ELSEVIER

Artificial Intelligence 103 (1998) 183–208

Artificial Intelligence

Let's plan it deductively!

W. Bibel

Technische Universität Darmstadt, Alexanderstr. 10, Darmstadt, Germany

Abstract

The paper describes a transition logic, TL, and a deductive formalism for it. It shows how various important aspects (such as ramification, qualification, specificity, simultaneity, indeterminism etc.) involved in planning (or in reasoning about action and causality for that matter) can be modelled in TL in a rather natural way. (The deductive formalism for) TL extends the linear connection method proposed earlier by the author by embedding the latter into classical logic, so that classical and resource-sensitive reasoning coexist within TL. The attraction of a logical and deductive approach to planning is emphasized and the state of automated deduction briefly described. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Reasoning about actions and causality; Planning; Automated deduction; Transition logic; Linear connection method; Frame problem; Ramification; Qualification

1. Introduction

Artificial Intelligence (AI, or Intellectics [12]) aims at creating artificial (or computational [53]) intelligence. Were there no natural intelligence, the sentence would be meaningless to us. Hence understanding natural intelligence by necessity has always been among the goals of Intellectics (as of Cognitive Science).

Different points of view for approaching the goal of creating artificial intelligence have been distinguished [39]. Logicism [51], cognitivism [43], and situated action [2] are three out of several such points of view. In a nutshell, the logistic point of view argues that man can describe his creations (including an artificial intelligence) only by natural linguistic, hence logical means; thus any way towards artificial intelligence must in some sense and at some level be a logical one. This author is strongly committed to the logistic approach. As a consequence he believes that any other approach is in fact a logistic one in disguise.

Intelligence has many features. Clearly one of them is the ability to reason about actions and causality and plan ahead in time. Intuitively, planning is logical reasoning of some kind. All the more one might expect that planning is the domain where logic and its

0004-3702/98/$ – see front matter
PII: S0004-3702(98)00064-2

deductive machinery excel. The fact is that it does not. There are many software systems in everyday use solving planning tasks, but to the author's best knowledge none of them is based on logic and has a deductive component. Does this imply that logic is irrelevant for planning, or even for Intellectics in general?

While intelligence implies the ability for planning, the converse needs not necessarily be true. It very much depends on what kind of planning is meant. In a fixed and relatively restricted domain (such as text layout) planning may well be realized in a purely functional way and with standard programming techniques. But functional (or procedural) programming has its limits as we enter more complex and unpredictable domains; in particular it will never be able to produce a behavior which rightly deserves to be named "intelligent" (surely as a user of computers you noticed the stupidity even of text layout systems). Section 8, as well as numerous texts in the literature, give arguments for this statement. It also gives reasons which explain the resistance of the software industry to a bolder move into a logic technology for planning or other applications. In other words, logic is essential for intelligent planning in the true sense of the term, but industry is not ready to build intelligent systems.

It is not the task of intellecticians to lament about this state of affairs but rather to prepare for the coming day when the market will be ripe for a broader use of a truly intelligent technology and to develop the best possible technological basis for it. In fact, if we are frank there is yet a lot to be developed before we can comfortably go out to industry and offer a coherent set of methods for dealing with the many facets of intelligence including planning.

In the present paper I review the state of the art in deductive planning with an emphasis on the contributions from research groups influenced by the author's own work. While much of the work in deductive planning has focused on representational issues we have always approached the problem with the necessary and available deductive techniques in mind. Since the methods and systems growing out of our work have finally achieved a prominent position in the deduction community by winning the CADE-96 competition in automated theorem proving with the SETHEO system [45,49], we are perhaps also well placed to import the best possible techniques into the planning community. In other words, the paper will focus on deductive planning as well as on the underlying deduction techniques. Since the author sees planning as just one among a number of aspects for achieving artificial intelligence, the case for deductive planning is presented in this paper in form of a paradigm case for achieving the grander goal of artificial intelligence. The paper will therefore not only point the way to intelligent planning but to some extent will also outline the author's envisaged route to artificial intelligence (the "it" in the title).

In the next section we introduce the logical language used in our approach and discuss the deductive aspects thereafter. The resulting computational logic is called *transition logic* (TL) which has classical as well as resource-sensitive features. Section 5 shows what TL has to do with planning and computation (or with temporal prediction or postdiction for that matter). Section 6 compares the logic with other known logics. Section 7 shows how the various aspects involved in reasoning about actions and causality can be taken into account within TL. Specifically, we discuss ramification, qualification, specificity, simultaneity, indeterminism, continuity, hierarchies, etc. Finally, we briefly describe the tensions between the specialistic and logistic approaches in AI and explain it by outlining

the underlying pattern. Given the impressive recent achievements in automated deduction we conclude with making a case for a logical path towards an artificial intelligence.

2. A logical language

Any textbook on AI also contains some introduction to first-order logic so that we may assume the reader to be familiar with it. Only to communicate our notational conventions we mention that there are objects named by constants (a, b, c), (n-ary) functions named by function symbols (f, g, h) and (n-ary) relations named by predicate symbols (P, Q, R). Terms (r, s, t), built from variables (x, y, z, ranging over objects), constants and function symbols, again denote objects. Literals (K, L) denote relations among objects or the negation ($\neg$) thereof. They correspond to simple factual sentences in natural language (such as "John is married to the mother of Bill").

For building more complicated sentences represented as formulas (F, G, H) we use the well-known classical (logical) operators $\wedge, \vee, \rightarrow, \leftrightarrow, \forall, \exists$ as well as the resource-sensitive operators & (non-idempotent conjunction), | (idempotent exclusive disjunction), and $\Rightarrow$ (transition). The latter need explanations which follow.

The language of predicate logic has been designed to express natural language sentences formally and unambiguously. This was done in a biased way since many of those involved in the design (such as Frege [22]) had mainly sentences of a mathematical nature in mind. Sentences involving actions were not taken into serious consideration until the publication of the situation calculus in 1969 [48] in which any n-ary relation P is extended to an $(n + 1)$-ary one by an extra argument for denoting the situation in which the relation is meant to hold (see Section 6.4).

Natural language apparently does not need such an extra vehicle for serving the same purpose. A (static) mathematical sentence (such as "if a prime number is greater than two then it is odd") looks exactly like a (dynamic) one about actions (such as "if the switch is off *and I turn it* then it is on"). In [9] the main idea for a logic has been outlined which resembles natural language more closely in this aspect of treating actions than does the situation calculus. The approach then was called *linear connection method* or shortly LCM; for the logic we introduce here on the basis of LCM we propose the name *transition logic* or TL. The idea underlying LCM spawned a great number of studies based on this idea such as [4,6,8,15,16,20,23,24,26,27,32–35,63–65] to mention several of them.

In TL certain facts may be treated as resources which may be consumed by actions. More specifically, a rule $K \Rightarrow L$, called an *action* (or *transition*) rule (or *effect axiom*), models an action which consumes K and produces L. For instance,

$$on\_table(book) \Rightarrow in\_hand(book)$$

can be seen as the equivalent in TL of the situation calculus rule

$$on\_table(book, s) \rightarrow in\_hand(book, result(take, s)).$$

In either case, predicates which may change their truth-value in these kinds of transitions (like *on_table*) are called *fluents* and the literals built from them *r-literals*.

Formulas built from r-literals by means of the quantifiers and the resource-sensitive operators only are called *r-formulas*. r-formulas without | are also called *conjunctive*

r-formulas. General *formulas* of TL are r-formulas and literals, and any expression built from those by means of the classical operators. For instance, $P \,\&\, Q \Rightarrow R$ is an r-formula, hence a formula, $(P' \rightarrow P) \wedge (P \Rightarrow Q) \rightarrow (P' \Rightarrow Q)$ is a formula but not an r-formula, and $P \,\&\, (P \rightarrow Q) \Rightarrow Q$ is not a formula (nor an r-formula) since the definition does not allow classical operators (other than quantifiers) below a resource-sensitive one in the formula tree. An r-subformula which is not a proper subformula of an r-subformula is also called an *r-part* in the given formula.

We will deal in this paper with a restricted class of formulas only which have the form $T \wedge (F_1 \Rightarrow G_1) \wedge \cdots \wedge (F_n \Rightarrow G_n) \rightarrow (G_0 \Rightarrow F)$ whereby $\Rightarrow$ does not occur in F_i, G_j, F. F is called the *query* in such a formula.

3. Semantics of TL

The semantics of the classical part of TL is exactly as in classical logic. Therein $L \wedge L$ is equivalent with L according to the rule of idempotence. In real-world scenarios it does matter, however, whether you have the same thing (say an euro) once or twice. Similarly, it does matter whether you take *your* euro or *mine*. That is why we need the two extra operators $\&, |$ which behave just like their classical counterparts $\wedge, \vee$ except for the rule of idempotence, which does *not* hold for $\&$, and for $|$ modelling an exclusive (rather than an inclusive) alternative. In consequence, we will not have the law of distributivity allowing $|$ to be distributed over $\&$. With these remarks it should be more or less obvious how to generalize the way to compute the truth-value of a given formula under a certain interpretation from standard logic to TL except for the treatment of $\Rightarrow$.

For understanding the latter, consider the formula $K \Rightarrow L$. Since it involves a transition it refers to two different worlds (or states), one before the transition, say σ_ε, and one after it, σ_1. For computing the truth-value of the formula we thus need an interpretation ι for each of these two different worlds. The formula then obviously is true in the case where we have $\iota(K, \sigma_\varepsilon) = \top$, $\iota(L, \sigma_\varepsilon) = \bot$, $\iota(K, \sigma_1) = \bot$, and $\iota(L, \sigma_1) = \top$ (assuming $K \neq L$).

