

**Flexible Support For Trauma Management
Through Goal-Directed Reasoning and Planning**

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Abstract

We describe a system, *TraumAID*, which has been designed to provide decision support throughout the initial definitive management of severely injured patients (i.e., after their initial evaluation, resuscitation, and stabilization). Over the course of initial definitive management, TraumAID recommends appropriate procedures to be carried out, based on currently available evidence and on the complexity and urgency of the situation. TraumAID's ability to deal flexibly with complex and often urgent situations comes from its ability to reason separately about the management *goals* that should be achieved and about the *means* that are situationally appropriate for achieving them.

In this paper, we describe TraumAID's approach to trauma management in more detail, showing in particular how it enables TraumAID to adapt its reasoning and recommendations to the urgency with which a patient's condition must be addressed.

keywords: decision support, trauma management, planning

1 Introduction

Injury is a major health problem in the United States, resulting in more years of human life lost than any other disease [7]. West et al. [14] have argued that the morbidity and mortality due to injury can be reduced through rapid delivery of expert care. To this end, the American College of Surgeons has developed an Advanced Trauma Life Support (ATLS) course that educates physicians in the initial evaluation, resuscitation, and stabilization of severely injured patients [2]. To this same end, we have developed a system – TraumAID – that can assist physicians in the initial definitive management of these patients [13].

From the perspective of providing decision support, there are three salient features of trauma management:

- The patient may have several injuries, each demanding attention.
- The diagnostic and therapeutic demands of different injuries compete for the physician's attention.

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- The physician’s decision as to what to attend to and act upon (be it diagnostic or therapeutic) depends on both the patient’s current state and the state of the physician’s knowledge, both of which change over time in response (in part) to the physician’s activities.

Now, one way of viewing diagnosis is as an act of *classification* [4, 10]: viewed this way, rule-based expert systems have shown themselves an effective way of classifying objects and/or situations, given a body of evidence. Another way of viewing diagnosis is as an act of *explanation*: viewed this way, systems using causal models can often discover a rich explanation of the relationship between surface evidence and underlying situation. Neither rules nor causal models however are adequate for expressing the knowledge that drives the *rational choice of action*, given multiple demands and limited resources. While causal models can be used to understand the *effects* of actions on a system, effects are not the only factors to be considered when deciding what should be done. As for rules, the number of different combinations of goals to be considered when deciding what should be done means an explosion of separate but related rules, the entire set of which is difficult to manage, update and validate. To map between goals and rational action, other methods are called for – methods employed in systems that Artificial Intelligence labels *planning systems* or *planners* [1].

In its structure, the current version of our system (TraumaAID 2.0) complements a rule-based reasoner with a planning system capable of recommending diagnostic and therapeutic activity appropriate to the current situation. That is, the knowledge and reasoning in TraumaAID 2.0 are factored into two linked components, as shown in Figure 1:

- a *rule-based reasoner* that addresses the questions: given the current situation (i.e., what is known about the patient), what *conclusions* can be drawn and therefore what *goals* are most appropriate for the physician to adopt.
- a *planner* that addresses the question: given the set of currently relevant goals, what *actions* are most appropriate for the physician to perform.

The result of having two such components is that both diagnostic and therapeutic *goals* and diagnostic and therapeutic *recommendations* (i.e., a plan) are available to the physician for immediate consideration and/or for retrospective review.

As we will illustrate briefly in Section 2, TraumaAID 2.0 reassesses the situation whenever new evidence is provided in the form of observations, diagnostic test results, or information about the performance and/or outcome of therapeutic actions. Such evidence activates the rule-based reasoner, causing it to generate a set of management goals, which are given to the planner. The planner uses its knowledge of goals and of the procedures that can address them (see Section 3) to develop a plan that satisfies this current set of goals. Any new evidence will reinvoke TraumaAID’s reasoner, allowing it to determine whether new goals are called for. If new goals are called for, there will be a new round of planning, resulting in a new plan of action being recommended to the physician.

Section 3 describes the system features that support TraumaAID’s reasoning and planning activities, and Section 4 discusses the examples from Section 2 in more detail, focussing on TraumaAID’s ability to adapt its recommendations to the complexity and urgency of the situation. Finally, Section 5 discusses directions in which our work is currently proceeding.

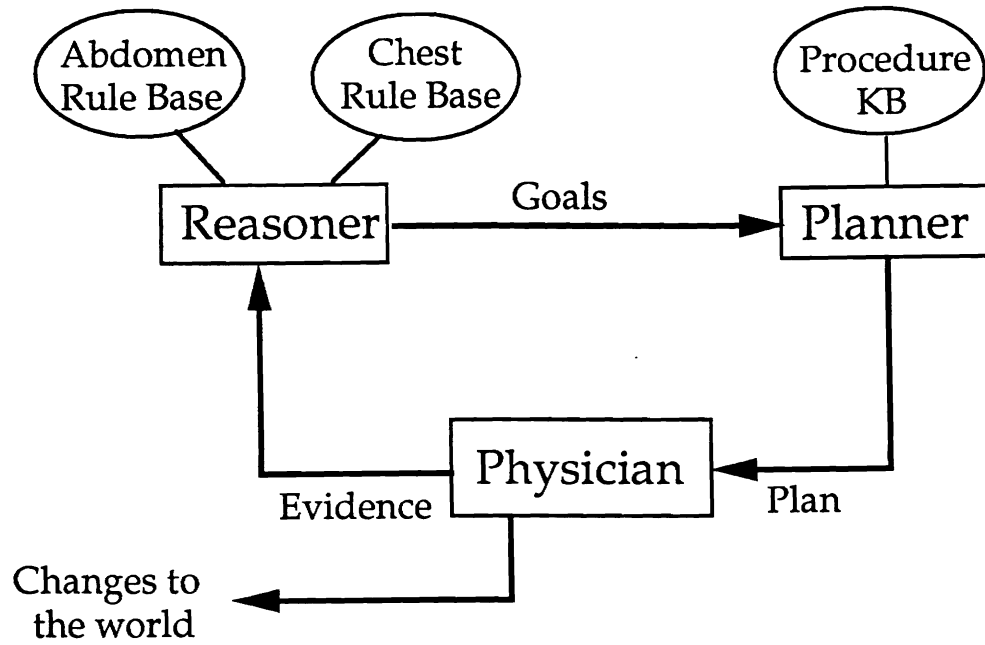


Figure 1: TraumaAID 2.0 System Architecture

2 Short Example

The following hypothetical case illustrates the kinds of support that TraumAID 2.0 is able to provide by virtue of reasoning independently about goals and about the means for satisfying them.

