LOGICAL DYNAMICS OF INFORMATION AND INTERACTION

Johan van Benthem

Amsterdam & Stanford, http://staff.science.uva.nl/~johan/

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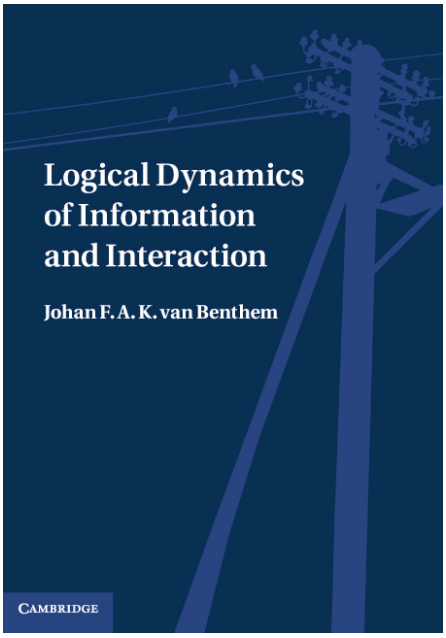

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PREFACE

This book is about Logical Dynamics, a theme that first gripped me in the late 1980s. The idea had many sources, but what it amounted to was this: make actions of language use and inference first-class citizens of logical theory, instead of studying just their products or data, such as sentences or proofs. My program then became to explore the systematic repercussions of this 'dynamic turn'. It makes its first appearance in my book *Language in Action* (1991), where categorial grammars are linked to procedures of linguistic analysis using relational algebra – viewing natural language as a sort of cognitive programming language for transforming information. My next book *Exploring Logical Dynamics* (1996) continued with this perspective, linking it to modal logic and process theories in computer science: in particular, dynamic logic of programs. This added new themes like process invariances and definability, dynamic inference, and computational complexity of logics. In the meantime, my view of logical dynamics has evolved again. I now see it as a general theory of agents that produce, transform and convey information – and in all this, their social interaction should be understood just as much as their individual powers. Just think of this: asking a question and giving an answer is just as logical as drawing a conclusion on your own. And likewise, I would see argumentation with different players as a key notion of logic, with proof just a single-agent projection. This stance is a radical break with current habits, and I hope it will gradually grow on the reader, the way it did on me.

The book presents a unified account of the resulting agenda, in terms of *dynamic epistemic logic*, a framework developed around 2000 by several authors. Many of its originators are found in my references and acknowledgments, as are others who helped shape this book. In this setting, I develop a systematic way of describing actions and events that are crucial to agency, and show how it works uniformly for observation-based knowledge update, inference, questions, belief revision, and preference change, all the way up to complex social scenarios over time, such as games. In doing so, I am not claiming that this approach solves all problems of agency, or that logic is the sole guardian of intelligent interaction. Philosophy, computer science, probability theory, or game theory have important things to say as well. But I do claim that logic has a long-standing art of choosing abstraction levels that are sparse and yet revealing. The perspective offered here is simple, illuminating, and a useful tool to have in your arsenal when studying foundations of cognitive behaviour.

Moreover, the logical view that we develop has a certain mathematical elegance that can be appreciated even when the grand perspective leaves you cold. And if that technical appeal does not work either, I would already be happy if I could convey that the dynamic stance throws fresh light on many old things, helps us see new ones – and that it is fun!

This book is based on lectures and papers since 1999, many co-authored. Chapter 1 explains the program, Chapter 2 gives background in epistemic logic, and Chapters 3–12 develop the logical theory of agency, with a base line for readers who just wish to see the general picture, and extra topics for those who want more. Chapters 13–16, that can be read separately, explore repercussions of logical dynamics in other disciplines. Chapter 17 summarizes where we stand, and points at roads leading from here. In composing this story, I had to select, and the book does not cover every alley I have walked. Also, throughout, there are links to other areas of research, but I could not chart them all. Still, I would be happy if the viewpoints and techniques offered here would change received ideas about the scope of logic, and in particular, revitalize its interface with philosophy.

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Chapter 1

LOGICAL DYNAMICS, AGENCY, AND INTELLIGENT INTERACTION

1.1 Logical dynamics of information-driven agency

Human life is a history of millions of actions flowing along with a stream of information. We plan our trip to the hardware store, decide on marriage, rationalize our foolish behaviour last night, or prove an occasional theorem, all on the basis of what we know or believe. Moreover, this activity takes place in constant interaction with others, and it has been claimed that what makes humans so unique in the animal kingdom is not our physical strength, nor our powers of deduction, but rather our planning skills in social interaction – with the Mammoth hunt as an early example, and legal and political debate as a late manifestation. It is this intricate cognitive world that I take to be the domain of logic, as the study of the invariants underlying these informational processes. In particular, my program of *Logical Dynamics* (van Benthem 1991, 1996, 2001) calls for identification of a wide array of informational processes, and their explicit incorporation into logical theory, not as didactic background stories for the usual concepts and results, but as first-class citizens. One of the starting points in that program was a pervasive ambiguity in our language between *products* and *activities* or processes. "Dance" is an activity verb, but it also stands the product of the activity: a waltz or a mambo. "Argument" is a piece of a proof, but also an activity one can engage in, and so on. Logical systems as they stand are product-oriented, but Logical Dynamics says that both sides of the duality should be studied to get the complete picture. And this paradigm shift will send ripples all through our standard notions. For instance, natural language will now be, not a static description language for reality, but a dynamic programming language for changing cognitive states.