In view of the class of formulas considered in this paper we now take $(F_1 \Rightarrow G_1) \wedge (F_2 \Rightarrow G_2)$ as our next example. It refers to five (possibly) different states. Let us call them σ_ε, σ_1, σ_{12}, σ_2, σ_{21} whereby the indices are meant to be (possibly empty) strings of names of the transitions involved in possible sequences. An interpretation ι makes this formula true if it holds that if $\iota(F_1, \sigma_s) = \top$ then $\iota(G_1, \sigma_{s1}) = \top$ and $\iota(F_1, \sigma_{s1}) = \bot$ unless $\iota(G_1 \rightarrow F_1, \sigma_{s1}) = \top$, and similarly for rule 2, for all prefixes s. Informally, if in state σ_s F_1 is true, then the facts supporting the truth of F_1 are removed and replaced by those supporting the truth of G_1 in state σ_{s1}. Talking about five possible states is correct only in the case of conjunctive r-formulas but not quite right in general as there may $|$ operators occurring in the F's and G's. These again may refer to different states like $\Rightarrow$.

The example just discussed is already generic for the general case where only more and longer sequences of transitions might get involved. To be more precise, in the case of conjunctive r-formulas we would have to consider all different substrings of the $n!$ possible sequences of the n transitions. $(F_1 \Rightarrow G_1) \wedge \cdots \wedge (F_n \Rightarrow G_n)$ then entails $G_0 \Rightarrow F$ if, for any interpretation ι, the premise is either false, or it is true under ι and there is a state σ_s whereby s is one of the possible sequences such that F becomes true under ι in that state

if G_0 is true in the initial state σ_ε. For instance, $T \wedge (K \Rightarrow L) \models F$ holds if the query F is classically entailed by T or if it is of the form $G \Rightarrow F'$ and for any interpretation ι and states $\sigma_\varepsilon, \sigma_1$ for which the transition in the premise becomes true the conclusion becomes true as well given T. As we see the classical background theory T carries over from state to state unchanged. Validity, $\models F$, is then defined as usual.

Altogether we are dealing here with a Kripke semantics whereby the number of possible worlds and their reachability is determined by the number of possible sequences of transitions. This semantics is special however as any interpretation in some world carries over to any other reachable by a transition unchanged except for the changes prescribed by the transition rule. Section 6 will resume the discussion of the semantics of TL while in the next section we focus on its deductive aspects.

4. Basic deductive machinery

As the original name of our approach, *linear connection method* (LCM), suggests, the basic deductive machinery is based on the connection method [11,14]. This deductive method is characterized by the fundamental theorem which in turn characterizes validity of a formula by the so-called spanning property explained shortly. Many different logical calculi can be based on this method.

In order to explain the spanning property we need the concepts of a path through a formula and of a connection. A *path* through a formula F is the set of literals of any conjunct of the conjunctive normal form of F. Paths can best be illustrated if formulas are displayed as matrices. Matrices (positively) represent disjunctions of clauses which in turn represent conjunctions of literals (or, in general, matrices). Consider the formula $P \wedge (P \rightarrow Q) \rightarrow Q$ (expressing the well-known logical rule of modus ponens). In negation normal form the same formula reads

$$\neg P \vee (P \wedge \neg Q) \vee Q,$$

which is a disjunction of three clauses. Hence as a matrix it looks as follows.

$$\begin{bmatrix} & \neg Q & \neg P \\ Q & P & \end{bmatrix}$$

As an aside we mention that a rotation of this matrix by 90° (counterclockwise) basically yields the corresponding PROLOG program except for the differences due to the negative representation used in PROLOG.

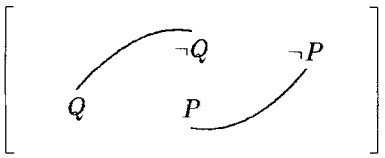
```
P.
Q   :-  P.
    ?-  Q
```

A path through such a matrix (or the formula it represents, or the corresponding PROLOG program) is now the set of literals obtained by selecting exactly one literal from each clause (or, in other words, traversing the matrix say from left to right). In the present example there

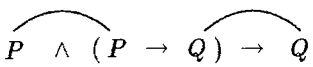
are exactly two such paths, namely $\{Q, \neg Q, \neg P\}$ and $\{Q, P, \neg P\}$. The disjunction of the literals of these two paths are obviously the disjuncts of the conjunctive normal form of

$$\neg P \vee (P \wedge \neg Q) \vee Q.$$

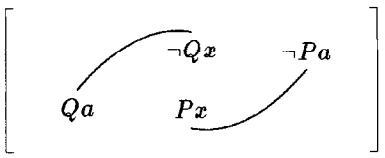
A *connection* is a subset of a path of the form $\{R, \neg R\}$. There are two connections in our present example illustrated as arcs in the following display.



A set of connections (or *mating*) is called *spanning* if each path through the matrix contains at least one connection. This is the case for the two connections of our example, hence the formula is (of course) valid according to the fundamental theorem mentioned at the outset of the section. Recall that the matrix form is used just for illustration and is thus not essential for the connection method. The connections (and the spanning property) could as well have been identified in the original formula as follows.



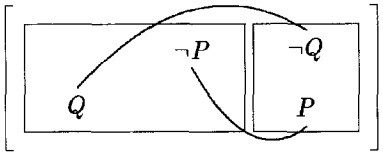
A chain of two (or more) connections like the two displayed in the matrix may thus be regarded as an encoding of one (or more) applications of modus ponens. This illustration also demonstrates that it is connections which lie at the heart of deductive reasoning (more so than rules like the $P \rightarrow Q$ in the example). In some sense a connection may also be seen as an encoding of an application of the well-known resolution rule. So far connections have been illustrated for propositional examples. They apply to first-order formulas in the obvious way, connecting literals with opposite signs and unifiable terms. An example is the following matrix.



Here validity is established by the two spanning connections along with the substitution $x\backslash a$, which makes the connected literals complementary.

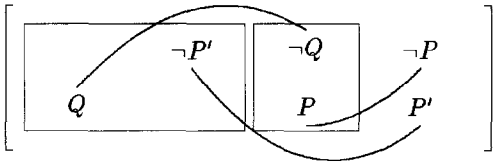
Up to this point we have restricted our discussion to deduction for purely classical formulas. The characterizing spanning property carries over to the case of general formulas in our logical language with one minor modification to be explained shortly. In fact, if we take the r-formula $(P \Rightarrow Q) \rightarrow (P \Rightarrow Q)$ as our first example then we may use exactly the same matrix as the one before to represent the formula in a two-dimensional way.

In fact, in spite of the modification in the formula exactly the same proof for validity is obtained.



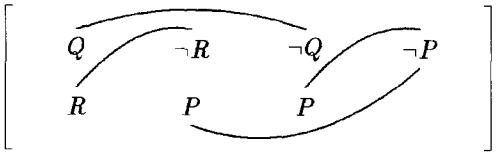
In order to distinguish it from the classical matrix we have used boxes around its r-parts rather than brackets. One should note, however, that the semantics of the operations represented by the structural arrangement this time is a different one. Again as in the classical case the matrix representation is more of an illustrative relevance, since the connections also here could as well have been placed in the original formula.

Let us now consider a general formula like $(P' \to P) \wedge (P \Rightarrow Q) \to (P' \Rightarrow Q)$ which in its classical part expresses that P' is just another name for P and which is represented by the following matrix.

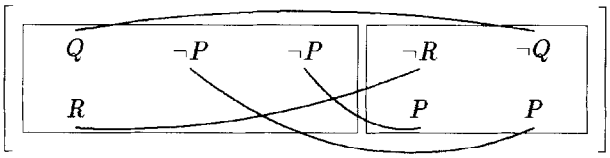


The (non-literal) r-parts are again boxed. The three connections are obviously spanning. Hence the formula is again valid.

The need for a modification of the validity criterion becomes clear if we compare the classically valid formula $P \wedge (P \to Q) \wedge (P \to R) \to Q \wedge R$ whose proof is



with the analogical r-formula $(P \Rightarrow Q) \wedge (P \Rightarrow R) \to (P \Rightarrow Q \,\&\, R)$. While the validity of the first formula is clear from the spanning property obviously satisfied for the matrix, the second formula should intuitively *not* be valid. Namely, if an euro (P) buys a coffee (Q), and if an euro buys a tea (R), and if I have just one euro (as the formula suggests) then clearly I cannot buy both coffee and tea since I would rather need *two* euros for that purpose. Since the matrix and its connections would be exactly the same for the second formula as for the first one, we are lead to conclude that the spanning property (characterizing validity in the classical case) needs some modification. The kind of modification becomes clear if we add another P to the present r-formula, i.e. $(P \Rightarrow Q) \wedge (P \Rightarrow R) \to (P \,\&\, P \Rightarrow Q \,\&\, R)$, which intuitively is valid as just illustrated and compare its proof



with the previous one. In the latter matrix *each literal is contained in at most one connection* while in the former this *linearity restriction in its original form* [9] is not satisfied because the literal $\neg P$ is contained in more than one, namely in two connections. To cover the general case considered in the present paper this linearity restriction needs a more general definition.

