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GAMES IN DYNAMIC-EPISTEMIC LOGIC

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ABSTRACT

The author discusses games of both perfect and imperfect information at two levels of structural detail: players' local actions, and their global powers for determining outcomes of the game. Matching logical languages are proposed for both. In particular, at the 'action level', imperfect information games naturally model a combined 'dynamic-epistemic language' – and correspondences are found between special axioms in this language and particular modes of playing games with their information dynamics. At the 'outcome level', the paper presents suitable notions of game equivalence, and some simple representation results.

I. GAMES AS STRUCTURES FOR LOGICAL LANGUAGES: A FIRST GLANCE

I.1. Modal logic of actions

The pictures in a typical game theory text have an immediate appeal to a logician. In particular, an extensive game tree depicts a many-agent process, where nodes are possible stages, with available actions for players indicated, and perhaps also with markings for relevant properties of these stages. This is exactly like *process graphs* ('Kripke models') for *modal logic* or related languages that are used by logicians and computer scientists for describing action structures. For example, consider a game tree for two players **A**, **E** with four possible actions *c*, *d*, *a*, *b*, and some special property *p* holding at two of the four possible end-states (Figure 1). Here is a typical modal assertion which is true at

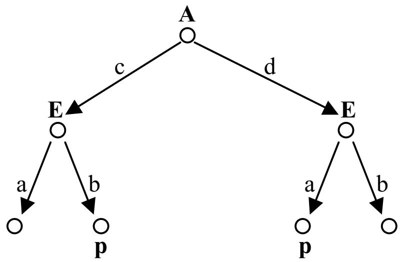

Fig. 1

the root:

$[c \cup d]\langle a \cup b \rangle p$ [each of the actions c and d leads to a state where either a or b can be executed to get to a final state where p holds]

This modal formula says in the given process graph that player **E** has a *strategy* ensuring that the outcome of the game satisfies p. For example, p might be the property that **E** wins, in which case the above modal formula expresses that '**E** has a winning strategy'. More complex strategies than this 'single response' can be analysed with longer $[]\langle\ \rangle$ sequences of modal operators. This strategic feature is one of the things which makes extensive games of such great interest to logicians and computer scientists: the modelling of processes between intelligent agents and their complex interactions over time.

Now, the above way of thinking about game trees may not be *quite* the interpretation that game theorists themselves have in mind. The aim of this paper is to develop the logical view in a bit more detail, hoping that there is enough difference to make for new insights, but also enough resemblance to allow for meaningful communication.

I.2. Imperfect information: adding epistemic logic

The modal view is only a first step, as it merely deals with pure game forms. Other features of real games suggest richer logical languages. The main topic in this paper is *imperfect information*, where players may be uncertain in which state they are in the course of a game. To model this, game theorists draw 'dotted lines', or 'information sets'. Consider again the above game, but now with an uncertainty for player **E** about which move was played by **A** initially. (Perhaps, **A** put his move in an envelope.) To a logician, this is a typical model for a combined *modal-epistemic* language (Figure 2).

The earlier modal formula $[c \cup d]\langle a \cup b \rangle p$ is still true at the root, since the action pattern is the same. But this time, we can make more subtle

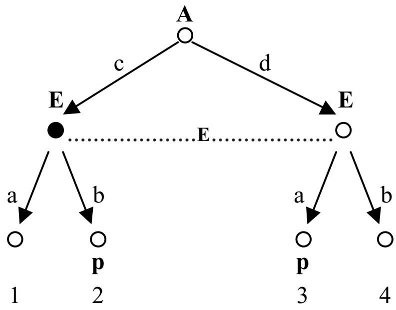

Fig. 2

assertions about players' adventures 'en route', using the dotted lines as an accessibility relation for epistemic *knowledge operators* in the usual way. At any stage s, a player 'knows' exactly those propositions that are true throughout the information set to which s belongs. This epistemic connection has also been known to game theorists, ever since the 1970s. For example, after **A** plays move c in the root, in the resulting 'black' state, **E** 'knows' that playing either a or b will give her p, since the disjunction $\langle a\rangle p \vee \langle b\rangle p$ is true at both 'middle states'. This may be expressed by means of the epistemic formula:

$$K_E(\langle a\rangle p \vee \langle b\rangle p).$$

On the other hand, there is no *specific* move of which **E** knows that it guarantees an outcome satisfying p – which shows in the black node in the truth of the formulas:

$$\neg K_E\langle a\rangle p \qquad \text{and} \qquad \neg K_E\langle b\rangle p.$$

Think of the tragic someone who knows that the right partner is walking around right in this city, but does not know of any particular person whether (s)he is that partner.

Such finer distinctions are typical for a language describing both actions and knowledge for agents. They also occur in other fields (e.g. with planning in AI), so there is nothing exotic to our way of reading the above diagrams. These generalize process graphs to more sophisticated computational systems, like those on the Internet today, where agents in a group have the indicated actions available in principle at each stage of the process, but must operate under epistemic uncertainties.

I.3. Preferences

Realistic games have still further essential structure, in particular, *preferences* of players between the different possible outcomes. These give rise to a next level of logical formalization, say by using the preference relations to interpret 'preference modalities'. But this evaluational structure will not be addressed in this paper, though it is certainly compatible with all that will be proposed below.

I.4. Game equivalence: actions or outcomes?

What are key issues in a logical perspective on games? This paper concentrates on two basic themes. The first is this. Choosing a language with a certain expressive power for describing the internal structure of games, or any class of models for that matter, is just one side of a coin. The other side is choosing a matching notion of *structural equivalence* between different presentations of a game. For instance, compare the two games in Figure 3. These are not the same, intuitively, in their extensive structure of possible *actions*. For example, on the left, the game can reach a state where **E** can choose between achieving outcome 2 or 3. No such stage occurs in the game on the right. Thus, at the level of possible *actions*, these games are intuitively different.

But when we merely look at possible *outcomes*, this verdict changes. In the left-hand game, player **A** has two strategies 'left' and 'right', which guarantee outcomes for the game in the two sets $\{1\}$ and $\{2, 3\}$, respectively. Likewise, **E** has two strategies, which guarantee outcomes in $\{1, 2\}$ and $\{1, 3\}$. We think of these sets as 'powers' that players have for forcing outcomes of the game. A set with more elements says the power is not strong enough for a unique outcome, just some 'upper range':

A's powers: $\{1\}$, $\{2, 3\}$
E's powers: $\{1, 2\}$, $\{1, 3\}$.

Now, when we compute powers in the right-hand game, we obtain the same outcomes! First **E** has two strategies, which force $\{1, 2\}$ and $\{1, 3\}$. Next **A** has 4 strategies LL, LR, RL, RR which yield, respectively, $\{1\}$, $\{1, 3\}$, $\{2, 1\}$, $\{2, 3\}$. Of these four, $\{1, 3\}$ and $\{2, 1\}$ can be dropped, as they represent weaker powers than $\{1\}$, and hence are redundant. Thus **A** has the powers $\{1\}$ and $\{2, 3\}$, just as in the left-hand game.

Thus, game equivalence depends on how much structure one wants to describe: with a spectrum running from 'just outcomes' to 'all actions'.