Patient JS is a 25-year old male in shock with a single stab wound to the left parasternal chest above the level of the nipple. (The direction of the stab wound is unknown.)

Based on simply the type and location of the wound, TraumAID will conclude that two goals should be adopted: one, a therapeutic goal of addressing the chest wall penetration, and the other, a diagnostic goal of determining possible injuries to the chest. For the former it recommends covering the chest wound with an occlusive dressing, and for the latter, a survey chest x-ray. The two procedures are not ordered with respect to one another, since the patient's wound can be covered at any reasonable time, including in parallel with other actions.

If however, prior to the survey chest x-ray, TraumAID is given the opportunity to request information about observations that have not yet been reported ("let system guide"), it will ask for such information because these *bedside questions* are regarded as being risk- and cost-free. These questions follow from injuries that TraumAID only *suspects* the patient may have sustained (based on the evidence so far) but has not yet so *concluded*. Here it questions whether the patient is unconscious, whether he shows distended neck veins, and whether he has decreased breath sounds. Evidence of distended neck veins (without decreased breath sounds) rules out the likelihood of a tension pneumothorax, and flags as relevant the goal of diagnosing a pericardial tamponade as the cause of the patient's shock.

Figure 2 shows a screen dump of the TraumAID Symbolics interface at the point at which it is asking these bedside questions. (The Symbolics interface is for system development. A graphics interface is being developed, in consultation with Emergency Room nurses at the Medical College of Pennsylvania (MCP), for actual clinical use.) The upper left window shows TraumAID's current suspicions, conclusions and recommended management goals. (As scrolled, it also shows the tail end of TraumAID's list of negative findings.) The bottom window shows the physician's response to TraumAID's first bedside question (unconsciousness), and the physician's request for an explanation of the system's next question (distended neck veins) in terms of the rules that justify it (see Section 3.1.2). The upper right window shows a list of these rules.

So far, the example has not really demonstrated TraumAID's claimed adaptive behavior. But at this point, it does: here TraumAID recognizes the goal of diagnosing a pericardial tamponade. In an urgent situation, TraumAID will recommend satisfying this goal through needle aspiration of the pericardial sac: it is invasive, but quick, and gives *prima facie* evidence of pericardial tamponade in a patient in shock. In a non-urgent situation, on the other hand, TraumAID will recommend ultrasound for effusion: it is slower, but non-invasive. The patient's condition of shock makes the current situation urgent, and needle aspiration is recommended. Since the goal of determining (and treating) the cause of shock takes precedence over that of determining if other chest injuries have been sustained, needle aspiration is recommended as the next procedure to be performed.

Figure 3 shows a screen dump of the TraumAID interface at this point in the interaction. In the bottom window, the physician has issued a command to create a plan based on

TraumaAID 2.0

Odd_Number_Of_Bullet_Holes
Unconsciousness

Suspected

Potential_Occult_Injury_Pleural_Space(Left)
Likely_Tension_Pneumothorax(Left)
Clinical_Possibility_Of_Bronchial_Injury(Left)
Clinical_Possibility_Of_Tracheal_Injury
Slight_Possibility_Of_Esophageal_Injury
Weak_Pulses_Leg(Positive,Right)
Weak_Pulses_Leg(Positive,Left)

Concluded

Chest_Wall_Penetration
Possibility_Of_Tension_Pneumothorax(Left)
Slight_Possibility_Of_Tracheal_Injury

Projected Goals

Need_Survey_Chest_X_Ray_Airway
Rx_Chest_Wall_Penetration

Justification for Distended_Neck_Veins:

Trying to prove Likely_Tension_Pneumothorax(Left): using

```
5220: Likely_Tension_Pneumothorax(SIDE=S) :-
      Wound(LOCATION='Chest,SIDE=S),
      -? Open_Sucking_Chest_Wound_(SIDE=S),
      Shock,
      Distended_Neck_Veins,
      Decreased_Breath_Sounds(SIDE=S),
      -? Tension_Pneumothorax_Unlikely(SIDE=S),
      -? Tension_Pneumothorax(SIDE=S),
      ? Tension_Pneumothorax(SIDE=S).
```

Trying to prove RO_Pericardial_Tamponade_Urgently: using
; Need to key off likely rather than definitive pneumothorax
; in order to avoid getting chest x-ray before aspirating pericardium

; for patients with shock and normal breath sounds.

```
5401: RO_Pericardial_Tamponade_Urgently :-
      Wound_With_Possible_Pericardial_Injury,
      Shock,
      Distended_Neck_Veins,
      - Likely_Tension_Pneumothorax(SIDE='LEFT'),
      - Likely_Tension_Pneumothorax(SIDE='RIGHT'),
      ? Tension_Pneumothorax_Unlikely(SIDE='LEFT'),
      ? Tension_Pneumothorax_Unlikely(SIDE='RIGHT').
```

Trauma command: Let System Guide

Is Unconsciousness: observed? : Why

Is Unconsciousness: observed? : [Abort]

Trauma command: Why Moribund Patient

Trauma command: List Dependent Rules

Moribund Patient

Trauma command: Why Likely_Tension_Pneumothorax(Left)

Trauma command: List Proving Rules

Likely Tension Pneumothorax

Trauma command: Let System Guide

Is Unconsciousness: observed? : No

Is Distended_Neck_Veins: observed? : Why

Is Distended_Neck_Veins: observed? :

Add Fact
Circularity Check
New Patient
Save Case

Add Many Facts
Get Case
No More Wounds
Secondary Status

Add Negative Fact
Hospital Environment
Other Wounds Possible
Status

Batch Verify
Let System Guide
Plan
Submarine Environment

Bullet Count
Load Knowledge Base
Retract Fact
Transfer Patient

House-R: Menu.

To see other commands, press Shift, Control, Meta-Shift, or Super.