For that purpose we inductively introduce the concept of the *directionality*[1] 0 (for consumption) and 1 (for resource) of the nodes in the formula tree of a formula. The root has directionality 0. If a node with directionality d is labelled by $\wedge$, $\vee$, & or by | then its successor nodes have the same directionality d; if it is labelled $\rightarrow$, $\Rightarrow$ then the directionality of the left successor node is $(d+1)$ mod 2 while that of the right successor node is d. The directionality partitions the occurrences of literals in an r-formula (or r-matrix) into *resource literals* if their directionality in the formula is 1, and *consumption literals* if it is 0. If needed we attach this directionality to a literal as an upper index. In all our matrix examples the directionality is 1 for a negated literal and 0 for an unnegated one.

A *chain of connections* in a matrix M is a sequence $(c_1, \ldots, c_n)$, $n \geqslant 1$, of directed (instances of) connections $(\overline{L}_i, L_i)$, such that for any i, $1 \leqslant i \leqslant n-1$, the *end literal* of c_i, i.e., L_i, and the *start literal* of c_{i+1}, i.e., $\overline{L}_{i+1}$, are literals in the same (top level)[2] clause of M but do not occur in one and the same path through M, i.e., they are *vertically related* [24]. A *cycle* is a chain such that also its *start literal* $\overline{L}_1$, i.e., the start literal of c_1, and its *end literal* L_n are vertically related in this sense. A chain is called an *r-chain* if, viewed as a list $(K_1, \ldots, K_{2n})$ of literals K_j, $1 \leqslant j \leqslant 2n$, $n \geqslant 1$, K_1 is a literal of directionality 1 in the r-part containing the query, K_{2n} is a literal of directionality 0 in the query. Two r-chains $(K_1, \ldots, K_{2n})$ and $(K'_1, \ldots, K'_{2n'})$ are called *r-compatible* if one of the following two conditions holds.

(1) $K_{i+1} = K'_{j+1}$ whenever $K_i = K'_j$ for odd i and j, and K_{i+1} and K'_{j+1} are in the same r-part whenever $K_i = K'_j$ for even i and j;

(2) K_{2n} and $K'_{2n'}$ occur in A and B, respectively, within a subformula of the form $A \mid B$ occurring in the query.

In all other cases we call the two chains *r-incompatible*. A set of connections in a matrix M *satisfies the linearity restriction* if, for each directionality-1 literal L in the r-part of M containing the query, all r-chains starting from L are r-compatible with each other.

These definitions in their details go a bit beyond what is intended with this paper simply because they are novel and have not been published before. In fact it could well be that they need further (minor) adjustments as the structure of formulas and their semantics evolve further. We just mention here that the definitions aim at yielding the fundamental theorem according to which a formula F is valid if (some compound instance F' of) F

[1] Note that directionality is a specialized form of the well-known concept of polarity.

[2] In the case of non-normal form matrices clauses may not be just sets of literals.

has a spanning and unifiable mating which satisfies the linearity restriction and has no (regular [24]) cycles within any of M's r-parts. Since none of our examples will need compound instances we refer to the ATP literature for the respective details (e.g., see [11]). Nor has any of our examples cycles. Therefore we also ignore this technically intricate issue and refer the interested reader to [24] for the details.

Let us briefly discuss the rationale behind the definition of r-compatibility in order to get a better understanding of the linearity restriction. The literals in a chain with an odd index are those of a "resource nature". If two chains have none of those in common then no resource conflicts may arise hence they are r-compatible. If, however, they have such two literals in common, then we must require that both chains continue through the same connection (condition (1), first part) so that the same resource is not used in different ways. If two possibly different chains end in two alternatives (condition (2)) then they may use the same resources in different ways as in each separate alternative a resource conflict cannot occur this way. The need for the second part of condition (1) is illustrated by the example $(P \to P_1 \,\&\, P_2) \to [P \Rightarrow P_1 \,\&\, P_2]$ which obviously is a valid formula but would not satisfy the linearity restriction unless the two chains $((\neg P, P), (\neg P_1, P_1))$ and $((\neg P, P), (\neg P_2, P_2))$ were sanctioned r-compatible by condition (1). The condition thus allows to define a resource in terms of different components.

All matrices considered so far satisfy the linearity restriction except the one discussed just before these definitions in which the directionality-1 literal $\neg P$ were the start of two different r-chains (each with one connection) if the matrix were regarded as an r-matrix. The restriction is also satisfied in the matrix associated with the general formula

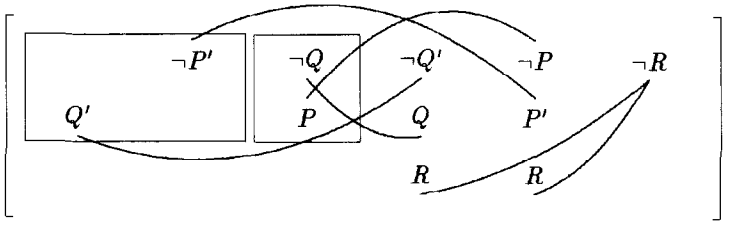
$$(P' \to P) \wedge (P \Rightarrow Q) \to (P' \Rightarrow Q)$$

shown above since there is only one r-chain starting in P' which according condition (1) trivially is compatible with itself. As an aside it is mentioned in the context of this example that fragments of r-chains such as $((\neg P', P'), (\neg P, P))$ may be regarded as theory connections [14].

A more complex example derived from the previous one, namely

$$R \wedge (R \to (P' \to P)) \wedge (R \to ((Q' \to Q) \to (P \Rightarrow Q))) \to (P' \Rightarrow Q')$$

yields the following proof.



As in the example before the linearity restriction is fulfilled in its spanning mating since there is only one r-chain starting from $\neg P'$ and ending with Q'. This is the case notwithstanding the fact that the literal R is involved in two connections; but these are involved in classical rather than resource-sensitive reasoning steps. The restriction is also fulfilled for

$$(P \,\&\, Q \to R \,\&\, S) \to (P \,\&\, Q \to R \,\&\, S).$$

On the other hand, the formulas

$$(P \to P \wedge P) \to (P \Rightarrow P \,\&\, P)$$

and

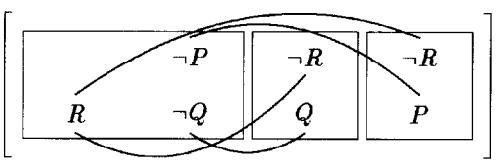
$$(P \to Q) \to (P \Rightarrow Q \,\&\, Q)$$

have spanning matings, but in line with intuition none of them satisfies the linearity restriction.

The solution presented here and illustrated with these examples informally was already given in [9] where it reads: "the linearity restriction applies to connections with one element in a transition rule only, not to those possibly required for additional 'static' reasoning in the usual way". The generalized definition of the linearity restriction just presented also covers the case of disjunction |, which has been the topic of the publications [6,8,26] where a different solution based on the restriction in its original form has been offered. We illustrate our solution for the formula

$$(P \Rightarrow R) \wedge (Q \Rightarrow R) \to (P \mid Q \Rightarrow R)$$

with the following matrix.



The two r-chains have no odd literals (condition (1)) in common so that the restriction is again fulfilled in this spanning mating although the literal R is contained in two different connections thus violating the restriction in its original form. As the example also demonstrates deductive reasoning in TL is skeptical reasoning in the sense used in the AI literature [53]. Similarly we get a proof for the formula

$$P \,\&\, (Q \mid R) \Rightarrow P \,\&\, Q \mid P \,\&\, R.$$

Just for simplicity we kept all our examples at the propositional level. In general, formulas may include quantifiers which require the additional property of unifiability of connected literals. Otherwise everything goes as described. In the presence of quantifiers we may also consider more than one instance of a given action rule each of which is to be treated as a separate rule just like the ones in our examples so far. In fact this enables us to avoid the !-operator used for this purpose in linear logic (although there would be nothing wrong with introducing it in TL as well).

5. Planning, temporal projection, and postdiction

Planning is the main topic of this paper. So what has the formalism, TL, introduced in the last two sections to do with planning? Well, given a description of an initial state (say G_0), of a goal state (F), and of the possible actions in terms of r-implicational formulas

$(F_i \Rightarrow G_i)$, then all we need to do is to activate a theorem prover for TL. Any proof it finds represents a plan which satisfies the description. The actions determined by the plan are those action rules used in the proof. Their order of execution is determined by the chains of connections establishing the proof from the initial to the goal situation.

For instance, consider the formula

$$(P_0 \Rightarrow P_1) \wedge (P_1 \Rightarrow P_2) \wedge (Q_0 \Rightarrow Q_1) \wedge (Q_1 \Rightarrow Q_2) \rightarrow (P_0 \,\&\, Q_0 \Rightarrow P_2 \,\&\, Q_2).$$

It may be interpreted as dressing one's left (P) and right (Q) foot (index 0) with a sock (1) and a shoe (2). There are no alternate choices for the 8 connections which establish the proof for this formula, so the reader may easily identify them. As these connections prescribe, the P_0-rule must precede the P_1-rule and similarly for the Q-rules. On the other hand the P-connections are independent from the Q-connections in terms of any order. So the plan leaves open in which order the actions for the left and right foot are mixed together which may therefore be determined arbitrarily. That is, the resulting plans are partially ordered ones as is desirable for applications.

For the formula

$$(P \,\&\, Q \Rightarrow P \,\&\, \neg Q) \wedge (P \Rightarrow \neg P) \rightarrow (P \,\&\, Q \Rightarrow \neg P \,\&\, \neg Q)$$

its five connections establishing validity determine a linearly ordered plan since the second rule can only be executed after the first one. The formula may be interpreted as the adultery drama by Drew McDermott (personal communication) whereby a husband (P) shoots his rival $(\neg Q)$ and *then* himself $(\neg P)$, and not the other way round, which obviously would not yield a proof in our logic.

