

Heifetz, Aviad; Meier, Martin; Schipper, Burkhard C.

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## Dynamic unawareness and rationalizable behavior

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## DEPARTMENT OF ECONOMICS

### Working Paper Series

**Dynamic unawareness and rationalizable behavior**

Aviad Heifetz

The Open University of Israel

Martin Meier

Institute for Advanced Studies, Vienna

Burkhard Schipper

University of California Davis

April 04, 2011

Paper # 11-3

We define generalized extensive-form games which allow for mutual unawareness of actions. We extend Pearce's (1984) notion of extensive-form (correlated) rationalizability to this setting, explore its properties and prove existence.

Department of Economics

One Shields Avenue

Davis, CA 95616

(530)752-0741

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# DYNAMIC UNAWARENESS AND RATIONALIZABLE BEHAVIOR\*

Aviad Heifetz<sup>†</sup>     Martin Meier<sup>‡</sup>     Burkhard C. Schipper<sup>§</sup>

March 22, 2011

## Abstract

We define generalized extensive-form games which allow for mutual unawareness of actions. We extend Pearce's (1984) notion of extensive-form (correlated) rationalizability to this setting, explore its properties and prove existence.

**Keywords:** Unawareness, extensive-form games, extensive-form rationalizability.

**JEL-Classifications:** C70, C72, D80, D82.

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<sup>†</sup>The Economics and Management Department, The Open University of Israel. Email: aviadhe@openu.ac.il

<sup>‡</sup>Institut für Höhere Studien, Wien, and Instituto de Análisis Económico - CSIC, Barcelona. Email: martin.meier@ihs.ac.at

<sup>§</sup>Department of Economics, University of California, Davis. Email: bcschipper@ucdavis.edu

# 1 Introduction

In real-life dynamic interactions, unawareness of players regarding the relevant actions available to them is at least as prevalent as uncertainty regarding other players' strategies, payoffs or moves of nature. Players frequently become aware of actions they (or other players) could have taken in retrospect, when they can only re-evaluate the past actions chosen by partners or rivals who *were* aware of those actions from the start, and hence re-assess their likely future behavior. Yet, while uncertainty can be captured within the standard framework of extensive-form games with imperfect information, unawareness and mutual uncertainty regarding awareness require an extension of this framework. Such an extension is the first task of the current paper.

At first, one may wonder why the standard framework would not suffice. After all, if a player is unaware of an action which is actually available to her, then for all practical purposes she cannot choose it. Why wouldn't it be enough simply to truncate from the tree all the paths starting with such an action?

The reason is that the strategic implications of unawareness of an action are distinct from the unavailability of the same action. To see this, consider the following standard "battle-of-the-sexes" game (where Bach and Stravinsky concerts are the two available choices for each player)

		II	
		B	S
I	B	3, 1	0, 0
	S	0, 0	1, 3

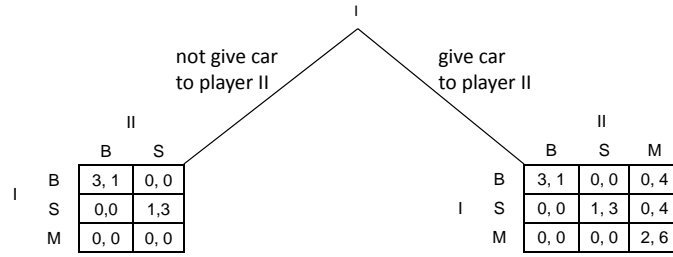
augmented by a dominant Mozart concert for player II:

		II		
		B	S	M
I	B	3, 1	0, 0	0, 4
	S	0, 0	1, 3	0, 4
	M	0, 0	0, 0	2, 6

The new game is dominance solvable, and (M,M) is the unique Nash equilibrium.

Suppose that the Mozart concert is in a distant town, and II can go there only if player I gives him her car in the first place: Here, if player I doesn't give the car to player II,

Figure 1:



player II may conclude by forward induction that player I would go to the Bach concert with the hope of getting the payoff 3 (because by giving the car to II, player I could have achieved the payoff 2). The best reply of player II is to follow suit and attend the Bach concert as well. Hence, in the unique rationalizable outcome, player I is not to give the car to player II and to go to the Bach concert.<sup>1</sup>

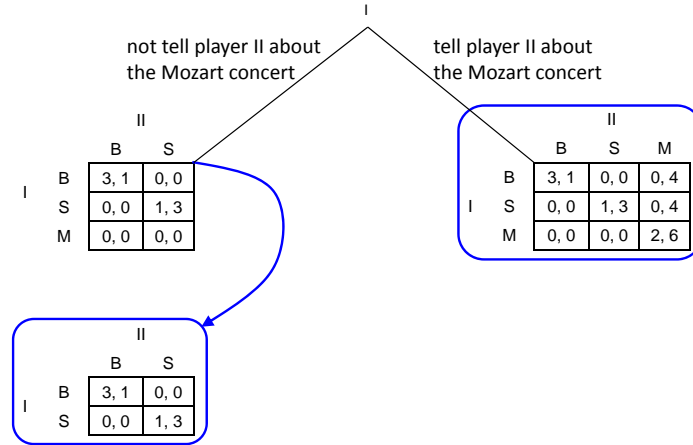
But what if, instead, the Mozart concert is in town but player II is initially unaware of the Mozart concert, while player I can enable player II to go to the concert simply by telling him about it? If player II remains unaware of the Mozart concert, then neither does he conceive that player I could have told him about the Mozart concert, and in particular he cannot carry out any forward-induction calculation. For him, the game is a standard battle-of-the-sexes game, where both actions of player I are rationalizable. This strategic situation is depicted in Figure 2.

The strategic situation is not a standard extensive-form game (more on this in Section 2.6 below). If player I chooses not to tell player II about the Mozart concert, then player II's information set (depicted in blue) consists of a node in a simpler game –namely the one-shot battle-of-the-sexes with no preceding move by player I.

This is a simple example of the general novel framework that we define in Section 2 for dynamic interaction with possibly mutual unawareness of actions, generalizing standard extensive-form games. The framework will not only allow modeling of situations in which one player is certain that another player is unaware of portions of the game tree, as in the above example, but also of situations in which a player is uncertain regarding the way another player views the game tree, as well as situations in which the player is uncertain regarding the uncertainties of the other player about yet other players' views of the game tree, and so forth.

<sup>1</sup>For a discussion of forward induction in battle-of-the-sexes games see van Damme (1989).

Figure 2:



In fact, this framework allows not just for unawareness but also for other forms of misconception about the structure of the game. Section 6 specifies further properties obtaining in generalized extensive-form games where the only source of players ‘misconception’ is unawareness and mutual unawareness of available actions and paths in the game. Since we focus on this type of unawareness, most of the examples in the paper satisfy the further properties specified in Section 6. Nevertheless, modeling *awareness of unawareness* does require the general framework in Section 2, as explained at its end.

In this new framework, for each information set of a player her strategy specifies – from the point of view of the modeler – what the player would do if and when that information set of hers is ever reached. In this sense, a player does not necessarily ‘own’ her full strategy at the beginning of the game, because she might not be initially aware of all of her information sets. That’s why a sensible generalization of Pearce’s (1984) notion of extensive-form rationalizability is non-trivial.

In Section 3 we put forward a modified definition, prove existence, and show the sense in which it coincides with extensive-form rationalizability in standard extensive-form games.

We focus here on a rationalizability solution concept rather than on some notion of equilibrium. While an equilibrium is ideally interpreted as a rest-point of some dynamic learning or adaptation process, or alternatively as a pre-meditated agreement or expectation, we find it difficult to carry over such interpretations to a setting in which every increase of awareness is by definition a shock or a surprise. Once a player’s view of

the game itself is challenged in the course of play, it is hard to justify the idea that a convention or an agreement for the continuation of the game are readily available.

We chose to focus on extensive-form rationalizability because it embodies forward induction reasoning. If an opponent makes a player aware of some relevant aspect of reality, it is implausible to dismiss the increased level of awareness as an unintended consequence of the opponent's behavior. Rather, the player should try to rationalize the opponent's choice, re-interpret the opponent's past behavior, and try to infer from it the opponent's future moves. Extensive-form rationalizability indeed captures a 'best rationalization principle' (Battigalli, 1997).

With rationalizability, generalized games are necessary for properly modeling unawareness; trying to model unawareness by having the unaware player assigning probability zero to the contingency of which she is unaware might give rise to a completely different rationalizable behavior, which does not square with unawareness in the proper sense of the word. To see this consider the following example.

A Decision Maker (DM) has to choose between two policies,  $a_0$  and  $a_1$ . Before choosing she gets a recommendation from an expert via a narrow communication channel, through which the expert can recommend either "0" or "1". The expert makes the recommendation after observing the state of nature, which may be either  $\gamma_0$  or  $\gamma_1$ , and which the DM does not see. The interests of the expert and the DM are completely aligned: They each bear a cost of 1 if  $a_1$  is implemented when the state of nature is  $\gamma_0$  or vice versa. The expert furthermore bears a cost of 10 from "lying", i.e. from recommending "0" when the state of nature is  $\gamma_1$  or recommending "1" when the state of nature is  $\gamma_0$ .

Assume the DM is aware only of the state  $\gamma_0$  and unaware of  $\gamma_1$ . The dynamic interaction is hence modeled by the generalized game in Figure 3.

In this generalized game the only extensive-form rationalizable strategy of the DM is to always implement the policy  $a_0$ : she does not conceive of a contingency that would make the policy  $a_1$  superior to  $a_0$  even if she hears from the expert the recommendation "1"; in such a case she regrettably concludes that the expert behaved in an irrational way and bore the cost of "lying".

However, if we were to model the DM alternatively as being aware of  $\gamma_1$  but assigning probability zero to it, the strategic interaction would be modeled by the standard game in Figure 4.

