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### TR-2003001: States of Knowledge and Group Action

Rohit Parikh

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# States of Knowledge and Group Action

Rohit Parikh  
City University of New York<sup>1</sup>  
Rohit Parikh

*Abstract:* In this paper we investigate the possible states of knowledge among a group of individuals and their relations to decision making.

*A travelling salesman found himself spending the night at home with his wife when one of his trips was accidentally cancelled. The two of them were sound asleep, when in the middle of the night there was a loud knock at the front door. The wife woke up with a start and cried out, ‘Oh my God! It’s my husband!’ Whereupon the husband leapt out of bed, ran across the room and jumped out the window.*

Schank and Abelson, 1977, p. 59.

Wimmer and Perner begin their paper [WM] on Beliefs about beliefs with this story from Schank and Abelson which may seem amusing to some and disturbing to others. But the point of the story seems to be that husband and wife each have their own scenario and neither corresponds to the actuality. The wife is a bit better off as she knows *where* she is though not *whom* she is with. The husband is unaware of the identity of his companion and even of the location where he is.

Wimmer and Perner themselves are concerned primarily with the perception by children of other people’s *mindsets*. The following quote from [WM] is a story about Maxi which they told a group of children:

*Mother returns from her shopping trip. She bought chocolate for a cake. Maxi may help her put away the things. He asks her, ‘Where should I put the chocolate?’ ‘In the blue cupboard’, says the mother.*

Later, with Maxi gone out to play, the mother transfers the chocolate from the blue cupboard to the green cupboard. Maxi then comes back from the playground, hungry, and he wants to get some chocolate.

In Wimmer and Perner’s experiment, little children who were told the Maxi story were then asked the *belief* question, “Where will Maxi look for the chocolate?”

Children at the age of 3 or less invariably got the answer wrong and assumed that Maxi would look for the chocolate in the *green* cupboard where *they* knew it was. Even children

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aged 4-5 had only a one third chance of correctly answering this question or an analogous question involving Maxi and his brother (who also wants the chocolate and whom Maxi wants to deceive). Children aged 6 or more were by contrast quite successful in realizing that Maxi would think the chocolate would be in the *blue* cupboard – where he had put it and that if he wanted to deceive his brother, he would lead his brother towards the green cupboard.

Thus it seems that representation of other people’s mindset comes fairly late in childhood, well after they have learned to deal with notions of belief and belief based action for themselves and for others who share their own view of reality. In [St] Chris Steinsvold investigates modal logics which are intended to represent the states of mind of young children. See also [SP].

Older children are not much better. In an experiment in my daughter’s 7th grade class, I found that they were unable to deal with the muddy children puzzle beyond the first one or two levels.

In this, by now well known puzzle, a number of children are playing in the mud and some of them get their foreheads dirty. At this the father comes on the scene and announces, “at least one of you has got her forehead dirty”.

*Scenario 1:* Suppose there is only one child, say Amy, who is dirty. Then she will realize that her own forehead must be dirty since she can see that the others are clean.

*Scenario 2:* Suppose now that there are two dirty children, Sarah and Amy, who are asked in turn, “Do you know if your forehead is dirty?” Now when Sarah is asked, she can see Amy’s dirty forehead and she replies, “I don’t know”. However, when Amy is asked, she is able to reason, “If *my* forehead were clean, Sarah would have known that hers must be dirty since all the others are clean. But Sarah did not know. So my forehead must be dirty.”

This reasoning on Amy’s part requires a representation by Amy of Sarah’s state of mind, and clearly Amy must be at least six for this to work. However, Sarah herself must have some reasoning ability and Amy must know that she has such abilities. It is not enough for Amy to know Sarah’s view of reality, she must also represent Sarah’s logical abilities in her own mind.

In particular, suppose that there are three dirty children, Jennifer, Sarah, and Amy who are asked in turn whether they know if they are dirty, and with Amy being asked last. If Sarah is only three, Amy would not be justified in concluding from Sarah’s “I don’t know” that in that case Amy herself must be dirty. Amy would need to know that *if* Amy were clean, Sarah would have carried out a representation in her own mind of Jennifer’s state of mind and concluded from Jennifer’s “I don’t know” that Sarah must herself be dirty. But if Sarah is only three, Amy cannot rely on such reasoning on Sarah’s part.

As the number of dirty children goes up, there is a need for higher and higher levels of “I know that he knows that she knows that...”. Common knowledge is at the end of

this road and has been offered as the explanation of co-ordinated behaviour ([Lew, HM, CM, Chw]). For instance Halpern and Moses in [HM] show that the co-ordinated attack problem requires common knowledge between the two generals, and that given the means of communication they have, such common knowledge is impossible to attain. Clark and Marshall [CM2] indicate similar difficulties with the referent of “the movie playing at the Roxy today”.

While it is true that co-ordinated actions and, supposedly, common knowledge do happen, it may also be relevant to consider other levels of knowledge, short of the infinite, common knowledge, level.<sup>2</sup> Such levels also arise in certain pragmatic situations, e.g. with email or snailmail or messages left on telephones as voice mail. Thus the purpose of this paper is to study levels other than common knowledge and how they affect the actions of groups.

