(\cdot, a_{-i})$ is constant. Then, a game G is *constant* if for all $i \in N$, G_i is constant for i .

Lemma 4 (Invariance of equilibria). *Let G be a game on A . Then,*

(i) for all $\alpha \in \mathbb{R}_{++}^N$ and $\beta \in \mathbb{R}^N$, $NASH(G) = NASH(\alpha G + \beta)$, and

(ii) for all constant games \tilde{G} on A , $NASH(G) = NASH(G + \tilde{G})$.

Proof. The statement follows from a straightforward calculation. \square

For $n = 2$, G is constant if every column for G_1 and every row of G_2 is constant. Hence, Lemma 4(ii) asserts that adding a constant to some column of G_1 or row of G_2 does not change the set of equilibria.

The second type of modification of payoff functions concerns multiplication by tensors. The following notation will be convenient.

Definition 5 (Hadamard product). Let $A \in \mathcal{F}(U)^n$ and $T, T': A \rightarrow \mathbb{R}$. Then, the Hadamard product $T * T': A \rightarrow \mathbb{R}$ of T and T' is defined by

$$(T * T')(a) = T(a)T'(a)$$

for all $a \in A$.

Lemma 5 (Contortion of equilibria). Let G be a game on A . Let $i \in N$, $q \in \mathbb{R}_{++}^{A_i}$, and $T_q: A \rightarrow \mathbb{R}$ so that for all $a \in A$, $T_q(a) = q(a_i)$. Then,

$$p \in NASH(G) \quad \text{if and only if} \quad (\tilde{p}_i, p_{-i}) \in NASH(G^{i, T_q}),$$

where $G_i^{i, T_q} = G_i$, for all $j \neq i$, $G_j^{i, T_q} = G_j * T_q$, and for all $a_i \in A_i$, $\tilde{p}_i(a_i) = (p_i(a_i)/q(a_i))/(\sum_{a'_i \in A_i} p_i(a'_i)/q(a'_i))$.

Proof. The statement follows from a straightforward calculation. \square

Note that T_q in Lemma 5 is constant for all $j \neq i$. For $n = 2$, the game G^{1, T_q} is obtained from G by multiplying the a_1 row of the matrix G_2 by $q(a_1)$ for all $a_1 \in A_1$.

The next lemma show that in some sense, it is enough to consider games where the payoff function of every player is slice-stochastic. This is explained in more detail after the lemma.

Lemma 6 (Universality of slice-stochastic tensors). Let $A \in \mathcal{F}(U)^n$ with $|A_1| = \dots = |A_n|$. Let p be a profile on A so that all p_i have full support. Then, there are

$T_1, \dots, T_n: A \rightarrow \mathbb{R}_{++}$ so that T_i is constant for all $j \neq i$ and for all games G on A and $p \in \text{NASH}(G)$, there is a game \bar{G} on A so that the following hold.

- (i) For all $i \in N$, $\bar{G}_i = G_i * T^{-i} + S_i$, where T^{-i} is the Hadamard product of all T_j with $j \neq i$, and $S_i: A \rightarrow \mathbb{R}$ is constant for i .
- (ii) For all $i \in N$, \bar{G}_i is slice-stochastic for i .
- (iii) $\bar{p} \in \text{NASH}(\bar{G})$, where \bar{p} and \bar{p}_i is the uniform distribution on A_i .

Proof. For all $i \in N$, let $T_i: A \rightarrow \mathbb{R}_{++}$ so that for all $a \in A$, $T_i(a) = \varepsilon p_i(a_i)$, where $\varepsilon > 0$ is small compared to (the reciprocal of) the largest payoff in G and $|A| = m^n$. Define a game \hat{G} on A so that for all $i \in N$, $\hat{G}_i = G_i * T^{-i}$. It follows from Lemma 5 that $\bar{p} \in \text{NASH}(\hat{G})$.

For all $i \in N$, let $S_i: A \rightarrow \mathbb{R}$ so that for all $a \in A$,

$$S_i(a) = \frac{1}{m} \left(1 - \sum_{a'_i \in A_i} \hat{G}_i(a'_i, a_{-i}) \right).$$

Note that S_i is constant for i .

Let \bar{G} be the game so that for all $i \in N$, $\bar{G}_i = \hat{G}_i + S_i$. By Lemma 4(ii), $\bar{p} \in \text{NASH}(\bar{G})$ and so for all $i \in N$, $\sum_{a_{-i} \in A_{-i}} \bar{G}_i(\cdot, a_{-i})$ is constant on A_i . Moreover, for all $a_{-i} \in A_{-i}$, $\sum_{a_i \in A_i} \bar{G}_i(a_i, a_{-i}) = 1$ by the choice of S_i . Lastly, since ε is small, $\hat{G}_i(a) \approx 0$ and $S_i(a) \approx \frac{1}{m}$ for all $a \in A$. Hence, \bar{G}_i is slice-stochastic. We have thus shown that \bar{G} satisfies all three conditions in the statement of the lemma. \square

The condition (iii) in Lemma 6 is redundant since the strategy profile where every player distributes uniformly automatically an equilibrium if the payoff function of every player is slice-stochastic (by Item (ii) in the definition of slice-stochasticity). We chose to state it to make it explicit.