Recent trends have enriched the thrust of this action-oriented program. 'Rational agency' stresses the transition from the paradigm of proof and computation performed by a single agent (or none at all) to agents with abilities, goals and preferences plotting a meaningful course through life. This turn is also clear in computer science, which is no longer about lonely Turing Machines scribbling on tapes, but about complex intelligent communicating systems with goals and purposes. Another recent term, 'intelligent interaction', emphasizes

what is perhaps the most striking feature here, the role of *others*. Cognitive powers show at their best in many-mind, rather than single-mind settings – just as physics only gets interesting, not with single bodies searching for their Aristotelean natural place, but on the Newtonian view of many bodies influencing each other, from nearby and far.

1.2 The research program in a nutshell

What phenomena should logic study in order to carry out this ambitious program? I will first describe these tasks in general terms, and then go over them more leisurely with a sequence of examples. A useful point of entry here is the notion of *rationality*. Indeed, the classical view of humans as 'rational animals' seems to refer to our reasoning powers:

To be rational is to reason *intelligently*.

These powers are often construed narrowly as deductive skills, making mathematical proof the paradigm of rationality. This book has no such bias. Our daily skills in the common sense world are just as admirable, and much richer than proof, including further varieties of reasoning such as justification, explanation, or planning. But even this variety is not yet what I am after. As our later examples will show, the essence of a rational agent is the ability to use information from many sources, of which reasoning is only one. Equally crucial information for our daily tasks comes from, in particular, observation and communication. I will elaborate this theme later, but right now, I cannot improve on the admirable brevity of the Mohist logicians in China around 500 BC (Zhang & Liu 2007):

"Zhi: Wen, Shuo, Qin" **知 问 说 亲** [1]

knowledge arises through questions, inference, and observation.

Thus, while I would subscribe to the above feature of rationality, its logic should be based on a study of all basic informational processes as well as their interplay.

But there is more to the notion of rationality as I understand it:

To be rational is to act *intelligently*.

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[1] Somewhat anachronistically, I use modern simplified Chinese characters.

We process information for a purpose, and that purpose is usually not contemplation, but action. And once we think of action for a purpose, another broad feature of rationality comes to light. We do not live in a bleak universe of *information*. Everything we do, say, or perceive is coloured by a second broad system of what may be called *evaluation*, determining our preferences, goals, decisions, and actions. While this is often considered alien to logic, and closer to emotion and fashion, I would rather embrace it. Rational agents deal intelligently with both information and evaluation, and logic should get this straight.

Finally, there is one more crucial aspect to rational agency, informational and evaluational, that goes back to the roots of logic in Antiquity:

> *To be rational is to* interact *intelligently*.

Our powers unfold in communication, argumentation, or games: multi-agent activities over time. Thus, the rational quality of what we do resides also in how we interact with *others*: as rational as us, less, or more so. This, too, sets a broader task for logic, and we find links with new fields such as interactive epistemology, or agent studies in computer science.

I have now given rationality a very broad sense. If you object, I am happy to say instead that we are studying 'reasonable' agents, a term that includes all of the above. Still, there remains a sense in which mathematical deduction is crucial to the new research program. We want to describe our broader agenda of phenomena with *logical systems*, following the methods that have proven so successful in the classical foundational phase of the discipline. Thus, at a meta-level, in terms of modeling methodology, throughout this book, the reader will encounter systems obeying the same technical standards as before. And meta-mathematical results are as relevant here as they have always been. That, to me, is in fact where the unity of the field lies: not in a restricted agenda of 'consequence', or some particular minimal laws to hang on to, but in its methodology and modus operandi.

So much for grand aims. The following examples will illustrate what we are after, and each adds a detailed strand to our view of rational agency. We will then summarize the resulting research program, followed by a brief description of the actual contents of this book.

1.3 Entanglement of logical tasks: inference, update, and information flow

The Amsterdam Science Museum *NEMO* (http://www.nemo-amsterdam.nl/) organizes regular 'Kids' Lectures on Science', for some 60 children aged around 8 in a small amphitheatre. In February 2006, it was my turn to speak – and my first question was this:

> *The Restaurant* "In a restaurant, your Father has ordered Fish, your Mother ordered Vegetarian, and you have Meat. Out of the kitchen comes some new person carrying the three plates. What will happen?"

The children got excited, many little hands were raised, and one said: "He asks who has the Meat". "Sure enough", I said: "He asks, hears the answer, and puts the plate on the table. What happens next?" Children said: "He asks who has the Fish!" Then I asked once more what happens next? And now one could see the Light of Reason suddenly start shining in those little eyes. One girl shouted: "He does not ask!" Now, *that* is logic … After that, we played a long string of scenarios, including card games, Master Mind, Sudoku, and even card magic, and we discussed what best questions to ask and conclusions to draw.