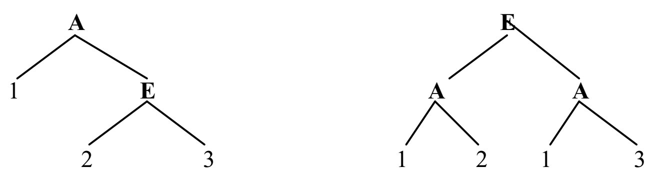

Fig. 3

This is a virtue, not a vice. Process logics in computer science, or grammars in linguistics, have the same options. For example, a process may be described as a 'black-box' merely in terms of input–output outcomes, or in terms of its internal choices and other actions. In specific applications, the 'level of identification' will depend on the practical purpose at hand. The same seems true for games. In what follows, I mainly describe games at their local 'action level', but will make excursions towards the global 'outcome level' as well.

Game equivalences also make sense with imperfect information. In terms of 'actions', one can now compare both physical game moves and epistemic 'uncertainty steps' across two games, looking for enough similarity in both. As for 'outcomes', we shall see later that, in terms of the appropriate powers for players in that setting, the game in Figure 2 is outcome-equivalent to the game tree in Figure 4, which has the roles of the two players plus some outcomes suitably interchanged.

I.5. General logics and special axioms

The second main logical theme is this. Once we have chosen a particular language, at any 'level of detail', we get a set of universally *valid formulas*, those that are true at every state in any model whatsoever. The resulting minimal logics are well-known for modal and epistemic models, being respectively the poly-modal versions of 'K' and 'S5'. But on top of such base systems, one finds special logics that are theories of special model classes satisfying additional restrictions. For instance, if we demand that players' moves are *partial functions*, then the modal logic acquires an extra axiom:

$$\langle a \rangle \phi \rightarrow [a]\phi.$$

We will encounter more such special axioms for the interplay of modal and epistemic operators in our study of imperfect information games,

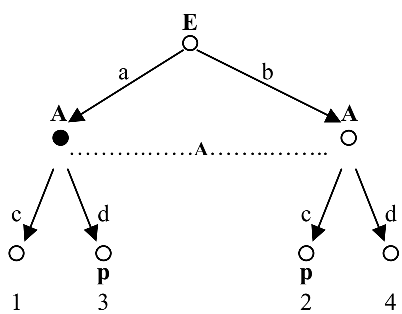

Fig. 4

such as the interchange law:

$$K_i[a]\phi \rightarrow [a]K_i\phi$$

(see Section III.3). Such principles reflect special assumptions about players' abilities, or the uncertainty inherent in the game. They yield different 'logics' for reasoning about the behaviour of players in different types of imperfect information game.

I.6. Overview of the paper

Section II introduces some basic logical notions for perfect information games, viewed as process graphs, at both action and outcome levels. I use these in Section III to deal with actions and knowledge in imperfect information games, viewed as many-agent processes with uncertainty. The results are used in Section IV to analyse several styles of playing such games, and in Section V, to analyze outcome equivalence. Section VI is a discussion of ways to go from here.

II. EXTENSIVE GAMES AS MODELS FOR DYNAMIC LOGICS

We proceed in two stages, starting our logical analysis with *finite perfect information games*. This section is a brief survey of some basic logical notions to be used later on.

II.1. Action languages

Perfect information game trees are models:

$$M = (S, \{R_a \mid a \in A\}, V)$$

where (a) S is a set of *states*, (b) the R_a are binary relations encoding the possible *transitions* for action/move types a, and (c) V is a *valuation* function for proposition letters denoting local properties of states.

In this most general logical setup, games may have some distinguished vocabulary. In particular, propositional atoms $turn_i$ and win_i say that player **i** is to move or wins, *end* holds at just the end-points, while other atomic statements may indicate values of final states to players. These models are described by a *dynamic modal language* with basic actions a, b, ... and operations of:

(a) union $\cup$	choice
(b) composition ;	sequential execution
(c) Kleene star *	arbitrary finite iteration
(d) (ϕ)?	test if assertion ϕ holds

Thus we can define further transition relations in a game, such as the single choice $a \cup b$, or the iterated choice $(a \cup b)^*$ which allows us to walk from a state to any state reachable from it by some finite sequence of a and b moves. For all resulting actions A (basic or compound), the dynamic language has modalities:

$\langle A \rangle \phi$ 'in some A-successor, ϕ holds'

$[A]\phi$ 'in all A-successors, ϕ holds'.

As we have seen above, this allows us to express single-response strategies, such as:

$$[c \cup d]\langle a \cup b \rangle p.$$

But one can also define much more complex assertions about possible actions and outcomes, using patterns of statement $[A]\langle B \rangle [C] \langle D \rangle \phi$, etc. Here is another example of this expressive power. Consider the simplest use of *backward induction*, computing which player has the winning strategy at any node in a finite two-player zero-sum game with outcomes marked win_i or $\neg win_i$ for each player **i**. One starts in the end nodes, and then works upwards. Let A be the union of all available actions. Then the rule for the winning positions may be defined by the following recursion:

$$WIN_i \leftrightarrow (end \;\&\; win_{\mathbf{i}}) \vee (turn_{\mathbf{i}} \;\&\; \langle A \rangle WIN_{\mathbf{i}}) \vee (\neg turn_{\mathbf{i}} \;\&\; [A] WIN_{\mathbf{i}}).$$

This language can also speak about *strategies* explicitly. A strategy for player **i** is just a partial function from those nodes where it is **i**'s turn to concrete moves. Thus, a strategy σ is a set of atomic transitions, just like any basic action. Then, for instance, saying that σ is a winning strategy for player **i** amounts to stating:

$$[A^*]\ (turn_{\mathbf{i}} \rightarrow \langle \sigma \rangle WIN_{\mathbf{i}})$$

[where A* goes from the root to any game node].

Using two strategy symbols in the same way, the language can analyse Nash equilibria (De Bruin, 2000). Dynamic logic is decidable, both in general and over the special class of finite trees; and in both cases there is a complete axiomatization for its set of valid principles. Refer to Blackburn *et al.* (2000) for details.

II.2. Bisimulation

The structural counterpart to the dynamic description language is the following notion of comparison between different games (see Figure 5).

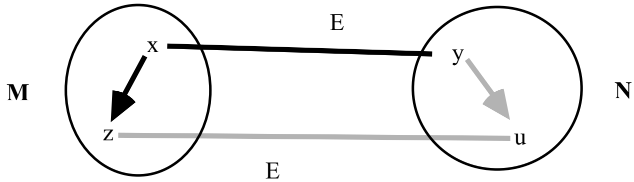

Fig. 5

It works on game trees, but equally well on any graph representation of possible actions and states:

Definition: A *bisimulation* is any binary relation E between states of two graphs **M**, **N** such that, if $x\mathrm{E}y$, then we have (1) atomic harmony, plus (2) zigzag clauses for all actions R:

(1) x, y verify the same proposition letters
(2a) if $x\mathrm{R}z$, then there exists u in **N** s.t. $y\mathrm{R}u$ and $z\mathrm{E}u$
(2b) vice versa.

Bisimulation is the typical 'action-similarity' for processes in logic and computer science. It preserves modal and dynamic formulas, and there are some converses, too. Here are two sample results that establish the link (cf. van Benthem, 1996, 1998).

Theorem 1: For finite graphs **M**, **N** *with nodes s, t, the following two assertions are equivalent:*

(a) **M**, *s and* **N**, *t satisfy the same modal formulas*
(b) *there is a bisimulation E between* **M**, **N** *with sEt.*

This says that the language and the similarity relation match. The next result says that at this level of description, the language provides complete descriptions for any graph.