The way in which we will use Lemma 6 is as follows. Given a game G with the same number of actions for every player and a full support equilibrium $p \in \text{NASH}(G)$, we want to show that $p \in f(G)$ if f is a nice total solution concept. To do this, we show that the game \bar{G} obtained from the lemma (by virtue of having slice-stochastic tensors as payoff functions) can essentially be written as a convex combination of

games for which \bar{p} is the unique equilibrium. Applying the inverse transformation of that in (i) to each of the summands and using Lemma 5 shows that G can essentially be written as a convex combination of games for which p is the unique equilibrium. Using consistency and the fact that $f \subseteq \text{NASH}$, this shows that $p \in f(G)$. The caveat “essentially” refers to the fact that one may need to multiply the G_i by positive scalars, add constant games to G , and clone actions to get the desired representation as a convex combination. Since neither of the first two operations changes the set of equilibria and the effect of introducing clones is controlled by consequentialism, this does not cause problems. Similarly, the restriction that every player has the same number of actions in G is without loss of generality by consequentialism.

Together, Lemma 2, Lemma 3, and Lemma 6 show the following. If we want to show that $p \in f(G)$ whenever $p \in \text{NASH}(G)$ and p has full support, then it is enough to do so in the case when G is a player i payoff game with G_i deterministic slice-stochastic. The full support assumption will be successively eliminated via Lemmas 10, 11, and 12.

B. Decomposition of Deterministic Slice-Stochastic Tensors

The first step is to construct a sufficiently rich class of games that have the strategy profile where every player randomizes uniformly as their unique equilibrium. This will be the class of cyclic games and almost cyclic games. In cyclic games, the payoff of every player only depends on the action of one other player and the dependencies form a cycle. Roughly, a player gets a payoff of 1 if she matches the action of the preceding player and 0 otherwise. The fact that every such game has uniform randomization as an equilibrium is not hard to see. Uniqueness is achieved by imposing a restriction on the notion of “matching” (see Definition 8(i)). Almost cyclic games differ only insofar that there is one exceptional player whose payoff not only depends on the action of the preceding player in the cycle but (for few action profiles) also on the actions of all other players. Making the concepts above precise requires two definitions.

Definition 6 (Fixed subsets). Let A be a set and $\pi \in \Sigma_A$. Then, $B \subseteq A$ is a *fixed*

subset of π if $\pi(B) = B$. We say that π has *no non-trivial fixed subset* if its only fixed subsets are \emptyset and A .

For any two permutations π, π' , $\pi' \circ \pi$ has a non-trivial fixed subset if and only if $\pi \circ \pi'$ does. At least when A is finite, permutations without a non-trivial fixed subset always exist. Any cyclic permutation is an example. Also, for any permutation π , there is a permutation π' so that $\pi' \circ \pi$ has no non-trivial fixed subset.

Definition 7 (Permutation sets). Let $A_1, \dots, A_n \in \mathcal{F}(U)$ with $|A_1| = \dots = |A_n|$ and let $A = A_1 \times \dots \times A_n$. A set $A^* \subseteq A$ is a *permutation set* if for all $i \in N$ and $a'_i \in A_i$, there is exactly one $a \in A^*$ with $a_i = a'_i$.

Another way of saying that A^* is a permutation set is that the projection from A^* onto each A_i is bijective. If $A_1 = \dots = A_n = [m]$, yet another way is requiring that there are permutations π_1, \dots, π_{n-1} of $[m]$ so that $A^* = \{(k, \pi_1(k), \dots, \pi_{n-1} \circ \dots \circ \pi_1(k)) : k \in [m]\}$. This characterization motivates the terminology.

Definition 8 ((Almost) cyclic games). Let $A = [m]^n$ and G be a game on A . We say that G is *cyclic* if there are $\pi_1, \dots, \pi_n \in \Sigma_{[m]}$ and $\alpha \in \mathbb{R}_{++}^N$ so that the following holds.

(i) $\pi_n \circ \dots \circ \pi_1$ has no non-trivial fixed subset,

(ii) for all $j \in N$ and $a \in A$,

$$G_j(a) = \begin{cases} \alpha_j & \text{if } a_j = \pi_{j-1}(a_{j-1}), \\ 0 & \text{otherwise.} \end{cases}$$

For $n \geq 3$, we say that G is *almost cyclic* if there are $i \in N$, $\pi_1, \dots, \pi_n \in \Sigma_{[m]}$, $A^* \subseteq A$, and $\alpha \in \mathbb{R}_{++}^N$ so that the following holds.

(i) $\pi_n \circ \dots \circ \pi_1$ has no non-trivial fixed subset,

(ii) for all $j \neq i$ and $a \in A$,

$$G_j(a) = \begin{cases} \alpha_j & \text{if } a_j = \pi_{j-1}(a_{j-1}), \\ 0 & \text{otherwise,} \end{cases} \quad \text{and}$$

$$G_i(a) = \begin{cases} \alpha_i & \text{if } a_i = \pi_{i-1}(a_{i-1}) \text{ and } a \notin A^* \\ 0 & \text{otherwise,} \end{cases}$$

(iii) A^* is a permutation set and for all $a \in A^*$, $a_i = \pi_{i-1}(a_{i-1})$ and there is $j \neq i, i+1$ with $a_j \neq \pi_{j-1}(a_{j-1})$.

Unless otherwise noted, we assume that $\alpha = (1, \dots, 1)$.

Example 1 ((Almost) cyclic games for $n = 2, 3$). Let $n = 2$ and consider the following game G where both players have three actions. The first (second) entry in each cell denotes the payoff of player 1 (player 2).

$$\begin{pmatrix} 1, 0 & 0, 1 & 0, 0 \\ 0, 0 & 1, 0 & 0, 1 \\ 0, 1 & 0, 0 & 1, 0 \end{pmatrix}$$

Then, G is a cyclic game with $\pi_1 = (123)$ and $\pi_2 = (1)(2)(3)$. Almost cyclic games for two players are degenerate in the sense that the payoff function of the exceptional player is 0.