In this game the unique extensive-form rationalizable strategy of the DM is to choose

Figure 3:

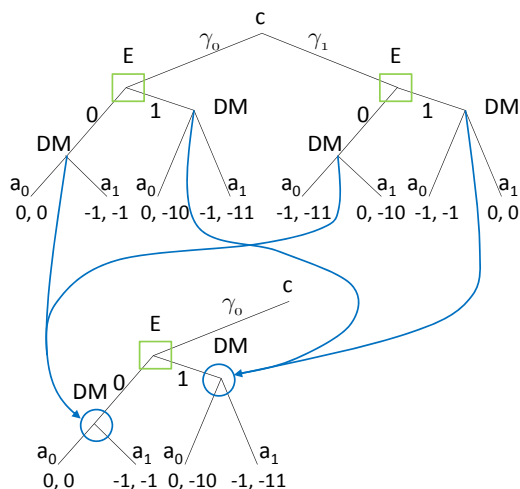
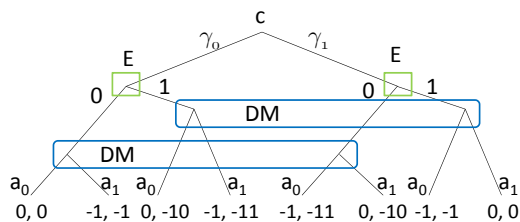


Figure 4:



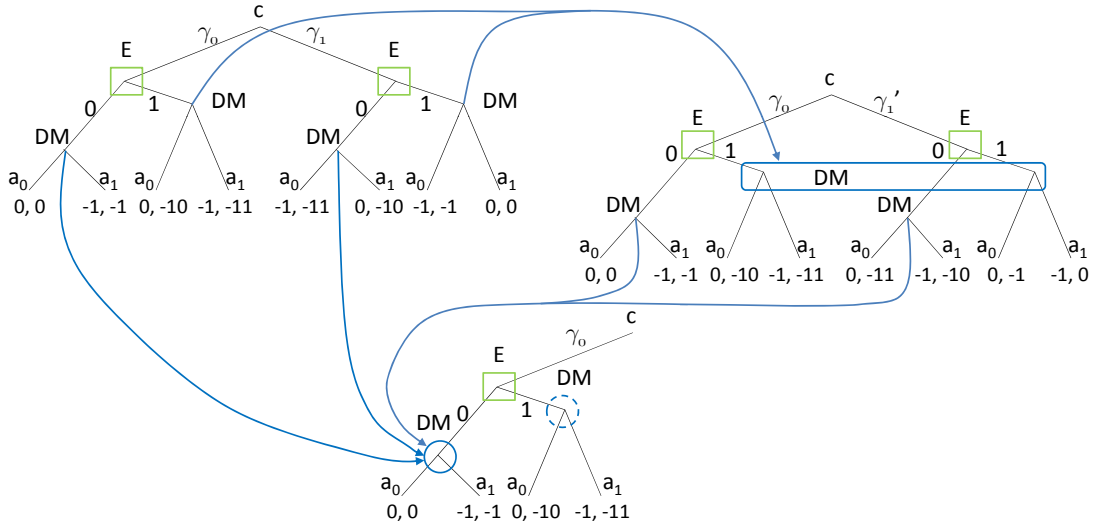
$a_0$  upon hearing “0” from the expert, but to implement  $a_1$  upon hearing the recommendation “1”. Indeed, extensive-form rationalizability requires the DM to base her choice on a system of beliefs about the expert’s strategies with which at every information set of hers she maintains a belief that best rationalizes the choices of the expert which could have led to that information set. In particular, upon hearing the recommendation “1” from the expert, the only way for the DM to rationalize it is to assume that the state of nature is *nevertheless*  $\gamma_1$ , where recommending “1” is strictly dominant for the expert; and in  $\gamma_1$  the optimal choice for the DM is  $a_1$ .

Conceptually, upon hearing the surprising recommendation “1” both choices of the DM have their internal logic. The former gives priority to “only  $\gamma_0$  is conceivable”, the latter to the rationality of the expert. But in the latter case, if initially the DM is *genuinely* unaware of  $\gamma_1$ , there is no reason why the DM would conceive *precisely* of  $\gamma_1$  and not of some alternative description  $\gamma'_1$  of nature that would also rationalize the expert’s



recommendation “1”; some such conceptualizations  $\gamma'_1$  need not necessarily induce the DM to adopt the expert’s recommendation. Generalized games lend themselves also to modeling such misconceptions that may arise upon a surprise, as demonstrated in Figure 5. Here, the DM’s rationalizable strategy is to choose  $a_0$  also upon hearing the

Figure 5:



(surprising) recommendation “1” , because the DM believes this recommendation was strictly dominant for the expert but that her interest and those of the expert are now opposed.

Our framework for dynamic interaction under unawareness seems to be simpler than the one proposed by Halpern and Rêgo (2006) and Rêgo and Halpern (2007), in which they investigated the notions of Nash and sequential equilibrium, respectively.<sup>2</sup>

<sup>2</sup>The simplification obtained in our framework is due to the fact that our initial building block is a tree representing *physical* moves, with information sets defined only in the sub-trees which represent subjective views of the game (and subjective views thereof, etc.); in contrast, Halpern and Rêgo (2006) had information sets defined already in their basic tree. As a result, not all sub-trees could be considered, and Halpern and Rêgo (2006) had to postulate additional conditions relating the information sets in sub-trees to those of the basic tree.

Our framework is also more parsimonious than the one proposed by Feinberg (2009). Feinberg (2009) defines unawareness with analogous properties both for static and dynamic games, by explicit *unbounded sequences* of mutual “views” of the game. In his dynamic setting, a view is identified with a decision node. This means that even a standard extensive-form game has to be described in Feinberg (2009) by infinitely many copies of the the same game tree, specifying explicitly how each player views the game in each of her decision nodes; how each player views, in each of her decision node, the way in which each other player views the game in each of their decision nodes; etc. In our setting such an infinite replication

## 1.1 Related Literature

Our framework for dynamic interaction under unawareness seems to be significantly simpler than the one proposed by Halpern and Rêgo (2006) and Rêgo and Halpern (2007), in which they investigated the notions of Nash and sequential equilibrium, respectively. The simplification obtained in our framework is due to the fact that our initial building block is a tree representing *physical* moves, with information sets defined only in the sub-trees which represent subjective views of the game (and subjective views thereof, etc.); in contrast, Halpern and Rêgo (2006) had information sets defined already in their basic tree. As a result, not all sub-trees could be considered, and Halpern and Rêgo (2006) had to postulate additional conditions relating the information sets in sub-trees to those of the basic tree.

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Li (2006) considered a model for dynamic unawareness with perfect information, in which at each decision node a player may have a subjective view of the game tree. Her model is more restricted than ours, since it requires there to be one particular default

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is avoided, since our definition of information sets encapsulates, by its design, all these mutual points of view.

Another important difference is that Feinberg (2009) does not define perfect recall, and this might hamper the extension of known solution concepts such as sequential equilibrium or extensive-form rationalizability that rely on perfect recall. Extensive-form rationalizability is the focal solution concept that we extend, define, and analyze in our paper, and to this effect we extend the definition of perfect recall to our setting.

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path of which all players are commonly aware, and since it does not allow for imperfect information.

Ozbay (2007) studied sender-receiver games, in which an ‘announcer’ can make an unaware decision maker aware of more states of nature before the decision maker takes an action. Such games can also be naturally formulated as a particular instance of our framework. For these games Ozbay studied an equilibrium notion incorporating forward-induction reasoning. Filiz-Ozbay (2007) studied a related setting in which the aware announcer is a risk neutral insurer, while the decision maker is a risk averse or ambiguity averse insuree. At equilibrium, the insurer does not always reveal all relevant contingencies to the insuree.

In a companion paper, Heifetz, Meier and Schipper (2011a) we introduce a refinement of extensive-form rationalizability, called prudent rationalizability, and show that it rules out less plausible outcomes in examples due to Pearce (1984) and Ozbay (2007). We apply to a model of verifiable communication of Milgrom and Roberts (1986) and show that prudent rationalizability implies full unraveling of information in their model. Yet, if the receiver is unaware of a dimension, then full unraveling does not need to occur. Thus, this is yet another example in which unawareness has strategic implications which are genuinely different than those implied by asymmetric information. In another companion paper, Heifetz, Meier and Schipper (2011b), we characterize extensive-form rationalizability (resp. prudent rationalizability) in generalized extensive-form games by iterated elimination of conditional strictly (resp. weakly) dominated strategies in the associated generalized normal-form game.<sup>4</sup>

Our aim is to provide a general framework for modeling misperceptions about the availability of actions in dynamic strategic situations. Different kinds of perception biases among players in games have been a popular topic in the recent literature on behavioral game theory. For instance, in static games Eyster and Rabin (2005) analyze players with correct conjectures about opponents’ actions but misperceptions about how those opponents’ actions are correlated with the opponents’ information. In multi-stage games with moves of nature, Jehiel (2005) studies players that bundle nodes at which other players choose into “analogy classes”, correctly anticipate the average behavior for each analogy class, and thus may have misperceptions about how others’ behavior is related others’ information. Recently there has been a renaissance of non-equilibrium iterative

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<sup>4</sup>Currently we are unaware of further papers focusing directly and explicitly on dynamic games with unawareness. The literature on unawareness in general is growing fast – see e.g. <http://www.econ.ucdavis.edu/faculty/schipper/unaw.htm>

solution concepts in behavioral game theory like level-k thinking and related models (e.g. Stahl and Wilson, 1995, Camerer, Hu and Chong, 2004, Crawford and Iriberri, 2007). Note that our iterative solution concept, extensive-form rationalizability, does not only provide behavioral predictions in the limit but also at every finite level of rationalization.

## 2 Generalized extensive-form games

To define a generalized extensive-form game  $\Gamma$ , consider first, as a building block, a finite game with perfect information and simultaneous moves <sup>5</sup> with a set of players  $I$ , a set of decision nodes  $N_0$ , active players  $I_n$  at node  $n$  with finite action sets  $A_n^i$  of player  $i \in I_n$  (for  $n \in N_0$ ), chance nodes  $C_0$ , and terminal nodes  $Z_0$  with a payoff vector  $(p_i^z)_{i \in I} \in \mathbb{R}^I$  for the players for every  $z \in Z_0$ . The nodes  $\bar{N}_0 = N_0 \cup C_0 \cup Z_0$  constitute a tree, i.e. they are partially ordered by a precedence relation  $\prec$  with which the  $(\bar{N}_0, \prec)$  is an arborescence (that is, the predecessors of each node in  $\bar{N}_0$  are totally ordered by  $\prec$ ), for each decision node  $n \in N_0$  there is a bijection  $\psi_n$  between the action profiles  $\prod_{i \in I_n} A_n^i$  at  $n$  and  $n$ 's immediate successors, and there is a unique node in  $\bar{N}_0$  with no predecessors – the root of the tree.