Theorem 2: For each finite graph **M** *and state s, there is a dynamic logic formula* $\delta(\mathbf{M}, s)$ *such that the following are equivalent for all graphs* **N**, *t:*

(a) **N**, $t \models \delta(\mathbf{M}, s)$
(b) **N**, *t is bisimilar to* **M**, *s*.

Similar definability and expressiveness results can be proved for all notions of game equivalence considered here (Barwise and Moss, 1997; van Benthem, 2000b). Thus, game structure can be described either via semantic equivalences between representations, or in terms of 'game formulas' in suitable formal languages (cf. Bonanno, 1993). In the rest of the paper, I concentrate mainly on the latter method of description.

II.3. Outcomes and powers

Moving now to outcomes, let us first sharpen up Section I.4. *Strategies* in extensive games are defined as usual, being functions from all nodes where it is the relevant player's turn to actions that are available at that node. *Forcing relations* for a game then encode what players can achieve:

$\rho^i_G sX$ *player* ***i*** *has a strategy for playing (the remainder of) game G from node s whose resulting states are always in the set of outcomes X.*

Given this explanation, it is clear that forcing relations are *closed under supersets*:

(C1) *if* $\rho^{\mathbf{i}}_G s$, *Y and* Y' *contains Y, then* $\rho^{\mathbf{i}}_G s$, Y'.

Another obvious constraint on these relations is *consistency*: players cannot force the game into disjoint sets of outcomes, or a contradiction would result:

(C2) *if* $\rho^{\mathbf{1}}_G s$, *Y and* $\rho^{\mathbf{2}}_G$ *s, Z, then Y, Z overlap.*

Moreover, all finite two-player games are *determined*: for any winning convention, one of the two players must have a winning strategy. Stated in the present terminology, this is a condition of *completeness*. Let *S* be the total set of outcome states:

(C3) *if not* $\rho^{\mathbf{1}}_G s$, *Y, then* $\rho^{\mathbf{2}}_G$ *s,* $S-Y$*; and the same for* **2** *vis-á-vis* ***1***.

Any finite perfect information game *G* between players **1**, **2** yields powers in the root *s* satisfying (C1), (C2), (C3). Conversely, these conditions are also *all* that must hold, witness the following representation result.

Proposition 1: Any two families F_1, F_2 *of subsets of some set S satisfying conditions (C1), (C2), (C3) are the root powers in some two-step game.*

Proof: Start with player **1** and let her choose between successors corresponding to the *inclusion-minimal* sets in F_1. At these nodes, player **2** gets to move, and can choose any member of that set. Clearly then, player **1** has the powers specified in F_1. In this game, player **2** can force any set of outcomes that overlaps with each of the sets in F_1. But by the constraints, it is easy to see that these are precisely the sets in F_2. For instance, if some set of outcomes A overlaps with all these sets, the complement $S-A$ cannot be among them, and hence A was in F_2, by the condition of determinacy. □

This result gives an outcome-level *normal form* for games, closely related to the usual 'strategic form'. It is also the 'distributive normal form' of standard propositional logic. Indeed, the usual Boolean operations that produce such normal forms form a *logical calculus of game equivalence* (van Benthem, 1999). Figure 3 is a typical case: the game equivalence stated there was nothing but the law of Boolean distribution:

$$p \,\&\, (q \vee r) \leftrightarrow (p\&q) \vee (p\&r).$$

II.4. A forcing language and its simulation

To describe games at this outcome level, one can introduce another logical language, whose key operator is this:

$\{G, \mathbf{i}\}\phi$ *is true at game node s if player* **i** *has a strategy for playing game G from there on which forces a set of outcomes all of which satisfy* ϕ.

This is the 'game-internal' version of the game modalities in Parikh (1985) and Pauly (2000). The corresponding notion of bisimulation between different games is as follows.

Definition: A *power bisimulation* between two games G, G' is a binary relation E between game states in G, G' satisfying:

(1) if x E y, then x, y satisfy the same proposition letters
(2) if x E y and $\rho^{\mathbf{i}}_{G}\, x, U$, then there exists a set V with $\rho^{\mathbf{i}}_{G'} y, V$ and $\forall v \in V \exists u \in \mathrm{U}\; u$ E v; and vice versa.

This analysis can be extended naturally to forcing sets of intermediate positions in a game.

II.5. Coda: internal versus external languages

The logical description of games, like that of processes, can proceed at various levels. The formal languages in this paper are *game-internal*. They define statements that may hold at the stages inside a play of a game. But the study of game equivalence also suggests a *game-external* point of view, with suitable expressions for whole games manipulated for equivalence. This calls for external logical languages, whose expressions denote games, using natural *game-forming operations* such as 'choice', 'role switch', or 'composition'. The Distribution law in Section II.3 was an example: the expression $p\&(q\vee r)$ stood for a game of a certain shape, not for an assertion about players' actions. The external viewpoint has its attractions too, especially when describing game equivalences in an algebraic manner. Moreover, the internal and external viewpoints can be combined – but in this paper, I will stick with the former.

III. IMPERFECT INFORMATION GAMES AND DYNAMIC-EPISTEMIC LOGIC

In games of imperfect information, during play, players may not know exactly where they are in the tree. This may come about for different reasons. Players may have cognitive limitations, such as bounded memory or limited perception of others' moves. But games may also impose ignorance by their definition, such as card or parlour games. Whatever the sources, one standard logical approach suggests itself.

III.1. The epistemic language

Games of imperfect information add epistemic structure among states, in the form of binary *'uncertainty'* relations $\sim_i$ for players **i**. The resulting models contain a 'multi-S5' structure:

$$\mathbf{M} = (S, \{R_a \mid a \in A\}, \{\sim_i \mid i \in I\}, V).$$

The *equivalence relations* $\sim_i$ encode that player **i** cannot tell one node from the other when she gets to them in the course of the game. This extends the game-theorist's usual 'information sets', which only encode informational constraints for a player on those nodes where it is his/her turn. In principle, in these models **M** any uncertainty pattern might occur. Players need not know what the opponent has played, or what they played themselves, they need not know if it is their turn, or whether the game has ended, etc. One can think up plausible scenarios with all of the pictures shown in Figure 6.

Pictures like this are not particular to games. They also occur in accounts of planning, where agents must act in partial ignorance of the true state of affairs (Moore, 1985). In what follows, I consider these game diagrams in great generality. My aim in doing this is not to 'improve' on the rich existing game-theoretic literature on imperfect information games (e.g. Osborne and Rubinstein, 1994; Bonanno, 1992; Battigalli and Bonanno, 1999), or take a stand on any current debate.

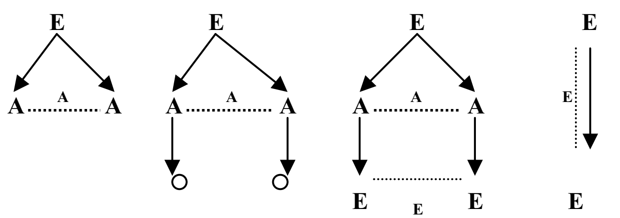

Fig. 6.

I merely wish to suggest a systematic logical perspective that may provide an interesting 'second opinion'.