[Tue 25 Jun 11:58:00] 8/17/08

CL USER: User Input

Figure 2: TraumaAID screen following initial bedside questions

TraumaID 2.0

Odd_Number_Of_Bullet_Holes
 Unconsciousness
 Decreased_Breath_Sounds(Left)

Suspected

Potential_Occult_Injury_Pleural_Space(Left)
 Clinical_Possibility_Of_Bronchial_Injury(Left)
 Clinical_Possibility_Of_Tracheal_Injury
 Slight_Possibility_Of_Esophageal_Injury
 Weak_Pulses_Leg(Positive,Right)
 Weak_Pulses_Leg(Positive,Left)

Concluded

Chest_Wall_Penetration
 Possibility_Of_Tension_Pneumothorax(Left)
 Slight_Possibility_Of_Tracheal_Injury

Projected Goals

Need_Survey_Chest_X_Ray_Airway
 Rx_Chest_Wall_Penetration
 RO_Pericardial_Tamponade

Emergency Room

Cover_Wound_Occlusive_Dressing
 Urgently
 Needle_Aspiration_Pericardial_Sac

 Survey_Chest_X_Ray

Is Decreased_Breath_Sounds[Left] observed? : No
 New goal: RO_Pericardial_Tamponade_Urgently.
 New goal: RO_Pericardial_Tamponade.
 Is Hemoptysis observed? : [Abort]
 Trauma command: Plan
 Trying to solve RO_Pericardial_Tamponade_Urgently.
 Trying to solve Need_Survey_Chest_X_Ray_Airway.
 Trying to solve Rx_Chest_Wall_Penetration.
 Trying to solve RO_Pericardial_Tamponade. ALREADY planned for by (Get_Needle_Aspiration_Pericardial_Sac)
 Optimizing:
 New Round : optimizing on Cover_Wound_Occlusive_Dressing
 possible goals addressed=(Rx_Chest_Wall_Penetration)
 Trauma command:

Add Fact	Add Many Facts	Add Negative Fact	Batch Verify	Bullet Count
Circularity Check	Get Case	Hospital Environment	Let System Guide	Load Knowledge Base
New Patient	No More Wounds	Other Wounds Possible	Plan	Retract Fact
Save Case	Secondary Status	Status	Submarine Environment	Transfer Patient

Planning diagnosis and therapy. Mouse-L, -R: Default arguments.
 To see other commands, press Shift, Control, Meta-Shift, or Super.

[Tue 25 Jun 12:05:48] RY170N CL USER: User Input

Figure 3: TraumaID screen after concluding the need to pursue a diagnosis of pericardial tamponade

TraumAID's goals. The upper right window shows TraumAID's currently recommended plan. As before, the upper left window shows TraumAID's suspicions, conclusions and recommended management goals.

As noted, if the patient had not been in shock, TraumAID would have recommended diagnosis by ultrasound for effusion and have ordered this procedure *after* the survey chest X-ray because it is not urgent. This behavior on the part of TraumAID illustrates both its ability to choose different *means* (e.g., aspiration vs. ultrasound) for satisfying the same goal depending on the circumstances and its ability to reassess the *order* (e.g., before vs. after X-ray) in which a set of goal-satisfying procedures should be carried out.

If the needle aspiration gives positive evidence of a pericardial tamponade, TraumAID will recommend the goal of treating it. This is always urgent, and the means of treatment do not depend on the current situation. Specifically, TraumAID recommends three separately schedulable procedures: continuous pericardial sac decompression (with the needle), bilateral thoracotomy with transverse sternotomy, and repair of the heart. However, TraumAID recognizes that there is sufficient time for a survey chest X-ray to be performed in the Emergency Room before moving the patient to the Operating Room for surgery. Because an X-ray may reveal other damage to the chest, it can provide useful information for planning the upcoming operative procedures. For example, if the X-ray film shows both a pneumoperitoneum and a herniated bowel (on the left side), TraumAID will add to the current pending goal of treating the patient's pericardial tamponade, goals of treating the patient's lacerated diaphragm and bowel injury and of treating a potential pleural injury (see figure 4). TraumAID recommends that these additional goals be satisfied during surgery, through laparotomy, diaphragm repair, and repair or diversion of the GI tract.

TraumAID's ability to reason separately about goals and the means of achieving them enables it to recognize that this non-urgent activity may be possible, even in urgent situations, if it doesn't interfere with more urgent goals.

As another illustration of TraumAID's flexibility, suppose this same patient is also suffering a stab wound to his abdomen (left upper quadrant), with evisceration. If the physician reports hematuria, TraumAID will set a goal of diagnosing renal injury. This is not an urgent goal, compared with that of diagnosing and treating the cause of the patient's shock, but it is one whose means of satisfaction depends on the urgency of the situation. The current patient is unstable and waiting for a major surgery. In such a situation, TraumAID will recommend an IVP as a fast means of diagnosing renal injury, even though in a stable patient, renal injury would normally be diagnosed with a CT scan. This illustrates TraumAID's ability to take account of the urgency of the situation when choosing the means of satisfying *any* diagnostic goal, not just ones suspected as the cause of an urgent condition.

Now, because TraumAID recognizes from the report of evisceration that the patient must have sustained an abdominal injury, it will post a goal of gaining access to the abdomen, to find and treat the injury. The presence of this goal will affect TraumAID's recommendation of how to treat renal injury, should the IVP result be positive. That is, if there is an independent need to gain surgical access to the abdominal cavity (as in the current case), the surgeon can also directly inspect the kidney for injury. If there isn't, further observation (for developing fever and for renal bleeding) is sufficient. Only if fever or urinary tract bleeding develop would surgery be considered. This is another illustration of TraumAID's ability to choose different means for satisfying the same goal (in this case, a therapeutic goal), depending on the current circumstances.

TraumaID 2.0

intra_Abdominal_GI_Tract_Injury
Pneumoperitoneum

Projected Goals

Rx_Potential_Pleural_Injury_Requiring_Prophylaxis(Left)
Rx_Pericardial_Tamponade
Rx_Lacerated_Diaphragm(Left)
Rx_Intra_Abdominal_GI_Tract_Injury

Goals Pursued

Rx_Chest_Wall_Penetration
RO_Pericardial_Tamponade
Need_Continuous_Pericardial_Sac-Decompression
Need_Survey_Chest_X-Ray_Airway
Need_Continuous_Pericardial_Sac-Decompression
RO_Pericardial_Tamponade

Procedures Performed

Std_Care_Chest_Wall_Penetration
Get_Needle_Aspiration_Pericardial_Sac
Perform_Continuous_Pericardial_Sac-Decompression
Get_Survey_Chest_X-Ray

Operating Room

Bilat_Thoracotomy_Transverse_Sternotomy
Heart_Repair
Laparotomy
Diaphragm_Repair(Left)
GI_Tract_Repair_Or_Divert

ir_Or_Divert_GI_Tract)))

Cost=100

Trying to solve Rx_Pericardial_Tamponade.