### 2.1 Partially ordered set of trees

Consider now a family  $\mathbf{T}$  of subtrees of  $\bar{N}_0$ . A subtree is defined by a subset of nodes  $\bar{N}'_0 \subseteq \bar{N}_0$  for which  $(\bar{N}'_0, \prec)$  is also a tree (i.e. an arborescence in which a unique node has no predecessors). For two subtrees  $T', T'' \in \mathbf{T}$  we write

$$T' \preceq T''$$

to signify that the nodes of  $T'$  constitute a subset of the nodes of  $T''$ .

One of the trees  $T_1 \in \mathbf{T}$  is meant to represent the modeler's view of the paths of play that are *objectively* feasible.<sup>6</sup> Each other tree  $T \in \mathbf{T}$  represents the feasible paths of play as *subjectively* viewed by some player at some node in  $T_1$ ; or as the frame of mind attributed to the player at some node of  $T_1$  by another player (or even by the same

<sup>5</sup>We follow here the terminology of Osborne and Rubinstein (1994) and Dubey and Kaneko (1984).

<sup>6</sup>In generalized extensive-form games modeling unawareness (see Section 2.5 below),  $T_1$  will coincide with  $\bar{N}_0$ . In more general applications including delusion (like in the game of Figure 5 above) or awareness of unawareness (see Section 2.6 below)  $\bar{N}_0$  may include additional nodes not in  $T_1$ . In such a case  $\bar{N}_0$  need be one of the trees in  $\mathbf{T}$ .

player at a later stage of the game, after her awareness regarding the feasible paths has evolved), whose own frame of mind regarding the feasible paths is represented by yet another  $T' \in \mathbf{T}$ ; and so forth.

Denote by  $N_i^T$  the set of nodes in which player  $i \in I$  is active in the tree  $T \in \mathbf{T}$ , and by  $N_i = \bigcup_{T \in \mathbf{T}} N_i^T$ .

We require three properties:

1. All the terminal nodes in each tree  $T \in \mathbf{T}$  are copies of nodes in  $Z_0$ .
2. For every tree  $T \in \mathbf{T}$ , every node  $n \in T$  and every active player  $i \in I_n$  there exists a subset of actions  $A_n^{i,T} \subseteq A_n^i$  such that  $\psi_n$  maps the action profiles  $A_n^T = \prod_{i \in I_n} A_n^{i,T}$  onto  $n$ 's successors in  $T$ .
3. If for two decision nodes  $n, n' \in N_i^T$  (i.e.  $i \in I_n \cap I_{n'}$ ) it is the case that  $A_n^i \cap A_{n'}^i \neq \emptyset$ , then  $A_n^i = A_{n'}^i$ .<sup>7</sup>

Property 1 is needed to ensure that each terminal node of each tree  $T \in \mathbf{T}$  is associated with well defined payoffs to the players. Property 2 means that at every node  $n \in T$  the actions available to each active player  $i \in I_n$  are independent of the actions the other active players choose at  $n$  (and hence  $A_n^T = \prod_{i \in I_n} A_n^{i,T}$  is a product set). Property 3 means that  $i$ 's active nodes  $N_i^T$  are partitioned into equivalence classes, such that the actions available to player  $i$  are identical within each equivalence class and disjoint in distinct equivalence classes. It will be needed for the definition of information sets which follows shortly.<sup>8</sup>

In each tree  $T \in \mathbf{T}$  denote by  $n_T$  the copy in  $T$  of the node  $n \in \bar{N}_0$  whenever the copy of  $n$  is part of the tree  $T$ , with the caveat that if the move  $a_n^i$  leads from  $n$  to  $n'$ , then  $a_n^i$  leads also from the copy  $n_T$  to the copy  $n'_T$ . Denote by  $N$  the union of all decision nodes in all trees  $T \in \mathbf{T}$ , by  $C$  the union of all chance nodes, by  $Z$  the union of terminal nodes, and by  $\bar{N} = N \cup C \cup Z$  (copies  $n_T$  of a given node  $n$  in different subtrees  $T$  are distinct from one another, so that  $\bar{N}$  is a disjoint union of sets of nodes).

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<sup>7</sup>Sometimes the modeler may want to impose an additional property: If in a subtree  $T'' \in \mathbf{T}$  the probabilities of reaching  $\bar{n}_1, \dots, \bar{n}_k \in \bar{N}$  from the chance node  $c \in C$  are  $p_c^{\bar{n}_1} > 0, \dots, p_c^{\bar{n}_k} > 0$  but some of these nodes do not appear in a subtree  $T' \preceq T''$ , then the probabilities of reaching the remaining nodes emanating from  $c$  are renormalized in so as to sum to 1 in  $T'$ . We do not impose this property here since it may be natural in some contexts but unnatural in others.

<sup>8</sup>The idea will be that in a given tree  $T$ , each action will correspond only to one view the player can have regarding the way the dynamic interaction has evolved that far, and will hence be available at (all the nodes of) a unique information set.

In what follows, when referring to a node in  $\bar{N}$  we will typically avoid the subscript  $T$  when no confusion may arise. For a node  $n \in \bar{N}$  we denote by  $T_n$  the tree containing  $n$ .

## 2.2 Information sets

In standard extensive-form game, an information set  $\pi_i(n)$  of a player  $i$  is both (1) the set of nodes that the player considers as possible at  $n$ , and (2) the set of nodes in which the player has the same state of mind as in the nodes which she considers as possible at  $n$ .

In generalized games the two notions need not coincide: at a node  $n$  of the tree  $T_n \in \mathbf{T}$ , the player may conceive the feasible paths to be described by a different tree  $T' \in T$ , and in particular to conceive the possible nodes  $\pi_i(n)$  she may currently be in to be a subset of  $T'$  rather than of  $T_n$ , and in such case  $n$  will not be contained in  $\pi_i(n)$ . The information set  $\pi_i(n)$  thus generalizes (1) above; the set of nodes (2) at which the player conceives  $\pi_i(n)$  to be possible may include additional nodes which belong to trees outside the tree  $T'$  containing  $\pi_i(n)$ .

Formally, for each decision node  $n \in N$ , define for each active player  $i \in I_n$  an information set  $\pi_i(n)$  with the following properties:

- I0 Confinement:  $\pi_i(n) \subseteq T$  for some tree  $T$ .
- I1 No-delusion given the awareness level: If  $\pi_i(n) \subseteq T_n$  then  $n \in \pi_i(n)$ .
- I2 Introspection: If  $n' \in \pi_i(n)$  then  $\pi_i(n') = \pi_i(n)$ .
- I3 No divining of currently unimaginable paths, no expectation to forget currently conceivable paths: If  $n' \in \pi_i(n) \subseteq T'$  (where  $T' \in \mathbf{T}$  is a tree) and there is a path  $n', \dots, n'' \in T'$  such that  $i \in I_{n'} \cap I_{n''}$  then  $\pi_i(n'') \subseteq T'$ .
- I4 No imaginary actions: If  $n' \in \pi_i(n)$  then  $A_{n'}^i \subseteq A_n^i$ .
- I5 Distinct action names in disjoint information sets: For a subtree  $T$ , if  $n, n' \in T$  and  $A_n^i = A_{n'}^i$  then  $\pi_i(n') = \pi_i(n)$ .
- I6 Perfect recall: Suppose that player  $i$  is active in two distinct nodes  $n_1$  and  $n_k$ , and there is a path  $n_1, n_2, \dots, n_k$  such that at  $n_1$  player  $i$  takes the action  $a_i$ . If  $n' \in \pi_i(n_k)$ , then there exists a node  $n'_1 \neq n'$  and a path  $n'_1, n'_2, \dots, n'_\ell = n'$  such that  $\pi_i(n'_1) = \pi_i(n_1)$  and at  $n'_1$  player  $i$  takes the action  $a_i$ .

The following figures (Figure 6) illustrate properties I0 to I6.

Properties (I1), (I2), (I4), and (I5) are standard for extensive-form games, and properties (I0) and (I6) generalize other standard properties of extensive-form games to our generalized setting. The essentially new property is (I3). At each information set of a player, property (I3) confines the player's *anticipation* of her future view of the game to the view she currently holds (even if, as a matter of fact, this anticipation is about to be shuttered as the game evolves).

We denote by  $H_i$  the set of  $i$ 's information sets in all trees. For an information set  $h_i \in H_i$ , we denote by  $T_{h_i}$  the tree containing  $h_i$ . For two information sets  $h_i, h'_i$  in a given tree  $T$ , we say that  $h_i$  precedes  $h'_i$  (or that  $h'_i$  succeeds  $h_i$ ) if for every  $n' \in h'_i$  there is a path  $n, \dots, n'$  in  $T$  such that  $n \in h_i$ . We denote  $h_i \rightsquigarrow h'_i$ .