Now let $m = n = 3$, $i = 1$, $\pi_1 = (123)$, and $\pi_2 = \pi_3 = (1)(2)(3)$. Clearly, $\pi_3 \circ \pi_2 \circ \pi_1$ has no non-trivial fixed subset. One can check that the permutation set $A^* = \{(1, 2, 1), (2, 3, 2), (3, 1, 3)\}$ satisfies (iii). The payoff function of player 1 is shown below (player 1 chooses the matrix, player two the row, and player 3 the column; the entries corresponding to A^* are marked in boldface).

$$\begin{pmatrix} 1 & 0 & 0 \\ \mathbf{0} & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 1 & 0 \\ 0 & 1 & 0 \\ 0 & \mathbf{0} & 0 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & \mathbf{0} \\ 0 & 0 & 1 \\ 0 & 0 & 1 \end{pmatrix}$$

Lemma 7 (Equilibria of (almost) cyclic games). *Let G be a cyclic game or an almost cyclic game. Then, G has a unique Nash equilibrium where every player randomizes uniformly over all of her actions.*

Proof. We prove the statement for almost cyclic games. The proof for cyclic games is easier. More specifically, for cyclic games, Case 1 and Case 2 below can be combined into one that is proved in the same way as Case 1.

Let $n \geq 3$. Let $i \in N$, $\pi_1, \dots, \pi_n \in \Sigma_{[m]}$, A^* , and α be as in the definition of almost cyclic games. By Lemma 4, it is without loss of generality to assume that $\alpha = (1, \dots, 1)$. Let p be the strategy profile where p_j is the uniform distribution on A_j for all $j \in N$.

It is easy to see that p is an equilibrium since for all $a_i \in A_i$,

$$\sum_{a_{-i} \in A_{-i}} G_i(a_i, a_{-i}) = m^{n-2} - 1,$$

where the -1 comes from the fact that A^* is a permutation set. Moreover, for all $j \neq i$ and $a_j \in A_j$,

$$\sum_{a_{-j} \in A_{-j}} G_j(a_j, a_{-j}) = m^{n-2}.$$

Now we show that p is the unique equilibrium. Assume that p' is an equilibrium. For all $j \in N$, let $B_j = \arg \max_{a_j \in A_j} p'_j(a_j)$. Note that for all $j \neq i$, the payoff of j only depends on her own strategy and the strategy of $j-1$. Hence, $a_j \in A_j$ is a best response to p'_{-j} if $a_j \in \pi_{j-1}(B_{j-1})$. So $B_j \subseteq \text{supp}(p'_j) \subseteq \pi_{j-1}(B_{j-1})$. In particular,

$$|\text{supp}(p'_i)| \geq |\text{supp}(p'_{i+1})| \geq \dots \geq |\text{supp}(p'_{i-1})|. \quad (2)$$

We distinguish two cases.

Case 1. Suppose that $|\text{supp}(p'_j)| \geq 2$ for some $j \neq i$. By (2), $|\text{supp}(p'_{i+1})| \geq 2$. Since $n \geq 3$ and A^* is a permutation set, it follows that $G_i(a_i, p'_{-i}) > 0$ for all $a_i \in \pi_{i-1}(\text{supp}(p'_{i-1}))$. Hence, $\text{supp}(p'_i) \subseteq \pi_{i-1}(\text{supp}(p'_{i-1}))$, and so $|\text{supp}(p'_i)| \leq |\text{supp}(p'_{i-1})|$. It follows that all inequalities in (2) hold with equality. But then for all

$j \in N$, $\text{supp}(p'_j) = \pi_{j-1}(\text{supp}(p'_{j-1}))$, and so $\text{supp}(p'_1)$ is a fixed subset of $\pi_n \circ \dots \circ \pi_1$. By assumption, this is only possible if $A_1 = \text{supp}(p'_1)$, which in turn implies that $\text{supp}(p'_j) = A_j$ for all $j \in N$. Hence, $p' = p$.

Case 2. Suppose that $|\text{supp}(p'_j)| = 1$ for all $j \neq i$ and let $a'_j \in A_j$ so that $p'_j(a'_j) = 1$. Note that $a'_j = \pi_{j-1}(a'_{j-1})$ for all $j \neq i, i+1$. Moreover, we have that $G_i(\pi_{i-1}(a'_{i-1}), a'_{-i}) = 1$ unless $(\pi_{i-1}(a'_{i-1}), a'_{-i}) \in A^*$. But by the second part of (iii) in the definition of almost cyclic games, $(\pi_{i-1}(a'_{i-1}), a'_{-i}) \notin A^*$. Hence, $G_i(\pi_{i-1}(a'_{i-1}), a'_{-i}) = 1$. By (ii) and the fact that $|\text{supp}(p'_{i-1})| = 1$, $G_i(a_i, p'_{-i}) = 0$ unless $a_i = a'_i = \pi_{i-1}(a'_{i-1})$. Thus, a'_i is the unique best response of player i to p'_{-i} . Since p' is an equilibrium, it follows that $p'_i(a'_i) = 1$ and $|\text{supp}(p'_i)| = 1$. Finally, since p'_{i+1} is a best response to p'_i , we have that $a'_{i+1} = \pi_i(a'_i)$. So $a'_j = \pi_{j-1}(a'_{j-1})$ for all $j \in N$, which means that $\{a'_1\}$ is a fixed subset of $\pi_n \circ \dots \circ \pi_1$ and contradicts (i). □

Definition 9 (Permutation tensors and permutation games). Let $A_1, \dots, A_n \in \mathcal{F}(U)$ with $|A_1| = \dots = |A_n|$ and let $A = A_1 \times \dots \times A_n$. A function $T: A \rightarrow \mathbb{R}$ is a *permutation tensor* if there is a permutation set $A^* \subseteq A$ so that $T(a) = 1$ for all $a \in A^*$ and $T(a) = 0$ for all $a \in A \setminus A^*$. A game G is a permutation game if there is $i \in N$ so that G is a player i payoff game and G_i is a permutation tensor.