III.2. Epistemic-dynamic logic

The above richer models naturally interpret a richer epistemic-dynamic language, which adds knowledge operators for each player:

$$\mathbf{M}, s \models K_i\phi \quad \textit{iff} \quad \mathbf{M}, t \models \phi \textit{ for all } t \textit{ s.t. } s \sim_i t.$$

Now we can talk about knowledge and ignorance of players when the game has reached a certain state. This was demonstrated in Section I using formulas like:

$$K_E(\langle a \rangle p \vee \langle b \rangle p)$$

$$\neg K_E\langle a \rangle p \ \& \ \neg K_E\langle b \rangle p$$

referring to the black state in Figure 2. Here player **E** has a strategy for achieving p in principle, but it is useless in practice, as its advice ('play a if c was played by **A**, otherwise, play b') depends on a distinction which **E** cannot resolve. In imperfect information games, players can only deliberately use *uniform strategies*, whose next action at any node is the same across their information set at that node.

For example, in Figure 4, **E** has only two uniform strategies LL and RR, of which she does not know if they guarantee outcome p. (NB: Game theorists *define* 'strategies' in imperfect information games as what we call uniform strategies here – but our distinction makes sense in logic, being similar to that between 'constructive' and more general 'nonconstructive' proof.) Our example suggests that uniform strategies are those for which players *know that they will work*. I will look at this later, because matters are more complicated than might seem from the above example.

A further important feature of epistemic languages are *iterations*. Players can have knowledge about each others' knowledge and ignorance (via formulas like $K_iK_j\phi$, $K_i\neg K_j\phi$), and this may be crucial to understanding the course of a game. Also, players may achieve *common knowledge* about certain facts, written as follows:

$C_{\{1,2\}}\phi$ ϕ is true in all those states that can be reached from the current one in a finite number of $\sim_1$ and $\sim_2$ steps.

For example, in the above-mentioned game, **E**'s plight is common knowledge between the players.

As for systematic reasoning about players' available actions, knowledge, and ignorance in arbitrary models of this kind, the complete set of *axioms for validity* in dynamic-epistemic logic is the following:

(a) the *minimal dynamic logic* for the modal operators $[A]$
(b) *epistemic S5* for each knowledge operator K_i.

With a common knowledge operator added, we also get the minimal logic of that (cf. Fagin *et al.*, 1995). There are no further axioms in general epistemic-dynamic logic.

III.3. Constraints for special axioms

But there is more to be said. Specific imperfect information games may validate additional epistemic-dynamic principles. Osborne and Rubinstein (1994, ch. 11) give a number of such constraints. These induce special axioms for reasoning about players following a certain style.

Example: 'The fact who is to move is common knowledge between players'. This is a reasonable requirement, e.g. in many parlour games. The relevant formula is:

$$turn_{\mathbf{i}} \rightarrow C_{\{1,2\}}\, turn_{\mathbf{i}}.$$

Example: 'All nodes in the same information set have the same possible actions'. The corresponding dynamic-epistemic formula reads as follows (with 'T' for *true*):

$$turn_{\mathbf{i}}\ \&\ \langle \mathrm{a}\rangle \mathrm{T} \rightarrow \mathrm{K_i}\langle \mathrm{a}\rangle \mathrm{T} \quad \text{or perhaps even} \quad \langle \mathrm{a}\rangle \mathrm{T} \rightarrow \mathrm{C}_{\{1,2\}}\langle \mathrm{a}\rangle \mathrm{T}.$$

As a final example, consider interactions between players' moves and their knowledge. *In general*, dynamic-epistemic logic validates no such laws.

Example: The Interchange Principle $K_{\mathbf{i}}[a]\phi \rightarrow [a]K_{\mathbf{i}}\phi$ says that, if player **i** knows right now that doing a will bring about ϕ, then doing a will result in her knowing that ϕ. This implication is reasonable for actions *without epistemic side-effects*, but not in general. It fails if action a is 'have one more beer', and ϕ the assertion that **i** is making a fool of himself. On game trees, the interchange formula only holds under the following constraint on action a and **i**'s uncertainties:

$$\forall xyz\colon ((xR_a y\ \&\ y \sim_i z) \rightarrow \exists u\colon ((x \sim_i u\ \&\ uR_a z)$$

This is a well-known *confluence property* for the relations of action and uncertainty (see Figure 7).

The converse axiom $[a]K_{\mathbf{i}}\phi \rightarrow K_{\mathbf{i}}[a]\phi$ also fails in general. Reading this paper will make you know certain things ϕ, even though you might not have known beforehand that it would do so. Both kinds of interchange principle will return in Section IV.3.

As a final technical point, natural semantic *correspondences* between dynamic-epistemic axioms and nice constraints on imperfect information games do not have to be found *ad hoc*. They can be *computed* using

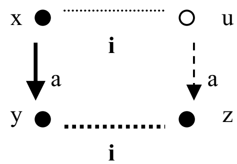

Fig. 7

well-known algorithms from modal logic (van Benthem, 1996; Blackburn *et al.*, 2000).

III.4. Bisimulation and characteristic formulas

Dynamic-epistemic logic provides a game-internal language speaking about possible actions and uncertainties. Alternatively, as in Section II.2, one can line up the following two perspectives:

(a) *the roots of two games satisfy the same dynamic-epistemic formulas*
(b) *there exists a* bisimulation *between the games connecting the roots.*

In this setting, bisimulations will now have zigzag conditions, both for possible actions and for 'uncertainty jumps' inside information sets. Likewise, we can use formulas of dynamic-epistemic logic to characterize finite games up to bisimulation equivalence.

IV. WAYS OF PLAYING GAMES

IV.1. Statics versus dynamics

Game trees are static pictures of all that can happen in a game. But in any specific run, there is an actual course of events, taking players to successive game states, each with possibly different knowledge and ignorance (see Figure 8).

This suggests a closer look at the logical 'dynamics' of game playing; in particular, the *update mechanisms* that produce or remove ignorance.

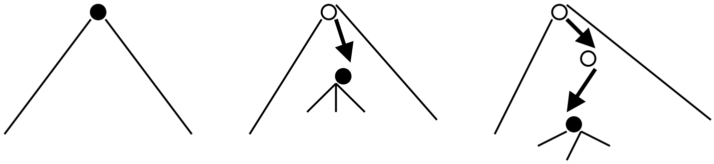

Fig. 8.

Our dynamic-epistemic languages describe what is true at successive nodes, keeping track of the changes in players' information. But one can be more systematic. We can also think about *different modes of playing a game*, and determine their modal-epistemic properties.

IV.2. Perfect recall

An important mode of game playing satisfies *perfect recall*: players remember their own previous moves, plus the uncertainties they had at each stage.

This notion is defined for a player **i** in Osborne and Rubinstein 1994 by the following demands on any two nodes related by its uncertainty relation $\sim_{\mathbf{i}}$:

going back along the unique histories determined by these nodes,
*one must find the same record of moves for player **i** when it is her turn,*
*and the same sets of **i**-indistinguishable alternatives at each node.*

Analysing this description stepwise, we find two semantic aspects to what happens during the game.

(a) When **i** is to move at x, and plays a to arrive at game state y, then any $\sim_{\mathbf{i}}$-uncertainty z after that must arise as follows: 'z was also reached via a, from some node u, and moreover, u and x must share the same uncertainty'. But the latter means no more or less than: $x \sim_{\mathbf{i}} u$. This may be pictured as a *commuting diagram* (Figure 9).

In terms of Sections II.2 and III.4, a modal logician might restate this condition as follows:

(i) $\sim_{\mathbf{i}}$ is a bisimulation: w.r.t *converse* actions $a^{\cup}$
(ii) **a** is a bisimulation: w.r.t. 'uncertainty jumps'

or in the physicists' parlance, in this type of situation, *action and uncertainty commute*!