Trying to solve Need_Access_To_Heart.

Trying to solve Rx_Lacerated_Diaphragm(Left).

Trying to solve Rx_Intra_Abdominal_GI_Tract_Injury.

Trying to solve Rx_Potential_Pleural_Injury_Requiring_Prophylaxis(Left). ALREADY planned for by (Perform_Bilat_Thoracotomy_Transverse_Sternotomy)

Trying to solve Rx_Pericardial_Tamponade.

Trying to solve Need_Access_To_Heart. ALREADY planned for by (Perform_Bilat_Thoracotomy_Transverse_Sternotomy)

Trying to solve Rx_Lacerated_Diaphragm(Left). ALREADY planned for by (Perform_Diaphragm_Repair(Left))

Trying to solve Rx_Intra_Abdominal_GI_Tract_Injury. ALREADY planned for by (Repair_Or_Divert_GI_Tract)

Was Bilat_Thoracotomy_Transverse_Sternotomy performed? :

Add Fact	Add Many Facts	Add Negative Fact	Batch Verify	Bullet Count
Circularity Check	Get Case	Hospital Environment	Let System Guide	Load Knowledge Base
New Patient	No More Wounds	Other Wounds Possible	Plan	Retract Fact
Save Case	Secondary Status	Status	Submarine Environment	Transfer Patient

Mouse-R: Menu.

To see other commands, press Shift, Control, Meta-Shift, or Super.

[Tue 25 Jun 12:25:06] RY170N

CL USER:

User Input

Figure 4: TraumaID screen after survey chest x-ray report

One final note – TraumAID does not assume that its recommendations will be taken. The physician may ignore goals that TraumAID has identified or choose some other means of satisfying them. TraumAID has been designed to make use of whatever information is provided, whether the information has been requested or not. This is another aspect of TraumAID’s flexibility.

In these examples, we have shown TraumAID 2.0 functioning as an *on-line advisor*. Although it is the simplest way of demonstrating the kind of flexible situation-specific reasoning that TraumAID is capable of performing, it is not the only clinical use of such reasoning. It is also necessary in order to perform timely *critiquing* [8, 11, 12] of physician’s orders, for post hoc *assessment* of cases, as part of a quality assurance program, and for education and training. These other applications are being explored as part of our research program.

3 The TraumAID 2.0 Architecture

The usefulness of a system like TraumAID 2.0, which is aimed at providing decision support throughout a complex, changing and possibly urgent situation, depends in large part on the ability to identify appropriate goals, appropriate means to use in addressing them, and an appropriate order in which to apply them.

In the first part of this section, we discuss the rule-based reasoning by which TraumAID identifies goals that are motivated by the evidence at hand, and in the second, the planning by which TraumAID forms a plan for satisfying them. TraumAID’s claimed flexibility derives primarily from its ability to form appropriate plans for satisfying a set of pending goals. If it reasoned directly from evidence to conclusions to therapeutic recommendations (as MYCIN [3] does), without going through a stage of formulating goals, much of this flexibility would be lost or more difficult to achieve. Thus, Section 3.1 describes some salient features of TraumAID’s reasoning from evidence to conclusions to goals, even though it does not directly affect our main point.

With respect to TraumAID’s management plans, as soon as new evidence appears (either in the form of additional findings, test results or reports of actions having been taken), previous goals may be replaced or superceded, and a new plan formed. Thus, while a plan accurately reflects the entire set of pending goals, it is not assumed that the physician will carry out the entire plan. As soon as new information is received, the situation will be reassessed, and a new plan may result.

3.1 Reasoning from Evidence to Conclusions and Goals

The relevant questions about any *rule-based* reasoner include at least the following:

- What do the propositions in its clauses represent?
- What truth values can a proposition take and how does it acquire a truth value?
- Under what conditions are rules fired, and what happens as a result?

3.1.1 What Propositions Represent

As in other rule-based systems that perform diagnosis, TraumAID uses propositions to represent:

1. *findings*, such as Distended-Neck-Veins, Shock, Wound(Location='Chest, Type='Stab), obtundation;
2. *test results*, such as Lavage-WBC(Result='Negative), X-Ray-Pelvis(Result='Positive), Needle-Aspiration-Pericardial-Sac(Result='Positive);
3. *definitive conclusions*, such as Chest-Wall-Penetration, Abdominal-Bleeding, Decompressed-Tension-Pneumothorax;
4. *intermediate conclusions*, such as Wound-With-Possibility-of-Esophageal-Injury, Likely-Tension-Pneumothorax.

(Definitive conclusions differ from intermediate conclusions in being associated with therapeutic recommendations.) In addition to these types of propositions however, TraumAID also uses propositions to represent two other aspects of patient management: (1) the *performance* of actions, and (2) *diagnostic and therapeutic goals*. Together, such propositions enable TraumAID to go beyond purely diagnostic reasoning.

The ability to refer to the performance of an action frees TraumAID from having to assume either of two things: (1) that the actions it recommends will be performed, and (2) that if performed, the actions will be carried out either correctly or successfully. Instead, a rule can express the need to gather relevant evidence after an action has been performed, to verify either correct performance (e.g., that a chest tube has been inserted correctly) or successful achievement of the goal that the action was intended to achieve (e.g., that shock has been relieved). For example, the following rule establishes a goal of verifying that a chest tube has been inserted correctly, after it has been reported to have been inserted. (The action performance clause is flagged by an exclamation point “!”.)

Goal-Setting Rule 5820

Need_Post_Primary_Tube_X-Ray :-

! Primary_Tube_Thoracostomy-Report(Side=S).