In typical co-operative situations even if a certain level of knowledge is needed, a higher level would also do. If Bob wants Ann to pick up the children at 4 PM, it is enough for him to know that she knows. Thus if he sends her email at 2 PM and knows that she always reads hers at 3 PM, he can be satisfied. In such a situation Bob knows that Ann will know about the children in time, or symbolically  $K_b(K_a(C))$  and he may feel this is enough. However, if he telephones her at 3 PM instead, this will create common knowledge of  $C$ , much *more* than is needed. But no harm done, since in this context, Ann and Bob have the same goals. Halpern and Zuck also state a knowledge level requirement for the sequence transmission problem, which suffices as a minimum, but since the parties are co-ordinating, a higher level does not harm.

But in other contexts one may wish for just a particular level of knowledge, no lower, and no *higher*. Suppose for instance that Bob wants Ann to know about a seminar talk he is giving, just in case she wants to come, but he does not want her to feel pressured to come – she should come only out of interest and not from politeness. In that case he will want to arrange that  $K_b(K_a(S))$ , (he himself knows that she knows about the seminar) but not  $K_a(K_b(K_a(S)))$  (Ann knows that Bob knows that Ann knows about the seminar), for in the latter case she *would* feel pressured. Instead of telling her about his talk, which would create common knowledge, he may arrange for some other method, perhaps for a student to tell her, but without saying that it is a message from Bob.

Suppose a pedestrian is crossing the street and sees a car approaching him. It happens in many cities, Boston, Naples, etc., that the pedestrian will pretend not to notice the car, thereby preventing  $K_d K_p(C)$  with  $C$  representing the car,  $d$  being the driver and  $p$  the

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<sup>2</sup>The following, possibly apocryphal story about the mathematician Norbert Wiener, well known for his absent mindedness, illustrates something even more subtle. At one time the Wieners were moving and in the morning as he was going to work, Mrs. Wiener said to him, “Now don’t come home to this address in the evening.” And she gave him a piece of paper with the new address. However, in the evening Wiener found himself standing in front of the old address and not knowing what to do – he had already lost the slip of paper with the new address. He went to a little girl standing by and said, “Little girl, do you know where the Wieners have moved to?” The little girl replied, “Daddy, Mom knew what would happen so she sent me to fetch you.” The moral of the story, for *us*, is that common knowledge works only if the memory of all parties involved is reliable.

pedestrian. If the driver knew that the pedestrian knew, he might drive aggressively and try to bully the pedestrian into running or withdrawing. But if he does not know that the pedestrian knows, he will be more cautious.

While the social questions are fascinating and are addressed elsewhere (Cf. [Pa3]), in this paper we shall concentrate on the technical aspects of knowledge, where it is assumed that everyone involved is logically perfect. One can still ask, what are the various levels of knowledge which can arise under various circumstances of communication and how will they affect how we may act?

## 1 Some examples

Our first example comes from the *Mahabharata*, one of the Indian epics and at 100,000 verses, believed to be the longest single work in the world. It describes the political struggle between two sets of cousins, the *Pandavas*, and the *Kauravas*. In a crucial battle between the two sets of cousins, *Krishna* is an adviser to the *Pandavas*, but out of a sense of fair play he gives his army to the *Kauravas*. At a crucial juncture *Drona*, a powerful warrior on the *Kaurava* side and also the teacher of both the *Pandavas* and *Kauravas*, turns out to be invincible in battle and the *Pandavas* are hard pressed.

However, the wily *Krishna* thinks up a strategem. *Drona's* only son is called *Ashvatthama* and so is an elephant owned by the *Pandavas*. *Krishna* suggests that the *Pandavas* kill the elephant *Ashvatthama* and then announce that the man *Ashvatthama* has been killed. After a great deal of hesitation and soul searching, self-interest prevails, the *Pandavas* do kill the elephant, and announce to *Drona* that *Ashvatthama* is dead. Not knowing about the elephant, *Drona* assumes it is his son who is dead, lays down his weapons, and is killed by a warrior on the *Pandava* side.

We now offer a game-knowledge theoretic analysis of this event.

Let *Drona's* two options be  $f$  for 'fight' and  $n$  for not fight. Before the announcement his preferences were  $f > n$  and given his prowess, any warrior who faced him faced death.

But after the announcement that *Ashwatthama* was dead, his preferences change to  $n > f$ , and he can be attacked with impunity.

*Ashwatthama* of course was not dead and took terrible revenge on the *Pandavas* including the killing of some unborn *Pandava* children. For this he was punished by being condemned (rather like Cain) to live forever, and to wander the earth as a pariah.

Our second example of the motorist and the pedestrian is a bit more complex as the deception consists of inducing a second order false belief. Let  $S$  be the situation where a pedestrian is crossing the street and a car is coming. Let  $S'$  be the same situation without the car. In  $S$  the pedestrian has two options,  $g$ , i.e. to go, and  $n$ , i.e. to not go. The

motorist also has two similar options  $G$  and  $N$ . Here are the payoffs for the two in state  $S$ .

*Motorist choices*

		$G$	$N$
<i>Pedestrian choices</i>	$g$	(-100,-10)	(1,0)
	$n$	(0,1)	(0,0)

Figure I

Note that there are two Nash equilibria: at  $(g, N)$  and at  $(n, G)$ . However, the penalty for the pedestrian (injury or loss of life) to depart from  $(n, G)$  is much greater than the penalty for the motorist (fine or loss of license) to depart from  $(g, N)$ . Thus the equilibrium  $(g, N)$  is less stable than  $(n, G)$ , and this fact creates the possibility for the motorist to ‘bully’ the pedestrian.

