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ARGUMENTATIVE AGENTS FOR DIAGNOSIS IN DEFEASIBLE LOGIC

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Abstract. *Our case study is the diagnosis of deep venous thrombosis. We present a new approach to attain evidence-based medicine with advice from controlled trials. Preferences on actions and policies are used to induce a preferred course of action, while past experience, gathered from controlled trials, offers counter-arguments to improve the diagnosis process. The outcome of actions, introduced in the scenario and agent model, allows argumentation on actions, in a defeasible logic. The argumentative interplay between the agent using the rules recommended by specialists and the agent using the experimental outcomes of the controlled trials leads to a rational decision making mechanism very close to the one expected from human experts in the field.*
Keywords: *agents, defeasible logic, medical diagnosis.*

Introduction

Medicine is a domain where conflicts of opinion between specialists, each pondering a given situation based on their own role and expertise, are not unusual. The nature of the conflict could be related to the diagnosis itself, but also to the procedures to be performed on the patient and their reliability on the one hand, and the involved risks and costs on the other hand. The diagnosis is the result of the interaction between specialists with access to different sources of knowledge.

Multi-agent systems are a natural way of representing the roles in real world interactions between individuals with different knowledge, opinions and goals. An agent can improve its performance by communicating with other agents for finding answers to questions which fall out of its domain of expertise, which is why protocols for agent communication are an intensive area of research. For inter-agent argumentation in particular, different protocols have been tried. An example is the PARMA protocol [3], which allows participants to propose, attack and defend a course of action. Automated monitoring of medical protocols has been already tackled with a multi-agent system [2].

We consider the case of diagnosing patients suspected of deep venous thrombosis (DVT), which can be defined as the presence of an occlusive thrombus (clot) within a deep vein, impairing the normal blood flow. While sometimes it is possible to make decisions in diagnosis taking into account just the information available [1], quite often the uncertain knowledge should be captured by other means, like Bayesian networks [12]. The medical care process may also be captured by making use of the knowledge base of each role and also by additional knowledge needed to solve conflicts of opinion between roles [8].

After presenting the DVT scenario in the next section, we show an agent model with outcomes that enables us to extend argumentation to the actions to be performed. We employ defeasible logic [5][9][10], for representing diagnosis rules and rules that prescribe future actions. Then the scenario model is described in terms of the action theory, to be used in the argumentation system being developed in the Open Agent Architecture (OAA)[1] with Deimos[2] as argumentative system for answering queries.

[1]http://www.ai.sri.com/oaa/
[2]http://www.cit.gu.edu.au/arock/defeasible/Defeasible.cgi

Diagnosis of Deep Venous Thrombosis

Suspected deep venous thrombosis (DVT) is a common condition with lifetime cumulative incidence of 2-5\%, which untreated can result in a potentially fatal outcome.

Accurate diagnosis of DVT minimizes the risk of complications and averts exposure of patients to the risk of anticoagulant therapy. An agent acting to achieve such goals must find a course of actions that minimizes the risk for the patient at each moment, considering the equipment available for investigation, with its positive and negative predictive value.

The clinical model for the diagnosis of deep venous thrombosis has been extensively studied, although we use here just the knowledge in [7][13]. It is therefore a proper challenge problem for realistic acting.

Rules for diagnosis
Findings that are diagnostic of DVT (quoted from [7]) include the following:

1. Venous ultrasonography: Noncompressibility of the common femoral vein or popliteal vein (grade A). Noncompressibility that is confined to the superficial femoral vein, the distal portion of the popliteal vein, or the deep veins of the calf is associated with a lower predictive value (approximately 80%) and should be evaluated with venography (grade B).

2. Impedance plethysmography: Abnormal result and a high clinical suspicion of deep venous thrombosis (grade A). An abnormal result of impedance plethysmography combined with a moderate or low clinical suspicion of deep venous thrombosis should be evaluated with venous ultrasonography or venography (grade B).

3. Venography: Intraluminal filling defect seen in more than one view (grade A). Nonfilling of the deep veins despite repeated injection of contrast, although highly suggestive of deep venous thrombosis (grade C), must be interpreted in the light of clinical presentation and other investigations (such as results of impedance plethysmography or venous ultrasonography).
Similar rules express findings that exclude DVT (see [7]).