Two logical tasks The Restaurant is about the simplest scenario of real information flow. And when the waiter puts that third plate without asking, you see a logical inference in action. The information in the two answers allows the waiter to infer (implicitly, in a flash of the 'mind's eye') where the third plate must go. This can be expressed as a logical form

$$A \text{ or } B \text{ or } C,\ \text{not-}A,\ \text{not-}B \Rightarrow C.$$

One can then tell the usual story about the power of valid inference in other settings. With this moral, the example goes back to Greek Antiquity. But the scenario is much richer. Let us look more closely: perhaps, appropriately, with the eyes of a child.

To me, the Restaurant cries out for a new look. There is a natural unity to the scenario. The waiter first obtains the right information by asking questions and understanding answers, acts of *communication* and perhaps *observation*, and once enough data have accumulated, he *infers* an explicit solution. Now on the traditional line, only the latter step of deductive elucidation is logic proper, while the former are at best pragmatics. But in my view, both informational processes are on a par, and both should be within the compass of logic. Asking a question and grasping an answer is just as logical as drawing an inference. And

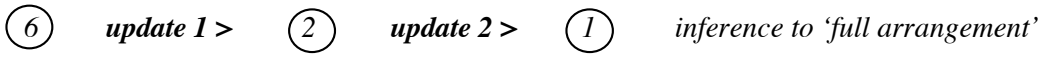
accordingly, logical systems should account for both of these, and perhaps others, as observation, communication, and inference occur entangled in most meaningful activities.

Information and computation And logic is up to this job, if we model the relevant actions appropriately. Here is how. To record the information changes in the Restaurant, a helpful metaphor is *computation*. During a conversation, information states of people – alone, and in groups – change over time, in a systematic way triggered by information-producing events. So we need a set of information states and transitions between them. And as soon as we do this, we will find some fundamental issues, even in the simplest scenarios.

Update of semantic information Consider the information flow in the Restaurant. The intuitive information states are sets of 'live options' at any stage, starting from the initial *6* ways of giving three plates to three people. There were two successive *update actions* on these states, triggered by the answers to the waiter's two questions. The first reduced the uncertainty from *6* to *2* options, and the second reduced it to *1*, i.e., just the actual situation. Here is a 'video' of how the answers for Meat and Fish would work in case the original order was ***FMV*** (fish for the first person, meat for the second, vegetarian for the third):

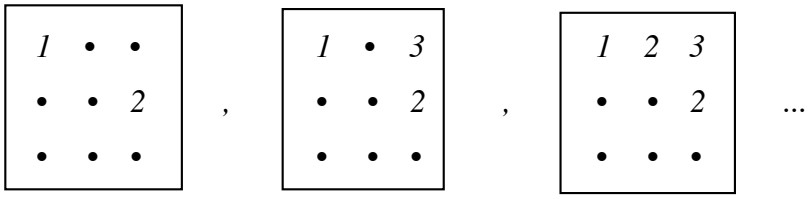
This is the common sense process of semantic update for the current *information range*, where new information is produced by events that rule out possibilities. In Chapters 2 and later, we will call this elimination scenario a case of 'hard information', and typical events producing it are public announcements in communication, or public observations.

Inference and syntactic information The first two updates have zoomed in on the actual situation. This explains why no third question is needed. But then we have a problem. What is the *point* of drawing a logical conclusion if it adds no further information? Here, the common explanation is that inferences 'unpack' information that we may have only implicitly. We have reached the true world, and now we want to spell it out in a useful sort of code. This is where inference kicks in, elucidating what the world looks like:



This sounds fine, but it makes sense only when we distinguish two different notions of information: one 'explicit', the other 'implicit' (van Benthem & Martinez 2008). Now, while there are elegant logics for semantic update of the latter, there is no consensus on how to model the explicit information produced by inference. Formats include syntactic accumulation of formulas, but more graphical ones also make sense. For instance, here is how propositional inferences drive stages in the solution of puzzles:

Example Take a simple 3x3 Sudoku diagram, produced by applying the two rules that 'each of the 9 positions must have a digit', but 'no digit occurs twice on a row or column':



Each successive diagram displays a bit more about the unique solution (one world) determined by the initial placement of the digits *1, 2*. Thus, explicit information is brought to light in logical inference in a process of what may be called deductive *elucidation*. Chapter 5 of this book will make a more systematic syntactic proposal for representing the dynamics of inference, that works in tandem with semantic update. For now, we just note that what happened at the Restaurant involves a basic issue in the philosophy of logic (cf. Chapter 13): capturing and integrating different notions of information.

Putting things together, the *dynamics* of various kinds of informational actions becomes a target for logical theory. But to make this work, we must, and will, also give an account of the underlying *statics*: the information states that the actions work over. As a first step toward this program, we have identified the first level of skills that rational agents have:

> *their powers of* inference*, and their powers of* observation*, resulting in information updates that change what they currently know*.

1.4 Information about others and public social dynamics

Another striking feature to the information flow in the Restaurant are the questions. Questions and answers typically involve more than one agent, and their dynamics is *social*,

having to do also with what people come to know about each other. This higher-order knowledge about others is crucial to human communication and interaction in general.