However, if the pedestrian is unaware of the existence of the car, then the picture is much simpler and his payoffs are 1 for  $g$  and 0 for  $n$ .  $g$  dominates  $n$ , and once this choice is made by the pedestrian, it is dominant for the motorist to choose  $N$ . This is why the pedestrian tries to achieve the state of knowledge represented by the formulas  $K_p(C), \neg K_m(K_p(C))$  indicating that the pedestrian knows the car is there but the motorist does not know that the pedestrian knows. The pedestrian chooses the action  $g$ , and knowing that the pedestrian will do this, the motorist must choose  $N$ . However, if the motorist has a horn, he can change the knowledge situation. The existence of the car becomes common knowledge and thus the possibility for the motorist to bully the pedestrian arises again.

We now reconsider the problem of the two generals which Halpern and Moses have considered. In this problem there are two generals  $A, B$  who are stationed on opposing hilltops and who wish to attack an enemy  $E$  in the valley below. General  $A$  sends a messenger to general  $B$  suggesting that the two should attack together at dawn. However, there is a possibility that the message might not reach  $B$ . Perhaps the messenger would be captured or killed by  $E$ , and general  $A$  attacking by himself would be badly defeated. So general  $A$  asks for an acknowledgement from  $B$  that his message *let us attack at dawn* has been received.

However, general  $B$  has the same problem. He does not wish to attack alone and so he agrees to the attack, but asks for an acknowledgement in turn. Clearly this process of saying *attack at dawn, please acknowledge* can never end. What is needed, Halpern and Moses argue, is common knowledge of the intended attack and no finite number of messages back and forth will achieve it.

However, there is a small twist in this problem to which we now turn. Let  $a$  stand for the event that general  $A$  attacks alone. Let  $b$  stand for the event that general  $B$  attacks alone. Let  $t$  stand for the event that they attack together, and finally Let  $n$  stand for the event that neither attacks.

The analysis which Halpern and Moses provide tacitly assumes that the priorities are:  $t > n > b > a$  for general  $A$ , and  $t > n > a > b$  for general  $B$ . “If only one general is going to attack, let it be the other guy”, is tacitly assumed. Suppose, however, that  $t > b > n > a$  for *both* generals. Perhaps general  $B$ ’s army is large enough to make the difference in a battle, but is also small enough so that its attacking alone and being defeated is not a disaster – in any case it is better than continued inaction. In such a case general  $A$  can issue the message “Let us plan to attack at dawn, please acknowledge, but I will not acknowledge *your* acknowledgement”. Thus  $A$  plans to attack iff he receives an acknowledgement and  $B$  has been ordered to attack without worrying about an acknowledgement from  $A$ . In such a case,  $A$  is guaranteed not to attack alone, and there may well be a good chance of  $t$ , provided only that the probability of a message getting through is high enough.

In other words, even though (as Halpern and Moses point out) common knowledge of the attack cannot be achieved, there may well be a strategy for general  $A$  which is better than doing nothing.

As our final example we consider the ballot box whose function is to create certain specific states of knowledge. Suppose that three people 1, 2, 3 are debating whether to have lettuce or cucumbers for salad. They cast their votes into a ballot box and the final count reveals that lettuce has won by 2 votes to 1.

Let  $C_i : i \leq 3$  mean that  $i$  voted for cucumber, and similarly for lettuce. Then the following is common knowledge:  $(L_1 \wedge C_2 \wedge L_3) \vee (L_1 \wedge L_2 \wedge C_3) \vee (C_1 \wedge L_2 \wedge L_3)$ . Also what is common knowledge is  $(\forall i, \forall j)(i \neq j \rightarrow \neg K_i(C_j))$  as well as  $(\forall i, \forall j)(i \neq j \rightarrow \neg K_i(L_j))$ . I.e. it is common knowledge that no one knows anyone else’s vote. I am sure the reader can see the game theoretic reasons for these two knowledge facts. Everyone must know the results of the election, and the lettuce party must not be in a position to take revenge on the lone cucumber.

We hope we have made a case that states of knowledge and belief which fall short of common knowledge and common belief do arise, are relevant, and can often be better than full common knowledge.

## 2 Levels of Knowledge

Given a group  $N = \{1, \dots, n\}$  of agents (whether people or processes) what are the properties of their state of knowledge relative to some fact  $A$ ? Assuming that  $A$  is true, there are still many options. At one extreme, perhaps  $N$  have no idea about  $A$ . At the other extreme is the possibility that  $A$  is common knowledge among  $N$ . What are the intermediate possibilities and how will a particular level of knowledge of  $A$  affect how the group  $N$  will act regarding some situation? To investigate this question formally we set up a formal language  $L$  and the notion of the *level* of a formula  $A$  as a set of formulas in  $L$ .

**Definition 1:** Assume given  $m$  propositional variables  $P_1, \dots, P_m$ . Let  $L_0 = \{P_1, \dots, P_m\}$  and let  $L_g$  be all boolean combinations of the  $P_i$ . If the  $P_i$  are *basic* ground facts, then  $L_g$  represents *all* ground (knowledge-free) facts. Given a group  $N = \{1, \dots, n\}$  of agents we define the full knowledge language  $L$  as follows:

- (i)  $L_0 \subseteq L$
- (ii) If  $A, B \in L$  then so are  $\neg A, A \vee B$ .
- (iii) If  $A \in L$  then for all  $i \leq n, K_i(A) \in L$ .