For $n = 2$, a permutation tensor is a permutation matrix.

We show that every permutation game can be written as a convex combination of cyclic games and almost cyclic games up to an additive constant. Note that even though permutation games are player i payoff games, the games in the decomposition are not.

Lemma 8 (Decomposition of permutation games). *Let $A_1, \dots, A_n \in \mathcal{F}(U)$ so that $|A_1| = \dots = |A_n| = m$, and let $A = A_1 \times \dots \times A_n$. Let $i \in N$ and $A^* \subseteq A$ be a permutation set. Let G be the permutation game for i and A^* on A . Then, G can be written as a convex combination of cyclic games, almost cyclic games, and a constant $\beta \in \mathbb{R}^N$.*

Proof. Let G be a game as in the statement of the lemma. For simplicity, assume that $i = n$ and for all $j \in N$, $A_j = [m]$.

Let $\pi_1, \dots, \pi_n \in \Sigma_{[m]}$ so that $A^* = \{(k, \pi_1(k), \dots, \pi_{n-1} \circ \dots \circ \pi_1(k)) \in [m]^N : k \in [m]\}$ and $\pi_n \circ \dots \circ \pi_1$ has no non-trivial fixed subset. This is possible since we may first choose π_1, \dots, π_{n-1} so that the first condition holds (using that A^* is a permutation set) and then choose π_n so that $\pi_n \circ \dots \circ \pi_1$ has no non-trivial fixed subset.

Let $\hat{A} = \{a \in A : a_n = \pi_{n-1}(a_{n-1})\}$. Note that $|\hat{A}| = m^{n-1}$ and $A^* \subseteq \hat{A}$. Let $B^1, \dots, B^M \subseteq A$ be a partition of $\hat{A} \setminus A^*$ into permutation sets, where $M = m^{n-2} - 1$. (Note that $M = 0$ if $n = 2$.) For example, one may take

$$B^{s_{-\{1,n\}}} = \{(a_1, a_2 + s_2, \dots, a_{n-1} + s_{n-1}, \pi_{n-1}(a_{n-1} + s_{n-1})) \in [m]^N : a \in A^*\},$$

where $s_{-\{1,n\}} \in [m]^{N \setminus \{1,n\}} \setminus \{0\}$. Since $s_{-\{1,n\}} \neq 0$, the last condition in (iii) holds for B^l . For all $l \in [M]$, let G^l be the almost cyclic game for $i = n, \pi_1, \dots, \pi_n, B^l$, and $\alpha = (1, \dots, 1)$. In particular, $G_n^l(a) = 0$ for all $a \in B^l$ and $G_n^l(a) = 1$ for all $a \in \hat{A} \setminus B^l$.

Now let

$$\hat{G} = \sum_{l \in [M]} G^l.$$

Then, the following hold.

- For all $a \in A^*$, $G_n(a) = M$; for all $a \in \hat{A} \setminus A^*$, $G_n(a) = M - 1$.
- For all $j \neq n$ and $a \in A$ with $a_j = \pi_{j-1}(a_{j-1})$, $G_j(a) = M$.
- For all $j \in N$ and $a \in A$ with $a_j \neq \pi_{j-1}(a_{j-1})$, $G_j(a) = 0$.

Recall that for all $j \in N$ and $(a_{j-1}, a_j) \in [m]^2$, there is a cyclic game G' for some $\pi'_1, \dots, \pi'_n \in \Sigma_{[m]}$ with $a_j = \pi'_{j-1}(a_{j-1})$ and arbitrary $\alpha' \in \mathbb{R}_{++}^N$ (see the remarks after Definition 6). For all $j \in N$ and $(a_{j-1}, a_j) \in [m]^2$ with $a_j \neq \pi_{j-1}(a_{j-1})$, let G^{j, a_{j-1}, a_j} be a cyclic game for some $\pi'_1, \dots, \pi'_n \in \Pi_{[m]}$ with $a_j = \pi'_{j-1}(a_{j-1})$, $\alpha'_{j'} = 1$ for all $j' \neq j$, and $\alpha'_j = M + 1$ if $j \neq n$ and $\alpha'_j = M$ if $j = n$. Then, let

$$\tilde{G} = \hat{G} + \sum G^{j, a_{j-1}, a_j} + \sum G', \quad (3)$$

where the first sum ranges over all $j \in N$ and $(a_{j-1}, a_j) \in [m]^2$ with $a_j \neq \pi_{j-1}(a_{j-1})$, and the second sum ranges over all cyclic games with $\alpha = (1, \dots, 1)$ whose tuple of

permutations does not already appear in one of the games in the first sum. Since for all $j \in N$ and $(a_{j-1}, a_j) \in [m]^2$, the number of cyclic games with $a_j = \pi'_{j-1}(a_{j-1})$ is the same (assuming α is fixed), the following hold.

- For all $a^* \in A^*$ and $a \in A \setminus A^*$, $\tilde{G}_n(a^*) = \tilde{G}_n(a) + 1$.
- For all $j \neq n$ and $a, a' \in A$, $G_j(a) = G_j(a')$.

Hence, $G = \tilde{G} + \beta$ for some $\beta \in \mathbb{R}^N$. More explicitly, if L is the total number of games in the first and second sum in (3), then

- For all $a \in A^*$, $\tilde{G}_n(a) = M + \frac{L}{m}$; for all $a \in A \setminus \bar{A}^*$, $G_n(a) = M - 1 + \frac{L}{m}$.
- For all $j \neq i$ and $a \in A$, $\tilde{G}_j(a) = M + \frac{L}{m}$.