**Remark 1** *The following property is implied by I2 and I4: If  $n', n'' \in h_i$  where  $h_i = \pi_i(n)$  is an information set, then  $A_{n'}^i = A_{n''}^i$ .*

**Proof.** If  $n', n'' \in h_i$  where  $h_i = \pi_i(n)$  is some information set, then by introspection (I2) we must have  $\pi_i(n') = \pi_i(n'') = \pi_i(n)$ . Hence by (I4)  $A_{n'}^i \subseteq A_{n''}^i$  and  $A_{n''}^i \subseteq A_{n'}^i$ .  $\square$

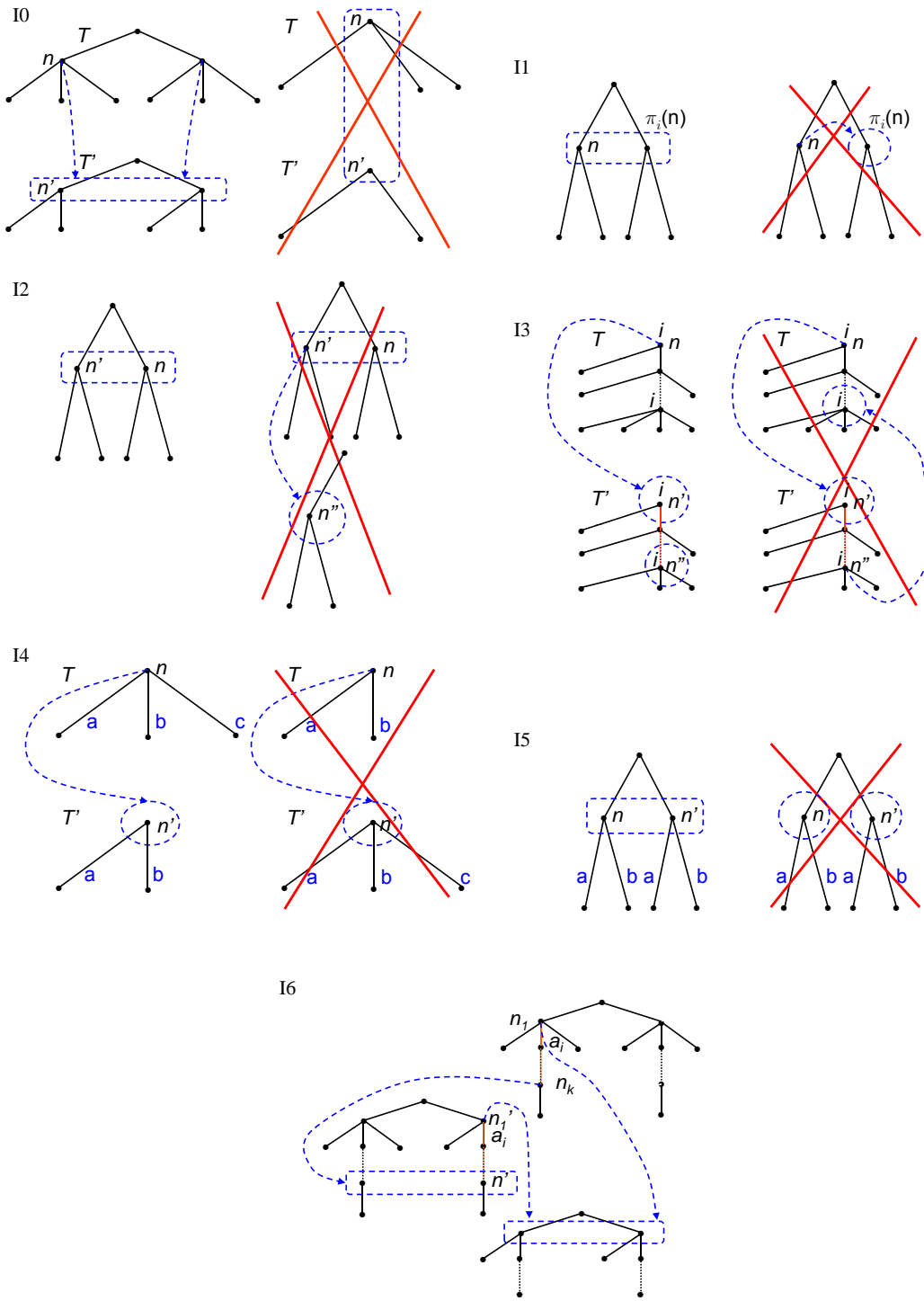
If  $n \in h_i$  we write also  $A_{h_i}$  for  $A_n^i$ .

**Remark 2** *Properties I0, I1, I2 and I6 imply no absent-mindedness: No information set  $h_i$  contains two distinct nodes  $n, n'$  on some path in some tree.*

**Proof.** Suppose by contradiction that there exists an information set  $h_i$  with a node  $n \in h_i$  such that some other node in  $h_i$  precedes  $n$  in the tree  $T_n$ . Denote by  $n'$  the first node on the path from the root to  $n$  that is also in  $h_i$ . By I1 we have  $n' \in \pi_i(n') = h_i = \pi_i(n)$ , and by perfect recall I6 there exists a path  $n'' = n'_1, \dots, n'_\ell = n'$ , such that at  $n''$  player  $i$  had the same state of mind as in  $n'$ , i.e.  $\pi_i(n'') = \pi_i(n')$ . By I1, we have  $n'' \in \pi_i(n'') = \pi_i(n') = h_i$  and  $n''$  is a predecessor of  $n'$ , a contradiction.  $\square$

The perfect recall property I6 and Remark 2 guarantee that with the precedence relation  $\rightsquigarrow$  player  $i$ 's information sets  $H_i$  form an arborescence: For every information set  $h'_i \in H_i$ , the information sets preceding it  $\{h_i \in H_i : h_i \rightsquigarrow h'_i\}$  are totally ordered by  $\rightsquigarrow$ .

Figure 6: Properties I0 to I6





For trees  $T, T' \in \mathbf{T}$  we denote  $T \succrightarrow T'$  whenever for some node  $n \in T$  and some player  $i \in I_n$  it is the case that  $\pi_i(n) \subseteq T'$ . Denote by  $\leftrightarrow$  the transitive closure of  $\succrightarrow$ . That is,  $T \leftrightarrow T''$  if and only if there is a sequence of trees  $T, T', \dots, T'' \in \mathbf{T}$  satisfying  $T \succrightarrow T' \succrightarrow \dots \succrightarrow T''$ .

### 2.3 Generalized games

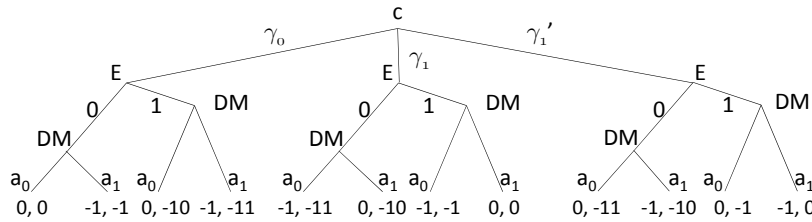
A generalized extensive-form game  $\Gamma$  consists of a partially ordered set  $\mathbf{T}$  of subtrees of a tree  $\bar{N}_0$  satisfying properties 1-2 above, along with information sets  $\pi_i(n)$  for every  $n \in T, T \in \mathbf{T}$  and  $i \in I_n$ , satisfying properties I0-I6 above.

For every tree  $T \in \mathbf{T}$ , the  $T$ -partial game is the partially ordered set of trees including  $T$  and all trees  $T'$  in  $\Gamma$  satisfying  $T \leftrightarrow T'$ , with information sets as defined in  $\Gamma$ . A  $T$ -partial game is a generalized game, i.e. it satisfies all properties 1-2 and I0-I6.

We denote by  $H_i^T$  the set of  $i$ 's information sets in the  $T$ -partial game.

For example, for the generalized game  $\Gamma$  in Figure 5, the tree  $\bar{N}_0$  appears below in Figure 7.  $\bar{N}_0$  starts by nature choosing between  $\gamma_0$  (following which  $a_0$  is the optimal action for both players),  $\gamma_1$  (following which  $a_1$  is optimal for both) or  $\gamma_1'$  (following which  $a_0$  is optimal for the Decision Maker (DM) but suboptimal for the Expert (E)).

Figure 7:



However, in the generalized game  $\Gamma$  of Figure 5 the tree which represents the physical paths of the game is not  $\bar{N}_0$  but rather  $T_1$ , which appears in the upper left part of Figure 5. Moreover,  $\bar{N}_0$  is none of the trees in  $\mathbf{T} = \{T_1, T_2, T_3\}$  of  $\Gamma$ , and hence  $\bar{N}_0$  does not appear in Figure 5.

In  $T_1$  if the Expert, after learning nature's move, announces '0', the DM is unaware of the fact that nature could have chosen  $\gamma_1$ . The DM's frame of mind is hence represented by the tree  $T_3$  at the bottom of figure 5. According to the DM's conception there she

does not miss any information, and her information set is a singleton. This single node is also the unique node considered as possible by the DM at  $T_1$  after hearing the message ‘0’ (and hence the two arrows going from  $T_1$  downwards to that singleton in  $T_3$ ). Moreover, under this frame of mind  $T_3$ , by which only  $\gamma_0$  is feasible, the DM conceives that she would have a singleton information set in  $T_3$  even if  $E$  were to announce ‘1’.

The truth of the matter, as portrayed in the tree of physical paths  $T_1$ , is different. If  $E$  announces ‘1’, the DM gets to believe that nature could have chosen not between  $\gamma_0$  and  $\gamma_1$  (as was actually the case) but rather between  $\gamma_0$  and  $\gamma'_1$ . This is portrayed by the fact that after hearing ‘1’ in  $T_1$ , the nodes that the DM considers as possible are in  $T_2$ , the tree in the upper left part of figure 5. The information set of the DM in  $T_2$  after hearing ‘1’ contains two nodes, corresponding to the two possible choices of nature that the DM considers as possible there –  $\gamma_0$  and  $\gamma'_1$ .

Moreover, in this state of mind the DM is surprised, in the sense that she realizes that had she heard ‘0’ from the Expert, she would not suspect that nature could choose anything beyond  $\gamma_0$ . This is reflected by the fact that in  $T_2$ , the information set of the DM had she heard ‘0’ is contained in  $T_3$ .

The  $T_1$ -partial game is the entire game  $\Gamma$  with the set of trees  $\{T_1, T_2, T_3\}$ . The  $T_2$ -partial game consists only of the trees  $\{T_2, T_3\}$ . The  $T_1$ -partial game is a standard extensive-form game with the unique tree  $T$ .

## 2.4 Strategies

A (pure) strategy

$$s_i \in S_i \equiv \prod_{h_i \in H_i} A_{h_i}$$

for player  $i$  specifies an action of player  $i$  at each of her information sets  $h_i \in H_i$ . Denote by

$$S = \prod_{j \in I} S_j$$

the set of strategy profiles in the generalized extensive-form game.