(b) Next, when **i** is not to move at x, there is still such a bisimulation, but now with the difference that we do not require the action to be the same on both sides. The reason is this. The only source of (increased) uncertainty that we acknowledge is lack of information *about another player's move*. In particular, the latter may happen starting from one

Fig. 9.

single node, say the root, and the other player's move generates uncertainty straightaway. The diagram for this case is essentially like that of Figure 9.

Proposition 2: Perfect recall holds for precisely those dynamic-epistemic models that satisfy the given two commutative diagrams for each player.

Proof: From PR to 'commutation'. Here is one case. Suppose **1** was to move at x, and $xR_a y \sim_1 z$. Because of PR for **1**, at z, the same last action a must have taken place there, while at the beginning of the latter, say u, the same uncertainty set existed as at x. But the latter is equivalent to just: $x \sim_1 u$. The other case is similar. Here, players can recognize moves as being their own, or by the other player, and also, they know the number of moves plus turn-taking record along any history.

From 'commutation' to PR. This uses induction down any two paths of equal length down the tree whose final nodes are $\sim_1$-related. It is easy to see that these paths shared a point somewhere, while afterwards, the bisimulation diagrams for both players ensure that (a) they have the same moves for both players, (b) there were uncertainty links between corresponding stages from then on until the end. □

Proposition 2 provides a dynamic-epistemic *axiomatization* for imperfect information games with perfect recall (cf. Section III.3.) In reasoning about players' adventures in games of this sort, we can use the earlier minimal dynamic-epistemic logic, but now enriched with the following interchange axioms:

(1) $turn_\mathbf{i}$ & $K_\mathbf{i}[a]\phi \rightarrow [a]K_\mathbf{i}\phi$
(2) $\neg turn_\mathbf{i}$ & $K_\mathbf{i}[A]\phi \rightarrow [A]K_\mathbf{i}\phi$

with A the union of all actions available to the other player.

Proposition 3: The following two statements are equivalent for arbitrary imperfect information games G:

(a) *G satisfies the commutation properties for perfect recall*
(b) *all instances of axioms (1), (2) are true at every node in G, no matter how we interpret the free propositional variables.*

Here, the 'free' variables are the ones that do not stand for special game structure such as 'turn' or 'win'. We leave the verification of this standard modal correspondence to the reader. The main purpose of this example is the correspondence method as such, not the particular outcome. For example, for notions of perfect recall without total knowledge of the preceding turn-taking pattern, a similar analysis is possible.

Digression: two ways of thinking

One can think of the above diagrams as constraints passing only *bona fide* game trees for perfect recall. Alternatively, one can allow any imperfect information game, but then use the diagrams as a *PR algorithm* for pruning the tree of dotted lines, leaving only those uncertainties that players with perfect memory will in fact encounter:

(1) *Remove all uncertainty links that do not originate in an immediately dominating node.*
(2) *If no role switch occurred, also remove all uncertainty links between outcomes of different actions.*

On analysing this algorithm, or just the above diagrams, we find another interesting feature of perfect recall. Each uncertainty link x ... y for a player **i** has a uniquely identifiable *cause* higher up. Working upward along the paths from the root to x, y, one finds some last node where they diverged (at which the other player moves) and a pair of actions there which lead to an uncertainty link for **i**. Figure 10 illustrates this.

Thus, *our own uncertainty is always caused by actions of other players that we cannot distinguish*. This point will return more generally in Section IV.4.

The same style of analysis applies to other phenomena. To give one example, the axioms so far say nothing about 'forward behaviour'. In particular, perfect recall does not exclude that ignorance has a 'miracle cure', by just playing on (see Figure 11).

This is reasonable for context-dependent actions like 'finding out where you are' – but it seems strange with playing 'exactly the same move'. Of course, one might assume that, at end-points, players *learn* that the game is over. But this would really be one more game move, perhaps in the form of a signal by Nature as an extra player, that should be represented explicitly. In any case, if we require that:

playing identical moves propagates the existing uncertainties

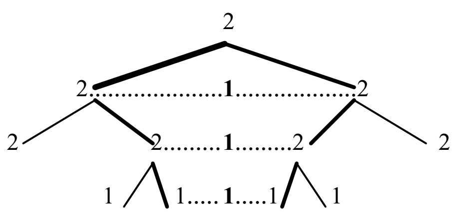

Fig. 10.

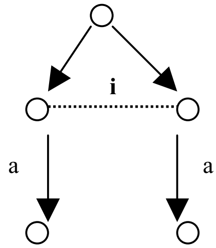

Fig. 11.

we again make an interchange principle valid, but this time working the other way around:

$$[a]\ K_{\mathbf{i}}\phi \rightarrow K_{\mathbf{i}}[a]\phi$$

Knowledge/action interchange principles of both kinds have been studied in temporal action logic (Halpern and Vardi, 1989) under the names of 'No Forgetting' and 'No Learning'. In particular, such extras can have a bad effect on the *complexity of validity* in these logics. The technical reason is this. When commuting diagrams enforce a 'grid-like' structure on our models, modal logics can potentially encode so-called tiling problems, and thereby even become undecidable. More informally, then, the logic of 'well-behaved' players may be more complex than that of arbitrary players.

IV.3. Information update

The preceding was all about abstract action types *a*. But one can also investigate specific cognitive game actions, such as questions or announcements, and see what knowledge or uncertainty they produce, either publicly or just for subgroups of players. There is an active research programme on information update in groups of agents, starting from Fagin *et al.* (1995), and continuing with, amongst many others, van Benthem (1996), Gerbrandy (1998), Baltag (1999) and van Ditmarsch (2000). In particular, in addition to just keeping track of factual information, *upgrading* of uncertainty relations may just affect what we know about each other, and it may affect different players differently:

> 'Suppose Nature has dealt me a red card (stating that proposition ϕ holds) or a blue one (stating that $\neg\phi$ holds) – say, it was in fact the red card. After this first move, none of us can distinguish the two situations ϕ, $\neg\phi$. Now I look at my card, without showing you the result: but you see what I am doing. Thus I learn what my card is, you still don't know, but you have learnt that I know now. Next, I tell you. Then ϕ becomes common knowledge among us'.

Let's suppose that I had the red card. Figure 12 shows a game tree from which one can read off our successive epistemic states under the moves described, indicated in black. At the end, both of us have also learnt the actual run of the game.

Generalizing from such examples, Baltag (1999) proposes a general update mechanism for cognitive actions in groups that applies very well to games. Its first idea is this. Instead of just having epistemic indistinguishability between states, we can also have plausible *epistemic indistinguishability between actions*. This made sense with perfect recall, where all dotted lines were eventually traceable to other players' actions.

This version of epistemic logic is more general than just using dotted lines between outcome states, as different actions can have the same outcomes. So, we include uncertainty between actions as a primitive in our game models, say, as an *equivalence relation* (Baltag update also works more generally). There is much to be said for encoding game actions in this way, such as 'making announcements' (to all or to some players), 'reading signals' (private or public), etc. But here, we just give a formal illustration of the basic update mechanism.

Product update: Take a game with current state x, and uncertainty relations $\sim_i$ among the nodes at x's tree level computed so far. Let a move be made. The new states are the nodes at the next level of the game tree, which can be identified with ordered pairs (previous state, action last made). Now we set $(y, b) \sim_i (z, c)$ iff $y \sim_i z$ *and* $b \sim_i c$.