(The denominator m comes from the fact that for a permutation game G' , the fraction of actions for which $G'_j(a) = \alpha_j$ is $\frac{1}{m}$.) This proves G can be written as a sum of games of the claimed types. Multiplying each game in that sum by the same appropriately chosen positive scalar gives the representation of G as a convex combination. \square

The last lemma in this section roughly shows that every game with deterministic slice-stochastic tensors as payoff functions can be written as a convex combination of permutation games. This conclusion is not literally true. More precisely, we show that every game with deterministic slice-stochastic tensors as payoff functions is the blow-down of a convex combination of permutation games (with the same number of clones of every action for every player). By Lemma 7 and Lemma 8, each of the games in this sum can, in turn, be written as a convex combination of games for which uniform randomization is the unique equilibrium. Consistency and consequentialism thus imply that uniform randomization has to be returned in the original game, possibly alongside other equilibria.

Lemma 9 (Decomposition of slice-stochastic games). *Let $A_1, \dots, A_n \in \mathcal{F}(U)$ with $|A_1| = \dots = |A_n| = m$, and let $A = A_1 \times \dots \times A_n$. Let G be a game on A so that G_i is a deterministic slice-stochastic tensor for all $i \in N$. Let p be the profile on A so that each p_i is the uniform distribution on A_i . Then, up to cloning actions, multiplying by positive scalars, and adding constants, G can be written as a convex combination*

of games for which p is the unique equilibrium. More precisely, there are $\alpha \in \mathbb{R}_{++}^N$, $\beta \in \mathbb{R}^N$, and a game \bar{G} so that

(i) G is a blow-down of $\alpha\bar{G} + \beta$ with surjection ϕ ,

(ii) $\phi_*(\hat{p}) = p$, where \hat{p}_j is the uniform distribution on the actions of player j in \bar{G} ,
and

(iii) \bar{G} is a convex combination of games for which \hat{p} is the unique equilibrium.

Proof. First, we observe that it suffices to consider the case that G is a player i payoff game (meaning that $G_j = 0$ for all $j \neq i$). The idea now is to “blow up” G by introducing m^{n-2} actions for each action of every player in G . Then, one can define a permutation game \hat{G} on the larger action sets so that for every action profile a in G for which player i has payoff 1, there is exactly one blow up \hat{a} of a for which i has payoff 1 in \hat{G} . Since \hat{G} is a permutation game, we know from Lemma 8 that, up to adding constants, it can be written as a convex combination of games for which the strategy profile where every player plays the uniform distribution is the unique equilibrium. Now permuting all actions in \hat{G} that come from blowing up the same action in G , summing up over all the resulting games, and multiplying by a positive scalar gives a game \bar{G} that is a blow-up of G . This achieves the desired decomposition. (Remark 1 explains why the blowing up is necessary.)

As noted above, we may assume that there is $i \in N$ so that G is a player i payoff game. Let $A^* = \{a \in A : G_i(a) = 1\}$ be the actions for which player i has payoff 1 in G . For all $j \in N$ and $a_j \in [m]$, let $B_j^{a_j} = \{a_{-j} \in A_{-j} : (a_j, a_{-j}) \in A^*\}$ be the set of opponents action profiles for which i gets payoff 1 when j plays a_j . Since G_i is slice-stochastic, $|B_j^{a_j}| = m^{n-2}$. (For $j = i$, this is (ii) in the definition of slice-stochastic games; for $j \neq i$, for all a_j and $a_{-\{i,j\}}$, there is exactly one a_i so that $G_i(a_i, a_j, a_{-\{i,j\}}) = 1$ by (i).) Let $\hat{A}_j = \bigcup_{a_j \in A_j} \{a_j\} \times B_j^{a_j}$ and $\hat{A} = \hat{A}_1 \times \cdots \times \hat{A}_n$. Note that \hat{A}_j has size m^{n-1} . Now let and

$$\hat{A}^* = \{((a_1, a_{-1}), \dots, (a_n, a_{-n})) \in \hat{A} : a \in A^*\}.$$

It is easy to see that \hat{A}^* is a permutation set in \hat{A} . Let \hat{G} be the permutation game for i on \hat{A} for the permutation set \hat{A}^* . By Lemma 8, we have that \hat{G} can be written as

a sum of cyclic games, almost cyclic games, and a constant. Moreover, by Lemma 7, we know that \hat{p} is the unique equilibrium of cyclic and almost cyclic games, where \hat{p}_j is the uniform distribution on \hat{A}_j .

For all $j \in N$, let $\phi_j: \hat{A}_j \rightarrow A_j$ be projection onto the first coordinate, and let $\phi = (\phi_1, \dots, \phi_n)$. That is, $\phi_j((a_j, a_{-j})) = a_j$. Let $\Sigma_j \subseteq \Sigma_{\hat{A}_j}$ be the set of all permutations π_j so that $\phi_j(\hat{a}_j) = \phi_j(\pi_j(\hat{a}_j))$ for all $\hat{a}_j \in \hat{A}_j$ (that is, all permutations that keep the first coordinate fixed). Let $\Sigma = \Sigma_1 \times \dots \times \Sigma_n$. So we have that for all $\hat{a} \in \hat{A}$ and $\pi \in \Sigma$,

$$G_i(\phi(\hat{a})) = G_i((\phi \circ \pi)(\hat{a})).$$

Consider the game

$$\bar{G} = \frac{M}{|\Sigma|} \sum_{\pi \in \Sigma} \hat{G} \circ \pi,$$

where $M = m^{(n-1)n}$. (The factor M is necessary since for all $a \in A$, there are M profiles $\hat{a} \in \hat{A}$ with $\phi(\hat{a}) = a$.)

