When Reactive Planning is Not Enough: Using Contextual Schemas to React Appropriately to Environmental Change [1]

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Abstract

A problem solver operating in the real world must adapt its behavior to an unpredictable and changing problem-solving environment. It must react *appropriately* to changes in the situation, where what is appropriate depends to a large extent on the overall problem-solving context. In order to do this, the reasoner needs to have explicit knowledge about the context it is in. In our approach, the problem-solving context is represented explicitly as a *contextual schema*. When presented with a problem, the reasoner finds an appropriate contextual schema, then uses it to influence its problem-solving behavior. The reasoner uses the contextual schema to recognize important changes in the problem-solving situation and to respond appropriately to those changes

Our approach is implemented in the MEDIC program (Turner, 1988b; Turner, in preparation). MEDIC is medical diagnostic consultant whose domain is pulmonology.

A real-world problem solver solves problems in a world that is both unpredictable and changing. Such a reasoner cannot adopt the typical planning approach of creating a plan and then executing it—the problem is likely to change during execution, thus invalidating the remainder of the plan. Instead, the reasoner must react appropriately to unexpected changes in the state of the world.

Reactive planning research (e.g., Agre & Chapman, 1987) is concerned with reacting to change; however, no reactive planning approach explicitly represents the reasoner's notion of what the problem-solving *context* is. This is unfortunate, because the appropriate response to a change in the environment depends to a great extent on the problem-solving context. Consider the following examples:

Example 1. An appropriate response to a knock on the door when expecting friends is to open the door and say "Come in!"; this is not such an appropriate response in a different context: one in which an axe murderer is suspected to be in the neighborhood.

Example 2. While diagnosing a patient, a doctor sees a finding that makes him consider requesting that another diagnostic service examine his patient. Normally, he would go ahead and request the consultation. However, if he is at a hospital where the diagnostic service is very interested in trying a new, somewhat risky operating procedure, he would likely forego the consultation and attempt to diagnose the patient himself.

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Example 3. A woman hails a cab, then waits calmly as it darts across two lanes of traffic and screeches to a halt beside the curb where she is standing. In another situation, the woman is waiting to cross a street when a cab darts across two lanes of traffic towards the curb where she is standing—this time, she backs quickly away.

In each of these examples, the reasoner's response is not solely determined by the stimuli (e.g., a knock on the door). Instead, the entire *problem-solving context*—all of the information about the problem solver's goals and the problem's features—is used to help determine the response. So it is in most real-world situations: reactions that are perfectly appropriate in one context will be inappropriate or even dangerous in another. An accurate judgment of the problem-solving context is crucial to responding appropriately to changes in the world.

In our approach, the reasoner explicitly represents the problem-solving contexts it knows about as *contextual schemas*. Contextual schemas are stored in a *conceptual memory* (cf. Kolodner, 1984; Simpson, 1985) from which they can be retrieved based on the reasoner's goals and features of the problem-solving situation. When a new situation occurs, or when the situation changes significantly, the reasoner retrieves a contextual schema which characterizes the new or changed situation. Information from the contextual schema is used by the reasoner to respond appropriately to future changes to the environment.

In the remainder of this paper, we discuss contextual schemas and how they are used to respond appropriately to changes that arise during problem solving. We draw examples from MEDIC, the program that is the testbed for our approach. MEDIC is a *schema-based reasoner* (Turner, 1988a; Turner, 1988b; Turner, in preparation) whose domain is medical diagnostic consultations in pulmonology.

REPRESENTING THE PROBLEM-SOLVING CONTEXT

In order to respond appropriately to changes, a reasoner must have an explicit representation of what its current problem-solving context is. A representation of a problem-solving context should provide the reasoner with information to allow it to behave appropriately in that context. This information includes:

- predictions about changes to the situation
- appropriate goals to activate in response to changes in the situation
- actions or procedures that are likely to be useful for achieving goals in that context
- relative worth of goals likely to occur in the context—i.e., information which focuses the reasoner's attention on appropriate goals to pursue

In MEDIC, we represent this knowledge in *contextual schemas*. These schemas represent general knowledge about specific types of problem-solving situations. The contextual schema in Figure 1, for example, describes pulmonary consultations, i.e., times when a doctor has to diagnose a pulmonary disorder. Other contextual schemas we would expect a pulmonary specialist to have would include those representing "pulmonary consultations involving alcoholics," "consultations involving a nodule in the lung," and "consultations involving lung cancer."