To consider common knowledge as well we extend  $L$  to  $L_c$  by adding the conditions

- (iv)  $L \subseteq L_c$
- (v) If  $A \in L_c$  and  $U \subseteq N$  then  $C_U(A) \in L_c$ .

For convenience we shall identify  $K_i$  with  $C_{\{i\}}$ .

**Definition 2:** A *Kripke structure*  $\mathcal{M}$  for  $L$  consists of a nonempty set  $W$  of states, a map  $\pi$  from  $W \times L_0$  into  $\{1, 0\}$  with 1 standing for *true* and 0 for *false*, and finally an equivalence relation  $R_i$  over  $W$  for each  $i \leq m$ .

**Definition 3:** Given a Kripke structure  $\mathcal{M}$  for  $L$ , a state  $s \in W$  and a formula  $A \in L_c$  we define  $\mathcal{M}, s \models A$  as follows by induction on the complexity of  $A$ . First, for each  $U \subseteq N$ , we define the relation  $R_U$  to be the transitive closure of  $\bigcup R_i : i \in U$ . Then we have:

- (i) If  $A$  is atomic then  $\mathcal{M}, s \models A$  iff  $\pi(s, A) = 1$
- (ii) If  $A = \neg B$  then  $\mathcal{M}, s \models A$  iff  $\mathcal{M}, s \not\models B$
- (iii) If  $A = B \vee C$  then  $\mathcal{M}, s \models A$  iff  $\mathcal{M}, s \models B$  or  $\mathcal{M}, s \models C$
- (iv) If  $A = C_a(B)$  where  $a$  is either some  $i$  or else some  $U$ , then  $\mathcal{M}, s \models A$  iff  $(\forall t)((s, t) \in R_a \rightarrow \mathcal{M}, t \models B)$

**Theorem 1:** Let  $\Sigma_C$  be the alphabet whose symbols are  $\{C_U\}_{U \subseteq N}$

For all  $x, y$  in  $\Sigma_C^*$ , and all formulae  $A$ , for all  $\mathcal{M}, s, V \subseteq U \subseteq N$ ,

$\mathcal{M}, s \models xC_UC_VyA$  iff  $\mathcal{M}, s \models xC_VC_UyA$  iff  $\mathcal{M}, s \models xC_UyA$ .

In other words, common knowledge by the larger group  $U$  absorbs common knowledge by the smaller one.

**Corollary 1:** Let  $\Sigma_K$  be the alphabet whose symbols are  $\{K_1, \dots, K_n\}$  For all  $a$  in



$\Sigma_K$ , and for all  $x, y$ , in  $\Sigma_K^*$ , and all formulae  $A$ ,

$$\vdash xayA \leftrightarrow xaayA$$

and hence for all  $\mathcal{M}, s$ ,  $\mathcal{M}, s \models xayA$  iff  $\mathcal{M}, s \models xaayA$ . I.e. repeated occurrences of  $a$  are without effect and if  $xay \in L_K(A, s)$  then  $\forall n xa^n y \in L_K(A, s)$ .

In other words, it is common knowledge that  $a$  knowing some  $B$  is the same as  $a$  knowing that  $a$  knows  $B$ .

**Definition 4:** Given a formula  $A$  and  $\mathcal{M}, s$  the *level* of  $A$  at  $s$ ,  $L(A, s)$  is the set of  $x$  in  $\Sigma_C^*$  such that  $\mathcal{M}, s \models xA$ , and  $x$  contains no substrings  $C_U C_V, C_V C_U$  for any  $V \subseteq U \subseteq N$ .

Strings  $x$  such that  $x$  contains no substrings  $C_U C_V, C_V C_U$  for any  $V \subseteq U \subseteq N$  will be called *simple*, and from now on we shall confine ourselves to simple strings.

If  $s$  is clear from the context, or not important, then we shall drop it as a parameter. If we restrict ourselves to the  $K_i$  operators, we denote the level of  $A$  at  $s$  by  $L_K(A, s)$ .

### 3 Embeddability

Now we will try to characterize levels of knowledge. First we need to introduce the embeddability ordering on strings which turns out to be important here.

**Definition 5:** Given two strings  $x, y \in \Sigma_K^*$ , we say that  $x$  is *embeddable* in  $y$  ( $x \leq y$ ), if all the symbols of  $x$  occur in  $y$ , in the same order, but not necessarily consecutively. Formally:

- 1)  $x \leq x, \epsilon \leq x$  for all  $x$
  - 2)  $x \leq y$  if there exist  $x', x'', y', y''$ , ( $y', y'' \neq \epsilon$ ), such that  $x = x'x'', y = y'y''$ , and  $x' \leq y', x'' \leq y''$ .
- and  $\leq$  is the smallest relation satisfying (1) and (2).

Thus the string  $aba$  is embeddable in itself, in  $aaba$  and in  $abca$ , but not in  $aabb$ .

**Properties of the embeddability relation  $\leq$**

**Fact 1:** Embeddability is a *well partial order*, i.e. it is not only well founded, but every linear order that extends it is a well order (equivalent condition: it is well founded and every set of mutually incomparable elements is finite).

**Fact 2:** Embeddability can be tested in linear time, e.g. by a nondeterministic finite automaton with two input tapes.

Fact 1 was proved first by Graham Higman. See [JP] for a discussion. Fact 2 is straightforward.