Controlled trials
An evaluation of d-dimer in the diagnosis of suspected DVT [13] has concluded that DVT can be ruled out in a patient who is judged clinically unlikely to have DVT and who has a negative d-dimer test, and therefore ultrasound testing can be safely omitted in such patients.

The results of this controlled trial are shown in Figure 1 (see [13]). All patients were first evaluated using a clinical model and divided into two groups considered (clinically) unlikely or likely to have DVT. They were then randomly assigned either to undergo ultrasound imaging alone (control group) or to undergo d-dimer testing.

Those in the later group then underwent ultrasound imaging (Ultrason) if they had been judged clinically likely or clinically unlikely to have DVT but the d-dimer test (!DD) was positive (+DD).

The primary outcome of this evaluation was the development of a venous thrombo-embolic event (VTE) in patients for whom DVT had initially been ruled out. They offer histories for re-evaluating the diagnosis model or, as we consider here, knowledge for an evaluation agent that can also provide cues for argumentation to the diagnosing agent.

For example, we can see that there were two patients judged clinically unlikely who, with a negative d-dimer test (¬DD), DVT was ruled out (¬DVT) but still developed a venous thrombo-embolic event (2 VTE).

For the patients judged clinically likely a second ultrasound imaging (Ultrason+) was performed after one week, which helped to reduce risk in the group with the d-dimer test.