For decades formalisms for planning were plagued by the notorious *frame problem* [48]: how to characterize the "frame" of an action, i.e., everything not affected by the action. The aspects of the frame problem now called *representational* and *inferential* frame problem [60] are no problems any more in our formalism, which is in stark contrast to the most popular competitor, namely the situation calculus (see Section 6). In fact, LCM has been the first method which actually solved these aspects of the frame problem and did so in the optimally possible way.

So our logic and its deductive machinery are fully appropriate for solving planning tasks of the sort considered so far. In certain contexts one might expect an explicit answer, i.e., a concrete plan. For that purpose [9] employed a well-known answer extraction technique [29] by introducing state literals, $S(x)$, which keep trace of the states passed through while executing a plan. This also requires that an action rule such as the suicide killing rule above would read $S(x) \,\&\, P \Rightarrow S(suicide(x)) \,\&\, \neg P$. By unification the variable denoting the goal situation will then along with a successful proof always provide a term which expresses the linearized sequence of actions. In this option the planning system might compute all possible proofs and offer all corresponding plans as alternatives. The option also allows for multiple copies of action rules (by way of the quantifier involved) if needed, the way mentioned at the end of the last section.

There are modes other than planning which are of interest in our context. One such mode is called *temporal projection*: given the initial state and the sequence of actions, determine the resulting state. Or, in another mode called *postdiction*, one would like to determine the initial state in order to explain with it the observed outcome of a sequence

of actions. Since theorem provers can be used in all these modes as well, namely theorem checking (i.e., planning), proof checking (i.e., temporal projection), abduction (i.e., a form of postdiction), all these and other modes can of course be modelled by proof systems for TL. That is, the deductive approach is as versatile as one would wish.

6. Semantics and alternative formalisms

In principle there are two ways to provide the logic TL introduced in the previous sections with a precise semantics, the direct and the indirect one. In Section 3 as well as in [4] the direct route has been taken. Informally, we may think of a Kripke-style semantics with an actual and further worlds. Whenever a proof activates a rule with a $\Rightarrow$ the transition from the premises to the conclusion amounts to a transition from the present world to some next one which differs from the present one only in the changes specified by the rule.

The indirect way to specify a semantics consists in embedding TL in an existing formalism for which a semantics is already known. In the next and the third subsection we describe two formalisms which were used for this purpose. Otherwise the section compares TL with several related formalisms.

6.1. TL and LL

A very close relative of TL is *linear logic* [28] which was first published about two years after the first publication of LCM [10], predecessor and part of TL.[3] We briefly summarize what is known about the relationship of TL with linear logic (LL).

For that purpose we restrict the language of TL to its r-formulas only, i.e., dispense with any classical background theory T and refer as rTL (or LCM for that matter) to this restricted part of TL. Further we consider only r-formulas without | and refer to crTL to this part of TL. Theorem 35 in [24] states (among other things) that crTL and the multiplicative part of LL with the exchange and the weakening rule, also known as (classical) BCK [59] (or affine logic), amount to the same thing (in terms of derivability). A similar result was obtained in [27]. Its Theorem 4.1 states (among other things) that crTL and conjunctive linear theories as defined in [50] on the basis of LL amount again to the same thing (in terms of derivability). In other words, TL and LL more or less coincide in their multiplicative parts so that crTL may inherit its semantics from LL [25].[4] Although it has not been shown in detail, it is conjectured that these results may be generalized to rTL. In fact, LL is as expressive as TL since classical logic can be embedded in LL [28]. On the other hand, we have proposed for practical purposes a much more restricted class of formulas both by the definition of the language of TL itself (no arbitrary nesting of classical and non-classical operators) and by the restriction of the formulas in its r-part (to a rule form). Finally, LL's proof nets are but another name of LCM's spanning matings satisfying the

[3] Only later it became clear that [40] as well as *relevance logic* [1] are important predecessors of LCM as of linear logic.

[4] Note that we did not follow the unintuitive notation used in LL: TL's $\Rightarrow$, &, | correspond to LL's $\multimap$, $\otimes$, $\oplus$, respectively (while the two remaining binary junctors of linear logic can be defined in terms of these three ones).

linearity restriction (with the minor difference that not *all* literals need to be connected in LCM, an advantage of LCM or TL over LL again from a practical point of view). In summary, although TL is a linear-logic-type of logic it offers more attractions than LL for practical purposes.

To [24] we owe much of the formal background. For instance, its Chapter 3 provides a formal justification of our use of the matrix representation (for crTL at any rate). There is a slight difference between the linearity restriction used in the present paper and the corresponding restriction in Theorem 35 of [24] as the latter uses the restriction in its original form (mentioned in Section 4).

6.2. TL and STRIPS

Many planning systems are based on the STRIPS formalism introduced in [21]. This uses operators defined by schemas using precondition, add, and delete lists. As an example consider the following move-operator in a blocks world.

MOVE(x, y, z)
PRE: CLEAR(x), ON(x, y), CLEAR(z)
ADD: CLEAR(y), ON(x, z)
DEL: CLEAR(z), ON(x, y)

In TL's notation the same is expressed as

$$\text{CLEAR}(x) \,\&\, \text{ON}(x, y) \,\&\, \text{CLEAR}(z) \Rightarrow \text{CLEAR}(x) \,\&\, \text{ON}(x, z) \,\&\, \text{CLEAR}(y)$$

The preconditions here are the same as in PRE above and the postconditions include all literals from ADD which both is true in general. In TL *all* preconditions are consumed, i.e., "deleted", so that there is nothing like DEL. In compensation non-deleted preconditions have to be stated explicitly again in the postcondition. As mentioned in the previous section the name of the operator could optionally be integrated in the rule within the state literal not shown here for simplicity. In summary, crTL may be regarded as an approximate logical version of the STRIPS formalism.[5] In other words, TL inherits all advantages from STRIPS but as an *additional* feature it has also the expressiveness of classical logic.

6.3. TL and the fluent calculus

In [32] a classical calculus, in the meantime named *fluent calculus* (FC), has been introduced, which represents the manipulations of actions on the term level of classical logic. This is done in the tradition of representing the object-level of a calculus logically at the meta-level (see, e.g., [37]), illustrated in the following with the previous blocks example.

Predicate symbols such as MOVE, CLEAR or ON become functional symbols, say mv, cl and on, respectively. The logical operation & is represented as a functional as well, say $\circ$. The entire action is then a formula $Action(c, a, e)$ which reads as follows:

$$c = cl(x) \circ on(x, y) \circ cl(z) \wedge a = mv(x, y, z) \wedge e = cl(x) \circ on(x, z) \circ cl(y).$$

[5] Section 8.2 in [24] gives examples which demonstrate that the correspondence is not an exact one.

As can be seen it specifies the preconditions, the name and the effects of the action in an equational setting. The transition $Result(s, a, s')$ from the state s to the state s' caused by the action a is represented by the following formula:

$$Action(c, a, e) \wedge c \circ z = s \wedge s' = z \circ e.$$

Note the variable z summarizing the part of the state not affected by the action. Planning problems are stated in this approach by a goal literal asking for a plan (i.e., a sequence of actions) which transforms the initial state (a term like the ones shown) to the goal state on the basis of a theory (i.e., a logic program) which describes all possible actions and specifies the properties of $\circ$ appropriately (associative, commutative, non-idempotent, neutral element). More details on FC can be found, e.g., in [65]. A different but closely related approach can be found in [19].

The main advantage of FC is that it has a standard classical semantics [64]. Further, the resulting programs can be run by any equational PROLOG system. It is not clear at this point whether these advantages outweigh the potential disadvantages of a representational and computational nature. Any unbiased reader will agree that the last two formulas specifying the result of an action is awkward and much harder to read than the corresponding formula in TL shown further above. While appropriate interfaces for casual users may provide a remedy for this, researchers and programmers have still to work on this representational level.

The already mentioned Theorem 4.1 in [27] also states that crTL and the (conjunctive) fluent calculus just presented amount again to the same thing (in terms of derivability) thus indirectly providing a classical semantics to TL. Somehow one might be able to generalize the fluent calculus to model the full TL. Future practice has to determine which of the two will eventually prevail.

6.4. *Situation calculus and others*

The most popular formalism for representing actions is clearly the *situation calculus* [48] described in any standard AI book such as [60]. Again this is just a classical predicate calculus (with its standard semantics) which encodes the change from one situation to the next in the form of an *effect axiom* by an extra parameter s in each *fluent* predicate such as ON above. In addition one needs numerous *frame axioms*, or alternatively *successor-state axioms* [58] which combine effect and frame axioms in an elegant way which clearly impede the efficiency of any implementation of the situation calculus. One of the main attractions of all formalisms mentioned so far (i.e., LCM, TL, LL, STRIPS, FC) is that *no* such additional axioms are needed at all. For a more detailed comparative analysis of this drawback for the situational calculus see [24].

Given that planning occurs in time it is not surprising that temporal or dynamic logics offer the potential for formalizing planning. One such approach for reasoning about plans and its properties (i.e., not for planning itself) using dynamic logic is reported in [62] which like the situation calculus suffers from the lack of resource-sensitivity. In addition there are numerous variants of the formalisms mentioned so far. The most noteworthy of these in terms of performance is the SATPLAN system which encodes planning within the STRIPS formalism as a satisfiability problem in classical propositional logic [36].