We also need a stronger relation defined on  $\Sigma_C^*$ , which we call *C-embeddability*.

**Definition :** Given two strings  $x, y \in \Sigma_C^*$ , we say that  $x$  is *C-embeddable* in  $y$  ( $x \preceq y$ ), if

1) If  $V \subseteq U$  then  $C_V \preceq C_U$

2)  $x \preceq y$  if there exist  $x', x'', y', y''$ , ( $y', y'' \neq \epsilon$ ), such that  $x = x'x''$ ,  $y = y'y''$ , and  $x' \preceq y'$ ,  $x'' \preceq y''$ .

and  $\preceq$  is the smallest relation satisfying (1) and (2).

**Fact 3:** For any  $x, y \in \Sigma_K^*$ ,  $x \leq y$  iff  $x \preceq y$ .

**Fact 4:** C-embeddability is a well partial order.

Fact 3 is easy. It is also easy to check that C-embeddability is a partial order. It is well founded, because regular embeddability is well founded and for given  $x \in \Sigma_C^*$  there are only finitely many  $y \in \Sigma_C^*$  s.t.  $|x| = |y|$  and  $y \preceq x$ .

There are only finitely many incomparable elements in  $\Sigma_C^*$  with respect to  $\leq$ , and there are more incomparable elements with respect to  $\leq$  than with respect to  $\preceq$ , so  $\preceq$  is a well partial order.  $\square$

If  $\leq$  is a partial order on  $S$ , we can define a notion of a *downward closed* subset of  $S$ :

**Definition :**  $R \subseteq S$  is *downward closed* iff  $x \in R$  implies  $\forall y \preceq x, y \in R$ .

We will look at downward closed sets with respect to embeddability and C-embeddability.

**Theorem 2:** Let  $\Sigma_C$  be the alphabet whose symbols are  $\{C_U\}_{U \subseteq N}$ . Then for all strings  $x, y$  in  $\Sigma_C^*$ , if  $x \preceq y$  then for all  $\mathcal{M}, s$ , if  $\mathcal{M}, s \models yA$  then  $\mathcal{M}, s \models xA$ .

## 4 The Main Results

**Corollary 1:** Every level of knowledge is a downward closed set with respect to  $\preceq$ .  $\square$

**Theorem 3:** There are only countably many levels of knowledge and in fact all of them are regular subsets of  $\Sigma^*$  (where  $\Sigma$  is either  $\Sigma_K$  or  $\Sigma_C$ ).

**Proof:** Let  $L$  be any downward closed set of some  $\Sigma^*$ . Let  $X = \Sigma^* - L$ . Then  $X$  is upward closed. But now let  $M$  be the set of *minimal* elements of  $X$ . Since embeddability is a WPO,  $M$  is finite and let  $M = \{x_1, \dots, x_p\}$ . Then for all  $y \in \Sigma^*$ ,  $y \in X \leftrightarrow (\exists i \leq p)(x_i \preceq y)$  and the condition  $(\exists i \leq p)(x_i \preceq y)$  can be tested by a finite automaton. Thus  $X$  is regular, and hence so is  $L$ .  $\square$

**Fact 5:** Eric Pacuit of the CUNY Graduate center and ourselves have shown that in contrast with *knowledge* there are *uncountably* many possible levels of rational *belief*. This is curious as truth is the only condition which (formally) separates knowledge from rational belief. These results will appear elsewhere.

**Corollary :** The membership problem for a level of knowledge can be solved in linear

time.

Now we consider what finite downward closed sets of strings can look like.

**Theorem 4:** If  $L$  is a non-empty finite subset of  $\Sigma_K^*$ , then  $L$  is downward closed iff for some  $k$ ,

$$L = \bigcup_{i=1}^k dc(\{x_i\})$$

where  $x_i \in \Sigma_K^*$ .

This theorem reiterates the fact that the finite levels are characterized by their maximal elements ( $x_1, \dots, x_k$  are maximal). The characterization of infinite levels of knowledge is more complex. The details are in [PK].

## 5 Model of a Distributed System

Just above we considered the levels of knowledge of arbitrary Kripke structures. But Kripke structures do not fall from the sky. They arise in normal social (or computational) contexts. In the rest of the paper we consider what sorts of levels of knowledge can arise among  $n$  processes who start out knowing nothing in common but who arrive at some shared knowledge through communication, either asynchronous, or synchronous.<sup>3</sup>

We assume that there are a finite number of processes,  $1, \dots, n$ , which compute and communicate with each other either by asynchronous messages or by broadcasts. Our network is assumed to be fully connected<sup>4</sup> (there is a channel from every process to every other process).

*Asynchronous* communication consists of two phases: send and receive. All messages sent are ultimately delivered (and they are delivered in the order in which they were sent) but the delay (transmission time) may be arbitrarily long.

*Broadcasts* are fully reliable, synchronous communications<sup>5</sup> where all processes involved simultaneously receive the message sent by one of them.

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<sup>3</sup>Below we give the definitions and main results. The full proofs are in [PK], which is unfortunately not easily accessible.

<sup>4</sup>If the network is not fully connected then some levels of knowledge may be impossible to realize due to the lack of communication capabilities, e.g. if a processor is isolated (cannot communicate with anyone) then the other processes cannot learn anything from that process. Interesting questions arise in case of a directed network where every process may communicate with every other process but some communications are necessarily indirect (go through other processes). We will not analyze this case here.