Questions and answers Take just one simple "Yes/No" question followed by a correct answer, a ubiquitous building block of interaction. Consider the following dialogue:

Me: "Is this Beihai Park?"

You: "Yes."

This conveys facts about the current location. But much more is going on. By asking the question in a normal scenario (not, say, a competitive game), I indicate that I do not know the answer. And by asking you, I also indicate that I think you may know the answer, again under normal circumstances. [2] Moreover, your answer does not just transfer bare facts to me. It also achieves that you know that I know, I know that you know that I know, and in the limit of such iterations, it achieves *common knowledge* of the relevant facts in the group consisting of you and me. This common knowledge is not a by-product of the fact transfer. It rather forms the basis of our mutual expectations about future behaviour. [3] Keeping track of higher-order information about others is crucial in many disciplines, from philosophy (interactive epistemology) and linguistics (communicative paradigms of meaning) to computer science (multi-agent systems) and cognitive psychology ('theory of mind'). [4] Indeed, the ability to move through an informational space keeping track of what other participants know and do not know, including the crucial ability to switch and view things from other people's perspectives, seems characteristic of human intelligence.

So, logical activity is interactive, and its theory should reflect this. Some colleagues find this alarming, as social aspects are reminiscent of gossip, status, and Sartre's "Hell is the Others". The best way of dispelling such fears may be a concrete example. Here is one,

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[2] All such presuppositions are off in a classroom with a teacher questioning students. The logics that we will develop in this book can deal with a wide variety of such informational scenarios.

[3] If I find your pin code and bank account number, I may empty your account – if I know that you do not know that I know all this. But if I know that you know that I know, I will not. Crime is triggered by fine iterated epistemic distinctions: that is why it usually takes experts.

[4] Cf. Hendricks 2005, Verbrugge 2009, van Rooij 2005, and many other sources.

using a card game, a useful normal form for studying information flow in logical terms. It is like the Restaurant in some ways, but with a further layer of higher-order knowledge.

The Cards (van Ditmarsch 2000) Three cards 'red', 'white', 'blue' are distributed over three players: *1, 2, 3*, who get one each. Each player sees her own card, but not the others. The real distribution over *1, 2, 3* is *red, white, blue*. Now a conversation takes place (this actually happened during the *NEMO* children session, on stage with thee volunteers):

2 asks 1 *"Do you have the blue card?"*
1 answers truthfully *"No"*.

Who knows what then, assuming the question is sincere? Here is the effect in words:

> "Assuming the question is sincere, *2* indicates that she does not know the answer, and so she cannot have the blue card. This tells *1* at once what the deal was. But *3* did not learn, since he already knew that *2* does not have blue. When *1* says she does not have blue, this now tells *2* the deal. *3* still does not know the deal; but since he can perform the reasoning just given, he knows that the others know it."

We humans go through this sort of reasoning in many settings, with different knowledge for different agents. In Chapters 2, 3, we will analyze this information flow in detail.

These scenarios can be much more complex. Real games of 'who is the first to know' arise by restricting possible questions and answers, and we will consider game logics later on. Also, announcements raise the issue of the reliability of the speaker, as in logic puzzles with meetings of Liars and Truth-Tellers. Our systems will also be able to deal with these in a systematic way, though separating one agent type from another is often a subtle manner of design. Logic of communication is not easy, but it is about well-defined issues.

Thus, we have a second major aspect of rational agents in place as a challenge to logic:

> *their* social powers *of mutual knowledge and communication.*

Actually, these powers involve more than pure information flow. Questions clearly have other uses than just conveying information: they define *issues* that give a purpose to a conversation or scientific investigation. This dynamics, too, can be studied per se, and Chapter 6 will show how to deal with 'issue management' within our general framework.

1.5 Partial observation and differential information

The social setting suggests a much broader agenda for logical analysis. Clearly, public announcement as we saw in the Restaurant or with the Cards is just one way of creating new information. The reality in many games, and most social situations, is that information flows differentially, with partial observation by agents. When I draw a card from the stack, I see which card I am getting. You do not, though you may know it is one of a certain set: getting *some* information. When you take a peek at my card, you learn something by cheating, degrading my knowledge of the current state of the game into mere belief. When you whisper in your neighbour's ear during my talk, this is a public announcement in a subgroup – where I and others need not catch what you are saying, and I may not even notice that any information is being passed at all.

Modeling such information flow is much more complicated than public announcement, and goes beyond existing logical systems. The first satisfactory proposals were made only in the late 1990s, as we shall see in Chapter 4. By now, we can model information flow in parlour games like "Clue", that have an intricate system of public and private moves. All this occurs in natural realities all around us, such as *electronic communication*:

> "I send you an email, with the message *'P'*: a public announcement in the group {*you, me*},
> You reply with a message *'Q'* with a *cc* to others: a public announcement to a larger group.
> I respond with *'R'* with a 'reply-to-all' plus a *bcc* to some further agents."