A contextual schema has four parts. First, there is a description of the problem-solving *situation* represented by the schema, including a description of the patient, expected findings, etc. This is used by the reasoner to determine if the contextual schema represents the current situation, and it also provides a source of predictions about expected features of the problem-solving situation. Second, a contextual schema has information about *goals* that are likely to occur during problem solving, along with information about changes to the environment that should trigger those goals. Associated with each goal is information about that goal's relative worth in the context represented by the contextual schema. Third, a contextual schema

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Situation:
    patient isa human, smokes (cf=:low)
    chief complaint = cough (cf=:moderate)
    findings = {dyspnea (cf=:low), cough (cf=:moderate),
                abnormal-chest-X-rays (cf=:very-low)}
    hypotheses = {pulmonary disease (cf=:high)}
Goals:
    G1: Diagnose a patient.
        priority: .3
    G2: Interpret finding of dyspnea
        trigger: finding of dyspnea added to STM
        priority: .4
            ...
    G5: Interpret a finding.
        trigger: finding is added to STM
        priority: .4
    G6: Confirm a hypothesis that pulmonary disease is present
        trigger: hypothesis of pulmonary disease is added to STM
        priority: .4
            ...
Scenes:
    main: S1
    S1: sc-consult ;; general consultation procedure
        goal: G1
    S2: sc-dyspnea ;; procedure tailored to interpret dyspnea
        goal: G2
            ...
    S5: sc-finding ;; general procedure for interpreting findings
    S6: sc-hypothesis ;; general procedure for evaluating hypotheses
        goal: G6, G7
            ...
Strategy:
    Hypothetico-deductive reasoning
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Figure 1: Part of a contextual schema representing the context of a pulmonary consultation.

contains a description of *scenes* (Schank, 1982) that generally occur in situations represented by the schema: i.e., actions or procedures that are performed to achieve problem-solving goals. This information is used by the reasoner to find appropriate actions and procedures when similar goals occur in the current situation. Finally, a contextual schema contains information which suggests a possible problem-solving *strategy* to use; e.g., the schema in Figure 1 recommends the strategy of "hypothetico-deductive reasoning" for pulmonary consultations.[1]

A contextual schema can be viewed as a generalization of prior, similar problem-solving episodes. On this view, a schema provides information about: goals that have usually arisen in similar episodes, and what usually triggers them; past decisions about the relative worths of those goals; actions and procedures that are usually useful for achieving goals in similar situations; and previously-useful strategies.

USING CONTEXTUAL SCHEMAS TO RESPOND TO CHANGES

Knowledge about the problem-solving context is used several different ways to help the reasoner react appropriately to changes in its problem-solving situation:

1. contextual schemas contain information that helps the reasoner decide which changes are important;

[1] Strategies are represented as schemas in MEDIC, similarly to the way contexts are represented. For details, see (Turner, 1988b) or (Turner, in preparation).

2. contextual schemas contain information that helps the reasoner select a goal to activate when a change occurs;
3. the strategy suggested by the contextual schema, along with knowledge contained in the schema about the relative worth of goals in the context, allows the reasoner to choose between several active goals; and
4. contextual schemas contain information about useful actions and procedures for goals in that context; this information is used to help the reasoner select actions and procedures to use to achieve its goals.

Deciding Which Changes are Important

A reasoner should not react to every change in its problem-solving situation, but only to those that are important. Which changes are important depends on the problem-solving context. For example, if during a problem-solving session concerned with planning a meal the client tells the reasoner that he has a chronic cough, the new information constitutes an unimportant change in the problem-solving situation; however, in the context of diagnosing the client's pulmonary problem, the same information constitutes an important change in the situation, one that may impact the final diagnosis.

Contextual schemas provide the reasoner with information about important changes that are expected to occur in a problem-solving situation. For example, the contextual schema in Figure 1, which represents the context of pulmonary consultations, predicts that findings of cough, dyspnea,[2] and abnormal chest X-rays will occur; if any of these *do* occur in the reasoner's current situation, then the reasoner knows that the change, i.e., the occurrence of the finding, is important and should be responded to.

Activating Goals

Part of a reasoner's response to a change in its problem-solving situation has to do with the change itself: the reasoner must determine an appropriate goal to activate to ensure that the change is handled. Which goal should be activated depends on the reasoner's problem-solving context. For example, an appropriate goal for the event of being told about back pain when in a social context is *express sympathy*; in the context of a doctor's office, this same event will give rise to the goal of *interpret the finding of back pain.*

A contextual schema can help the reasoner select an appropriate goal for its context. Associated with most goals in a schema is information about environmental events that should trigger the goal. When a change occurs, the reasoner can use this information to determine which goal it should activate. The contextual schema in Figure 1, for example, suggests activating the goal *interpret finding of dyspnea* when a finding of dyspnea occurs.