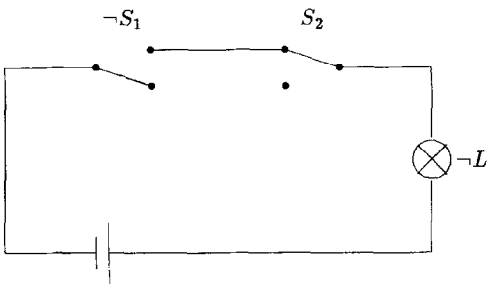


Fig. 1. An electric circuit consisting of a battery, two switches, and a light bulb which shines if the two switches are in the upper position.

7. Modelling action and causality

Providing a deductive formalism for planning is one thing; a different is to show how it is used to model the various aspects underlying actions and causality. In the present section we will discuss the most important among these aspects and show how TL is able to deal with them. Although we always take the planning for illustration, it should be clear that all the other modes of reasoning discussed in the previous section are handled similarly.

7.1. Ramification

It is said that the wing-stroke of a butterfly might be the cause of a tornado somewhere else on the globe. Human reasoning is clearly unable to consider such remote consequences. Rather we assume the *law of persistence*, which states that nothing is changed by some action except for the changes caused directly by it and by the indirect but overseeable consequences from these. The problem how to compute such indirect consequences is called the *ramification problem*. Consider the electric circuit depicted in Fig. 1 for illustration. [6]

We tacitly assume that there is voltage. The depicted state can formally be captured as $\neg S_1 \,\&\, S_2 \,\&\, \neg L$. Now assume we toggle S_1 by means of the action described as $\neg S_1 \Rightarrow S_1$ in TL. The resultant state $S_1 \,\&\, S_2 \,\&\, \neg L$ is inconsistent with physics which teaches that in consequence of this action also light will go on. The problem is how a planning formalism may cope with this ramification. We present here a solution which in essence is the same as the one in [65] but accommodated to TL's (rather than FC's) formalism.

Obviously, we need an additional action of the form $S_1 \,\&\, S_2 \,\&\, \neg L \Rightarrow S_1 \,\&\, S_2 \,\&\, L$ which causes light whenever both switches are on without changing the state of the switches. Further we must teach the reasoning mechanism that (i) this latter action is never activated except in consequence of toggling one of the two switches and (ii) the action is indeed activated whenever its conditions become fulfilled by toggling one or the other switch. There are many ways to implement the control of the proof mechanism specified by these two points. We describe here a rather simple one which does the trick along with a general control specification.

[6] The discussion in this section closely follows [65] from which the examples are borrowed.

In this simple solution the transition rules are partitioned into primary and secondary ones. The primary rules are our action rules considered so far. The secondary ones are called *causal* rules and are characterized by the occurrence of so-called *causal* literals, denoted as L^c, among the actions preconditions. In our example both switches are causal for the light to go on. Hence the rule along with this additional control information now reads $S_1^c \,\&\, S_2^c \,\&\, \neg L \Rightarrow S_1 \,\&\, S_2 \,\&\, L$. *In the initial situation as well as in any situation resulting from a primary action all causal rules are activated whose causal conditions became true in the situation either directly by the action or indirectly by the activation of causal rules.* That is, any action (including the one "leading" to the initial situation) triggers the activation of causal actions until a stable state is reached. We refer to this as the *causality-has-preference* strategy, or CP for short.

In our example the light action is not applicable in the initial state. But once the S_1-rule is activated the causal rule follows suite according to CP so that the resulting state becomes $S_1 \,\&\, S_2 \,\&\, L$ as expected. The complete formal description of the example would thus altogether have four (primary) rules for opening and closing the switches and three causal rules, namely $\neg S_i^c \,\&\, L \Rightarrow \neg S_i \,\&\, \neg L$, $i = 1, 2$, and the one already presented.

An immediate objection to this solution might be that the transition rules will become cumbersome as the number of conditions increases. Among others it is here where our general approach pays off. Namely, we may of course abbreviate these conditions by a definition in the classical part of the formula, say $C^c \leftrightarrow S_1^c \,\&\, S_2^c$ and thus reduce any such transition rule to something like $C^c \,\&\, \neg L \Rightarrow C \,\&\, L$. Specifying the conditions, under which there will be light, can of course not fully be dispensed with. But there is a full range of varieties how this may be done. For instance, it may be broken down into a set of rules in the present case: current causes light; if (there is voltage and) the circuit is closed then there is current; if the circuit except for S_1 is closed and S_1 is closed then the entire circuit is closed; and so forth.

CP has been tested for a number of examples discussed in the literature, also for those where other methods have failed [65]. For instance, [31] handles already the given example incorrectly. The remedy suggested in [41] is insufficient either, as the extended circuit depicted in Fig. 2 demonstrates.

The depicted state can formally be captured as $\neg S_1 \,\&\, S_2 \,\&\, \neg S_3 \,\&\, \neg R \,\&\, \neg L$. Physics determines the following rules. $\neg S_1^c \,\&\, S_3^c \,\&\, \neg R \Rightarrow \neg S_1 \,\&\, S_3 \,\&\, R$, i.e., the relay becomes

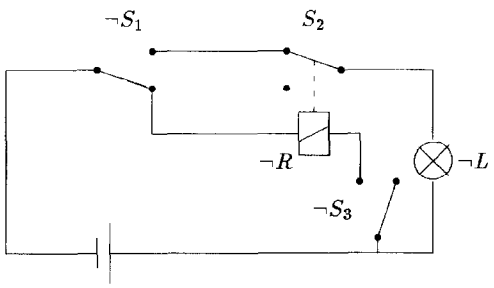


Fig. 2. An extended electric circuit, which includes a third switch, S_3, and a relay, R, which attracts switch S_2 if activated.

activated; $R^c \,\&\, S_2 \Rightarrow R \,\&\, \neg S_2$, i.e., the relay opens S_2; and $S_1^c \,\&\, S_2^c \,\&\, \neg L \Rightarrow S_1 \,\&\, S_2 \,\&\, L$, i.e., light goes on. Closing S_1 in the current state causes light (rather than S_2) to open which suggests that S_2 be a *frame* fluent in the sense of [41]. On the other hand, closing S_3 in the state depicted in the figure results in an activation of the relay and, in consequence, in S_2 opening which suggests that it be a *non-frame* fluent. In other words, Lifschitz' categorization of fluents does *not* work in this example. We need to *categorize the actions* into primary and secondary ones (rather than the fluents) as done in the solution presented in this section.

In [64] an example of two coupled switches (if one is closed or opened the other follows suite) is given which demonstrates that indeed we need distinguish the preconditions of causal rules into causal and conditional ones as we did. The coupling rules are $S_1^c \,\&\, \neg S_2 \Rightarrow S_1 \,\&\, S_2$ and $\neg S_2^c \,\&\, S_1 \Rightarrow \neg S_2 \,\&\, \neg S_1$. Logically the preconditions of the two rules are identical, but only the first is triggered if S_1 is closed and only the second if S_2 is opened as desired.

7.2. *Qualification*

Although we have now a formalism which is capable of modelling actions and their consequences, there are still a number of additional issues to be considered before we can expect the formalism to play a crucial role in the reasoning of an intelligent agent. In the present section we will show how to deal with situations where certain transition rules normally available should reasonably not be applied.

In all previous examples we tacitly assumed that the actions are executable. In reality this assumption often depends on numerous conditions, too many in fact to be checked in detail. Switches can be brocken, circuits cut, light bulbs be damaged, and so forth. How to deal with this infinity of possibilities is known as the *qualification problem* [46]. There is a rich literature on nonmonotonic reasoning coping with this problem [7]. TL opens a new way to deal with the problem. Why not using Tweety again to illustrate it.

Tweety is a bird (Bt) as well as a penguin (Pt). Birds fly (F) and have wings (W). Penguins are exceptional birds in that they do not fly which we express as a transition rule in the following valid formula: [7]

$$(Bx \to Fx \wedge Wx) \wedge (Px \to Bx) \wedge [Px^c \,\&\, Fx \Rightarrow Px \,\&\, \neg Fx] \to (Bt \,\&\, Pt \Rightarrow \neg Ft \,\&\, Wt).$$

The technique introduced in the previous section guarantees that the transition rule is triggered to achieve sort of an update in the form of a pseudo-causal effect (causing a change in one's mental state) which prevents the wrong conclusion of Tweety flying.

The technique is applicable even beyond nonmonotonic reasoning because we may additionally account for causal relationships. The solution is again adapted to TL from [63]'s FC using the example discussed there in great detail.

Assume we want to start the car's engine (E). This might be prevented by a potato in the tail pipe (T) which clogs (C) it. In order to put the potato into the tail pipe, one must lift it which again may be prevented if it is too heavy (H). The point of the example is twofold.

[7] The example could as well be modeled using an abnormality literal the way demonstrated in the subsequent example.

First, we normally expect to be able to start the engine and to put a potato into the tail pipe unless there is reason to believe otherwise. Following McCarthy's idea we therefore additionally introduce an abnormality fluent for the two actions, i.e., A_s and A_p. So the start action reads $\neg E \,\&\, \neg A_s \Rightarrow E \,\&\, \neg A_s$ and the put action $\neg T \,\&\, \neg A_p \Rightarrow T \,\&\, \neg A_p$. The clogging is a causal consequence of the potato in the tail pipe, hence we also have the causal rule $T^c \Rightarrow C$. In the case of more than one car we of course better switch to a first-order version of these rules.