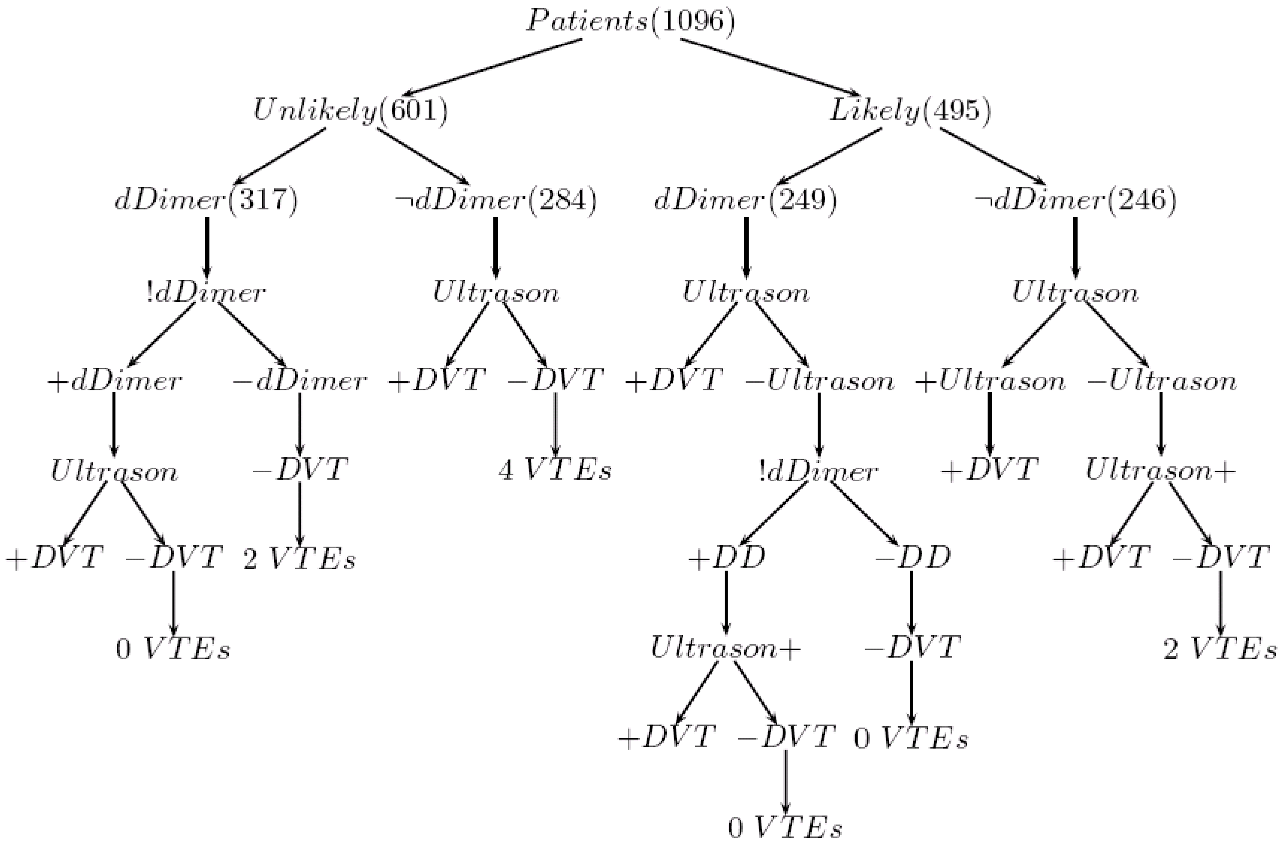

Figure 1. Patient outcomes in the evaluation trial.

Model of Acting Agent

The knowledge of the BAGO agent is represented by the tuple ⟨B, A, G, O⟩ with B: *beliefs* about the world, A: *actions* the agent is capable to carry out, G: agent *goals*, and O: *outcomes* of the actions of the agent and/or events, which are bipolar, that is a tuple⟨O+, O−⟩.

The fluents F used in the model have two subsets: *inertial fluents* F_I and *non-inertial fluents* F_N, with $F = F_I \cup F_N$ and $F_I \cap F_N = \phi$ as in [11]. We express dynamic causality by rules of the form:

$$f \xleftarrow{d} a, p_1,.., p_n \quad (1)$$

with $f \in F$, $a \in A$, $p_i \in F$ and static causality by rules like:

$$f \xleftarrow{s} p_1,.., p_n \quad (2)$$

where $f \in F_I$, $p_i \in F$ while executability conditions are given by:

$$a \xleftarrow{e} p_1,.., p_n \quad (3)$$

with $a \in A$, $p_i \in F$.

Preferences

The diagnosis process takes place on a time line and can be visualized as in (4).

$$\underbrace{s_0 a_0 s_1 .. a_{i=1}}_{\substack{H \\ \downarrow \\ past}} s_i \underbrace{a_i s_{i+1} .. s_{n-1} a_{n-1} s_n}_{\substack{F \\ \downarrow \\ future}} \quad (4)$$

In the state s_i the agents know the history H of the diagnosis process for the patient and have to decide about the future F, the remaining course of actions so that the proper conclusion is reached. That means that the patient will finally be diagnosed either as +DVT and the corresponding treatment will be applied or −DVT and no VTE event should occur in a reasonable period of time (three months in the controlled trial).

Argumentation theory

The defeasible theory we use (a knowledge base in defeasible logic, or a defeasible logic program) [5][9][10] consists of five different kinds of knowledge: facts, strict rules, defeasible rules, defeaters, and a superiority relation.

Facts are indisputable statements, for example, "John Smith is one of our patients", or "The result of the D-dimer test on John Smith was normal". These two facts would be expressed as:

→ patient(john smith).
→ dDimer(john smith, normal).

Strict rules are rules in the classical sense: whenever the premises are indisputable (e.g. facts), then so is the conclusion. An example of a strict rule is: "A patient with high clinical result is suspected of having DVT".

cl(P, h) → suspicious(P).

Defeasible rules are rules that can be defeated by contrary evidence. An example of such a rule is: "Patients with normal result on a d-Dimer test usually do not have DVT":

dDimer(Patient, normal)) ⇒ dvt(Patient).

The idea is that if we know a patient to have had a normal result on a dDimer test, then we may conclude that he/she does not have dvt, unless there is other, not inferior, evidence suggesting that he/she may have DVT.

Defeaters are rules that cannot be used to draw any conclusions. Their only use is to prevent some conclusions. An example is "If the d-Dimer test is performed on a patient and the result is abnormal, he/she might have DVT". This rule can not prove the DVT condition of the patient under discussion, but it prevents the negative diagnosis.

dDimer(Patient, abnormal) ⇝ dvt(Patient).