Choosing a Goal to Pursue

Another part of a reasoner's response to changes in its problem-solving situation is deciding which of its active goals is appropriate to pursue, given the new, changed state of the environment. A problem solver will often have several goals active simultaneously. For example, a pulmonary consultant such as MEDIC might have goals such as *form a diagnosis*, *explain the finding of dyspnea*, *gather information about the patient's history*, and *evaluate the hypothesis that pneumonia is present*. Each goal may be difficult, and most or all of the reasoner's attention may be required to achieve it. The reasoner must have some way to choose which goal to focus on.

Contextual schemas provide a nice way of judging the relative worth of goals in context. First, a contextual schema suggests a reasoning strategy to use in the context. Strategies provide

[2]Shortness of breath.

information about the relative worth, or priority, of each goal when the strategy is being followed. For example, the strategy *hypothetico-deductive reasoning* gives goals related to hypotheses (e.g., *evaluate hypothesis*) greater priority than goals related to gathering information.[3] Second, each goal in a contextual schema provides information about its relative worth in that context. For example, in most consultations, a finding of anemia is important, and goals related to it should have a reasonably high priority. However, in consultations involving alcoholic patients, goals relating to anemia have low priority since anemia is a complication of alcoholism. In most contextual schemas (e.g., the one in Figure 1), goals relating to findings are given a high priority; if anemia occurs in contexts represented by these schemas, goals associated with it would be considered important. However, a contextual schema representing *pulmonary consultations involving alcoholic patients* would explicitly give a low priority to the goal of following up anemia, preventing the reasoner from wasting time on the unimportant goal in that context.

In MEDIC, information about the worth of a goal comes from the representation of the goal itself (i.e., all things being equal, some goals are more important than others), from the current strategy, and from the contextual schema. Information from each source is combined in a weighted sum to give the overall priority of the goal;[4] the goal with the highest priority is the one selected by the reasoner to pursue. When the situation changes, MEDIC re-evaluates its goals based on the new situation; this leads to different goals being pursued at different times during problem solving.

Selecting Actions

The third part of a reasoner's response to a change involves selecting an action or procedure to use to achieve the goal that was activated as a result of the change. This, too, depends on reasoner's problem-solving context, since some actions are more appropriate in one context than in another. For example, asking the question *How far can the patient walk before becoming short of breath?* is one way of gathering information about dyspnea from a patient; the answer can be used to determine the severity of the dyspnea. However, in another context, one in which the patient cannot walk, this action is inappropriate; instead, the reasoner should perhaps ask *How much activity can the patient perform before becoming short of breath?*.

A contextual schema provides the reasoner with a context-specific repertoire of ways to achieve goals. Contextual schemas contain information about useful actions and procedures for goals that they predict will arise. The reasoner uses this information as a source of actions and procedures to achieve goals in its problem-solving situation. For example, if the reasoner is working on the goal of interpreting dyspnea, then the contextual schema in Figure 1 would suggest achieving it by using the specialized procedure **sc-dyspnea**.[5] This procedure asks standard questions designed to elaborate what is known about the finding, including *How far can the patient walk before becoming short of breath?* If the problem-solving context is instead one in which the patient cannot walk, the contextual schema used will recommend a different procedure, one which does not ask questions about walking.

In MEDIC, procedures are organized in specialization hierarchies based on the goals they achieve and the features of situations in which they are useful. With no contextual schema, the specialization hierarchies must be searched for an appropriate procedure, which is computationally expensive. By using a contextual schema, however, the reasoner needs only to perform the equivalent of a table look-up within the schema to find an appropriate procedure. The reasoner may then either use the procedure or try to find a more specific one using the

[3] See (Turner, 1988b) for details.

[4] For details, see (Turner, in preparation).

[5] Procedures are represented in MEDIC as a kind of schema; see (Turner, 1988b) or (Turner, in preparation) for details.

procedure as a starting point to search the specialization hierarchies. In either case, the schema provides a short-cut to finding an appropriate procedure.

CHOOSING A CONTEXTUAL SCHEMA

Contextual information can only help a reasoner respond to changes if the context can be appropriately identified. In our approach, this means choosing an appropriate contextual schema for the reasoner's problem-solving situation. The contextual schema selected should be the most specific schema the reasoner knows that matches the problem-solving situation. For example, if the problem description is *diagnose a patient whose chief complaint is dyspnea*, the most specific contextual schema is one representing consultations involving cardiopulmonary problems, not one representing consultations in general, since dyspnea would be expected in the former and not the latter. There are three issues to resolve in finding an appropriate contextual schema:

1. retrieving schemas from memory;
2. choosing between competing schemas; and
3. switching contexts during problem solving.