Thus, new uncertainty equals 'old uncertainty + indistinguishable actions'. This rule produces the intuitively correct results in many cases. For example, the above envelope example works in this way, with two actions 'see red' and 'see blue' (which can only be performed successfully when their content is true), which I can distinguish, but you cannot. Figure 13 is an illustration of the effects of product update on general

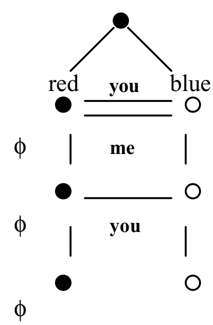

Fig. 12.

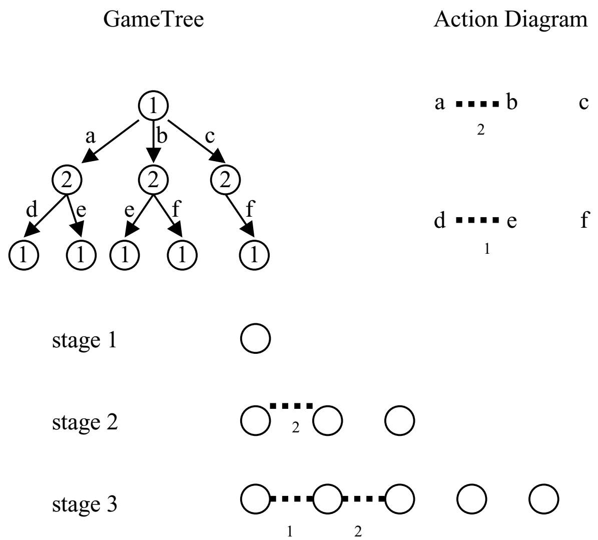

Fig. 13.

game trees. The top part shows updates during play, propagating ignorance along a game tree. The bottom shows the successive updates.

IV.4. Update mechanisms and logical axioms

Again, we can analyse such update mechanisms by means of their general dynamic-epistemic properties. For product update, we find three major ingredients with a dynamic-epistemic 'reflection':

(a) First, product update implies *perfect recall*: the earlier commutation diagrams both follow from the 'product rule', if a player can tell his own actions apart.
(b) Next, product also *propagates uncertainty* (there are no 'miracles'): *if* $x \sim_{\mathbf{i}} y$, *then after performance of a in both cases,* $(x, a) \sim_{\mathbf{i}} (y, a)$. With further **i**-indistinguishable actions, we can also allow different moves a, b here.
(c) But there is also a third feature, that one may call *uniformity:* Actions are either always distinguishable, or never: *if* $(x, a) \sim_{\mathbf{i}} (y, b)$, then, whenever $u \sim_{\mathbf{i}} v$, also $(u, a) \sim_{\mathbf{i}} (v, b)$, provided the latter moves can be performed at all.

Proposition 4: The three mentioned properties determine product update.

Proof: In one direction, we have already shown that the imperfect information trees produced by product update satisfy the three mentioned properties. Conversely, suppose that we have a game tree with all three conditions satisfied. Then we can retrieve an action diagram as follows. Set $a \sim_i b$ if it ever happens in the tree that two nodes $x \sim_i y$ are followed by a, b resp., ending in new nodes that are still $\sim_i$-related. Then, starting from the root, the $\sim_i$-links in the tree are precisely those that would be constructed by product update. The reason is this. *Perfect recall* says that every uncertainty link in the given tree comes from an uncertainty link one level down, while *propagation* says that uncertainty links are inherited downward by indistinguishable actions. Taken together, this is precisely the effect of product update. □

These properties again correspond to special dynamic-epistemic axioms that must hold at every stage of the relevant games. (a) The first are the axioms for perfect recall. For (b), we had the converse axiom $[a]K_i\phi \rightarrow K_i[a]\phi$. Finally, for (c), we need a slight extension of the modal language with *universal modalities* $E\phi$, $U\phi$ stating that ϕ holds at *some* world, at *all* worlds, resp. (Blackburn *et al.*, 2000):

$$E(\langle a^{\cup}\rangle T \;\&\; \neg K_i\neg\langle b^{\cup}\rangle T) \rightarrow U(\langle a^{\cup}\rangle\neg K_i\neg\phi \rightarrow K_i[b^{\cup}]\phi).$$

Thus, also the product update mechanism corresponds to a special dynamic-epistemic game logic.

IV.5. Playing with bounded memory

At the other extreme of the cognitive spectrum, so to speak, lie ways of playing games with bounded memory (Osborne and Rubinstein, ch. 9). Suppose that players *forget* all earlier moves, up to k last moves. Perfect recall then disappears, but the above style of dynamic-epistemic analysis of the resulting game structures still applies. Consider the simplest case of 1-memory, where only the last move is remembered. The dynamics now becomes as follows. At every new stage, for both players, we join all nodes that resulted from the same last action. Then in modal logic terms – again using an auxiliary universal modality – the following axiom will typically be valid on the resulting structures:

$$E(\langle a\rangle T \;\&\; \phi) \rightarrow U[a^{\cup}]\neg K_i\neg\phi.$$

It will be clear how to extend this modal analysis to the case of a k-cell memory. This gives a modal take on the considerable body of research in game theory and computer science on strategies that use finite-state machines as their memory.

IV.6. Statics and dynamics again

The above is just a demonstration of the dynamic-epistemic language at work, not a systematic study of game phenomena. But we think it can address such broader issues as the watershed between players' deficiencies and 'objective' ignorance by definition of the game, or the dynamics of further information passing mechanisms such as 'signalling'. But in doing this, the full system would eventually have to combine a *dynamic update logic* for cognitive actions with our more traditional dynamic-epistemic descriptions of the resulting states.

IV.7. Appendix: the influence of modeling decisions

In order to apply dynamic-epistemic logic, one needs a 'modeling phase' for the real phenomena, mapping them to formal actions and uncertainty links. This slack must be kept in mind when judging the framework: formal models can 'fit' to reality in different ways. For instance, actions in real games can be described at different levels of generality. In a card game, a player may 'show a card', which is a generic action, instantiated by concrete actions of showing a specific card. Such decisions may again influence which actions we consider indistinguishable for a player. When showing you one of my cards without looking at it myself, I am uncertain between various concrete show-actions (you are not) – but I am *not* uncertain about my showing you a card as opposed to doing something else. Thus, the above diagram for perfect recall will hold for the latter action, though not for the former. Nice examples of modelling decisions occur in 'knowledge games' (van Ditmarsch, 2000) involving cards, questions, and show-actions.

V. POWER EQUIVALENCE

Having dealt with the action level of imperfect information games, we will also briefly look at the more global outcome level, looking for analogues of Sections II.3 and II.4.

V.1. Uniform strategies, powers and representation

First, the earlier definition of players' powers may be adapted in an obvious way: *at each node, a player can force those sets of outcomes that are produced by following one of her* uniform *strategies.*

Example: Diminished powers in imperfect information games. Consider Figures 1 and 2. In the former, player **A** has two strategies, and player **E** has four, producing the following set powers:

A: $\{1, 2\}$, $\{3, 4\}$
E: $\{1, 3\}$, $\{1, 4\}$, $\{2, 3\}$, $\{2, 4\}$.

With imperfect information added for **E**, **A**'s powers are not affected, but **E**'s are: her two *uniform* strategies only give her two set powers:

A: $\{1, 2\}$, $\{3, 4\}$
E: $\{1, 3\}$, $\{2, 4\}$.