The second aspect illustrated by the example is that we obtain unintuitive results if we simply minimize the truth of the abnormality predicates as done in nonmonotonic reasoning of a non-causal nature [63]. This is because the successful execution of an action (like putting a potato into the tail pipe) may *change* the state of our beliefs in the executability of other actions (like starting the engine). In other words, we additionally need a causal rule $C^c \,\&\, \neg A_s \Rightarrow C \,\&\, A_s$ for changing the state of abnormality under such circumstances. Similarly, we have the causal rule $H^c \,\&\, \neg A_p \Rightarrow H \,\&\, A_p$.

Among all occurring fluents $\mathcal{F}$ a subset $\mathcal{F}_a$ is singled out whose members are initially assumed not to hold, by default. In the present example we have $\mathcal{F}_a = \{T, C, H, A_s, A_p\}$ in accordance with the example's intentions. Of these as many as consistent with the available knowledge are "assumed away", i.e., their negation is included in the specification of the initial state. For the precise definition of the underlying model preference see [63] where besides the theoretical underpinnings also other issues such as spontaneous change are discussed.

If nothing specifically is known about abnormalities then starting the car will work by way of the start action and the given knowledge. If a potato is known to be (or by the appropriate action is put) in the tail pipe then both clogging and A_s becomes a causal consequence by the corresponding causal rules. Similarly, in the case of too heavy potatoes this is prevented to happen by the causal rule which makes A_p true. In other words, with the formal model presented here the reasoning leads to the expected consequences under all circumstances.

7.3. *Specificity*

If you hold (H) a penny (p) and drop it, it will end up lying on the floor (F); i.e., the drop action may be described as $Hx \Rightarrow Fx$. If you drop a fragile (or breakable B) glass (g) rather than a penny, it will be broken (or destroyed D) afterwards, i.e., $Hx \,\&\, Bx \Rightarrow Fx \,\&\, Dx$. How should a system distinguish the two cases and correctly choose the latter action in the case of a glass in hand, i.e., an initial state described by $Hg \,\&\, Bg$?

[33,34] give an easy solution for this problem which seems to work in many other occasions of a similar nature. *If in a given state more than one rule applies, the control of the deductive system prefers the most specific one*, referred to as the *more-specific-has-priority*, or SP, strategy. Thereby, r_1 is called *more specific* than r_2, $r_1 > r_2$, if for $r_i = A_i \Rightarrow B_i$, $i = 1, 2$, and some r-formula A_3, $A_1 = A_2 \,\&\, A_3$ (modulo associativity and commutativity of $\&$).

Since obviously $Hx \,\&\, Bx > Hx$, the system will indeed choose the right action in our illustrating example if its control is determined by SP.

7.4. Timing of actions

In order to achieve goals in a dynamic world the required actions often need to interact in a timely way. For instance, think of a table with glasses on it which needs to be carried in another corner of the room by two agents. If the persons do not lift the table simultaneously, the glasses will fall down and break. How could an appropriate timing be achieved in TL?

Similarly as in [16] we introduce a *compound* transition rule $A_1\overline{x} \,\&\, A_2\overline{x} \Rightarrow B_1\overline{x} \,\&\, B_2\overline{x}$ for any two (atomic or compound) transition rules $A_i\overline{x} \Rightarrow B_i\overline{x}$, $i = 1, 2$. A compound rule (as any rule) represents an action whose parts are carried out at the same time. To model our example, the two ends, t_1 and t_2, of the table initially are standing on the floor, $St_1 \,\&\, St_2$. The compound rule $Sx_1 \,\&\, Sx_2 \Rightarrow Hx_1 \,\&\, Hx_2$ is the most specific rule in this scenario which is applicable to the initial state. Hence the SP strategy from the previous subsection will choose it thus leading to the desired state of holding the table at both ends at the same time after lifting it simultaneously. This illustrates one solution to the question raised above.

A different solution may be obtained by introducing time explicitly and thus force actions to occur at a certain time point (e.g., at the same time) or time interval. Since communication of information is an action as well, we may model the negotiation and the agreement over a certain time point t_l for lifting the table ends among the two agents. In this case the lifting rule might look like $Sx \,\&\, Tt_l \Rightarrow Hx \,\&\, T(t_l + 1)$. Each agent would be provided with an initially synchronized and ticking clock, $T(x) \Rightarrow T(x + 1)$, and this way each could make sure that it lifts the table end at the agreed time. These techniques have particular relevance for modelling hardware circuitry and its behavior.

If for other applications we need to fix the time point of states occurring *during* the execution of an action, $A\overline{x} \Rightarrow B\overline{x}$, we may break up and partition the action, for instance, into initial situation, action event, and resultant situation, $A\overline{x} \Rightarrow N\overline{x}$ and $N\overline{x} \Rightarrow B\overline{x}$ [30]. Thereby N is a unique n-ary predicate serving as the *name* of the event occurring during the action, and n is the number of variables involved in the rule.

7.5. Indeterminism

Planning supports a more rational behavior. Yet it is a feature of life that much will remain unpredictable. Rational planning must therefore take indeterminism into account explicitly.

There are different kinds of undeterminism. No one, for instance, achieved so far to determine in a reliable way the outcome of throwing a dice in advance. Hence the throwing action has an undetermined outcome, $D \Rightarrow 1 \mid 2 \mid 3 \mid 4 \mid 5 \mid 6$. Similarly, we must account for our ignorance of the details of the physics determining the outcome of many actions in reality. We may think of nature as an agent whose intentions we know only up to a certain degree in these cases. As the example demonstrates, TL is able to model such examples to some extent. In a more elaborate approach one would have to integrate probabilities and possibilities into TL the way already achieved for classical logic (see Section 4.4 in [7] for more details and references). A particularly attractive approach for doing this has been described in [54,55].

Nature is more predictable than other agents such as human beings where probabilities might not help either. Here we must take into account even contradictory actions. For

instance, if you try to open (O) a closed (C) door, $C \Rightarrow \neg C$, which some other agent simultaneously tries to keep closed from the door's other side, $C \Rightarrow C$, the compound action formalizing the two simultaneous actions, $C \,\&\, C \Rightarrow C \,\&\, \neg C$, does lead to nothing explicitly. From a practical point of view we may exclude connections within the same situation such as the one in the conclusion of this rule, and go on with the reasoning in spite of the contradiction. In fact we may even teach the system to consider either outcome of the conclusion in such a case (cf. also [16]).

In modeling agents in their decision behavior we have further to include utilities. Influence diagrams [53] are general means for this purpose. It is rather straightforward to model such a decision network in terms of TL so that again this logic proves appropriate for modeling intelligent action in this context.

7.6. *Miscellaneous*

It is clear that planning and reasoning about action and causility cannot be treated exhaustively in a single paper. In fact we believe that a number of important issues have yet to be settled before an autonomous agent built on the basis of TL (or any other formalism for that matter) will behave intelligently in a dynamic and uncertain environment. We conclude this entire section, therefore, with just mentioning a few further issues which would merit a more extensive treatment were there further space available. The list is certainly not a comprehensive one.

Deductive planning will have to take into account important features from classical planning in some way. An example for these are *causal* and *protected links* [60]. Often such features are already supplied by the deductive engine itself. For instance, a causal link is just a connection and protecting them is subsumed by any sophisticated proof strategy designed to identify a spanning mating as efficiently as possible. In particular if a causal link is the only one to achieve a certain subgoal then we have exactly what in automated deduction is known under the term ISOL reduction [14]. Since reductions are not reconsidered in any deductive system, link protection is taken care there automatically.

Hierarchical planning is of crucial importance for successful applications. In our view it is a matter of structuring the knowledge base containing action descriptions and of controlling the deduction engine. For instance, at the highest level (0) we would have actions of the sort "*go from here to the train station*", $H \Rightarrow^0 T$. On the next level of detail (1) the system would try to refine the 0-level rule with 1-level rules such that altogether the same global effect is achieved, i.e., $(H \Rightarrow^1 I_1) \wedge (I_1' \Rightarrow^1 I_2) \wedge \cdots \wedge (I_n' \Rightarrow^1 T)$. A related solution has been worked out for FC in [20].

In dynamic environments any plan is bound to fail to some extent. It is therefore essential to be able to react to such failure with efficient *replanning*. This requires among other things a technique for the manipulation of partial plans [42,66].

Autonomous agents need to carry out their planning under strict *time constraints*. A logical solution for this particular problem has been proposed in [52] which could be adapted to TL.

In reality we have to cope with *continuous* processes while it seems that TL could cope with discrete actions only. Modelling continuous processes within a logic has become an active area of research though. One issue concerns the partitioning of such a process

into reasonable discrete parts [35]. Another issue concerns the integration of differential equations and their computation within a logic such as TL (cf. [61]).

As a final point we mention that TL may also be seen as a logical version of an imperative programming language. For instance, destructive assignment $x := t$ may be modelled as the transition rule $\exists y\, \mathrm{cont}(x, y) \Rightarrow \mathrm{cont}(x, t)$, an attractive potential of TL (or some of its cousins) as a future logic programming language. Some steps into such a direction have already been made in [17,44].