<sup>5</sup>The two kinds of communications can be looked at as two kinds of communication media e.g. mailing system (asynchronous) and telephone lines (synchronous). Since we allow for synchronous communication between more than two processes at a time, our telephone system must have “conference call” capability.

Now we formally specify our class of models. Let  $N = \{1, \dots, n\}$  be the set of all processors. Every processor  $i$  has infinitely many possible initial states  $v$ . Every initial state is a string of 0's and 1's ( $v \in \{0, 1\}^*$ ). The set of initial states for  $i$  we denote by  $V_i$ . The set of global initial states is  $\mathcal{V} = \prod_{i=1}^n V_i$ .

From now on we will use lower case letters to denote everything pertaining to a single process. Capitals will be used where all the processes are involved (e.g.  $v_i$  is an initial state of a processor  $i$ , while  $V$  is an initial configuration of the whole system:  $V = (v_1, \dots, v_n)$ ).

**Events:**  $E_i$  denotes the set of all events in which processor  $i$  can participate (events *local* to  $i$ ). There are the following types of events (or actions):

1.  $L_i$ : Local computation steps.
2.  $s(i, j, m)$ : Sending a message  $m$  to a processor  $j$ ,  $j \in N$ .
3.  $r(j, i, m)$ : Receiving a message  $m$  from a processor  $j$ ,  $j \in N$ . ( $M$  is the set of all possible messages)
4.  $bc(i, U, m)$ : Sending a broadcast  $m$  to a group of processors  $U$ ,  $i \in U \subseteq N$ . The same event is receiving a broadcast  $m$  by a group of processes  $U$ .

$$E_i = L_i \cup \{s(i, j, m) | m \in M, j \in N\} \cup \{r(j, i, m) | m \in M, j \in N\} \\ \cup \{bc(j, U, m) | m \in M, i, j \in U \subseteq N\} \cup \{bc(i, U, m) | m \in M, i \in U \subseteq N\}$$

We define the set of *global events*  $\mathbf{G}$  in our system.  $\mathbf{G} \subseteq \prod_{i=1}^n (E_i \cup \{null\})$  (a cartesian product) s.t. if  $(e_1, \dots, e_i, \dots, e_n) \in \mathbf{G}$  for some  $i$  and  $e_i = bc(j, U, m)$  then for all  $i' \in U$ ,  $e_{i'} = bc(j, U, m)$ . If  $e_i = null$  for some  $i$ , it means that there is no local event at  $i$  at this point. Note that *null* is *not* local to any process. We use the notation  $(G)_i$  to denote the  $i$ th coordinate of  $G$ , so  $(e_1, \dots, e_i, \dots, e_n)_i = e_i$ .

**Histories:** A history (a run) is an input value followed by a sequence of events. Let's call the set of all possible histories of the system – a protocol  $\mathbf{P}$ . So  $\mathbf{P} \subseteq V; \mathbf{G}^*$ . Protocols are always closed under taking an initial segment of a history:  $H \in \mathbf{P}$  implies that every  $H'$  which is an initial segment of  $H$  is in  $\mathbf{P}$ .

We will require that for every receive in every history in every protocol there is exactly one corresponding send and it occurs before receive (this condition we will call *time-consistency*).

We say that two histories  $H$  and  $H'$  are *compatible* iff they start with the same input values.

We can define the *concatenation* of compatible histories:

If  $H_1 = V; G_1; \dots; G_k$ , and  $H_2 = V; G'_1; \dots; G'_l$ , then  $H$  is the concatenation of  $H_1$  and  $H_2$  iff  $H = V; G_1; \dots; G_k; G'_1; \dots; G'_l$ ,

*Local histories* are the projections of global histories onto the sets of local events of the processors. They are “time-forgetting”.

We assume that a global event – the ticking of the clock – takes place even if no local events take place at a particular moment. Given  $i$ , and the global history  $H$ , the local history  $h_i$  consisting of the events seen by  $i$ , is uniquely defined and we let  $\Phi_i$  be the map which takes us from  $H$  to  $h_i$ .

The local history is everything the processor sees, so all the global histories which correspond to the same local history  $h_i$  look the same to the processor  $i$ . Note that the length of  $\Phi_i(H)$  is less than or equal to the length of  $H$ . In fact  $length(\Phi_i(H)) = length(H)$  iff there are no *null* events on  $i$  in  $H$ .

For every  $i$  we can define an equivalence relation on the set of global histories:

$$H \approx_i H' \text{ iff } \Phi_i(H) = \Phi_i(H')$$

This relation is extended to groups  $U$  by letting  $H \approx_U H'$  iff there exists a chain  $H = H_1, H_2, \dots, H_m = H'$  and for all  $i < m$ , there is a  $j \in U$  such that  $H_i \approx_j H_{i+1}$ .

We use capital letters to denote global histories, events etc, lower case letters denote local histories, events etc.

**Closure Conditions for the Protocol:** We impose some additional conditions on the protocol  $\mathbf{P}$ . We want to ensure that the initial state of  $i$  ( $v_i$ ) cannot be *known* to any other process  $j$  at any run of the system, unless  $j$  *learns* about  $v_i$  from some communication. We want to exclude the possibility that something is common knowledge “accidentally”. To achieve that we will make sure that all the initial states are possible. Moreover, if  $v_i$  is the initial state of  $i$ , all other strings  $v'_i$  will remain possible for  $j$  as initial states of  $i$ , unless  $j$  gets some message from  $i$  to the contrary (directly or via some other processors).