If  $s_i = (a_{h_i})_{h_i \in H_i} \in S_i$ , we denote by

$$s_i(h_i) = a_{h_i}$$

the player’s action at the information set  $h_i$ .

With the strategy  $s_i$ , at node  $n \in N_i$  define the player's action at  $n$  to be  $s_i(\pi_i(n))$ . Thus, the strategy  $s_i$  specifies what player  $i$  does at each of her active nodes  $n \in N_i$ , both in case  $n \in \pi_i(n)$  and in case  $\pi_i(n)$  is a subset of nodes of a tree which is distinct than the tree  $T_n$  to which  $n$  belongs.

As Rubinstein (1991) pointed out, even in standard extensive-form games the interpretation of the notion of a strategy is involved: an action prescribed by a strategy at an information set which is excluded by an earlier move of that very strategy is implicitly interpreted in game theory as the beliefs the other players entertain regarding the player's move if that information set were reached.

A similar interpretation pertains even more forcefully in generalized games. In a generalized game  $\Gamma$  only the tree  $T_1 \in \mathbf{T}$  represents the physical paths in the game; every other tree in  $\mathbf{T}$  represents the subjective view of the feasible paths in the mind of a player, or the view of the feasible paths that a player believes that another player may have in mind, etc. Moreover, as the actual game in  $T_1$  evolves, a player may become aware of paths of which she was unaware earlier, and the way she views the game may alter as well.

Thus, in generalized extensive-form games, a strategy cannot be conceived as an ex ante plan of action, both for the reason elaborated by Rubinstein (1991) and the additional reasons above. Formally, a strategy  $s_i$  of player  $i$  is a list of answers to the questions "what would the player do if  $h_i$  were the set of nodes she considered as possible?", for  $h_i \in H_i$ . This list of answers should be interpreted as follows. For every given frame of mind  $T \in \mathbf{T}$  that player  $i$  may entertain about the feasible paths (a frame of mind which  $i$  actually has at some node in the actual game tree  $T_1$ , or attributed to  $i$  by player  $j$  at some node of  $T_1$  [at which  $j$ 's frame of mind may be yet another  $T' \in \mathbf{T}$ ], etc.),

1. for every information set  $\pi_i(n) \subseteq T$  the action  $s_i(\pi_i(n))$  should be interpreted as the action that player  $i$  actually takes at  $n$  under the strategy  $s_i$ , if and when  $n$  is reached; and
2. for every information set  $\pi_i(n'') \subseteq T'' \neq T$  the action  $s_i(\pi_i(n''))$  should be interpreted as the action that player  $i$  would have taken at  $n''$  if her frame of mind were  $T''$  rather than  $T$ . This means that when player  $j$  considers as possible that the node  $n''$  can be reached,  $j$  believes that under the strategy  $s_i$  player  $i$  would take the action  $s_i(\pi_i(n''))$  at  $n''$ , if and when  $n''$  were reached.

For a strategy  $s_i \in S_i$  and a tree  $T \in \mathbf{T}$ , we denote by  $s_i^T$  the strategy in the  $T$ -partial game induced by  $s_i$  (i.e.,  $s_i^T(h_i) = s_i(h_i)$  for every information set  $h_i$  of player  $i$  in the  $T$ -partial game). If  $R_i \subseteq S_i$  is some set of strategies of player  $i$ , denote by  $R_i^T$  the set of strategies induced by  $R_i$  in the  $T$ -partial game. The set of  $i$ 's strategies in the  $T$ -partial game is thus denoted by  $S_i^T$ . Denote by  $S^T = \prod_{j \in I} S_j^T$  the set of strategy profiles in the  $T$ -partial game.

We say that a strategy profile  $s = (s_j)_{j \in I} \in S$  reaches a node  $n \in T$  if the players' actions  $s_j(\pi_j(n'))_{j \in I_{n'}}$  and nature's moves in the nodes  $n' \in T$  lead to  $n$  with a positive probability. Notice that by property (I4) ("no imaginary actions"),  $s_j(\pi_j(n'))_{j \in I}$  is indeed well defined: even if  $\pi_j(n') \notin T$  for some  $n' \in T$ , the action profile  $s_j(\pi_j(n'))_{j \in I_{n'}}$  is an action profile which is actually available in  $T$  to the active players  $j \in I_{n'}$  at  $n'$ .

We say that a strategy profile  $s \in S$  reaches the information set  $h_i \in H_i$  if  $s$  reaches some node  $n \in h_i$ .

We say that the strategy  $s_i \in S_i$  reaches the information set  $h_i$  if there is a strategy profile  $s_{-i} \in S_{-i}$  of the other players such that the strategy profile  $(s_i, s_{-i})$  reaches  $h_i$ . Otherwise, we say that the information set  $h_i$  is excluded by the strategy  $s_i$ .

Similarly, we say that the strategy profile  $s_{-i} \in S_{-i}$  reaches the information set  $h_i$  if there exists a strategy  $s_i \in S_i$  such that the strategy profile  $(s_i, s_{-i})$  reaches  $h_i$ .

As is the case also in standard games, for every given node, a given strategy profile of the players induces a distribution over terminal nodes in each tree, and hence an expected payoff for each player in the tree.

For an information set  $h_i$ , let  $s_i/\tilde{s}_i^{h_i}$  denote the strategy that is obtained by replacing actions prescribed by  $s_i$  at the information set  $h_i$  and its successors by actions prescribed by  $\tilde{s}_i$ . The strategy  $s_i/\tilde{s}_i^{h_i}$  is called an  $h_i$ -replacement of  $s_i$ .

The set of *behavioral* strategies is

$$\prod_{h_i \in H_i} \Delta(A_{h_i}).$$

To exemplify the above definitions, consider again the game of figure 5. The Expert (E) has two information sets in  $T_1$ , two information sets in  $T_2$ , and one information set in  $T_3$ . The following therefore describes a strategy  $s_E$  of the expert: '0' after  $\gamma_0$  in  $T_1$ ; '1' after  $\gamma_1$  in  $T_1$ ; '0' after  $\gamma_0$  in  $T_2$ ; '1' after  $\gamma_1'$  in  $T_2$ ; '0' after  $\gamma_0$  in  $T_3$ .

What about the DM? She has no information sets contained in  $T_1$  (!), one information

set in  $T_2$  (with two nodes in it) and two singleton information sets in  $T_3$ . The following therefore describes a strategy  $s_{DM}$  of the DM: play  $a_0$  in every information sets.

The profile of strategies  $(s_E, s_{DM})$  described above induces the following actual paths in  $T_1$ :

1. If nature chooses  $\gamma_0$ , the path is  $(\gamma_0, '0', a_0)$ . Notice that after  $\gamma_0, '0'$  in  $T_1$ , we read the choice of the DM by following the arrow that leads to her information set down in  $T_3$ , and check her choice with the strategy  $s_E$  there.
2. If nature chooses  $\gamma_1$ , the path is  $(\gamma_1, '1', a_0)$ . After  $\gamma_1, '1'$  in  $T_1$ , we read the choice of the DM by following the arrow that leads to her information set, which this time is in  $T_2$ .

Observe that the Expert is never actually (in  $T_1$ ) deluded to think that the strategic interaction is described by the  $T_2$ -partial game, nor is he ever actually (in  $T_1$ ) unaware so as to think that the strategic interaction is described by  $T_3$ . Thus, the moves of  $s_E$  in  $T_2$  (in particular after nature chooses  $\gamma'_1$ , which can never actually happen in reality, i.e. in  $T_1$ ) describe the DM's belief about the Expert's choice that led to her information set if she believes that the Expert is using the strategy  $s_E^{T_2}$  – the restriction of the strategy  $s_E$  to the  $T_2$ -partial game. Under any solution concept we would need indeed to analyze what the DM believes at her information set in  $T_2$  about the Expert's past actions that have led her to that information set, and those past moves are determined by a strategy of the expert in the  $T_2$ -partial game. This is the reason that we need to define a strategy at all the information sets of each player, including those in which he will never actually move: the latter parts of the strategy become the object of contemplation and analysis of the other player (or players) when they are deluded or unaware of parts of the actual game.

## 2.5 Unawareness

Generalized games can describe many types of games with subjective reasoning. In a generalized game, a player cannot imagine that she can take an action which is physically unavailable to her (property I4), but at a given information set  $\pi_i(n)$  she can nevertheless imagine that in a succeeding information set she will have an action which is actually nowhere available in the tree  $T_n$  as in the example of Figure 8. Furthermore, she can imagine that along the path of play another player will forget the history of play, i.e.

that at a later information set this other player will imagine he is playing in a game tree which is completely unrelated to the game tree he imagined at an earlier stage along the path.

Since our main motivation is to analyze games with unawareness rather than games with arbitrary kinds of subjective reasoning, it is worthwhile spelling out additional properties of generalized games in which the only reason for players' misconception of the game is unawareness (and mutual unawareness) of available actions. In *extensive-form games with unawareness* the set of trees  $\mathbf{T}$  forms a join semi-lattice under the inclusion partial order relation  $\preceq$ . The maximal tree in this join semi-lattice is the modeler's objective description of feasible paths of play.

The following additional properties parallel properties of static unawareness structures in Heifetz, Meier and Schipper (2006).<sup>9</sup>

U0 Confined awareness: If  $n \in T$  and  $i \in I_n$  then  $\pi_i(n) \subseteq T'$  with  $T' \preceq T$ .

U1 Generalized reflexivity: If  $T' \preceq T$ ,  $n \in T$ ,  $\pi_i(n) \subseteq T'$  and  $T'$  contains a copy  $n_{T'}$  of  $n$ , then  $n_{T'} \in \pi_i(n)$ .

U2 Introspection: If  $n' \in \pi_i(n)$  then  $\pi_i(n') = \pi_i(n)$ . (I.e. property I2.)

U3 Subtrees preserve awareness: If  $n \in T'$ ,  $n \in \pi_i(n)$ ,  $T \preceq T'$ , and  $T$  contains a copy  $n_T$  of  $n$ , then  $n_T \in \pi_i(n_T)$ .