The superiority relation among rules is used to define priorities among rules, that is, where one rule may override the conclusion of another rule. For example, given the defeasible rules

r : dd(P, n) ⇒ dvt(P).
r' : ultra(P, nc(cf)) ⇒ dvt(P).

which contradict one another, no conclusive decision can be made about whether a patient with normal result on the dDimer test, and the ultrasonography test showing non-compressibility of the common femural vein has DVT. But if we introduce a superiority relation > with:

r' > r ,

with the intended meaning that r' is strictly stronger than r, then we can indeed conclude that the patient should be diagnosed positive for DVT.

All rules *r* have a consequent *C(r)* and a finite set of antecedents *A(r)*. We denote by R_s the set of strict rules in a theory, by R_d the set of defeasible rules, and their union by R_{sd}.

A conclusion of a defeasible theory *D* is a tagged literal that may be proved by *D*, and can have one of the following forms:

$+\Delta q$ which means that *q* is definitely provable in *D* (Figure 2).

$-\Delta q$ which means that *q* is not definitely provable in *D* (Figure 2).

$+\partial q$ meaning *q* is defeasibly provable in *D* (Figure 3).

$-\partial q$ meaning that *q* is not defeasibly provable in *D* (Figure 4).

A derivation *P = P(1),..,P(n)* is a finite sequence of tagged literals, satisfying the conditions in Figures 2, 3 and 4.

$$+\Delta:$$
$$\textit{If } P(i+1) = +\Delta q \textit{ then}:$$
$$\exists r \in R_s[q]\ \forall a \in A(r): +\Delta a \in P(1..i)$$
$$-\Delta:$$
$$\textit{If } P(i+1) = -\Delta q \textit{ then}:$$
$$\forall r \in R_s[q]\ \exists a \in A(r): +\Delta a \in P(1..i)$$

Figure 2. Definitely (not definitely) provable.

Figure 2 states the conditions for concluding whether a query is definitely provable. At step *i + 1* one can assert that *q* is definitely provable if there is a strict rule *r* with consequent *q* and all the antecedents of *r* have been asserted to be definitely provable in previous steps.

Similarly, the conclusion that *q* is not definitely provable can be reached at step *i + 1* if all strict rules having as consequent *q* have at least one antecedent previously asserted as not definitely provable.

A goal q which is not definitely provable is defeasibly provable if we can find a strict or defeasible rule r having q as a consequent for

$+\partial$:

If $P(i+1) = +\partial q$ *then either*

(1) $+\Delta q \in P(1..i)$ *or*

(2) (2.1) $\exists r \in R_{sd}[q]\ \forall a \in A(r) + \partial a \in P(1..i)$ *and*

(2.2) $-\Delta \sim q \in P(1..i)$ *and*

(2.3) $\forall s \in R[\sim q]\ \exists a \in A(s) : -\partial a \in P(1..i)$

Figure 3. Defeasibly provable.

which all antecedents are defeasibly provable, ~q is not definitely provable, and for every rule having q as a consequent we can find an antecedent which does not satisfy the defeasibly provable condition.

$-\partial$:

If $P(i+1) = +\partial q$ *then*

(1) $-\Delta q \in P(1..i)$ *and*

(2) (2.1) $\forall r \in R_{sd}[q]\ \exists a \in A(r) - \partial a \in P(1..i)$ *or*

(2.2) $+\Delta \sim q \in P(1..i)$ *and*

(2.3) $\exists s \in R[\sim q]$ *such that*

$\forall a \in A(s) : +\partial a \in P(1..i)$

Figure 4. Not defeasibly provable.

A goal *q* is not defeasibly provable if it is not definitely provable, and one of the following conditions hold: all strict or defeasible rules implying q have a body term which is not defeasibly provable, or ~q is definitely provable, or there is a rule having ~q as a consequent and all its antecedents are defeasibly provable.

An important property of defeasible logic is that it is coherent, that is, there is no defeasible theory *D* and literal p such that:

$T \vdash +\partial p$ and $D \vdash -\partial p$, or

$T \vdash +\Delta p$ and $D \vdash -\Delta p$

(we cannot establish that a literal is simultaneously provable and unprovable).