In the third round, we have a partly hidden act again: my *bcc* made an announcement to some agents, while others do not know that these were included. The information flow in this quite common episode is not simple. After a few rounds of *bcc* messages to different groups, it becomes very hard to keep track of who is supposed to know what. And that makes sense: differential information flow is complex, and so is understanding social life.

There are intriguing thresholds here. Using *bcc* is not misleading to agents who know that it is a possible event in the system. A further step is *cheating*. But even judicious lies seem a crucial skill in civilised life. Our angelic children are not yet capable of that, but rational agents at full capacity can handle mixtures of lies and truths with elegance and ease.

Thus, we have a further twist to our account of the powers of rational agents:

different observational access *and processing differential information flow*.

This may seem mere engineering. Who cares about the sordid realities of cheating, lying, and social manoevering? Well, differential information is a great good: we do not tell everyone everything, and this keeps things civilized and efficient. Indeed, most successful human activity is social, from hunting cave bears to mathematics. And a crucial feature of social life is organization, including new procedures for information flow. Even some philosophy departments now do exams on Skype, calling for new secret voting procedures on a public channel. What is truly amazing is how this fascinating informational reality has been such a low priority of mainstream logicians and epistemologists for so long.

1.6 Epistemic shocks: self-correction and belief revision

So far, we considered information flow and knowledge. It is time for a next step. Agents who correctly record information from their observations, and industriously draw correct conclusions from their evidence, may be rational in some Olympian sense. But they are still cold-blooded recording devices. But knowledge is scarce, and rationality does not reside in always being cautious, and continual correctness. Its peak moments occur with warm-blooded agents, who are opinionated, make mistakes, but who subsequently *correct* themselves. [5] Thus, rationality is about the dynamics of being wrong just as much as about that of being right: through belief revision, i.e., *learning* by giving up old beliefs. [6] Or maybe better, rationality is about a balance between two abilities: jumping to conclusions, and subsequent correction if the jump was over-ambitious.

Here, events become more delicate than with information flow through observation. Our knowledge can never be falsified by true new information, but beliefs can, when we learn new facts contradicting what we thought most plausible so far. Feeling that an earthquake

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[5] Compare a lecture with a mathematician writing a proof on a blackboard to a research colloquium with people guessing, spotting problems, and then making brilliant recoveries…

[6] In a concrete setting, revision comes to the fore in *conversation*. People contradict each other, and then something more spectacular is needed than update. Maybe one of them was wrong, maybe they all were, and they have to adjust. Modeling this involves a further distinction between information coming from some source, and agents' various attitudes and responses to it.

is hitting the Stanford campus, I no longer believe that a short nocturnal bike ride will get me home in 10 minutes. There is much for logic to keep straight in this area. For instance, the following nasty scenario has been discussed by computer scientists, philosophers, and economists in the 1990s. Even true beliefs can be sabotaged through true information:

> *Misleading with the Truth*
>
> You know that you have finished *3rd, 2nd,* or *1st* in the election, and you find lower outcomes more plausible. You also know that being *2nd* makes your bargaining chances for getting some high office small ('dangerous heavy-weight'). In fact you were *1st*. I know this, but only say (truly) that you are not *3d*: and you become unhappy. Why?

Initially, you find being *3rd* the most plausible outcome, and may believe you will get high office by way of compensation. So, this is a true belief of yours, but for the wrong reason. Now you learn the true fact that you are not *3rd*, and being *2nd* becomes the most plausible world. But then, you now believe, falsely, that you will not have any high office – something you would not believe if you knew that you won the election.

Our logics of belief revision in Chapter 7 of this book can deal with such scenarios. They even include others with a softer touch, where incoming *soft information* merely makes certain worlds less or more plausible, without ever removing any world entirely from consideration. In this same line, Chapter 8 will show how dynamic logics can also incorporate *probability*, another major approach to beliefs of various strengths.

Thus, in addition to the earlier update that accumulates knowledge, we have identified another, more complex, but equally important feature of rational agents:

> *their capacity for hypothesizing, being wrong, and then* correcting themselves.

In many settings, these capacities seems the more crucial and admirable human ability. A perfectly healthy body is great, but lifeless, and the key to our biological performance is our immune system responding to cuts, bruises, and diseases. Likewise, I would say that flexibility in beliefs is essential: and logic is all about the immune system of the mind.

1.7 Planning for the longer term

So far, we have mostly discussed single moves that rational agents make in response to incoming information, whether knowledge update or belief revision. But in reality, these single steps make sense only as part of longer processes through time. Even the Restaurant involved a conversation, that is, a sequence of steps, each responding to earlier ones, and directed toward some goal, and the same is true for games and social activities in general. There is relevant structure at this level, too, and as usual, it is high-lighted by well-known puzzles. Here is an evergreen:

> *The Muddy Children* (Fagin et al. 1995):
> After having played outside, two of three children have got mud on their foreheads. They can only see the others, so they do not know their own status. [7]Now their Father comes along and says: "At least one of you is dirty". He then asks: "Does anyone know if he is dirty?" Children answer truthfully, and this is repeated round by round.
> As questions and answers repeat, what will happen?