U4 Subtrees preserve ignorance: If  $T \preceq T' \preceq T''$ ,  $n \in T''$ ,  $\pi_i(n) \subseteq T$  and  $T'$  contains the copy  $n_{T'}$  of  $n$ , then  $\pi_i(n_{T'}) = \pi_i(n)$ .

U5 Subtrees preserve knowledge: If  $T \preceq T' \preceq T''$ ,  $n \in T''$ ,  $\pi_i(n) \subseteq T'$  and  $T$  contains the copy  $n_T$  of  $n$ , then  $\pi_i(n_T)$  consists of the copies that exist in  $T$  of the nodes of  $\pi_i(n)$ .

The following remark is analogous to Remark 3 in Heifetz, Meier and Schipper (2006).

**Remark 3** *U5 implies U3.*

**Proof.** If  $n \in T'$ ,  $n \in \pi_i(n)$ ,  $T \preceq T'$ , and  $T$  contains a copy  $n_T$  of  $n$ , then by U5  $\pi_i(n_T)$  must consist of the copies that exist in  $T$  of the nodes of  $\pi_i(n)$ . Since by assumption  $n \in \pi_i(n)$  and the copy  $n_T$  exists in  $T$ , we must have  $n_T \in \pi_i(n_T)$ .  $\square$

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<sup>9</sup>The number of each property corresponds to the respective property in Heifetz, Meier and Schipper (2006).

**Remark 4**  $U0$  implies  $I0$ .  $U1$  implies  $I1$ .

**Remark 5**  $U0$  is equivalent to  $I0$  and  $T \succrightarrow T'$  implies  $T' \preceq T$ .

**Proof.**  $I0$  and  $T \succrightarrow T'$  implies  $T' \preceq T$  are equivalent to if there exists  $n \in T$  and  $i \in I_n$  such that  $\pi_i(n) \subseteq T'$  then  $T' \preceq T$ .  $\square$

All these properties are static properties in the sense that they relate nodes on one tree with copies of those nodes in another tree. One may wonder about dynamic properties of unawareness. The following property states that a player can not become unaware during the play.

DA Awareness may only increase along a path: If there is a path  $n, \dots, n'$  in some subtree  $T$  such that player  $i$  is active in  $n$  and  $n'$ , and  $\pi_i(n) \subseteq T$  while  $\pi_i(n') \subseteq T'$  then  $T' \succeq T$ .

Recall that  $I3$  is the only completely new property imposed on information sets in generalized games.

**Remark 6** Suppose that  $U0$  to  $U2$  hold. Then DA if and only if  $I3$ .

**Proof.** More precisely, we will show first that if  $I1$  holds, then  $I3$  implies DA. Second, if  $U0$  and  $I2$  holds, then DA implies  $I3$ . This implies the result by Remark 4.

If  $n, \dots, n'$  is path in  $T$  such that  $i \in I_n \cap I_{n'}$ ,  $\pi_i(n) \subseteq T$  while  $\pi_i(n') \subseteq T'$  then by  $I1$  we have  $n \in \pi_i(n) \subseteq T$ . Then by  $I3$ ,  $\pi_i(n') \subseteq T$ , which implies DA.

If  $n' \in \pi_i(n) \subseteq T$  and  $n', \dots, n''$  is path in  $T'$  such that  $i \in I_{n'} \cap I_{n''}$  then by  $I2$ ,  $\pi_i(n') = \pi_i(n)$  and thus by DA if  $\pi_i(n'') \subseteq T''$  then  $T'' \succeq T'$ . By  $U0$ , if  $n'' \in T'$  then  $\pi_i(n'') \subseteq T''$  with  $T'' \preceq T'$ . Hence  $T'' = T'$ , which implies  $I3$ .  $\square$

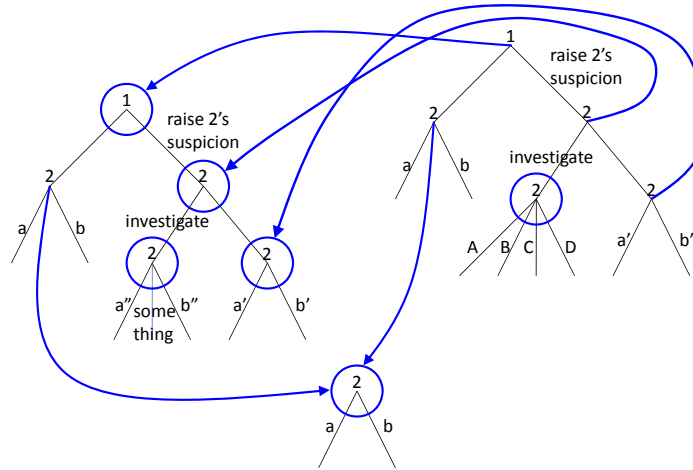
## 2.6 Awareness of unawareness

In some strategic situations a player may be aware of her unawareness in the sense that she is suspicious that *something* is amiss without being able to conceptualize this ‘something’. Such a suspicion may affect her payoff evaluations for actions that she knows are available to her. More importantly, she may take actions to investigate her suspicion if such actions are physically available.

To model awareness of unawareness some of the trees may include *imaginary actions* as placeholders for actions that a player may be unaware of and terminal nodes/evaluations of payoffs that reflect her awareness of unawareness. (The approach of modeling awareness of unawareness by “imaginary moves” was proposed by Halpern and Rêgo, 2006.)

Consider the example in Figure 8. In both right and left trees, player 1 can decide

Figure 8: Game form with awareness of unawareness



whether or not to raise the suspicion of player 2. If he does not, then player 2 can decide between two actions. Since in this case player 2's information set is in the lower tree, she does not even realize that player 1 could have raised her suspicion. If player 1 raises player 2's suspicion, then player 2's information set is in the left tree. She must decide whether to investigate her suspicion or not. If she doesn't, then she can decide between two actions but this time she realizes that player 1 raised her suspicion (and could have refrained from doing so); and that she could have chosen to investigate, in which case she may have had 'something' else to do, that she cannot conceptualize in advance. Once she investigates, she becomes aware of two more actions and her information set is in the right tree. She also realizes that player 1 initially raised her suspicion without being explicitly aware of those actions of hers by himself. Note that before she decides whether or not to investigate, she is not modeled as anticipating to be in the right tree, because she cannot conceptualize the nature of the actions she reveals if and when she investigates.

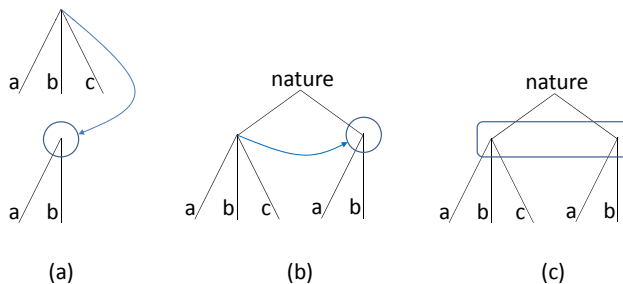


## 2.7 The connection to standard extensive-form games

Harsanyi (1967) showed how to transform games with asymmetric information into games with imperfect information about a move of nature. Can a similar idea be used to transform any generalized extensive-form game into a standard extensive-form game? Given a generalized extensive-form game  $\Gamma$  with a partially ordered set of trees  $\mathbf{T}$ , one could define the transformation of  $\Gamma$  to be the extensive-form game with an initial move of nature, in which nature chooses one of the trees in  $\mathbf{T}$ .

Notice, however, that the resulting structure would not be a standard extensive-form game. To see this, notice that every standard extensive-form game has the following property (E): the equivalence class of nodes in which a player considers as possible a given possibility set of nodes is *identical* with that possibility set; this set is called an information set of the player, and in all of its nodes the player has the same set of available actions. In contrast, in the transformation considered above for games with misperceptions, this equivalence class may be a *strict super-set* of the possibility set. For example, when the generalized game in Figure 9(a) is transformed so as to have an initial move of nature, the possibility set for the (unique) player is the right node, while the equivalence class contains both the right and left node.

Figure 9:



Thus, if after adding the initial move of nature the information sets are defined to be synonymous with the possibility sets, the resulting game would be non-standard, because for some information set there may be additional nodes *outside it* in which the player considers it as possible (as in Figure 9(b), where in the left node the player considers only the right node as possible). If, in contrast, we choose the alternative definition, by which an information set is the equivalence class in which a player has a particular set of nodes that she considers as possible, the resulting game would again be non-standard,

this time because the actions available to the player in the nodes of a given information set might not be identical across these nodes (as in Figure 9(c), where in the left node the player has more available actions than in the right node, even though both are within the same information set).<sup>10</sup>

There is also another aspect that prevents the above transformation from yielding a standard extensive-form game. In a standard extensive-form game each player has a full-support prior on the moves of nature.<sup>11</sup> Using Bayes rule, the player therefore has a well-defined belief about nature at each stage of the game. In contrast, in the above transformation each player ascribes probability 1 only to one of the initial moves of nature; moreover, along the path of play the player may switch completely the move of nature in which she confides even if nothing in the path of play itself imposed such a switch. Such a switch corresponds to a node in the generalized game in which the player is **defined** as *becoming aware* of new aspects of the dynamic interaction; such an increase of awareness may occur even when the physical path of play *per se* did not imply a surprise, and may have also been compatible with the player’s previous conception of the game. Thus, if we do add an initial move of nature to connect the trees of the generalized game, the player’s (evolving) belief about nature cannot be encapsulated within an initial probabilistic belief about nature, and must be represented explicitly by a *belief system* as part of the *definition* of the game.