Since each $\hat{a} \in \hat{A}^*$ is completely determined by its first coordinates, for all $a \in A^*$, there is exactly one $\hat{a} \in \hat{A}^*$ with $\phi(\hat{a}) = a$. Thus, the following hold.

- For all $\hat{a} \in \hat{A}$ with $\phi(\hat{a}) \in A^*$, $\bar{G}_i(\hat{a}) = 1$.
- For all $\hat{a} \in \hat{A}$ with $\phi(\hat{a}) \in A \setminus A^*$, $\bar{G}_i(\hat{a}) = 0$.
- For all $j \neq i$ and $\hat{a} \in \hat{A}$, $\bar{G}_j(\hat{a}) = 0$.

So for all $j \in N$ and $a_j \in A_j$, all actions in $\{a_j\} \times B_j^{a_j}$ are clones of each other in \bar{G} . This gives that \bar{G} is a blow-up of G . Moreover, $\phi_*(\hat{p}) = p$ since for all $j \in N$ and $a_j \in A_j$, there is the same number of clones (namely m^{n-2}) in \hat{A}_j . This gives the desired decomposition of G . \square

Remark 1 (Decomposition into permutation games). The “blowing up” of G to \bar{G} in the proof of Lemma 9 by introducing m^{n-2} clones of every action is necessary since not every deterministic slice-stochastic tensor can be written as a sum of permutation tensors. For example, let $n = 3$, $m = 2$, $i = 1$, and $G_1(a) = 1$ for

$a \in \{(1, 1, 1), (1, 2, 2), (2, 1, 2), (2, 2, 1)\} \subseteq \{1, 2\}^3$ and $G_1(a) = 0$ otherwise. Then, there is no permutation set $B \subseteq \{1, 2\}^3$ so that $G_1(a) = 1$ for all $a \in B$.

So far, we have shown the following. To prove that $p \in f(G)$ whenever $p \in \text{NASH}(G)$ and p has full support, it suffices to show this for the case when each G_i is slice-stochastic by Lemma 6. By the generalization of the Birkhoff-von Neumann theorem, Lemma 3, the fact that in every such game uniform randomization is an equilibrium, and consistency, we can further restrict to G_i 's that are deterministic slice-stochastic. Now Lemma 9 shows that all those games can, in essence, be written as convex combinations of games for which uniform randomization is the unique equilibrium and, thus, has to be returned by f . Consistency then gives the desired conclusion. The last step is to extend the statement beyond full support equilibria.

C. Reduction to Full Support Equilibria

We show that it suffices to prove that all full support equilibria have to be returned, which we have done in the previous section. There are three steps to the argument. First, we reduce to equilibria with support equal to the set of all rationalizable actions, then to quasi-strict equilibria, and lastly to arbitrary equilibria.¹¹ The strategy is always to write a game with some type of equilibrium as a convex combination of games where the same equilibrium is of the type in the preceding step. For example, Lemma 10 shows that any nice total solution concept has to return all equilibria whose support consists of all rationalizable actions.

Lemma 10 (Equilibria with full support on rationalizable actions). *Let f be a nice total solution concept. Let G be a game on A . Let $\bar{A}_i \subseteq A_i$ be the sets of rationalizable actions of $i \in N$ in G and $\bar{A} = \bar{A}_1 \times \cdots \times \bar{A}_n$. Then, if $p \in \text{NASH}(G)$ so that for all $i \in N$, $\text{supp}(p_i) = \bar{A}_i$, then $p \in f(G)$.*

Proof. Consider a decreasing sequence of action profiles obtained by successively removing dominated actions until no more deletions are possible. That is, let

¹¹We say that an action (profile) is rationalizable if it survives iterated elimination of strictly dominated actions.

$(A_1^0, \dots, A_n^0), \dots, (A_1^K, \dots, A_n^K) \in 2^{A_1} \times \dots \times 2^{A_n}$ so that for all $k \in [K]$, there is $i \in N$ for which the following holds.

- $A_i^k \subsetneq A_i^{k-1}$ and for all $j \neq i$, $A_j^k = A_j^{k-1}$.
- For all $a_i \in A_i^{k-1} \setminus A_i^k$, there is an action $\psi(a_i) \in A_i^k$ that dominates a_i when restricting G to $A_1^{k-1} \times \dots \times A_n^{k-1}$.
- For all $j \in N$, $A_j^0 = A_j$ and $A_j^K = \bar{A}_j$.

For all $i \in N$ and $a_i \in A_i \setminus \bar{A}_i$, let $\bar{\psi}(a_i) = \psi^s(a_i) \in \bar{A}_i$, where $s \in \mathbb{N}$ is the unique power so that $\psi^s(a_i) \in \bar{A}_i$ (here we mean ψ applied s times).

Denote by \bar{G} the game G restricted to action profiles in \bar{A} . We make several reductions. By consequentialism, we may assume that $|\bar{A}_1| = \dots = |\bar{A}_n|$. By Lemma 5 and Lemma 6, we may assume that for all $i \in N$, \bar{G}_i is slice-stochastic and p_i is the uniform distribution on \bar{A}_i . By consequentialism, Lemma 9, and Lemma 4, we may further assume that \bar{G} can be written as a convex combination of games for which p is the unique equilibrium. That is, there are games $\bar{G}^1, \dots, \bar{G}^M$ on \bar{A} so that for all $m \in [M]$, p is the unique equilibrium of \bar{G}^m , and

$$\bar{G} = \frac{1}{M} \sum_{m \in [M]} \bar{G}^m. \quad (4)$$

For all $m \in [M]$, we define a game G^m on A so that for all $i \in N$ and $a \in A$,

$$G_i^m(a) = \begin{cases} \bar{G}_i^m(a) & \text{if } a \in \bar{A}, \\ G_i(a) + \bar{G}_i^m(\bar{\psi}(a_i), a_{-i}) - G_i(\bar{\psi}(a_i), a_{-i}) & \text{if } a \in (A_i \setminus \bar{A}_i) \times \bar{A}_{-i}, \text{ and} \\ G_i(a) & \text{if } a_{-i} \in A_{-i} \setminus \bar{A}_{-i}. \end{cases}$$