**1)** All vectors of input values are possible:  $\forall V$  s.t.  $V = (v_1, \dots, v_n)$  where every  $v_i$  is a sequence of 0’s and 1’s there is some  $H \in \mathbf{P}$  s.t. for some  $H'$ ,  $H = V; H'$ .

**2)** No sequence of local events on some group of processes can influence possible actions of some other group of processes unless there are some communications (of course assuming that both groups are disjoint).

For that we need some closure conditions on the set of all protocols. The first condition we use is due to [CM] (it is the first of their *principles of computation extension* ).

We need one definition:

Let  $G = (e_1, \dots, e_n)$ ,  $G$  is *on*  $U$  if  $U = \{i | (G)_i \neq null\}$  (so  $U$  is the set of processes which have some local events in  $G$ ).

**Closure conditions:**

(i) **Extension Rule:**

Let  $\forall i \in U, H \approx_i H', G$  is on  $U$ , none of  $(G)_i$  is receive  $r(j, i, m)$  for any  $j$  not in  $U$ , then

$$(H' \in \mathbf{P}, H; G \in \mathbf{P}) \Rightarrow H'; G \in \mathbf{P}$$

The extension rule guarantees that if we have a protocol  $\mathbf{P}$ , some history  $H$  in  $\mathbf{P}$  and some action of a group of processes  $U$  is possible in  $\mathbf{H}$ , then the same action must be possible in every history  $H'$  which looks the same to all processes in  $U$  unless it violates time-consistency. In order to explain why  $e_i$  cannot be a receive from a processor outside of  $U$  let us examine an example:

Let  $N = \{1, 2, 3\}, U = \{1, 2\}$ .

$H = (\text{null}, \text{null}, s(3, 1, m)), H' = (\text{null}, \text{null}, \text{null})$ . Clearly  $H \approx_1 H'$  and  $H \approx_2 H'$ . If we take  $G = (r(3, 1, m), \text{null}, \text{null})$  s.t.  $H; G \in \mathbf{P}$  then requiring  $H'; G$  to be in  $\mathbf{P}$  would violate time-consistency.

The following conditions ensure that no process can get any additional information about the other processes by observing its own local events (no hidden synchronization). These conditions are necessary because (unlike [CM]) we allow local events at different sites at the same instant of time. Condition (ii) says that if some local events have occurred in parallel, and the sets of participating processes were disjoint, they could have occurred in sequence. We'll call it the splitting rule.

(ii) **Splitting Rule:**

$G = (e_1, \dots, e_n), G \notin V, G$  is on  $U$ . Given  $U_1, U_2$  s.t.  $U_1 \cup U_2 = U$  and  $U_1, U_2$  disjoint, then we can "split" any  $G$  into  $G_1$  and  $G_2$ :

$$(H; G \in \mathbf{P}) \Rightarrow H; G_1; G_2 \in \mathbf{P}$$

where  $(G)_i = (G_1)_i$  for  $i \in U_1, (G)_i = (G_2)_i$  for  $i \in U_2, (G_1)_j = \text{null} = (G_2)_k$  for  $j \notin U_1, k \notin U_2$  provided that we don't split any broadcasts:  $(G)_i = bc(i, V, m) \rightarrow V \subseteq U_1 \vee V \subseteq U_2$ .

Condition (iii) says that if some local events have occurred in sequence, the sets of participating processes were disjoint, and there was no send receive pair in them, they could have occurred in parallel.

(iii) **Joining Rule:**

Given  $U_1, U_2$  s.t.  $U_1 \cup U_2 = U$  and  $U_1, U_2$  disjoint, Let  $G_1$  be on  $U_1, G_2$  on  $U_2$ , and if  $(G_1)_i = s(i, j, m)$  then  $(G_2)_j \neq r(i, j, m)$ .

$$(H; G_1; G_2 \in \mathbf{P}) \Rightarrow H; G \in \mathbf{P}$$

where  $(G)_i = (G_1)_i$  for  $i \in U_1, (G)_i = (G_2)_i$  for  $i \in U_2$ .

**Systems:** We consider three kinds of systems. *Asynchronous* systems are the systems as described above but *without broadcasts*. So in asynchronous systems the only communications are via send and receive. *Synchronous* systems are the systems in which all

the communications are done using broadcasts where we don't have the events *send* and *receive*. Finally, we use the name *mixed* communications systems for the systems with both kinds of communications available.

## 5.1 Language and Semantics

Let  $L_0$  be a language which describes properties of the global histories in a protocol  $\mathbf{P}$ . So for every sentence  $A$  in  $L_0$ , and for every history  $H \in \mathbf{P}$ ,  $A$  is either true or false in  $H$ .

We want to make sure that in every history initially every processor has some “private” information not known to any other processor. To accomplish that we assume that we have in our language a countable set of propositions  $L_1 = \{Q_{i,j}\}_{i,j \in N}$ .  $Q_{i,j}$  is the proposition that the  $j$ th input value of  $i$  is 1. All  $Q_{i,j}$  are independent. Private information of  $i$  in  $H$  are  $P_{i,j}$  which are  $Q_{i,j}$  or its negation depending on whether  $Q_{i,j}$  is true in  $H$  or not. Note that the private information is not a *truth value* of any formula, but *which* formula we're looking at.