Adding an initial move of nature has a further conceptual drawback. In classical extensive-form games the implicit assumption is that the players understand the entire structure of the dynamic interaction as embodied in the game tree.<sup>12</sup> Assigning probability zero to some move of nature is still compatible with realizing what could have happened if this zero-probability move were nevertheless to materialize. This is conceptually distinct from being completely *unaware* of a subset of paths in the game, and it is the latter concept that we want to model here. Moreover, as we have seen in the example of the introduction (Figures 3 and 4), it may lead to behavioral predictions different from

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<sup>10</sup>In this example of a game with a single player who is unaware of her action  $c$ , one could obviously describe the game simply as a single-person decision problem between  $a$  and  $b$ . This would not be possible, however, in more complex games like the one in Figure 2. There, one cannot do away with any of the nodes in the upper tree or in the lower tree; if these two trees are joined by a preceding move of nature, then when player 1 doesn’t tell player 2 about the Mozart concert, player 2’s information set becomes non-standard.

<sup>11</sup>Moreover, in the classical definition of an extensive-form game the priors of the different players about nature are actually identical, i.e. the players have a common prior about nature.

<sup>12</sup>For instance, Myerson (1991, p. 4) puts forward explicitly the tenet that game theory deals with *intelligent* players, where “a player in the game is *intelligent* if he knows everything that we know about the game and he can make any inference about the situation that we can make.”

unawareness.

Thus, standard extensive-form games are neither technically fit (without further generalization) for modeling behavior under dynamic misperceptions and unawareness, nor do they convey the appropriate conceptual apparatus for modeling such interactions, hence the need for our definition of generalized games.<sup>13</sup>

### 3 Extensive-form rationalizability

Pearce (1984) defined extensive-form (correlated) rationalizable strategies by a procedure of an iterative elimination of strategies. The idea behind the definition involves a notion of forward induction. In generic perfect-information games, rationalizable strategy profiles yield the backward induction outcome, though they need not be subgame-perfect equilibrium strategies (Reny 1992, Battigalli 1997).

In what follows we extend this definition to generalized extensive-form games.

A *belief system* of player  $i$

$$b_i = (b_i(h_i))_{h_i \in H_i} \in \prod_{h_i \in H_i} \Delta(S_{-i}^{T_{h_i}})$$

is a profile of beliefs - a belief  $b_i(h_i) \in \Delta(S_{-i}^{T_{h_i}})$  about the other players' strategies in the  $T_{h_i}$ -partial game, for each information set  $h_i \in H_i$ , with the following properties

- $b_i(h_i)$  reaches  $h_i$ , i.e.  $b_i(h_i)$  assigns probability 1 to the set of strategy profiles of the other players that reach  $h_i$ .
- If  $h_i$  precedes  $h'_i$  ( $h_i \rightsquigarrow h'_i$ ) then  $b_i(h'_i)$  is derived from  $b_i(h_i)$  by Bayes rule whenever possible.

Denote by  $B_i$  the set of player  $i$ 's belief systems.

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<sup>13</sup>Even if one nevertheless prefers to model such interactions using an initial move of nature and generalizing accordingly the notions of information sets and beliefs about nature in standard extensive-form games, the properties (I0)-(I6) of our definition constitute *restrictions* on the structure of such "extended" standard games that are needed in order to guarantee e.g. that the expectations of each player about future paths are dynamically consistent (property I3) and perfect recall is well-defined (property I6).

For a belief system  $b_i \in B_i$ , a strategy  $s_i \in S_i$  and an information set  $h_i \in H_i$ , define player  $i$ 's expected payoff at  $h_i$  to be the expected payoff for player  $i$  in  $T_{h_i}$  given  $b_i(h_i)$ , the actions prescribed by  $s_i$  at  $h_i$  and its successors, assuming that  $h_i$  has been reached.

We say that with the belief system  $b_i$  and the strategy  $s_i$  player  $i$  is *rational* at the information set  $h_i \in H_i$  if there exists no action  $a'_{h_i} \in A_{h_i}$  such that only replacing the action  $s_i(h_i)$  by  $a'_{h_i}$  results in a new strategy  $s'_i$  which yields player  $i$  a higher expected payoff at  $h_i$  given the belief  $b_i(h_i)$  on the other players' strategies  $S_{-i}^{T_{h_i}}$ .

We now turn to define extensive-form rationalizability in generalized extensive-form games.<sup>14</sup>

**Definition 1 (Extensive-form Rationalizable strategies)** *Define, inductively, the following sequence of belief systems and strategies of player  $i$ .*

$$B_i^1 = B_i$$

$$R_i^1 = \{s_i \in S_i: \text{there exists a belief system } b_i \in B_i^1$$

*with which for every information set  $h_i \in H_i$  player  $i$  is rational at  $h_i$*

$\vdots$

$$B_i^k = \{b_i \in B_i^{k-1} : \text{for every information set } h_i, \text{ if there exists some profile of the other players' strategies } s_{-i} \in R_{-i}^{k-1} = \prod_{j \neq i} R_j^{k-1} \text{ such that } s_{-i} \text{ reaches } h_i, \text{ then } b_i(h_i) \text{ assigns probability 1 to } R_{-i}^{k-1, T_{h_i}}\}$$

$$R_i^k = \{s_i \in S_i: \text{there exists a belief system } b_i \in B_i^k \text{ with which for every information set } h_i \in H_i \text{ player } i \text{ is rational at } h_i\}$$

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<sup>14</sup>The following definition generalizes Battigalli's (1997) definition of (correlated) extensive-form strategies, which he proved to be equivalent to that of Pearce (1984), with the a slight modification: our definition requires an extensive-form rationalizable strategy  $s_i$  to be optimal w.r.t. some belief also at information sets which are excluded by the actions of  $s_i$  at some preceding information set.

This means that in standard extensive-form games our definition refines the Pearce-Battigalli definition, but gives rise to the same plans of action. (A plan of action of a player is an equivalence class of her strategies which are identical in all the player's information sets that are not excluded by any of these strategies.)

Another slight difference between the definition here and that of Battigalli (1997) for standard extensive-form games is that for a given belief system and a strategy  $s_i$ , at an information set  $h_i$  not excluded earlier by  $s_i$  Battigalli compares  $s_i$  to all its  $h_i$ -replacements, while we restrict attention only to 'local'  $h_i$ -replacements which alter  $s_i$  solely at  $h_i$ . By the one-deviation principle (see e.g. Perea, 2002), for a given belief system  $b_i$  a strategy  $s_i$  is dominated by no  $h_i$ -replacement at no information set  $h_i$  unexcluded by  $s_i$  if and only if  $s_i$  is dominated by no 'local'  $h_i$ -replacement at no information set  $h_i$  unexcluded by  $s_i$ . Hence, in standard extensive-form games, at each iteration of the inductive definition below the plans of actions of the surviving strategies are identical to those surviving Battigalli's definition.

The set of player  $i$ 's *extensive-form rationalizable strategies* is

$$R_i^\infty = \bigcap_{k=1}^{\infty} R_i^k.$$

The definition captures rationality and common strong belief in rationality (Battigalli and Siniscalchi, 2002): At each information set, a rationalizable strategy should be optimal vis-a-vis some belief over the opponents strategy; if the information set is reached by some tuple of *optimal* opponents' strategies (vis-a-vis some beliefs of theirs), then the player's belief is further required to be concentrated on such tuples; if, furthermore, the information set is reached by some tuple of the opponents' strategies which are optimal vis-a-vis a belief system of theirs concentrated on optimal strategies of *their* opponents, the player's belief should be concentrated on *those* tuples; and so forth.

In other words, along each feasible path of play, in the first information set an active player believes that all her opponents will behave rationally, will believe that *their* opponents will behave rationally, etc. If at some information set in the game all the opponents' strategy profiles which could lead to that information set fail this ideal condition, the player seeks a *best rationalization* (Battigalli, 1996) which could have led to that information set.

For example, if player  $i$  has a unique opponent  $j$ , who has only two strategies that lead to an information set of  $i$ - $s'_j$  which is strictly dominated for  $j$ , and  $s_j$  which is optimal for  $j$  but only under a belief of  $j$  that  $i$  is (or was, or will be) irrational, then at that information set  $i$  is required to believe that in the sequel  $j$  will continue to employ  $s_j$  (because  $s_j$  embodies a better rationalization of  $j$ 's past behavior than does  $s'_j$ ). Forward induction reasoning then implies that from that information set onwards,  $i$ 's rationalizable strategy should be optimal vis-a-vis  $s_j$ , unless a further information set  $h'_i$  is reached which is compatible only with  $s'_j$ ; at  $h'_i$  player  $i$  has no choice but to revert to the belief that  $j$  is irrational, and react accordingly.

The definition of this solution concept for generalized extensive-form games highlights the need to define the notion of a strategy as we did, by the actions taken not only at the tree  $T_1$  which represents the physical paths of the game, but also at all the other trees  $T \in \mathbf{T}$ . True, to track the physical paths compatible with profiles of extensive-form rationalizable strategies it is enough to look at their restrictions to  $T_1$ . However, at each given node  $n \in T_1$  in which player  $i$  is active, the set of nodes  $\pi_i(n)$  that she considers as possible is a subset of her subjective view of the feasible paths  $T_{\pi_i(n)}$ , and at that point

she can only contemplate her strategy in terms of the  $T_{\pi_i(n)}$ -partial game. Furthermore, in order to rank the opponents' strategies according to their rationality, player  $i$  has to weigh them in the terms the opponents conceive the game, i.e. in the  $T$ -partial games which represent *their* subjective view of the strategic interaction *within* the  $T_{\pi_i(n)}$ -partial game (which may be different than the actual subjective views the opponents have on the game at various nodes of  $T_1$ ); and so forth.

This means that profiles of extensive-form rationalizable strategies have a different significance in their different domains. In  $T_1$  they define paths which could actually be realized; for  $n \in T_1$  for which  $T_{\pi_i(n)} \neq T_1$ , in  $T_{\pi_i(n)}$  these profiles define paths conceived as feasible by player  $i$  when the actual node at  $T_1$  is  $n$ ; for  $n' \in T_{\pi_i(n)}$  for which  $T_{\pi_j(n')} \neq T_{\pi_i(n)}$ , in  $T_{\pi_j(n')}$  these profiles define paths that at node  $n \in T_1$  player  $i$  conceives player  $j$  to conceive as possible if and when  $n'$  is reached in  $i$ 's subjective view of the game  $T_{\pi_i(n)}$ ; etc.