This may be seen as a weakness, but it also shows the much greater modelling power of behaviour by imperfect information games.

We can see this by extending the earlier representation result of Section II.3. First note that the conditions of *superset closure* (C1) and *consistency* (C2) are still valid for powers in imperfect information games. This may be seen in the above list. What fails there is *determinacy*, as we saw above: **A** does not have the power $\{1, 4\}$, but neither does **E** have its complement $\{2, 3\}$.

Proposition 5: Any two finite families of sets satisfying conditions (C1), (C2) can be realized as the powers in a two-step imperfect information game.

Proof: Instead of stating the procedure formally, we do one illustrative example displaying all the necessary tricks. Suppose that we are given:

minimal powers for player **A**: $\{1, 2, 3\}$, $\{3, 4\}$
minimal powers for player **E**: $\{2, 3\}$, $\{1, 4\}$.

We start with player **A** and provide a number of successor nodes for the power sets, this time with possible duplications, at which player **E** gets to move. The relevant actions here may also involve various duplications. First, we take action types for each set of player **E**, making sure that these get represented via uniform strategies. There may still be 'excess' outcomes in the powers for **E** which we need to 'dilute' by copying and permuting so that they end up in supersets of $\{2, 3\}$, $\{1, 4\}$ (see Figure 14). The sets for the third and fourth uniform strategy are supersets of $\{2, 3\}$, $\{1, 4\}$.

A further complication arises when **A**'s sets involve outcomes not mentioned in the minimal list for **E**. Say we have:

minimal powers for player **A**: $\{1, 2, 3\}$, $\{3, 4\}$
and those for player **E**: $\{2, 3\}$, $\{1, 4, 5\}$.

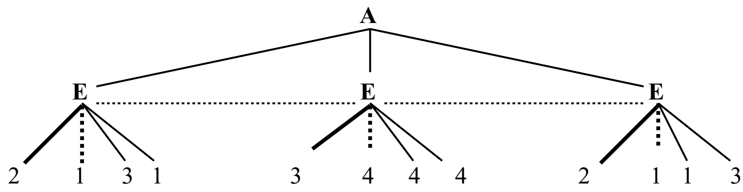

Fig. 14.

Then we need to 'dilute' still more, using similar tricks – this time, involving additional **A**-moves to cases where **E** gets to chose between 1, 4, 5 in such a way that the resulting set powers of **E** are all extensions of $\{1,2,3\}$, $\{3,4\}$.

Here is the more precise procedure. (a) First make sure that all atomic outcomes in players' sets occur for each of them, by adding 'redundant' supersets if needed. Then (b) create a preliminary branching for **A** making sure all of its sets are represented. (c) Now make sure each outcome set for **E** gets represented as a uniform strategy, by choosing enough branchings from the middle level, starting from the left. This may involve duplication of nodes, as illustrated by the simple case **A** $\{1,2\}$, **E** $\{1,2\}$. (d) In case there are outcomes 'left over', repeat the following routine. Suppose outcome i occurring at some mid-level point x was not needed in step (c) so far. Then fix any outcome set for **E** produced by some uniform strategy σ; say, the latter chose outcome j at x. Then duplicate this node x, and now add *two new* branchings throughout (for all mid-level nodes considered so far) to obtain two further uniform strategies: one choosing j at x, and i in its duplicate, the other doing the opposite – both following σ at all other nodes. This makes outcome j appear as it should for **A**, generating only a harmless superset of outcomes for **E**. □

As in the perfect information case, this result suggests a *logical calculus of game equivalences* for finding these normal forms, which should be a generalization of ordinary Boolean propositional logic. I defer this matter until Section V.2.

V.2. Game transformations

The above provides a logic angle to the 'Thompson transformations' of Osborne and Rubinstein, that transform 'normal form-equivalent' imperfect information games into each other. We take them one by one.

Example 1: Addition of a superfluous move = Idempotence. Figure 206.1 in O&R typically tells us that we can tolerate a new uncertainty by duplicating a move, switching between game trees like those in Figure 15. Computing power relations, we see that nothing changes from left to right at the root. The duplication on the right does not add new outcomes for player **2**, while the two available uniform strategies for player **1** still capture the same two outcome sets $\{A, B\}$, $\{A, C\}$. This picture is precisely like the propositional Idempotence law:

$$A \wedge (B \vee C) \leftrightarrow (A \bigvee A) \wedge (B \bigvee C)$$

where the larger bold face disjunctions indicate the new uncertainty link.

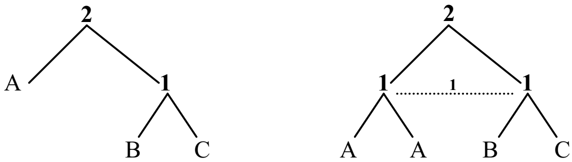

Fig. 15.

Of course, we are into a nonstandard use of propositional logic now, where duplications may matter, and operators can be 'linked'. In a sense, finite game trees with imperfect information *are* a natural extension of propositional formulas!

Example 2: Interchange of moves = a deviant form of Distribution. Figure 208.1 in O&R tells us how to interchange moves of players. The essential transformation here is really one between our earlier Figures 2 and 4. In both cases, the set powers for the players are (compare the calculation in Section V.1):

A: $\{1,2\}$, $\{3,4\}$
E: $\{1,3\}$, $\{2,4\}$

This is a sort of nonstandard propositional 'Distribution law':

$$(A \bigvee B) \wedge (C \bigvee D) \leftrightarrow (A \bigwedge C) \vee (B \bigwedge D)$$

with the larger font indicating relevant dotted links. For readers familiar with Hintikka–Sandu IF-games, this is also an equivalence between extended first-order formulas:

$$\forall x\ \exists y/\mathbf{x}\ \mathrm{R}xy \leftrightarrow \exists y\ \forall x/\mathbf{y}\ \mathrm{R}xy.$$

Next, I consider the remaining two Thompson transformations:

(a) *Inflation–deflation* adds a link that will not materialize in play. This reflects perfect recall, and is one of the moves stated in Section IV.2.
(b) *Coalescing moves* says that the zone where a player is to move can be re-encoded as just one bunch of choices. This reflects the emphasis on powers only – disregarding the particular moves, and their order, that players make when it is their turn. This merely states a choice for an 'outcome-oriented' notion of game equivalence (rather than a more 'action-oriented' one), and has nothing to do with imperfect information as such.

Summarizing our analysis, we have the following proposition.

Proposition 6: Powers of players in imperfect information games remain the same under the Thompson transformations.

As stated before, we take this to mean that the Thompson transformations are really a kind of complete calculus for a generalized propositional logic. From a more logical point of view, the same effect might be achieved by some modification of 'information-friendly' games, in the style of the three-valued approach of Hintikka and Sandu (1997). Also of logical interest is the *occurrence* character of the above rules. One occurrence of A need not have the same effect any more as several occurrences, when dealing with uniform strategies. This is reminiscent of *linear logic*, whose game semantics typically involves nondetermined games (Abramsky and Jagadeesan, 1994).

Question: Reformulate the complete calculus of finite imperfect information games as a form of propositional logic.

To emphasize the analogy once more, let us look at the sequence of transformations in O&R (pp. 210/211). It starts with a perfect information game (see Figure 16). Here, by the computation of Section I.4:

powers for player **1** are	$\{A, B\}$, $\{C, D\}$, $\{C, E\}$
and for player **2**	$\{A, C\}$, $\{B, C\}$, $\{A, D, E\}$, $\{B, D, E\}$.