$L$  is the closure of  $L_0$  under truth functional connectives.  $L$  can be extended to a larger language  $L_C$  which is the closure of  $L$  under common knowledge operators  $C_U$  (for  $U \subseteq N$ ) and the usual truth functional connectives.  $C_U(A)$  means that there is common knowledge of  $A$  among processes from  $U$ .

The knowledge of a single process corresponds to  $C_{\{i\}}$ . We will then use the notation<sup>6</sup>  $K_i$  for  $C_{\{i\}}$ . When we restrict ourselves to a subset of  $L_C$  in which all common knowledge operators are in fact the knowledge operators (the sets  $U$  in  $C_U$  are always singletons) then we use the notation  $L_K$ .

The class of all models we consider is the class of all protocols  $\mathbf{P}$  as described in the previous section. Fix  $\mathbf{P}$ . Now we define the notion  $H \models A$  for  $A$  in  $L_c$  by recursion on the complexity of  $A$ .

0) If  $A$  is from  $L_0$  then the semantics is given.

1) If  $A$  is  $Q_{i,j}$  then  $A$  is true in  $H$  if the  $j$ th bit of an input of processor  $i$  in  $H$  is 1:

$$H \models A \quad \text{iff} \quad H = (v_1, \dots, v_n); H', (v_i)_j = 1$$

2) If  $A$  is  $\neg A'$  then

$$H \models A \quad \text{iff} \quad H \not\models A'$$

If  $A$  is  $B \vee C$  then

$$H \models A \quad \text{iff} \quad (H \models B \quad \text{or} \quad H \models C)$$

3) If  $A$  is of the form  $K_i(B)$  then

$$H \models K_i A \quad \text{iff} \quad \forall H' \in \mathbf{P} \quad H \approx_i H' \rightarrow H' \models A$$

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<sup>6</sup>Fact that  $C_{\{i\}} = K_i$  was noticed earlier, compare e.g. [FI]. It is important that we assume that  $L_K$  and  $L_C$  are S5 (we need at least S4).

4) If  $A$  is of the form  $C_U(B)$ , then

$$H \models A \text{ iff for all } H', H' \approx_U H, H' \models B$$

Also if  $U$  is empty, then  $C_U A$  iff  $A$ .

**Definition 6:** A formula  $A$  is *persistent* if whenever  $H \models A$  and  $H'$  extends  $H$ , then  $H' \models A$ .

**Theorem 5:** If  $A$  is persistent then so is  $K_i(A)$  for any  $i$ .

**Theorem 6:** Every formula  $A$  which is a boolean combination of  $P_i$ 's is persistent.  $\square$

**Theorem 7:** Every formula of the form  $xA$  where  $A$  is a boolean combination of  $P_i$ 's, and  $x$  is a string of knowledge operators is persistent.  $\square$

**Theorem 8: [Chandy, Misra]:** If communication is purely asynchronous, and for some histories  $H, H'$ , s.t.  $H$  is an initial segment of  $H'$ :

$$H' \models K_1 K_2 \dots K_n A \text{ and } H \not\models K_n A$$

then in  $H' - H$  there must be a sequence of messages:  $m_{n-1}, m_{n-2}, \dots, m_1$  s.t.  $m_{n-1}$  is sent by  $n$  and reaches  $n-1$  (maybe via some other processes),  $\dots, m_1$  is sent by 2 and (maybe indirectly) reaches 1 (messages may be different but they all must imply  $A$ ). Moreover if  $A$  doesn't depend on any local event of  $n$  (its truth value depends on some event  $e \notin E_n$ ) then there must be some event of the form  $r(i, n, m)$  occurring after  $H$  but before  $s(n, n-1, m_{n-1})$ .

**Theorem 9:** Every finite downward closed set is the set  $L(A, H)$  for an appropriate  $A$  and  $H$  in some asynchronous protocol.

**Theorem 10:** : Every downward closed set  $L$  of strings without repetitions is  $L(A, H)$  for suitable  $A$  and  $H$  in a synchronous system with at least 3 processors.

**Theorem 11:** In a two processor system with only synchronous communication available, no finite level containing strings of length  $\geq 2$  can be achieved for any formula  $A$ .

**Theorem 12:** In system with  $k$ -casts, i.e. with broadcasts involving at most  $k$  processors, it is impossible to achieve common knowledge of any new fact in a group of size  $> k$ .

## 6 Further Work and Open Questions

In this paper we have looked only at levels of knowledge for single formulas. However, levels of knowledge for related formulas may be connected. For example if  $A = B \vee C$  then  $L(B, s) \cup L(C, s) \subseteq L(A, s)$ . So one could ask, given the Lindenbaum algebra  $\mathcal{A}$  of ground formulas and the Boolean algebra  $\mathcal{B}$  of subsets of  $\Sigma_c^*$ , which maps from  $\mathcal{A}$  to  $\mathcal{B}$  can arise



as level maps? We know that the maps must preserve order and that the images must be regular, downward closed sets, but what more can we show?

A second direction of inquiry is to ask how actual game playing and knowledge interact. We have shown what sorts of levels can arise and shown that they are relevant to group strategies as well as to individual strategies within groups. But clearly much more needs to be done.

A final line of research is to bring the current work into closer contact with a lot of other work on knowledge revision which begins with Plaza and proceeds through [Ger], [BMP], [Dit]. We also need to relate the work with the work of Stalnaker on models of knowledge where probabilities are taken into account.

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