Scenario Model

The set of actions A = fc, u, d, p, vg covers clinical, ultrasonography, d-dimer, plethysmography and venography, with the results of these actions expressed as beliefs B = fcl(l), cl(m), cl(h), ul(cF), ul(p), ul(sF), ul(dP), (dC), ul(n), dd(a), dd(n), pp(a), pp(n), ve(n), ve(d), ve(s)g. The clinical investigation has three possible results: low, medium or high. The outcome of the D-dimer and plethysmography procedures can be normal or abnormal. Ultrasonography can show noncompressibility of the common femoral vein, popliteal vein, superficial femural, distal popliteal or the deep calf veins, or normal result. The venography can yield normal, defect or suggestive results.

The effects of these actions are specified by dynamic causality

$$D^1 = \begin{cases} d_0 : ve(X) \xleftarrow{d} v, \textit{venograph} \\ d_1 : ul(X) \xleftarrow{d} u, \textit{ultrasonograph} \\ d_2 : pl(X) \xleftarrow{d} p, \textit{plethysmograph} \\ d_3 : dd(X) \xleftarrow{d} d, \textit{serum} \\ d_4 : cl(X) \xleftarrow{d} c \end{cases} \quad (5)$$

if the executability conditions are satisfied.

$$\varepsilon^1 = \begin{cases} e_0 : v \xleftarrow{e} \textit{suspicious}, \textit{qualified} \\ e_1 : u \xleftarrow{e} \textit{suspicious}, \textit{qualified} \\ e_2 : p \xleftarrow{e} \textit{suspicious} \\ e_3 : d \xleftarrow{e} \textit{suspicious} \\ e_4 : c \xleftarrow{e} \end{cases} \quad (6)$$

Venography (v) as action can produce a result (e.g. ve(X)) if a venograph is available, qualified personnel is available and the patient is clinically suspicious.

A venous thrombo-embolic event (VTE) should be avoided at any time *G = {¬vte}*, by deciding whether the patient has DVT or not *O+={dvt, ¬dvt}*, while also avoiding an invasive procedure, if possible, *O−={invasive, vte}*. Preferences over the situation of the patient are then:

$$P^0 = \begin{cases} p_0 : \neg dvt \succ dvt \\ p_1 : dvt \succ vte \\ p_2 : invasive \succ vte \end{cases} \quad (7)$$

with static causality expressing suspicion and invasiveness.

$$S^1 = \begin{cases} s_0 : invasive \xleftarrow{s} ve(x) \\ s_1 : suspicious \xleftarrow{s} cl(X), X \neq n \end{cases} \quad (8)$$

It is preferable for the patient not to have DVT, or to have the DVT diagnosed rather than have a venous thrombo-embolic event (VTE), or to perform an invasive test like venography rather than have a VTE.

Rules recommended by experts

For our diagnosing agent we show some rules recommending actions extracted from [7] (and presented in sub-section *Rules for diagnosis*).

$$R^0 = \begin{cases} a_0 : v \leftarrow ul(sF) \vee ul(dP) \vee ul(dC) \\ a_1 : u \leftarrow pl(a) \wedge (cl(m) \vee cl(l)) \\ a_2 : v \leftarrow pl(a) \wedge (cl(m) \vee cl(l)) \\ a_3 : u \leftarrow ve(s) \\ a_4 : p \leftarrow ve(s) \end{cases} \quad (9)$$

The rules for a diagnostic of DVT from [7] are:

$$R^1 = \begin{cases} r_0 : dvt(a) \leftarrow ul(cF) \vee ul(p) \\ r_1 : dvt(b) \leftarrow ul(sF) \vee ul(dP) \vee ul(dC) \\ r_2 : dvt(a) \leftarrow pl(a), cl(h) \\ r_3 : dvt(b) \leftarrow pl(a), (cl(m) \vee cl(l)) \\ r_4 : dvt(a) \leftarrow ve(d) \\ r_5 : dvt(c) \leftarrow ve(s) \end{cases} \quad (10)$$

and similarly for those that exclude DVT.