One might think that nothing happens, since the father just tells the children something they already know – the way parents tend to do – viz. that there is at least one dirty child. But in reality, he does achieve something significant, making this fact into *common knowledge*. Compare the difference between every colleague knowing that your partner is unfaithful: no doubt unpleasant, but maybe still manageable, with this fact being common knowledge, including everyone knowing that the others know, etcetera: the shame at department meetings becomes unbearable. Keeping this in mind, here is what happens:

> Nobody knows in the first round. But in the next round, each muddy child reasons like this: "If I were clean, the one dirty child I see would see only clean children, and so she would know that she was dirty. But she did not. So I must be dirty, too!"

Note that this scenario is about what happens in the long run: with more children, common knowledge of the muddy children arises after more rounds of ignorance announcement, after which, in the next step, the clean children will know that they are clean. There is a formal structure to this. The instruction to the children looks like a computer program:

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[7] This observational access is the inverse of our earlier card games, but formally very similar.

REPEAT (IF you don't know your status THEN say you don't know ELSE say you do).

This is no coincidence. Conversation involves *plans*, and plans have a control structure for actions also found in computer programs: choice, sequential composition, and iteration of actions. The muddy children even have *parallel composition* of actions, since they answer simultaneously. Thus, actions may be composed and structured to achieve long-term effects – and this, too, will be an aspect of our logics. But for the moment, we note this:

> *Rational agency involves planning in* longer-term scenarios*, and its quality also lies in the ways that agents compose their individual actions into larger wholes.*

We will study long-term perspectives on agent interaction in Chapter 11, with connections to temporal logics of branching time as the Grand Stage where human activity takes place: as in Jorge Luis Borges' famous story 'The Garden of Forking Paths'.

1.8 Preferences, evaluation, and goals

Now we move to another phenomenon, that is crucial to understanding the driving force of much informational behaviour as discussed so far. Just answering 'a simple question' is rare. Behind every question, there lies a *why*-question: why does this person say this, what does she want, and what sort of scenario am I entering? Pure informational activities are rare, and they tend to live in an ether of preferences, and more generally, *evaluation* of situations and actions. This is not just greed or emotion. 'Making sense' of an interaction involves meaning and information, but also getting clear on the goals of everyone involved. This brings in another level of agent structure: crucially,

> *logic of rational agency involves* preferences *between situations and actions and agents'* goals, *usually aligned with these preferences.*

Preferences determine actions, and knowing your preferences helps me make predictions about what will happen. [8] It is hard to separate information from evaluation, and this may reflect some deep evolutionary entanglement of our cognitive and emotional brain systems.

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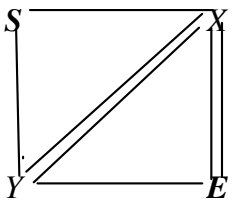
[8] If you think this is just daily life, not science, think of how a referee will judge your paper on its interest rather than truth, where 'interesting' depends on the preferences of a scientific community.

While preference has been studied extensively in decision theory and game theory, it has been more marginal in logic. In Chapter 9 of this book, we incorporate preference logic, and show how it fits well with logical analysis of knowledge update and belief revision. Indeed, it might be said that this provides the explanatory dynamics in the physicists' sense behind the 'kinematics' of knowledge and belief that we have emphasized so far. [9]

1.9 Games, strategies, and intelligent interaction

Temporal perspective and preference combine in the next crucial feature of rational agents that we noted earlier, their responding to others and mutually influencing them. Even a simple conversation involves choosing assertions depending on what others say. This interactive aspect means that dynamic logics must eventually come to turn with *games*:

True interaction and games To sample the spirit of interaction, consider the following game played between a Student and a Teacher. The Student is located at position *S* in the following diagram, but wants to reach the position of escape *E* below, whereas the Teacher wants to prevent him from getting there. Each line segment is a path that can be traveled. At each round of the game, the Teacher cuts one connection, anywhere in the diagram, while the Student can, and must travel one link still open to him at his current position:



If Teacher is greedy, and starts by cutting a link *S–X* or *S–Y* right in front of the Student, then Student can reach the escape *E*. However, Teacher does have a *winning strategy* for preventing the Student from reaching *E*, by doing something else:

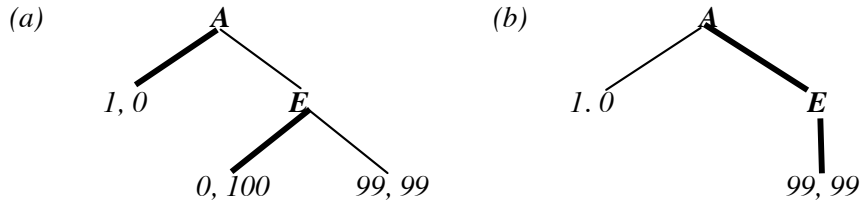
> first cutting one line between *X* and *E*, and then letting his further cutting
> be guided in a straightforward manner by where Student goes subsequently.

[9] I take this analogy seriously. *Rationality* (cf. Chapters 10, 15) links preference, belief and action in ways reminiscent of Newton's Laws for the dynamics of moving bodies using force, mass and acceleration. We mix theoretical and observational terms, and then base explanations on them.