8. The case for logic

Intellectics as well as computer science are general disciplines whose generic methods turn out to be applicable in many different areas. For instance, expert system technology has successfully been used in a great variety of applications. The logical approach within intellectics (as within computer science) is even one level more general than the remainder of this field as it attempts to mechanize the reasoning required by those who build traditional AI systems. In theory, generality wins in the long run, in practice specialization always wins in the short run. These facts explain why engineers are extremely skeptical with general approaches such as the logical one. In fact, there is still some resistance even against the less general areas in intellectics or computer science. The facts also explain why the following pattern in the history of intellectics may be observed.

Some subject—e.g., knowledge representation in the early seventies—gains in importance for applications. The engineers are the first to notice the need for activity and start developing specialized solutions. As soon as preliminary solutions are emerging the logicists get notice and claim their competence in the subject due to the logical generality—cf. the KR debate in the mid-seventies. Overwhelming theoretical evidence supporting the claim is provided by logicists over the subsequent years which finally leads to its acceptance (as it happened for KR in the eighties and is currently happening in the case of planning). Yet the logical approach is still not entering the engineering practice because it is believed to lack efficiency in comparison with specialized systems. Eventually, someone in automated deduction disproves this belief experimentally (see, e.g., [56] in the case of KR). Nevertheless the well established tools persist in applications for obvious reasons (resistence against transition costs and such).

Logicists deplore the time "lost" by the multiple development of the same techniques in many disguises and dream of a state of the art where all these myriads of man-years are rather invested into the advancement of logical tools. For each application they are bound always to come too late in competition with the specialists. This is not only because there are always more specialists than logicists, but also because the logicists face far more complex problems to be solved than the specialists due to the generality of their approach.

The pattern just described will not be changed by the complaints of the logicists. But change it will at some point in the future for the following reasons. The applications of AI techniques are all rather limited in scope so far. There is still no technological push towards more generally intelligent systems. Only when such a push sets in will generality count in a crucial way. Intelligence has so many aspects that no individual (group of) specialist(s) will ever be able to build systems featuring more than one or two of these

aspects. Rather a truly intelligent system will require the incorporation of knowledge available only through a great many specialists—from small niches such as planning, nonmonotonic reasoning, scheduling, theorem proving, vision, speach, NL, ..., you name further ones of the hundreds of others—which cannot be realized by the present technology of systems building.

To understand why, note that the current technology is intrinsically functional (in a broad sense of the word). Any complex system consists of numerous modules which functionally depend on each other. That means that there must be at least one single person who oversees the whole, at least at some level of abstraction. This in turn means that the present technology is limited to the extent that single persons can cope with the complexity of systems and the huge variety of languages in which they are coded. A breakthrough is needed before this barrier is overcome. It will happen by way of the logical approach since only logic features the property of *conjunctivity* (versus functionality): a logical specification remains a specification if additional knowledge is added conjunctively to it. This way many people may contribute their knowledge in the most natural form into a common system which would then be synthesized from the joint specification in a rather formal (i.e., again logical) manner [13]. Section 7 demonstrates a bit of the conjunctive nature of logic since there we have drawn from knowledge in a number of different areas of intellectics.

Synthesis just brought into the picture is an important part of the vision outlined here. Generality does have a price in terms of lack of efficiency. With synthesis incorporated efficiency is not determined by the general logical specification with which the system is composed but by the functional systems obtained through a formal and reuseable synthesis process controlled if not discovered by machine. The unsubstantiated claim often made that deductive methods for planning and other applications do not scale is probably always made in ignorance of the important fact that functionality and specialization can and are meant to be introduced by synthesis in this way.

Much progress will be needed before all this may happen on a grander scale. Yet the progress made so far in the field of deduction is promising indeed, as can be seen from numerous results achieved lately. Among these the success of the system EQP/Otter stands out which automatically found a proof for the conjecture that any Robbins algebra is Boolean, a widely discussed mathematical problem which was open for more than sixty years [47]. From a technological point of view systems such as SETHEO [49] or KoMeT [3] have even an advantage over Otter (in the case of SETHEO demonstrated by its first place in the ATP competition during CADE-96) and have thus the potential for more such striking results. Before concluding this paper we give pointers to impressive results of a different sort from the area of planning.

Section 8.3 in [24] describes a simple and straightforward implementation of crTL on top of SETHEO, called *linear backward chainer* (LBC). The performance of LBC/SETHEO is then compared there with a widely used specialized planning system, UCPOP [57]. In these experiments with randomly generated blocks-world problems with five to seven blocks LBC/SETHEO outperforms UCPOP by several orders of magnitude. Because TL is so close to classical logic it can take advantage from the cumulative investment in advanced deductive systems for classical logic such as SETHEO, which can serve as the logic engine

in an expert system or as a theorem prover or as a planner or what have you. Note that no specialization to planning whatsoever is encoded in this approach.

Similarly, but even more impressively, [38] coded one of the best specialized planning systems, Graphplan [5], as a propositional satisfiable problem which is then solved by one of the best complete satisfiability algorithms, TABLEAU [18], or, alternatively, by the authors' Walksat, a stochastic local search algorithm for solving general SAT problems. The experiments outperform any known planning system again by several orders of magnitude. Note that this performance again is achieved by general logical systems which were used for a variety of other purposes. It would be interesting to see how a first-order prover such as SETHEO would fare for the specialized coding used in these experiments.

These successes show the way to future progress in AI: invest as much as could reasonably be afforded into the advancement of deductive techniques and systems like TABLEAU, SETHEO, or Walksat; code your special problem as efficiently as possible like in Graphplan; run the deductive system of your choice. In particular let's forget about specialized programming! Rather let us program deductively; let us plan deductively; above all, let's attack the challenge of creating artificial intelligence in a logical and deductive way!

Acknowledgments

An earlier version of this paper appeared in the *Proceedings of the 15th International Joint Conference on Artificial Intelligence*, published by IJCAII. The author is indebted to his students and collaborators for their continuing support. Among these as well as others, I want to thank especially Marc Friedman, Bertram Fronhöfer, Pat Hayes, Steffen Hölldobler, Vladimir Lifschitz, David Poole, Eric Sandewall, Enno Sandner, Stephan Schmitt and Michael Thielscher for numerous discussions and suggestions concerning contents and text of this paper. Among those just mentioned Bertram Fronhöfer has helped most with substantial contributions.

References

[1] A.R. Anderson, N.D. Belnap Jr, Entailment: The Logic of Relevance and Necessity, Vol. 1, Princeton University Press, Princeton, NJ, 1975.

[2] P. Agre, Computational research on interaction and agency, Artificial Intelligence 72 (1–2) (1995) 1–52.

[3] W. Bibel, S. Brüning, U. Egly, T. Rath, Towards an adequate theorem prover based on the connection method, in: I. Plander (Ed.), Proc. 6th International Conference on Artificial Intelligence and Information-Control of Robots, World Scientific Publishing Company, Singapore, 1994, pp. 137–148.

[4] W. Bibel, L.F. del Cerro, B. Fronhöfer, A. Herzig, Plan generation by linear proofs: on semantics, in: D. Metzing (Ed.), Proc. GWAI-89, Springer, Berlin, 1989, pp. 49–62.

[5] A.L. Blum, M.L. Furst, Fast planning through planning graph analysis, in: Proc. International Joint Conference on Artificial Intelligence (IJCAI-95), Montreal, Quebec, Morgan Kaufmann, San Mateo, CA, 1995, pp. 1636–1642.

[6] S. Brüning, G. Große, S. Hölldobler, J. Schneeberger, U. Sigmund, M. Thielscher, Disjunction in plan generation by equational logic programming, in: A. Horz (Ed.), Beiträge zum 7 Workshop Planen und Konfigurieren, GI, Arbeitspapiere der GMD 723, St. Augustin, Germany, 1992, pp. 18–26.

[7] W. Bibel, S. Hölldobler, T. Schaub, Wissensrepräsentation und Inferenz, Vieweg, Brauschweig, 1993.

[8] S. Brüning, S. Hölldobler, J. Schneeberger, U. Sigmund, M. Thielscher, Disjunction in resource-oriented deductive planning, in: D. Miller (Ed.), Proc. International Logic Programming Symposium (ILPS), Poster-session, MIT Press, Cambridge, MA, 1993, p. 670.

[9] W. Bibel, A deductive solution for plan generation, New Generation Computing 4 (1986) 115–132.

[10] W. Bibel, A deductive solution for plan generation, in: J.W. Schmidt, C. Thanos (Eds.), Foundations of Knowledge Base Management, Crete, 1986, pp. 413–436.

[11] W. Bibel, Automated Theorem Proving, Vieweg, Braunschweig, 2nd. ed., 1987.

[12] W. Bibel, Intellectics, in: S.C. Shapiro (Ed.), Encyclopedia of Artificial Intelligence, John Wiley, New York, 1992.

[13] W. Bibel, Towards predicative programming, in: M.R. Lowry, R. McCartney (Eds.), Automating Software Design, AAAI Press, Menlo Park, CA, 1992, pp. 405–423.

[14] W. Bibel, Deduction: Automated Logic, Academic Press, London, 1993.

[15] S. Brüning, Globally linear connection method, New Generation Computing Journal 15 (1997) 369–402.

[16] S.-E. Bornscheuer, M. Thielscher, Explicit and implicit indeterminism: reasoning about uncertain and contradictory specifications of dynamic systems, Journal of Logic Programming 31 (1–3) (1997) 119–156.

[17] I. Cervesato, F. Pfenning, A linear logical framework, in: E. Clarke (Ed.), Proc. 11th Annual Symp. on Logic in Computer Science, IEEE Computer Science Press, Silverspring, MD, 1996, pp. 264–275.