Since $\bar{\psi}(a_i) = \bar{\psi}(a'_i)$ for $a_i, a'_i \in A_i \setminus \bar{A}_i$ with $\psi(a_i) = a'_i$, we have that \bar{A} is the set of rationalizable action profiles of G^m . It follows that p is the unique equilibrium in G^m and so $p \in f(G^m)$. Observe that for $a \in (A_i \setminus \bar{A}_i) \times \bar{A}_{-i}$, we have by (4) that

$$\sum_{m \in [M]} \bar{G}_i^m(\bar{\psi}(a_i), a_{-i}) - G_i(\bar{\psi}(a_i), a_{-i}) = 0.$$

Hence, $G = \frac{1}{m} \sum_{m \in [M]} G^m$. Consistency then implies that $p \in f(G)$. \square

A profile p is a quasi-strict equilibrium of G if $p \in \text{NASH}(G)$ and

$$G_i(a_i, p_{-i}) > G_i(a'_i, p_{-i}) \text{ for all } a_i \in \text{supp}(p_i), a'_i \in A_i \setminus \text{supp}(p_i), \text{ and } i \in N.$$

We show that nice total solution concepts have to return quasi-strict equilibria.

Lemma 11 (Quasi-strict equilibria). *Let f be a nice total solution concept. Let G be a game on A . Then, if $p \in \text{NASH}(G)$ is quasi-strict, then $p \in f(G)$.*

Proof. For all $i \in N$, let $\hat{A}_i = \text{supp}(p_i)$ and $\hat{A} = \hat{A}_1 \times \cdots \times \hat{A}_n$. By consequentialism, we may assume that $|\hat{A}_i| = 2|A_i \setminus \hat{A}_i|$ and the number of clones of each action in \hat{A}_i is even. Moreover, by Lemma 6 and the remarks thereafter, we may assume that p_i is the uniform distribution on \hat{A}_i . Write $\hat{A}_i = \{a_i^1, \dots, a_i^K, b_i^1, \dots, b_i^K\}$ so that a_i^k and b_i^k are clones for all $k \in [K]$ and $A_i \setminus \hat{A}_i = \{c_i^1, \dots, c_i^K\}$. The idea is to write G as a convex combination of two games G^1, G^2 for which all actions in $A_i \setminus \hat{A}_i$ are dominated and p is an equilibrium of G^1, G^2 . Lemma 10 and consistency of f will then give that $p \in f(G)$.

Let $i \in N$. Since p is quasi-strict and p_{-i} is uniform on \hat{A}_{-i} , we have for all $a_i \in \hat{A}_i$ and $a'_i \in A_i \setminus \hat{A}_i$,

$$\sum_{a_{-i} \in \hat{A}_{-i}} G_i(a_i, a_{-i}) > \sum_{a_{-i} \in \hat{A}_{-i}} G_i(a'_i, a_{-i}). \quad (5)$$

For all $k \in [K]$, let $v_i^k \in \mathbb{R}^{A_{-i}}$ so that

$$\sum_{a_{-i} \in \hat{A}_{-i}} v_i^k(a_{-i}) = 0 \quad (6)$$

and for all $a_{-i} \in A_{-i}$,

$$G_i(a_i^k, a_{-i}) + v_i^k(a_{-i}) = G_i(b_i^k, a_{-i}) + v_i^k(a_{-i}) > G_i(c_i^k, a_{-i}). \quad (7)$$

By (5), such v_i^k exist. (Note that the sum in (6) is taken over \hat{A}_{-i} and (7) is required to hold for all action profiles in A_{-i} .)

Now define games G^1, G^2 on A as follows. For all $i \in N$ and $a \in A$,

$$G_i^1(a) = \begin{cases} G_i(a_i^k, a_{-i}) + v^k(a_{-i}) & \text{if } a_i = a_i^k \text{ for some } k \in [K], \\ G_i(b_i^k, a_{-i}) - v^k(a_{-i}) & \text{if } a_i = b_i^k \text{ for some } k \in [K], \text{ and} \\ G_i(c_i^k, a_{-i}) & \text{if } a_i = c_i^k \text{ for some } k \in [K]. \end{cases}$$

Define G^2 similarly with the roles of a_i^k and b_i^k exchanged. By (6), p is an equilibrium of G^1, G^2 , and by (7), all actions in $A_i \setminus \hat{A}_i$ are dominated. More specifically, in G^1 , each c_i^k is dominated by a_i^k and in G^2 , each c_i^k is dominated by b_i^k . Hence, the set of rationalizable action profiles in G^1, G^2 is \hat{A} . By Lemma 10, $p \in f(G^1) \cap f(G^2)$. Since $G = 1/2 G^1 + 1/2 G^2$, consistency implies that $p \in f(G)$. \square

Lemma 11 together with consequentialism allows us to push slightly beyond quasi-strict equilibria. If p is an equilibrium of a game G so that for every player i , every action of i that is a best response against p_{-i} is either in the support of p_i or a clone of such an action, then we get from consequentialism that $p \in f(G)$. In that case, we say that p is essentially quasi-strict.

Definition 10 (Essentially quasi-strict equilibrium). Let G be a game on A . An equilibrium p of G is *essentially quasi-strict* if there is a blow-down G' of G with surjection ϕ so that $\phi_*(p)$ is a quasi-strict equilibrium of G' .