Here *strategies* for players are rules telling them what to do in every eventuality. Solving games like this can be complex, emphasizing the non-trivial nature of interaction. [10]

Digression: learning Formal Learning Theory (Kelly 1996) concentrates on single-agent settings where a student forms hypotheses on the basis of some input stream of evidence: there is a Student, but no Teacher, unless we think of Nature as a disillusioned teacher doing a minimum of presentation without adjustment. But the realities of teaching and learning are social, with Students and Teachers responding to each other – and learning is a social process. We even learn at two levels: 'knowledge that', and know-how or skills.

Logic and game theory These multi-agent scenarios are close to game theory (Osborne & Rubinstein 1994 is an excellent introduction whose style also speaks to logicians) where information, evaluation, and strategic interaction are entangled. For a start, *Zermelo's Theorem* says that extensive two-player games of finite depth with perfect information and zero-sum outcomes are *determined*: that is, one of the players has a winning strategy. In our teaching game, this explains why Student or Teacher has a winning strategy. [11] Real game theory arises when players have preferences and evaluate outcomes. The reasoning extending Zermelo's is *Backward Induction*. Starting from values on leaves, nodes get evaluated up the tree, representing players' intermediate beliefs as to expected outcomes, given that both are acting 'rationally'. Here is an example, with nodes indicating the turns of two players ***A***, ***E***, while branching indicates different available moves. At end nodes, values are indicated for the players, in the following order ('value for ***A***', 'value for ***E***'):



[10] Rohde 2005 shows that solving 'sabotage graph games' like this is *Pspace*-complete, a high degree of complexity. The reader will get an even better feel for the complexity of interaction by considering a variant. This time, the Teacher wants to force the Student to *end up in E* without any possibility of escape. Who of the two has the winning strategy this time, in the same graph?

[11] For details of this and the next examples, cf. Chapter 10.

The thick black lines in Tree (a) indicate the backward induction moves of 'rational' players who choose those actions whose outcomes they believe to be best for themselves. Interestingly, this is an equilibrium with a socially undesirable outcome, as *(1, 0)* makes both players worse off than *(99, 99)*. Thus, we need to reassess the assumptions behind the usual solution procedures for games. Dynamic logics of communication help here, with new takes. Think of *promises* that change a game by announcement of intentions. ***E*** might promise that she will not go left, changing game (a) to game (b) – and the new equilibrium *(99, 99)* results, making both players better off by restricting the freedom of one. [12]

Finally, games are not just an analytical tool. They are also a ubiquitous human activity across cultures, serving needs from gentle elegant wastes of time to training crucial skills:

> *a full logical understanding of rational agency and intelligent interaction*
> *requires a logical study of* games*, as a crucial model for human behaviour.*

This theme is mostly the subject of van Benthem, to appearA, but Chapters 10, 11, 15 take it up in some detail, including games with partial observation and imperfect information.

1.10 Groups, social structure, and collective agency

Single agents need not just interact on their own: typically, they also form *groups* and other collective agents, whose behaviour does not reduce to that of individual members. For instance, groups of players in games can form coalitions, and social choice theory is about groups creating group preferences on the basis of individual preferences of their members. We saw some of this in the notion of common knowledge, which is about the degree of being informed inside a group. But there are more themes that concern group agency, and in Chapter 12 we will show how our dynamic logics interface with group behaviour, and even may help provide a 'micro-theory' of information-based rational deliberation.

[12] Van Benthem 2007F proposes alternatives to Backward Induction in history-oriented games, where players remind themselves of the *legitimate rights of others*, or of past favours received.

1.11 The program of Logical Dynamics in a nutshell

Rational agency involves information flow with many entangled activities: inference, observation, communication, and evaluation, all over time. Logical Dynamics makes all of these first-class citizens, and says that logical theory should treat them on a par. The resulting dynamic logics add subtlety and scope to classical systems, going beyond agent-free proof and computation. [13] Thus, we get new interdisciplinary links beyond old friends of mathematics, philosophy, [14] and linguistics, including computer science and economics. While reclaiming a broader agenda, with formal systems a means but not the end, logic also becomes a central part of academic life, overflowing the usual disciplinary boundaries.

A historical pedigree Is this new-fangled tinkering with the core values of logic? I do not think so. The ideas put forward here are ancient. We already mentioned broader Chinese views from Mohist logic. Likewise, traditional Indian logic stressed three ways of getting information. The easiest route is to observe, when that is possible. The next method is inference, in case observation is impossible or dangerous – the example being a coiled object in a room where we cannot see if it is a piece of rope, or a cobra. And if these two methods fail, we can resort to communication, and ask an expert. And also in the Western tradition, the social interactive aspect of information flow was there from the start. While many see Euclid's *Elements* as the paradigm for logic, with its crystalline mathematical proofs and eternal truths, the true origin may be closer to Plato's *Dialogues*, an argumentative practice. It has been claimed that logic arose out of legal, philosophical, and political debate in all its three main traditions. [15] And this multi-agent interactive view has emerged anew in modern times. A beautiful case are the *dialogue games* of Lorenzen 1955, that explained logical validity pragmatically in terms of a winning strategy for a

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[13] Moreover, we find a side benefit to the Dynamic Turn. Chapter 13 shows how to replace 'non-standard logics', that have sprung up in droves in recent years, by perfectly classical systems, once we identify the right information-changing events, and make them an explicit part of the logic.