Finally, propositions may represent diagnostic or therapeutic goals. (Goal propositions beginning with “RO” represent diagnostic goals, ones beginning with “Rx” represent therapeutic goals, and ones beginning with “Need” may be either.) Most are specific goals that will be posted to the planner, to be incorporated into the current management plan. But there is one problem that necessitates the reasoner setting tentative goals that will trigger further reasoning rather than being immediately sent off to the planner: that is that the planner has no way of *questioning* the physician, to acquire the information relevant to deciding how a goal should be satisfied. (The reasoner already acquires information relevant to deciding *what goals* should be set.) For example, evidence of extensive prior peritoneal scarring would contraindicate peritoneal lavage being used as a means of diagnosing abdominal bleeding, but would not have been checked earlier by the reasoner (or even by the physician), when working to set the goals of patient management.

Because only the reasoner can request information (through “bedside questions” – see Section 3.1.3), it must be able to set tentative goals such as *RO-AbdominalBleeding* in order

to then request the information about extensive peritoneal scarring as a way of determining whether or not peritoneal lavage is contraindicated. If it is, the reasoner sets a more specific goal of *RO_AbdominalBleeding_Scarred_Patient* and if not, the more specific goal of *RO_AbdominalBleeding_Non-Scarred_Patient*, as per the following rules:

Goal-Setting Rule 56321

RO_AbdominalBleeding_Non-Scarred_Patient :-
 RO_AbdominalBleeding,
 - *Lavage_Contraindicated*.

Goal-Setting Rule 56325

RO_AbdominalBleeding_Scarred_Patient :-
 RO_AbdominalBleeding,
 Lavage_Contraindicated.

The fact that the generation of questions is entirely within the purview of the reasoner is a feature left-over from TraumAID 1.0 and, for reasons of clarity, is likely to change in the future.

3.1.2 Truth Values of Propositions

To be usable in an environment in which knowledge is pursued and acquired over time, it is as important for a system to be able to represent and reason about its current lack of knowledge of some condition as about its knowledge that the condition does or doesn't obtain. Thus besides being true or false, TraumAID propositions are allowed to have truth values of "unknown". Each clause in a rule specifies the truth value that a proposition must have for the rule to apply, with unmarked propositions required to be true, propositions marked "-" required to be false, ones marked "-%" required to be false or unknown, and ones marked "%" required to be true or unknown.

The status "false or unknown" (-%) is used with conclusions that have been pursued successfully and found to be false, or pursued unsuccessfully (i.e., with no reachable conclusion). Similarly, the status "true or unknown" (%) is used with conclusions that have been pursued successfully and found to be true, or pursued unsuccessfully. That is, both imply that a conclusion has been pursued, and is not merely as yet "unknown".

For example, the following Goal-Setting rule will only fire if TraumAID has already determined that the patient does not have a pericardial tamponade or has not been able to acquire sufficient information to conclude that the patient does so.

Goal-Setting Rule 5395

RO_MyocardialContusion :-
 Wound(TYPE='Gunshot, Location='Sternal),
 CompoundFracture_Sternum,
 -% *PericardialTamponade*.

The system explicitly acquires knowledge from the physician that a proposition associated with a finding or test result is false (e.g., the physician asserts that the patient does not have distended neck veins). A conclusion, on the other hand, (i.e., a proposition whose truth value follows from reasoning) can only become false if all the rules headed by that proposition become false. (A rule becomes false if any of its clauses become false.) That is, TraumAID does not contain rules for directly concluding $\neg P$, for any proposition P. Because of our use of a three-valued logic, this is not the same as Prolog's "negation as

failure” reasoning. A conclusion cannot be falsified simply on the basis of information being unknown.

For example, consider the conclusion *moribund*. TraumAID has only one rule for concluding that a patient is moribund:

Evidential Rule 605
Moribund_patient :-
 shock,
 unconscious.

It will conclude that a patient is moribund only if he or she is in shock and unconscious. (This rule would have to be modified if the domain were extended to include head injuries as well as injuries of the chest and abdomen.) If it is asserted that the patient is not unconscious, then TraumAID will conclude that he is not moribund. If the patient is asserted to be unconscious, but it is not known whether he is in shock, then *no* conclusion will be drawn about whether or not he is moribund.

TraumAID’s inability to derive a negative conclusion from the failure of a single rule (where more than one relevant rule exists), means that something must be done to enable it to dismiss a diagnosis on the basis of a *single* negative test result – for example, to rule out further consideration of tension pneumothorax if the results of either x-ray or needle aspiration are negative. (The rules for positively concluding tension pneumothorax on the basis of either piece of evidence are given below.)

Evidential Rule 5205
Tension-Pneumothorax(SIDE=S) :-
 Needle_Aspiration_Chest_for_Pressure(SIDE=S, Result='Positive).

Evidential Rule 5206
Tension-Pneumothorax(SIDE=S) :-
 X-Ray_Tension_Pneumothorax(SIDE=S, Result='Positive).

To be able to dismiss a diagnosis on the basis of a single negative test result, TraumAID contains propositions representing the conclusion that a particular diagnosis is unlikely and rules such as the following, for drawing such a conclusion as soon as a negative result is returned (where a positive conclusion has not already been drawn by other means):

Evidential Rule 5207
Tension-Pneumothorax_Unlikely(SIDE=S) :-
 – Needle_Aspiration_Chest_for_Pressure(SIDE=S, Result='Positive),
 –% Tension-Pneumothorax(SIDE=S).

Evidential Rule 5208
Tension-Pneumothorax_Unlikely(SIDE=S) :-
 – X-Ray_Tension_Pneumothorax(SIDE=S, Result='Positive),
 –% Tension-Pneumothorax(SIDE=S).

This stops TraumAID’s further pursuit of the diagnosis, although it does not mediate the situation where both tests are actually performed, with conflicting results.

TraumAID 2.0 does not follow MYCIN in using *certainty factors* [3] because (according to co-author Clarke) experts in the acute care of multiple injuries tend to reason categorically, using protocol-like rules to avoid time-consuming contemplation. Nevertheless, TraumAID does support at least one *function* that certainty factors serve – that of thresholding definitive action. It does this through the use of evidence-gathering *protocols*, implemented

through a series of intermediate conclusions, each associated with a goal of gathering further evidence.