[18] J.M. Crawford, L.D. Auton, Experimental results on the crossover point in satisfiability problems, in: Proc. 11th National Conference on Artificial Intelligence (AAAI-93), Washington, DC, AAAI Press, Menlo Park, CA, 1993, pp. 21–27.

[19] S.J.S. Cranefield, A logical framework for practical planning, in: Proc. 10th European Conference on Artificial Intelligence (ECAI-92), Vienna, Austria, Wiley, London, UK, 1992, pp. 633–637.

[20] K. Eder, S. Hölldobler, M. Thielscher, An abstract machine for reasoning about situations, actions, and causality, in: R. Dyckhoff, H. Herre, P. Schroeder-Heister (Eds.), Proc. International Workshop on Extensions of Logic Programming (ELP), Lecture Notes in Artificial Intelligence, Vol. 1050, Springer, Berlin, 1996, pp. 137–151.

[21] R.E. Fikes, N.J. Nilsson, STRIPS: a new approach to the application of theorem proving to problem solving, Artificial Intelligence 2 (1971) 189–208.

[22] G. Frege, Begriffsschrift, Louis Nebert, Halle, 1879.

[23] B. Fronhöfer, Linearity and plan generation, New Generation Computing 5 (1987) 213–225.

[24] B. Fronhöfer, The Action-as-Implication Paradigm, CS Press, München, 1996.

[25] J. Gallier, Constructive logics. Part II: Linear logic and proof nets, Research Report PR2-RR-9, Digital Equipment Corporation, Paris, May 1991.

[26] G. Große, S. Hölldobler, J. Schneeberger, U. Sigmund, M. Thielscher, Equational logic programming, actions and change, in: K. Apt (Ed.), Proc. International Joint Conference and Symposium on Logic Programming, MIT Press, Cambridge, MA, 1992, pp. 177–191.

[27] G. Große, S. Hölldobler, J. Schneeberger, Linear deductive planning, Journal of Logic and Computation 6 (2) (1996) 233–262.

[28] J.-Y. Girard, Linear logic, Theoretical Computer Science 50 (1) (1987) 1–102.

[29] C. Green, Theorem proving by resolution as a basis for question-answering systems, in: B. Meltzer, D. Michie (Eds.), Machine Intelligence 4, Edinburgh University Press, 1969.

[30] G. Große, State event logic, Ph.D. Thesis, Technical University Darmstadt, Darmstadt, Germany, 1996.

[31] M.L. Ginsberg, D.E. Smith, Reasoning about action I: a possible worlds approach, Artificial Intelligence 35 (2) (1988) 165–195.

[32] S. Hölldobler, J. Schneeberger, A new deductive approach to planning, New Generation Computing 8 (1990) 225–244.

[33] S. Hölldobler, M. Thielscher, Actions and specificity, in: D. Miller (Ed.), Proc. International Logic Programming Symposium, 1993, pp. 164–180.

[34] S. Hölldobler, M. Thielscher, Computing change and specificity with equational logic programs, Annals of Mathematics and Artificial Intelligence 14 (1995) 99–133.

[35] C. Herrmann, M. Thielscher, Reasoning about continuous processes, in: W. Clancey, D. Weld (Eds.), AAAI-96—Proceedings of the National Conference on Artificial Intelligence, Portland, OR, AAAI Press, Palo Alto, CA, 1996, pp. 639–644.

[36] H. Kautz, D. McAllester, B. Selman, Encoding plans in propositional logic, in: L.C. Aiello, J. Doyle, S. Shapiro (Eds.), Proc. 5th International Conference on Principles of Knowledge Representation and Reasoning (KR-96), Cambridge, MA, Morgan Kaufmann, San Mateo, CA, 1996, pp. 374–384.
[37] R. Kowalski, Logic for Problem Solving, North-Holland, New York, 1979.
[38] H. Kautz, B. Selman, Pushing the envelope: planning, propositional logic, and stochastic search, in: Proc. National Conference on Artificial Intelligence (AAAI-96), Portland, OR, Morgan Kaufmann, San Mateo, CA, 1996, pp. 1194–1201.
[39] N. Kushmerick, Cognitivism and situated action: two views on intelligent agency, Computers and Artificial Intelligence 15 (5) (1996) 393–417.
[40] J. Lambek, The mathematics of sentence structure, Amer. Math. Monthly 65 1958.
[41] V. Lifschitz, Frames in the space of situations, Artificial Intelligence 46 (1990) 365–376.
[42] M. Lindner, Interactive planning for the assistance of human agents, Ph.D. Thesis, Techn. University Darmstadt, Germany, 1997.
[43] J.E. Laird, A. Newell, P.S. Rosenbloom, SOAR: an architecture for general intelligence, Artificial Intelligence 33 (1) (1987) 1–64.
[44] F. Lin, R. Reiter, Rules as actions: a situation calculus semantics for logic programs, Journal of Logic Programming 31 (1–3) (1997) 299–330.
[45] R. Letz, J. Schumann, S. Bayerl, W. Bibel, SETHEO—a high-performance theorem prover for first-order logic, Journal of Automated Reasoning 8 (2) (1992) 183–212.
[46] J. McCarthy, Epistemological problems of artificial intelligence, in: Proc. International Joint Conference on Artificial Intelligence, Cambridge, MA, Morgan Kaufmann, San Mateo, CA, 1977, pp. 1038–1044.
[47] W. McCune, Robbins algebras are boolean, Association for Automated Reasoning Newsletter 35 (1996) 1–3.
[48] J. McCarthy, P. Hayes, Some philosophical problems from the standpoint of artificial intelligence, in: B. Meltzer, D. Michie (Eds.), Machine Intelligence, Vol. 4, Edinburgh University Press, Edinburgh, 1969, pp. 463–502.
[49] M. Moser, O. Ibens, R. Letz, J. Steinbach, C. Goller, J. Schumann, K. Mayr, SETHEO and E-SETHEO, Journal of Automated Reasoning 18 (2) (1997) 237–246.
[50] M. Masseron, C. Tollu, J. Vauzielles, Generating plans in linear logic, in: Foundations of Software Technology and Theoretical Computer Science, Lecture Notes in Computer Science, Vol. 472, Springer, Berlin, 1990, pp. 63–75.
[51] N.J. Nilsson, Logic and artificial intelligence, Artificial Intelligence 47 (1–3) (1991) 31–56.
[52] M. Nirkhe, S. Kraus, D. Perlis, How to plan to meet a deadline between now and then, Journal of Logic and Computation, 1994.
[53] D.L. Poole, A.K. Mackworth, R.G. Goebel, Computational Intelligence—A Logical Approach, Oxford University Press, New York, 1998.
[54] D.L. Poole, Probabilistic Horn abduction and Bayesian networks, Artificial Intelligence 64 (1) (1993) 81–129.
[55] D. Poole, Probabilistic partial evaluation: Exploiting rule structure in probabilistic inference, in: M. Pollack (Ed.), 15th International Joint Conference on Artificial Intelligence (IJCAI-97), Nagoya, Japan, Morgan Kaufmann, Los Altos, 1997.
[56] M. Paramasivam, D.A. Plaisted, Automated deduction techniques for classification in description logic systems, Journal of Automated Reasoning, to appear.
[57] J.S. Penberthy, D. Weld, UCPOP: a sound, complete, partial order planner for ADL, in: Proc. International Conference of Knowledge Representation and Reasoning (KR-92), Cambridge, MA, Morgan Kaufmann, San Mateo, CA, 1992, pp. 103–114
[58] R. Reiter, The frame problem in the situation calculus: a simple solution (sometimes) and a completeness result for goal regression, in: V. Lifschitz (Ed.), Artificial Intelligence and Mathematical Theory of Computation: Papers in Honor of John McCarthy, Academic Press, New York, 1991, pp. 359–380.
[59] G. Restall, On logics without contraction, Ph.D. Thesis, University of Queensland, Australia, 1994.
[60] S.J. Russell, P. Norvig, Artificial Intelligence: A Modern Approach, Prentice-Hall, Englewood Cliffs, NJ, 1994.
[61] E. Sandewall, Combining logic and differential equations for describing real-world systems, in: R. Brachman, H.J. Levesque, R. Reiter (Eds.), Proc. International Conference on Principles of Knowledge

Representation and Reasoning (KR-89), Toronto, Ontario, Morgan Kaufmann, San Mateo, CA, 1989, pp. 412–420.

[62] W. Stephan, S. Biundo, A new logical framework for deductive planning, in: R. Bajcsy (Ed.), 13th International Joint Conference on Artificial Intelligence (IJCAI-93), Chambery, France, Morgan Kaufmann, San Mateo, CA, 1993, pp. 32–38.

[63] M. Thielscher, Causality and the qualification problem, in: L.C. Aiello, J. Doyle, S. Shapiro (Eds.), KR-96—Proc. International Conference of Knowledge Representation and Reasoning, KR Inc., Morgan Kaufmann, San Mateo, CA, 1996, pp. 51–62.

[64] M. Thielscher, Challenges for action theories: solving the ramification and qualification problem, Habilitation thesis, Techn. Universität Darmstadt, Darmstadt, Germany, 1997.

[65] M. Thielscher, Ramification and causality, Artificial Intelligence 89 (1–2) (1997) 317–364.

[66] D.E. Wilkins, K.L. Myers, J.D. Lowrance, L.P. Wesley, Planning and reacting in uncertain and dynamic environments, Journal of Experimental and Theoretical Artificial Intelligence 6 (1994) 197–227.