[14] In particular, I see strong connections with (social) *epistemology*, cf. Goldman 1999.

[15] The Mohists in early China discuss the Law of Non-Contradiction as a principle of conversation: 'resolve contradictions with others', 'avoid contradicting yourself'. Cf. Zhang & Liu 2007.

proponent arguing a conclusion against an opponent granting the premises. Similar views occur in Hintikka 1973, another pioneer of games and informational activities inside logic.

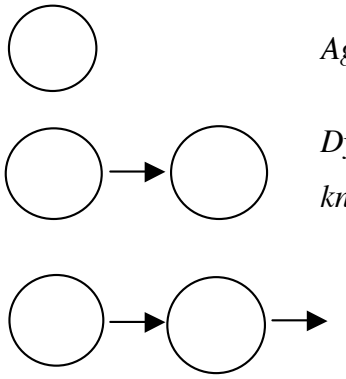
But in the end, I see no opposition between Platonic and Euclidean images. This book is about a broad range of logical activities, but still pursued by mathematical means. Logical dynamics has no quarrel with classical standards of explicitness and precision.

The promised land? The area staked out here may be the logician's Promised Land, but it is hardly virgin territory. Like Canaan in the Old Testament, it is densely settled by other nations, such as philosophers, computer scientists, or economists, worshipping other gods such as probability or game theory. Can we just dispossess them? Indeed we must not. Rational agency is a deep subject, calling for all the help we can. I think logic has fresh insights to offer, beyond what is already there. But it has no favoured position: polytheism is a civilized idea. I do predict new fruitful liaisons between logic and its neighbours. [16]

A bridge too far? On top of the logical micro-structure and discrete temporal processes that we will study, there is emergent statistical behaviour of large groups over a long time. That is the realm of probability, evolutionary games and *dynamical systems*. The intriguing interface of dynamic logics and dynamical systems is beyond the scope of this book.

I.12 The chapters explained

Some students find it helpful to think of the whole program here pictorially, in stages:



Agents' powers: knowledge, belief, preference, ….

Dynamics of single actions that change agent attitudes: knowledge update, belief revision, preference change, …

… …

Long-term phenomena and interactive processes [17]

[16] For a wonderful sample of what can be learnt by combining disciplines, cf. Shoham & Leyton-Brown 2007 on multi-agent systems in terms of computer science, game theory, and logic.

[17] One might add a second dimension of *group size*, but it would overload the picture.

Our chapters follow these lines, high-lighting activities and powers of agents. We start with semantic information and update, taking knowledge in the relaxed sense of what is true according to the agent's hard information. Our tools are epistemic logic over possible worlds model in a concrete sense (Chapter 2), its dynamified version of public announcement logic (*PAL*; Chapter 3) for communication and observation, and the more sophisticated dynamic-epistemic logic (*DEL*) of Chapter 4 with private scenarios and many agents. These systems are our paradigm for analysis of definable changes in current models of the agents' information. This methodology is applied in Chapter 5 to deal with inference, and other actions turning implicit into explicit knowledge. Chapter 6 shows how this also works for questions and issue management. Next, we turn to belief revision in Chapter 7, using changes in plausibility orders to model learning systematically. Chapter 8 is a digression, showing how similar ideas work for probabilistic update, with a richer quantitative view of learning mechanisms. Then we move to agents' evaluation of worlds and actions, and show how our techniques for plausibility change also apply to preferences and ways of changing them, providing a unified account of information, belief, and goals (Chapter 9). Next, moving beyond one-step dynamics, Chapter 10 is about longer-term multi-agent interaction, with a special emphasis on games. A still wider perspective is that of Chapter 11, with embeddings of our dynamic logics in epistemic temporal logics of branching time, and logics of protocols that add 'procedural information' to our study of agency. Completing the development of our theory, Chapter 12 considers groups as new logical agents, showing how the earlier systems lift to this setting, including new phenomena such as belief merge, as well as links with social choice theory.

Advice to the reader These chapters are all arranged more or less as follows. First comes the motivation, then the basic system, then its core theory, followed by a conclusion explaining how one more building block of our logic of agency has been put in place. Readers could opt out at this stage, moving on to the next topic in the chapter sequence. What follows in a chapter is usually a logician's pleasure garden with further technical themes, open problems, and a brief view of key literature. Our open problems are both technical and conceptual – and non-logicians, too, may find some of them worthwhile.

The remaining Chapters 13–16 show how the logical dynamics developed here applies to a range of disciplines. Chapter 13 is concerned with philosophy, putting many old issues in a fresh light, and in that same light, adding new themes. Chapters 14–16 extend the interface to computer science, game theory, and cognitive science. These chapters can be read independently: there is no sequence, and they are different in style and level of technicality. Finally, Chapter 17 states our main conclusions and recommendations.

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