For example, TraumAID will conclude on the basis of any of several wound types (including a wound to the left upper parasternal region above the level of the nipple that is not directed left, such as in the case presented in Section 2) or a finding of hemoptysis, that there is a *Slight Possibility of Tracheal Injury*. This conclusion (or that of a potential mediastinal injury) will lead TraumAID to ask all “bedside questions” relevant to tracheal injury – that is, questions about hemoptysis and stridor. Positive findings of both lead TraumAID to conclude that there is a *Clinical Possibility of Tracheal Injury*, which in turn sets the goal of ruling out tracheal injury. (Other conditions which will lead to this same goal being set include the presence of a bullet in the superior or posterior mediastinum, or a persistent pneumothorax following tube thoracostomy.) TraumAID will recommend that this goal be accomplished via a bronchoscopy, which if positive will finally lead TraumAID to a definitive conclusion of *Tracheal Injury*. At this point, definitive therapeutic goals would be set, whose means of satisfaction would depend, in part, on other goals that might also be pending.

3.1.3 Rules and their Control Structure

The reasoner acts to produce *management goals*, which then drive the formation of a management plan. To do this, the reasoner has one type of rule that links *evidence* to *conclusions* (“Evidential Rules”) and another type that links both evidence and conclusions to diagnostic and therapeutic *goals* (“Goal-setting Rules”). Examples of both types have appeared throughout this section. Simple Evidential and Goal-Setting rules that were used in the case described in Section 2 include:

Evidential Rule 5376
Chest.Wall.Penetration :-
 Wound(Location='Chest, TYPE='Stab).

Goal-Setting Rule 5378
Rx.Chest.Wall.Penetration :-
 Chest.Wall.Penetration.

The first rule enables the reasoner to conclude chest wall penetration on the basis of wound type and location, while the latter leads it to set a goal of treating the chest wall penetration, simply on the basis of its presence.

Whenever new evidence is presented to the reasoner, it forward-chains on both types of rules, to form new conclusions and goals. (Unless explicitly changed, the truth value of a proposition persists from one activation of the reasoner to the next.) In addition, the reasoner may backward-chain on an Evidential Rule as a way of identifying relevant “bedside questions”. Conceptually, “bedside questions” should be viewed as means of satisfying “information-seeking” goals. (Propositions that correspond to “bedside questions” are so marked. As noted earlier, having the reasoner generate “bedside questions” rather than the planner (see Section 3.2) is a feature leftover from TraumAID 1.0: it does not mean that we believe that linguistic actions such as questions differ significantly from non-linguistic actions.)

The reasoner forward chains on all new evidence, including responses to bedside questions, flagging any new conclusions (which may cause other rules to fire), and posting new goals, until all rules that can fire have done so. At this point, the planner takes control and

forms a plan that can satisfy the set of current pending goals.

3.2 Planning – Reasoning to Satisfy Goals

Having described the mechanisms by which TraumAID 2.0 sets goals, we can now describe the knowledge and mechanisms that it uses to develop a (partially-ordered) plan of action for satisfying a set of goals that are currently pending.

The planner knows about three kinds of entities: *goals*, *procedures* and *actions*. *Goals* can often be satisfied by any of a number of alternative procedures. *Procedures* can be carried out through an ordered sequence of *actions* to be performed and/or *goals* to be achieved (“sub-goalling”). *Actions* are the entities that make up TraumAID’s recommended management plan. Information about the relationship between these three types of entities is stored in the system’s *Procedure Knowledge Base* in the form of *goal-procedure mappings* and *procedure-action mappings*.

For example, the following goal-procedure mapping expresses the fact that the diagnostic goal of ruling out abdominal bleeding in a non-scarred patient can be satisfied by either a peritoneal lavage or CT scan of the abdomen, or when performing a laparotomy.

Goal-Procedure Mapping 56322

```
RO_Abdominal_Bleeding_Non_Scarred_Patient →  
  Get_Peritoneal_Lavage,  
  Get_CT_Scan_Abdomen,  
  Perform_Laparotomy.
```

Other goal-procedure mappings show that peritoneal lavage and CT scan of the abdomen can each be used for other diagnostic goals as well, such as ruling out a suspicious abdominal wall injury (lavage) or ruling out renal injury (CT scan). Other goal-procedure mappings show laparotomy achieving access to the abdomen in therapy for lacerated diaphragm, non-specific intra-abdominal injury, ureteral injury, etc.

Procedure-action mappings are sequences of actions and/or goals, where the latter will themselves be mapped to procedures and thence to actions, for inclusion in the management plan. All goals and actions in a procedure-action mapping must be realized in the current management, in an order *compatible with* that given in the mapping. For example, the following procedure-action mapping expresses the fact that the *procedure* of performing repair of the heart first requires satisfying the *goal* of gaining access to the heart and then doing the *action* of repairing it.

Procedure-Action Mapping 54006

```
Perform_Heart_Repair →  
  Need_Access_to_Heart,  
  Heart_Repair.
```

The goal of gaining access to the heart is shown in separate goal-procedure mapping to be satisfiable by performing either a bilateral thoracotomy and transverse sternotomy, or a median sternotomy.

Goal-Procedure Mapping 25067

```
Need_Access_to_Heart →  
  Perform_Bilat_Thoracotomy_Transverse_Sternotomy,  
  Perform_Median_Sternotomy.
```

Such “sub-goalling” here, as in other planning systems, allows for modular and efficient

packaging and use of knowledge about actions.

As for the planning process itself, conceptually, TraumAID's planning task can be divided into (a) *choosing* appropriate procedures for addressing the current set of diagnostic and therapeutic goals and (b) *ordering* those procedures into a coherent plan that respects clinical priorities and practice. In practice, the two are interleaved.

Algorithmically, planning is done in two stages. The first stage iterates over the set of goals, selecting a procedure for addressing each one and ordering its associated actions with respect to previously selected procedures. The second stage attempts to optimize the initial actions in the plan, to eliminate certain redundancies that could not be identified during the first stage.

Both stages of the algorithm make use of the fact that goals can often be satisfied by any of a number of alternative procedures, while procedures can often be used to satisfy any of a number of goals. While a goal-procedure mapping may identify several procedures as being able to satisfy a given goal, this does not mean that they are equally preferable in all cases. In particular, the procedures are ordered in each goal-procedure mapping such that the first one would be recommended, should its goal be the only one currently pending. (If there are more than two procedures capable of satisfying a goal, the remainder are ordered by a rough notion of preference. This allows another type of flexibility: where preferences are specific to a particular physician, or a particular hospital or a particular region of the country, rather than following from a "gold standard", it is a simple matter to re-order the list of procedures to reflect different preferences.)