**Remark 7**  $R_i^k \subseteq R_i^{k-1}$  for every  $k > 1$ .

**Proof.** Consider  $s_i \in R_i^k$ . By definition,  $s_i$  is rational at each of player  $i$ 's information sets given some belief system  $b_i \in B_i^k$ . Since  $B_i^k \subseteq B_i^{k-1}$ ,  $s_i$  is also be rational at each of player  $i$ 's information sets given a belief system in  $B_i^{k-1}$ , namely given  $b_i$ . Hence  $s_i \in R_i^{k-1}$ .  $\square$

**Proposition 1** *The set of rationalizable strategies is non-empty.*

The proof is in the appendix.

It may be instructive to compare explicitly the extensive-form rationalizability strategies in our battle-of-the-sexes example from the introduction (Figures 1 and 2).<sup>15</sup>

**Remark 8** *In the Bach-Stravinsky-Mozart example with unavailability of actions from the introduction (Figure 1) both players have a unique rationalizable strategy while in the Bach-Stravinsky-Mozart example with unawareness (Figure 2), no player has a unique rationalizable strategy.*

The proof is contained in the appendix.

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<sup>15</sup>We thank an anonymous referee for this suggestion.

When we compare these examples, then the main difference arises from the the lack of forward induction of player II under unawareness. In the Bach-Stravinsky-Mozart example with unawareness (Figure 2), player II can not forward induce anything from the action “don’t tell” taken by player I since former is unaware of this action. Yet, in the Bach-Stravinsky-Mozart example with the unavailability of an action (Figure 1) player II can forward induce from the action “don’t give the car” player I’s intention to go to the Bach concert. In other words, awareness of an available action (providing the car for going to the Mozart concert) and certainty that it hasn’t been taken has stronger strategic implications than unawareness of the very same action.

In the Bach-Stravinsky-Mozart example with unawareness (Figure 2), the rationalizable outcome is not unique. This is in contrast to the example with unavailability of actions instead, where there is a rationalizable outcome. However, there exist also games where with unavailability of actions there are more rationalizable outcomes than with unawareness of the same actions. Such an example is presented in Heifetz, Meier, and Schipper (2011b).

## A Proofs

### A.1 Proof of Proposition 1

We proceed by induction.

$B_i^1$  is non-empty. Indeed, to construct a belief system  $b_i$ , for each information set  $h_i$  with no predecessors (according to the precedence relation  $\rightsquigarrow$ ) in the arborescence of information sets  $H_i$ , assign to player  $i$  a full-support belief  $b_i(h_i)$  on the other players’ strategies  $S_{-i}^{T_{h_i}}$  that reach  $h_i$ . The full-support guarantees that Bayes rule is applicable for deriving the beliefs of player  $i$  in all her remaining information sets.

Suppose, by induction, we have already shown that  $B_i^k$  is non-empty. We have to show that  $R_i^k$  is non-empty. For a typical belief system  $b_i \in B_i^k$  we have to construct a strategy  $s_i \in R_i^k$ , i.e. a strategy with which player  $i$  is rational at each of her information sets  $H_i$  given the belief system  $b_i$ . Since  $H_i$  is an arborescence, it is standard to construct such a strategy  $s_i$  by backward induction on  $H_i$ .

To complete the induction step, observe that  $B_i^{k+1}$  is non-empty, because by definition it singles out a non-empty subset of  $B_i^k$ .

Now, since player  $i$ 's set of strategies  $S_i$  is finite and by Remark 7  $R_i^{k+1} \subseteq R_i^k$  for every  $k \geq 1$ , for some  $\ell$  we eventually get  $R_i^\ell = R_i^{\ell+1}$  for all  $i \in I$  and hence  $B_i^{\ell+1} = B_i^{\ell+2}$  for all  $i \in I$ . Inductively,

$$\emptyset \neq R_i^\ell = R_i^{\ell+1} = R_i^{\ell+2} = \dots$$

and therefore

$$R_i^\infty = \bigcap_{k=1}^{\infty} R_i^k = R_i^\ell \neq \emptyset$$

as required. □

## A.2 Proof of Remark 8

Note first that a strategy for player I in the game of Figure 1 is a function that prescribes an action at the root of the tree and each matrix whereas in the game of Figure 2 it is a function that prescribes an action at the root of the tree, the left and right matrices in the upper tree as well as an action in the lower matrix. Consequently, the belief systems of player II differ accordingly in those examples.

To make the differences and similarities between the examples more transparent, we will derive the extensive-form rationalizable strategies for both examples side-by-side.

At the first level, any strategy is rational for player I except all strategies that prescribe going to the Mozart concert after “don’t give”. For player II, both the Bach concert and the Stravinsky concert are rational if player I does not give him the car. If player I does give him the car, then only the Mozart concert is rational since it is a dominant action conditional on being the right matrix. Thus,

$$R_{II}^1 = \{(B, M), (S, M)\},$$

where the first component of a strategy refers to player II’s action in the left matrix and the second refers to the right matrix.

At the first level, any strategy is rational for player I except all strategies that prescribe going to the Mozart concert after “don’t tell”. For player II, both the Bach concert and the Stravinsky concert are rational if he is unaware of the Mozart concert. If he is aware of the Mozart concert, then only this concert is rational since it is a dominant action conditional of being in the right matrix. Thus,

$$R_{II}^1 = \{(M, B), (M, S)\},$$

where the first component of a strategy refers to player II’s action in the right matrix and the second refers to the lower matrix.



At the second level, player I is certain that player II will go to the Mozart concert when given the car. Thus, any second level rational strategy for player I must prescribe going to the Mozart concert after “give the car”. Not giving the car to player II and going to the Stravinsky concert is dominated by giving the car to player II and going to the Mozart concert. Not giving player II the car and going to the Bach concert is rational for player I assuming that she believes with probability at least  $\frac{1}{4}$  that player II will go to the Bach concert. Giving the car to player II and going to the Mozart concert is rational for player I if she believes with probability at least  $\frac{3}{4}$  that player II would go to the Stravinsky if not given the car. To summarize,

$$R_I^2 = \left\{ (\text{“don’t give”}, B, M), (\text{“give”}, B, M) \right\}$$

where the second (resp. third) component of the strategy vector refers to player I’s choice after history “don’t give” (resp. “give”). For player II,  $R_{II}^2 = R_{II}^1$  since the deletion of  $M$  in the left matrix for player I at the first level does not influence the optimality of any strategy of player II because when player I takes  $M$  any of player II’s actions yields the same payoff in the left matrix.

So far, the arguments are analogous in both examples. A difference arises at the third level for player II. For player I, any second level strategy is also third level rational for player I since in both examples no strategies of player II have been eliminated at the second level.

At the second level, player I is certain that player II will go to the Mozart concert when told about it. Thus, any second level rational strategy for player I must prescribe going to the Mozart concert after “don’t tell”. Not telling player II about the Mozart concert and going to the Stravinsky concert is dominated by telling player II about the Mozart concert and going to the Mozart concert. Not telling player II about the Mozart concert and going to the Bach concert is rational for player I assuming that she believes with probability at least  $\frac{1}{4}$  that (the unaware) player II will go to the Bach concert. Telling player II about the Mozart concert and going to the Mozart concert is rational for player I if she believes with probability at least  $\frac{3}{4}$  that player II would go to the Stravinsky concert if not told about the Mozart concert. In the lower tree, both players are unaware of the Mozart concert. Going to Bach is rational for player I if she believes with probability at least  $\frac{1}{4}$  that player II goes to Bach as well. Going to the Stravinsky concert is rational for player I if she believes with probability at least  $\frac{3}{4}$  that player II goes to Stravinsky. This is just the standard Battle-of-Sexes game. To summarize,

$$R_I^2 = \left\{ (\text{“don’t tell”}, B, M, B), (\text{“tell”}, B, M, B), (\text{“don’t tell”}, B, M, S), (\text{“tell”}, B, M, S) \right\}$$

where the second (resp. third) component of the strategy vector refers to player I’s choice after history “don’t tell” (resp. “tell”), and the last component denotes the action in the lower subtree. For player II, note that his strategy does not prescribe an action in the left matrix. Hence, the deletion of  $M$  in the left matrix for player I at the first level has no effect on the optimality of any strategy of player II. Thus  $R_{II}^2 = R_{II}^1$ .

At the third level, when player II is not given the car, he can “forward induce” that player I will go to the Bach concert. This is because any second level rational strategy of player I prescribes the Bach concert after the history “don’t give the car”. Consequently, a third level rational strategy of player II must prescribe going to the Bach concert as well when not given the car. Thus,

$$R_{II}^3 = \{(B, M)\}.$$

At the fourth level, if player I gives the car to player II, then latter will go to the Bach concert. Otherwise, if player I does not give the car to player II, then latter will go to the Mozart concert. Since player I strictly prefers to the Mozart concert together with player II, any fourth level rational strategy of player I must involve her not giving the car to player II. Thus,

$$R_I^4 = \{(\text{“don’t give”}, B, M)\} = R_I^k, \text{ for all } k \geq 4.$$

Hence, the extensive-form rationalizable strategies are

$$\begin{aligned} R_I^\infty &= \{(\text{“don’t give”}, B, M)\}, \\ R_{II}^\infty &= \{(B, M)\}. \end{aligned}$$

At the third level, when player II is not told about the Mozart concert, he can *not* “forward induce” that player I will go to the Bach concert. This is because he is unaware of the Mozart concert and his information set is located in the lower subtree of Figure 2. At this matrix, both Bach and Stravinsky are second level rational actions for player I. Thus, no strategies can be eliminated

$$R_{II}^3 = R_{II}^1.$$

For both players, no strategies were eliminated at the third level. Thus, no further strategies can be eliminated at any level  $k \geq 3$ .

Hence, the extensive-form rationalizable strategies are

$$\begin{aligned} R_I^\infty &= \left\{ \begin{array}{l} (\text{“don’t tell”}, B, M, B), (\text{“tell”}, B, M, B), \\ (\text{“don’t tell”}, B, M, S), (\text{“tell”}, B, M, S) \end{array} \right\}, \\ R_{II}^\infty &= \{(M, B), (M, S)\}. \end{aligned}$$

□

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