$$R^2 = \begin{cases} r_6 : \neg dvt(a) \leftarrow ve(n), cl(l) \\ r_7 : \neg dvt(c) \leftarrow dd(n) \\ r_8 : \neg dvt(b) \leftarrow pl(n), dd(n) \\ r_9 : \neg dvt(a) \leftarrow ul(n), cl(l) \end{cases} \quad (11)$$

We also need the strength of the diagnostic rules given by experts as class A, B, C, expressed by preferences.

$$GR^1 = \begin{cases} gr_0 : dvt(a) \succ \neg dvt(b) \\ gr_1 : dvt(a) \succ \neg dvt(c) \\ gr_2 : dvt(b) \succ \neg dvt(c) \\ gr_3 : \neg dvt(a) \succ dvt(b) \\ gr_4 : \neg dvt(a) \succ dvt(b) \\ gr_5 : \neg dvt(a) \succ dvt(b) \end{cases} \quad (12)$$

A better rated diagnosis is always preferred.

In a state where there is not enough information for stating a diagnosis, one has to consider the next procedure to be performed on the patient. The invasive venography test is only the last resort for a ferm diagnosis, if the results of the other actions are not conclusive enough. Typically, the clinical evaluation is performed first, and then, if the patient is suspected of dvt, depending on the previous results in each case and on the available resources and personnel, dDimer and/or plethysmography and/or ultrasonography. If the diagnosis after these tests is still questionable, the venography test should follow.

Facts in the controlled trial

The facts of the controlled trials, expressed by rules like:

cl(l), dd(n),~known(ul),~known(ve) → vte
cl(l), ul(n),~known(dd),~known(ve) → vte
cl(h), ul(n),~known(dd),~known(ve) → vte

are used in the argumentation process by the evaluator agent.

Argumentation System

The main actors in our diagnosing process are:

- The *DVT specialist*, its role being played by the diagnosing agent, who employs the knowledge presented in [7] and summarized in *Rules recommended by experts* to draw conclusions on the tests to be performed on the patient and on its condition (DVT positive or negative),
- The *DVT consultant*, represented by the evaluation agent, who checks the experiments illustrated in Figure 1 [13] to validate the specialist's conclusion, and
- The *patient*, with its symptoms and possibly test results and diagnosis.

Our agents are developed in the Open Agent Architecture (OAA), using delegation for expressing agent interaction. Agents delegate their needs to the Facilitator, who coordinates the agent community in achieving the tasks, getting across different programming languages. Our system employs two levels of argumentation. First, the diagnosing agent reaches a conclusion applying agent level argumentation. Then, inter-agent argumentation is used when the evaluation agent is inquired about the validity of the conclusion submitted to it. The current protocol used for inter-agent argumentation is:

- The diagnosing agent requests validation for a negative or positive diagnosis.
- The evaluation agent checks its history and validates the diagnosis or, if contrary precedents are found for patients with similar records, posts a counterargument.
- The diagnosing agent checks the response of the evaluator, and either commits to the diagnosis in case of a validation, or looks for another form of evaluating the state of the patient in case of a counter-argument.

This protocol prevents a negative diagnosis in cases similar to those when venous thrombo-embolic events are known to have occurred.

We use Deimos as an argumentative system for answering queries. The A, B, C grades used for diagnosis rules for asserting priorities, with the superiority relation, so that a rule with grade A will be preferred to any rule with grade B or C, and a graded B rule will be preferred to one with grade C. These priorities are particularly important when rules with opposite conclusions are defeasibly provable.

Reasoning about the current state of the patient and the action to be considered is the key of the diagnosing process. Actions take the patient from one state to another, as illustrated in Figure 6. The task of the system is to set a safe diagnosis on the patient. The conclusion of the diagnosis agent for a patient in a given state can be: diagnosis achieved, or action recommended. The diagnosis agent is trying to find a defeasibly provable diagnosis ($+\partial$dvt(P) or $+\partial\ \neg$dvt(P)). If no diagnosis is found, it means that neither diagnosis is defeasibly provable ($-\partial$dvt(P) and $-\partial\neg$dvt(P)). An action is considered for recommendation when it is executable ($+\partial$executable(Action)), but also on consideration of the outcome ($+\Delta$outcome(Action)) on the patient.