As mentioned earlier though, the choice of procedure must be sensitive to the other goals that are currently pending. For example, if both a goal of diagnosing abdominal bleeding in a non-scarred patient (goal-procedure mapping 56322) and a goal of diagnosing renal injury (goal-procedure mapping 56341) are pending, the single procedure, CT scan of the abdomen, could be chosen to satisfy both, even though it would not be the procedure of choice, if only the former goal were pending.

Goal-Procedure Mapping 56322

RO_Abdominal_Bleeding_Non_Scarred_Patient →
Get_Peritoneal_Lavage,
Get_CT_Scan_Abdomen,
Perform_Laparotomy.

Goal-Procedure Mapping 56341

RO_Renal_Injury(Side=S) →
Get_CT_Scan_Abdomen,
Get_IVP.

In the algorithm's first stage, the set of pending goals is first ordered by urgency and standard priorities of trauma care, with urgent goals (i.e., those related to diagnosing or treating the cause of shock) being ordered first. Within both groups, goals are ordered by standard practices of trauma care, which call for attending to goals in an order that reflects the following classification of patient conditions: airway, breathing, circulation (of blood), neurology, contamination, orthopedic stabilization, and only then other problems. (TraumAID combines the first two, with each goal tagged as to the highest priority condition it serves.)

Following this sorting process, each goal in the resulting sequence is mapped to its most preferred procedure, with the exception of a goal addressed by a procedure already included

in the plan. In that case, the coverage is simply recorded. (Some combinations of goals not caught at this stage of planning will be caught during the second stage, optimization, if this would affect the next set of actions to be recommended by the planner.)

After a procedure is chosen to satisfy a goal, the following domain localities and regularities are used to order its set of associated actions (currently as a block) with respect to actions that have already been included in the plan.

1. *Urgency*, as above – actions related to diagnosing and/or treating shock, then other actions.
2. *Logistics*. Typically, a trauma patient is admitted to a hospital's *Emergency Room* (ER). A need for radiographic tests may then require his transfer to the *X-Ray room* (XR). The patient may then be brought to the *Operating Room* (OR) for major surgery. Finally, he may be brought to the *Trauma Unit* (TU) for further non-operative management. Standard practice is for patients to continue along this path: they will not normally be taken back to an earlier location. Thus procedures performable at one site are ordered prior to those that require facilities of a later site. This ordering makes use of TraumAID's knowledge of those hospital locations in which each procedure can be performed.
3. *Standardized priorities*, as above – airway and breathing, circulation (of blood), neurology, contamination, orthopedic stabilization, and only then other problems.
4. *Approximate temporal extent*. Often procedures cannot be started as soon as their relevance is recognized. This is even true, to some extent, of urgent goals. It is standard practice to try to fill in any gap until the start of the next major pending procedure with low-cost, relatively quick procedures. If a gap can be filled in productively, it makes for more efficient care.

The algorithm used in this first stage of planning is greedy and may result in certain sub-optimality, such as the inclusion in the plan of two procedures where one would serve at less cost. Our focus is on the initial actions in a plan: we attempt to remove sub-optimality at the start of the plan, since they are more likely to be performed. For example, given only the two goals of diagnosing abdominal bleeding and diagnosing renal injury, in that order, the two goal-procedure mappings given above would lead the planner to choose a peritoneal lavage for the former and a CT scan for the latter. Only during the second stage of planning (optimization) would the planner notice that the CT scan could serve both purposes. (If the goals were given in the opposite order, a CT scan would have been chosen for the first, and no additional procedure chosen for the second, since it would be satisfied by a procedure already included in the plan.)

Two types of optimization are currently used by the planner: *removing redundant actions* and *preferring broader coverage*. The former involves noticing that the action ordered second in the plan is capable of satisfying both the goal that motivated its inclusion in the first place *and* the goal motivating the first action. Since the second action can be used to satisfy both goals simultaneously, the first action can be removed. (The reverse situation – where an action already in the plan can be used to satisfy another, lower priority pending goal as well – is recognized during the first stage of planning, and therefore does not require separate optimization.) The second technique recognizes that a subset of actions at the start of the plan can be covered by a single action at lower total cost or at no higher total risk.

As noted earlier, only the *initial* actions of the plan are optimized. There are two reasons for this: First, complete optimization is NP-Hard. Secondly, in a situation of only partial knowledge of the patient's condition, complete exploration may be wasteful. Further discussion of the complexity of optimization, the optimization techniques used, and the decision to optimize only the initial part of the plan can be found in [9].

In the next section, we will discuss in more detail aspects of the case presented in Section 2, to see precisely how these features arise from TraumAID's knowledge and methods of reasoning.

4 Detailed Analysis

Recall the hypothetical case presented in Section 2.

Patient JS is a 25-year old male in shock with a single stab wound to the left parasternal chest above the level of the nipple. (The direction of the stab wound is unknown.)

Trauma care shares with critical care the need to make decisions that are appropriate to the current level of urgency. Here we show in detail the means by which two of TraumAID's urgency-related management recommendations were made – specifically,

1. TraumAID's choice of a means of diagnosing the patient's suspected pericardial tamponade;
2. TraumAID's choice of a means of diagnosing the patient's non-urgent renal injury,

We also show how concomitant goals influence TraumAID's choice of a means of treating renal injury.

4.1 Diagnosing Pericardial Tamponade

As soon as TraumAID receives report of a chest wound, it concludes the possibility that the patient has sustained pericardial injury

Evidential Rule 5398
Wound_With_Possible_Pericardial_Injury :-
Wound(Location='Chest).

Certain injuries will bring on shock in all instances. In contrast, Pericardial tamponade is an injury that may or may not bring on shock. TraumAID's recommended means of pursuing a diagnosis of pericardial tamponade will differ, depending on the presence or absence of shock.

Because the patient JS is in shock, as soon as evidence is received concerning decreased breath sounds (negative) and distended neck veins (positive), the reasoner draws a negative conclusion about the likelihood of a tension pneumothorax on either side, another possible cause of shock (already addressed because it has a higher priority associated with the patient's breathing). TraumAID also uses the following rule to conclude the goal of diagnosing a pericardial tamponade urgently. (The reasoner will have already drawn a negative conclusion of likely tension pneumothorax, due to the absence of decreased breath sounds in the

patient. The motivation for the last two clauses in the rule, concerning the unlikelihood of tension pneumothorax, was discussed in Section 3.1.2.)