By standard propositional transformations as in Section II.3, this has a distributive normal form which is still a perfect information game (see Figure 17).

All steps displayed in O&R preserve powers, too, according to the definition given in Section II.3, but they result in another normal form (see Figure 18).

This analysis is very close to Thompson's original result that his transformations are precisely those that leave the reduced normal form of a game unchanged.

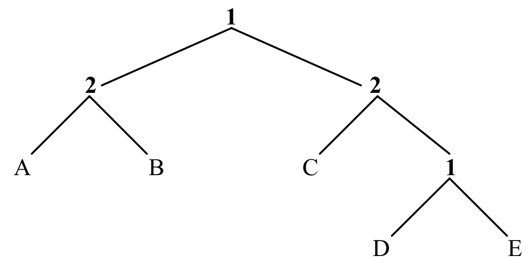

Fig. 16.

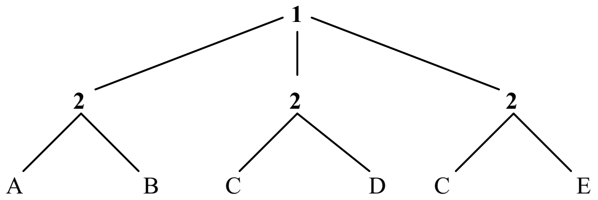

Fig. 17.

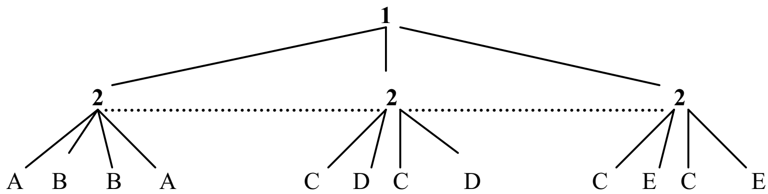

Fig. 18.

V.3. Language, uniform strategies and knowledge

Our main approach in this paper has highlighted the language of epistemic dynamic logic. The latter's 'structural' counterpart for comparing games is epistemic-dynamic bisimulation. But in this section I also considered a coarser game equivalence: up to players' powers for controlling outcomes. Closing the circle, is there also a natural linguistic counterpart to this power equivalence? The answer is positive. We need a suitable epistemic version of the forcing language of Section II.4 with its 'strategy modalities':

$\mathbf{M}$, s $\models \{G, \mathbf{i}\}\phi$ *player* $\boldsymbol{i}$ *has a* uniform *strategy for playing game G starting from state s which forces a set of outcomes satisfying* ϕ *in* $\boldsymbol{M}$.

But the richer epistemic setting hides a subtlety concerning the relevant outcome sets. Suppose a player is in an end-node x satisfying p, but cannot distinguish this from another end-node y satisfying $\neg p$. Does the uniform strategy 'do nothing' force p in the end-node x? Yes, if we look at the actual outcomes produced (just x); but no, if we think of the outcomes that seem relevant to the player's deliberations, being both x and y. The same point may be made in terms of *knowledge*. If the truth of $\{G, \mathbf{i}\}\phi$ at game state s is to imply knowledge for player $\mathbf{i}$ at s of the eventual forced proposition ϕ, then we need a broader notion of 'relevant outcomes'. This also fits with the game-theoretic fact that the *compositional structure* of imperfect information games is less clear than for perfect information games. We are not just interested in the action subtree generated by the point s, but also in all its 'indistinguishable variants' for player **i**. Because of this, we propose computing the relevant outcomes for a uniform strategy σ as follows:

as before, follow all possible moves of the other player, plus their σ-response, but also close off under transitions to $\sim_E$-indistinguishable states in the game.

The resulting uniform **i**-strategy modality seems plausible. It works like computing outcome sets allowing some *third player* arbitrary jumps across uncertainty links for **i**.

We conclude by comparing this notion to our action language. Can we define this strategy modality in dynamic-epistemic logic, which should be the richer formalism? For *perfect information* games and dynamic logic by itself, the answer was positive. The 'fixed-point equation' of Section II.1 for winning positions can easily be extended to define those game positions from where a player has a 'ϕ-strategy':

$$\langle G, \mathbf{i}\rangle\phi \leftrightarrow (end \wedge \phi) \vee (turn_i \wedge < > \langle G, \mathbf{i}\rangle\phi) \vee (turn_j \wedge [\,]\langle G, \mathbf{i}\rangle\phi).$$

In this recursive definition, the big modalities $< >$, $[\,]$ range over all actions locally available to the players – and **j** stands for the counter-player to **i**. With imperfect information games, however, the situation is more delicate. Dynamic-epistemic logic can express subtle distinctions about strategies, and their properties. Should these just 'do the right thing'; or should

players *know* at each stage that the current strategy is taking them to the relevant outcome state?

Let us call strategies with this special epistemic property *predictive* (see Section I.2 for its original motivation). To proceed, let us at least assume that we have *perfect recall.*

Proposition 7: In imperfect information games with perfect recall, all uniform strategies are predictive.

Proof: Perfect Recall allows us to assume that players know at which level they are in the game tree. Moreover, uncertainties arise in the first place because of moves by the *other* player that you could not distinguish somewhere higher up in the game tree. Now the above uniform strategy modality satisfies the following fixed-point equation:

$$\langle G, \mathbf{i}\rangle\phi \leftrightarrow ((end \,\&\, K_i\phi) \vee (turn_i \,\&\, \vee_a K_i\langle a\rangle\langle G, \mathbf{i}\rangle\phi) \vee (turn_j \,\&\, \&_a K_i[a]\langle G, \mathbf{i}\rangle\phi).$$

Here the subscript 'a' ranges only over available actions at the relevant game state. In checking this, the direction from left to right is easy. Conversely, one must show, in particular, that uniform strategies emanating from different information sets at the current level can be 'patched' to give one uniform strategy at the current node. □

One way of understanding this defining equivalence is as follows. As stated above, the relevant moves are now 'game actions plus uncertainty jumps'. This gives an analogy with the original forcing analysis for *perfect information* games, treating combinations of those jumps and the original moves as extra game moves. Then, the above epistemic-dynamic combinations $K_i[a]$ are precisely sequential action modalities $[\sim_i; a]$ for that case. In this setting, Perfect Recall says it does not matter in which order we perform the new combined move. Alternatively, we could do the fixed-point analysis by including the moves of the above Third Player explicitly. But note that uniformity still requires a *uniform* response by player **i** to what the uncertainty player cooks up.

We have not been able to settle the converse question: *Are all predictive strategies uniform?* Even if they are broader, or sometimes incomparable *vis-à-vis* uniform strategies, predictive strategies seem an interesting class of behaviours in their own right.

VI. CONCLUSION

This work has taken a look at imperfect information games as models for a dynamic-epistemic logic describing actions and outcomes. A systematic analysis like this may help in finding coherent scenarios for the various imperfect information phenomena described in Osborne and Rubinstein (1994). It can also be applied to the much-discussed logical 'IF-games' of Hintikka and Sandu, as shown in van Benthem (2000a). Finally, it suggests a number of more general ways in which logic and game theory can be related. Our next most pressing business is extending this account is to real games with players' preferences indicated, aspiring to the level of formal sophistication in Stalnaker (1991). In another direction, however, this approach may be seen as an extension of process logics in computer science to deal with imperfect information, something which is needed to really understand modern 'computing systems' such as Internet activities.

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