Figure 5 depicts a sequence of events for diagnosing a patient with low likelihood of having DVT. Suppose ultrasonography is the only executable safe procedure, and it shows normal results. The diagnosis agent will try to conclude negative diagnosis, but the evaluator will object, because its history shows that venous thrombo-embolic events have occurred in the past when a negative diagnosis on patients

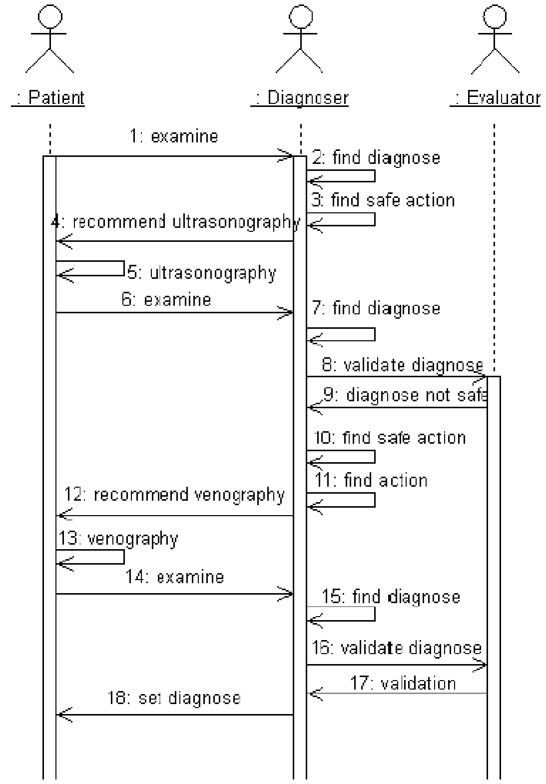

Figure 5. Diagnosing a patient.

clinically unlikely to have DVT was concluded solely on the base of the ultrasonography procedure. Further, suppose that after this

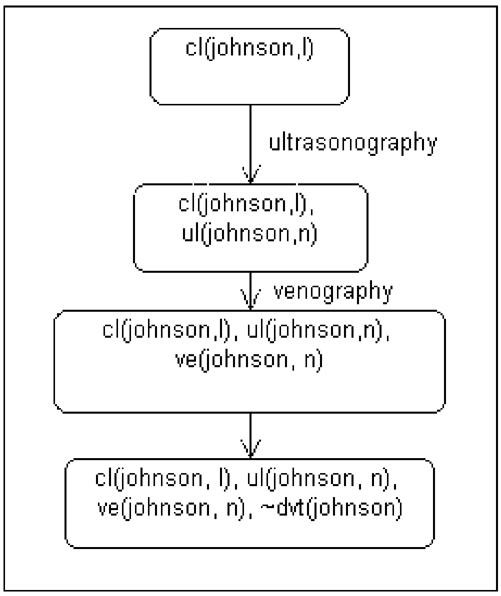

Figure 6. Course of action for a patient.

procedure is executed, the ultrasonograph goes out of order, so we have no safe executable actions.
This is one of the few cases when the invasive venography procedure is recommended. The result of this test will be enough for establishing a correct diagnosis. The course of action and the corresponding states are illustrated in Figure 6.
The DProver of Deimos (compiled using Haskell) is used in the decision making process when queries on both the current state, action to perform or the next state are required in the life cycle of the multi-agent system. The controlled trials of the evaluator agent are currently stored as Prolog predicates, used in the query ($-\Delta$vte), when needed to validate a diagnosis. A future version will also cover the access to controlled trials when they are public (in OWL).

Conclusions

The challenge to deal with incomplete and uncertain knowledge, coming from different sources, and the contradictions that may occur has been tackled here by argumentation between parties. In our case the parties are represented by agents that are cooperating to solve a common goal: a correct diagnosis for the patient, with minimum risk and discomfort.
The contribution of this paper is: (1) a diagnosis scenario, which is quite pervasive; (2) an embedding of an action theory in most preferred trajectories [11]; (3) usage of bipolar outcomes in argumentation to achieve reasoning about actions [4][6].

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