Goal-Setting Rule 5401

RO_Pericardial_Tamponade_Urgently :-
Wound_With_Possible_Pericardial_Injury,
Shock,
Distended_Neck_Veins,
- Likely_Tension_Pneumothorax(SIDE='Left'),
- Likely_Tension_Pneumothorax(SIDE='Right'),
% Tension_Pneumothorax_Unlikely(Side='Left'),
% Tension_Pneumothorax_Unlikely(Side='Right').

When the set of pending goals is sent to the planner, the planner addresses the urgent goals first, using goal-procedure mapping 54000 and procedure-action mapping 21910 to schedule needle aspiration of the pericardial sac at the top of the current management plan.

Goal-Procedure Mapping 54000

RO_Pericardial_Tamponade_Urgently →
Get_Needle_Aspiration_Pericardial_Sac,
Perform_Catastrophic_Chest_Wound_Procedure.

Procedure-Action Mapping 21910

Get_Needle_Aspiration_Pericardial_Sac →
Needle_Aspiration_Pericardial_Sac.

If the patient JS had not been in shock, then as soon as the new evidence of decreased breath sounds and distended neck veins had been received, the reasoner would have concluded the goal of diagnosing a non-urgent pericardial tamponade.

Goal-Setting Rule 5413

RO_Pericardial_Tamponade :-
Wound_With_Possible_Pericardial_Injury,
- Shock,
Distended_Neck_Veins,
Tension_Pneumothorax_Unlikely(Side='Left'),
Tension_Pneumothorax_Unlikely(Side='Right').

The priority of this non-urgent goal comes from its addressing a circulatory problem. Unless there were independent call for needle aspiration of the pericardial sac, this goal would be addressed via ultrasound effusion, carried out in the Emergency Room.

Goal-Procedure Mapping 54001

RO_Pericardial_Tamponade →
Get_Ultrasound_Effusion,
Get_Needle_Aspiration_Pericardial_Sac.

Procedure-Action Mapping 22010

Get_Ultrasound_Effusion →
Ultrasound_Effusion.

4.2 Managing Renal Injury

In the hypothetical case of JS, we also considered a second stab wound to the patient's abdomen (left upper quadrant). This second wound, along with a finding of hematuria,

would lead the reasoner to recommend pursuing a goal of diagnosing renal injury:

Goal-Setting Rule 6341

RO_Renal_Injury(SIDE=S) :-
Wound(TYPE='Stab, Location='Abdom, SIDE=S,
but-not Location='LLQ, Location='RLQ),
Hematuria.

Setting this goal triggers another goal-setting rule which specifies that, if the patient is in shock when the goal of diagnosing renal injury is set, a second goal should be added, of diagnosing renal injury in an unstable patient.

Goal-Setting Rule 56340

RO_Renal_Injury_Unstable_Patient(SIDE=S) :-
RO_Renal_Injury(SIDE=S),
Shock,
% Continued_Shock.

Since goals that involve instability are always considered before those that do not, and IVP (the action recommended for satisfying the goal of ruling out renal injury in an unstable patient) also suffices in a stable patient

Goal-Procedure Mapping 56341

RO_Renal_Injury(Side=S) →
Get_CT_Scan_Abdomen,
Get_IVP.

Goal-Procedure Mapping 56342

RO_Renal_Injury_Unstable_Patient(Side=S) →
Get_IVP.

IVP will already be part of the current recommended management plan when the non-urgent goal is considered. This goal will therefore not result in any new actions being added to the plan.

As for treating renal injury, should the IVP have come up positive, we made the point in Section 2 that TraumAID's recommended means of treating it depended on the presence or absence of an independently motivated goal of gaining access to the patient's abdominal cavity. These alternatives are effected through setting a tentative goal of Rx_Renal_Injury, whenever the reasoner has concluded Renal_Injury through either CT scan or IVP. This tentative goal leads to one of two definitive goals – that of inspecting the kidney for renal injury (in the presence of an independent goal of gaining access to the abdominal cavity) or of observing the patient for further signs of renal injury (in the absence of such an independent goal).

Goal-Setting Rule 56351

Need_Inspect_Kidney_for_Renal_Injury :-
Rx_Renal_Injury(SIDE=S),
Patient_Needs_Access_Abdominal_Cavity.

Goal-Setting Rule 56345

Need_Observe_Renal_Injury(Side=S) :-
Rx_Renal_Injury(SIDE=S),
-% Patient_Needs_Access_Abdominal_Cavity.

The former goal will result in urologic consultation and kidney inspection being added to the current management plan.

Procedure-Action Mapping 56356

Inspect_Kidney_for_Renal_Injury →
 Urologic_Consultation,
 Laparotomy,
 Inspection_of_Kidney.

(Laparotomy will already be part of the plan – its presence in the above procedure-action mapping is to indicate the relative order of the other two actions with respect to laparotomy.) The goal of observing the patient for renal injury will result in urologic consultation, observation for fever and renal bleeding being added to the plan.

Procedure-Action Mapping 56350

Observe_Renal_Injury →
 Urologic_Consultation,
 Observation_for_Fever,
 Observation_for_Renal_Bleeding.

5 Next Steps

TraumaAID is currently being tested in a three-year validation and evaluation study. During this study, it will be tested to show that

1. its recommendations are equivalent to actual care provided by trauma centers and by national experts;
2. its recommendations avoid errors in judgment;
3. its decision rules are readily revisable, so that its recommendations in all cases are judged acceptable in accordance with current national norms;
4. it is practical, using workstations installed in clinical settings other than the one in which it was developed;
5. it can improve actual management plans.

Evaluation studies have previously been done on an earlier version of the system, TraumaAID 1.0 [5, 6]. The current version, TraumaAID 2.0, is both more powerful and more flexible. To date, we have nearly completed initial validation of the system on 220 theoretical cases. A further 100 cases were collected when TraumaAID 1.0 was made available for use in the Emergency Room at the Medical College of Pennsylvania, and will be the nidus for further validation using actual patients. In October 1991, we will begin abstracting a new set of 100 actual cases, to begin TraumaAID's formal evaluation.

When TraumaAID's formal evaluation is complete, we hope we will have a strong argument for our approach to management support in trauma care, which distinguishes consideration of goals from consideration of the means by which those goals are satisfied. We hope the results will be of interest, and perhaps, of value for critical care applications as well.

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