Similarly, one could define essentially unique and essentially full support equilibria, but we will not need these notions. Note that if a solution concept satisfies consequentialism and returns all quasi-strict equilibria, then it also has to return all essentially quasi-strict equilibria. We use this fact in the proof of the last step: if a solution concept satisfies consequentialism and consistency and returns all quasi-strict equilibria, then it, in fact, has to return all equilibria.

Lemma 12 (Reduction from quasi-strict to all equilibria). *Let f be a solution concept that satisfies consequentialism and consistency so that $p \in f(G)$ whenever p is a quasi-strict equilibrium of G . Then, $NASH \subseteq f$.*

Proof. Let G be a game on A and $p \in NASH(G)$. For $i \in N$, let $\hat{A}_i = \text{supp}(p_i)$ and

for any game G' on A with $p \in \text{NASH}(G')$, let

$$\bar{A}_i(G') = \{a_i \in A_i \setminus \hat{A}_i : G'_i(a_i, p_{-i}) = G'_i(p_i, p_{-i}) \text{ and } a_i \text{ is not a clone of an action in } \hat{A}_i\}.$$

That is, $\bar{A}_i(G')$ is the set of actions that are best responses against p_{-i} and not in the support of p_i or clones of actions in the support of p_i . We write $\bar{A}_i = \bar{A}_i(G)$. Note that p is an essentially quasi-strict equilibrium of G' if $\bar{A}_i(G') = \emptyset$ for all $i \in N$.

We prove that $p \in f(G)$ by induction on the number of players for which $\bar{A}_i \neq \emptyset$. If $\bar{A}_i = \emptyset$ for all $i \in N$, the statement follows from the assumption that f satisfies consequentialism and returns quasi-strict equilibria. Otherwise, let $i \in N$ with $\bar{A}_i \neq \emptyset$. We write G as a convex combination of two games G^1, G^2 so that $p \in \text{NASH}(G^1) \cap \text{NASH}(G^2)$, and

$$\{j \in N : \bar{A}_i(G^l) \neq \emptyset\} \subseteq \{j \in N : \bar{A}_i \neq \emptyset\} \setminus \{i\} \quad (8)$$

for $l = 1, 2$.

By Lemma 6 and the remarks thereafter, we may assume that p_i is the uniform distribution on \hat{A}_i . Moreover, by consequentialism, we may assume that $\hat{A}_i = \{a_i^1, \dots, a_i^K, b_i^1, \dots, b_i^K\}$, $\bar{A}_i = \{c_i^1, \dots, c_i^K\}$, and a_i^k, b_i^k are clones in G for all $k \in [K]$. Let G^1, G^2 be games on A so that for all $j \in N$ and $a \in A$,

$$G_j^1(a) = \begin{cases} G_j(c_i^k, a_{-i}) & \text{if } a_i = a_i^k \text{ or } a_i = c_i^k \text{ for some } k \in [K], \\ G_j(a_i^k, a_{-i}) + G_j(b_i^k, a_{-i}) - G_j(c_i^k, a_{-i}) & \text{if } a_i = b_i^k \text{ for some } k \in [K], \text{ and} \\ G_j(a_i, a_{-i}) & \text{if } a_i \in A_i \setminus (\hat{A}_i \cup \bar{A}_i), \end{cases}$$

and

$$G_j^2(a) = \begin{cases} G_j(c_i^k, a_{-i}) & \text{if } a_i = b_i^k \text{ or } a_i = c_i^k \text{ for some } k \in [K], \\ G_j(a_i^k, a_{-i}) + G_j(b_i^k, a_{-i}) - G_j(c_i^k, a_{-i}) & \text{if } a_i = a_i^k \text{ for some } k \in [K], \text{ and} \\ G_j(a_i, a_{-i}) & \text{if } a_i \in A_i \setminus (\hat{A}_i \cup \bar{A}_i). \end{cases}$$

Then, $G = 1/2G^1 + 1/2G^2$ and for all $k \in [K]$, a_i^k, c_i^k are clones in G^1 and b_i^k, c_i^k are clones in G^2 . Moreover, $p \in \text{NASH}(G^1) \cap \text{NASH}(G^2)$ by the definition of \bar{A}_i . To see

that p_i is a best response to p_{-i} , recall that for all $k \in [K]$,

$$G_i(a_i^k, p_{-i}) = G_i(b_i^k, p_{-i}) = G_i(p_i, p_{-i}) = G_i(c_i^k, p_{-i}),$$

since c_i^k is assumed to be in \bar{A}_i . So for all $a_i \in A_i$, $G_i^1(a_i, p_{-i}) = G_i^2(a_i, p_{-i}) = G_i(a_i, p_{-i})$. Also, for $j \neq i$ and $a_j \in A_j$, we have

$$\begin{aligned} G_j(a_j, p_{-j}) &= \frac{1}{2K} \sum_{k \in [K]} G_j(a_j, a_i^k, p_{-\{i,j\}}) + G_j(a_j, b_i^k, p_{-\{i,j\}}) \\ &= \frac{1}{2K} \sum_{k \in [K]} G_j^1(a_j, a_i^k, p_{-\{i,j\}}) + G_j^1(a_j, b_i^k, p_{-\{i,j\}}) \\ &= G_j^1(a_j, p_{-j}), \end{aligned}$$

where we use that p_i is uniform on \hat{A}_i for the first equality, and the definition of G^1 for the second equality. In particular, p_j is a best response to p_{-j} in G^1 . The same holds for G^2 with a similar argument. Thus, (8) holds. Now, by induction, $p \in f(G^1) \cap f(G^2)$, and so by consistency, we get $p \in f(G)$. \square

The fact that any nice total solution concept is a coarsening of *NASH* now follows from Lemma 11 and Lemma 12. This completes the proof of Theorem 1.