Retrieval, in our approach, is from a *conceptual memory* (cf. Simpson, 1985) similar to CYRUS (Kolodner, 1984). In this scheme, contextual schemas representing general contexts, such as *diagnostic consultations*, index more specific similar contexts, such as *consultations involving cardiopulmonary problems*, using as indices the features that differentiate between them. Contextual schemas can be retrieved from the memory by presenting it with a description of the problem-solving situation: goals, findings, etc. The memory responds with the most specific schemas that match the situation.

This does not completely solve the problem of finding an appropriate contextual schema, however, since more than one schema may be returned by the memory. The reasoner needs some way of choosing between "competing" schemas.

Our approach is to make use of a set of *preferences* when selecting between competing schemas. These include:

- Favor schemas whose goals include all of the goals given in the initial problem statement.
- Choose a specialization of a contextual schema over its parent if
  - it matches the situation by some feature that is missing in the parent, or
  - it matches by a feature that is more specific in the child than the parent.
- Choose a parent over its specializations if all specializations match some feature to the same degree and otherwise match the situation no better than the parent.
- Compare contextual schemas based on the features of the situation matched, taking into account the degree of confidence each schema has in each predicted feature being present.

Often the reasoner cannot simply select a contextual schema at the start of problem solving, then use that schema throughout the problem-solving session. The reasoner's problem-solving situation will change as problem solving progresses, and, as this happens, the contextual schema in use may cease to be a good match for the situation. Some mechanism is needed for *switching contexts*: i.e., for re-evaluating the reasoner's notion of what the current context is.

In our approach, the reasoner remembers all contextual schemas it considers when selecting one as the current context. When its problem-solving situation changes, the reasoner re-evaluates its choice of context by re-examining these schemas. In addition, new candidate schemas are added to those the reasoner already is considering by a separate process called the *prober*. The prober monitors the reasoner's problem-solving situation and, when there is a change, tries to find

a new contextual schema which fits the changed situation. If one is found, it is added to those the reasoner is already considered, and the reasoner is notified. When the reasoner re-evaluates its context, the new contextual schema will be available as a candidate.

CONTEXTUAL SCHEMAS AND OPPORTUNISM

Responding appropriately to changes is closely related to *opportunistic reasoning* (cf. Hayes-Roth & Hayes-Roth, 1979). The use of contextual schemas promotes opportunism in two ways. First, information from contextual schemas is used by the reasoner to recognize important changes and to activate goals to handle them. This allows the reasoner to take the opportunity of activating important problem-solving goals that might otherwise be activated much later or not at all. The importance of this is evident in diagnosis. When a finding is discovered, the reasoner responds by activating a goal to interpret that finding. Pursuing this goal will lead to the generation of hypotheses, which, in turn, serve to focus the reasoner's problem-solving behavior (cf. Patel et al., 1987). Second, contextual schemas provide information the reasoner uses to recognize an opportunity for pursuing a goal. This takes the form, in our approach, of information about a goal's priority in the context. If a situation changes, it may cause the reasoner to switch the contextual schema it is using; this, in turn, will provide a new estimate of the goal's priority, which may cause it to be pursued.

Other researchers studying *opportunistic reasoning* (e.g., Hayes-Roth & Hayes-Roth, 1979) have also had the goal of making their problem solvers respond appropriately to environmental change. However, as Hammond (Hammond, 1988) notes, most of this work "is a model of opportunism at planning-time rather than execution-time," and thus suffers the same shortcomings as more traditional planners: these planners ignore the effects of the planner's own actions on the environment.

Hammond's work in opportunistic reasoning deals with satisfying suspended goals as the opportunity to do so arises (Hammond, 1988). Unfortunately, both his model and that of Birnbaum (Birnbaum, 1986) seem to to make little provision for the activation of goals in the first place, but concentrate instead on their *reactivation* once blocked. Yet goal activation is a crucial part of both reactivity and opportunism. Perhaps combining the approach presented here with one of their approaches would be a reasonable step towards a more complete view of real-world problem solving.

CONCLUSION

Real-world problem solvers must not only react to changes when they occur, but they must react *appropriately*. The response that is appropriate depends heavily on the situation the reasoner is in; thus, if the reasoner is to respond appropriately to changes, it must have an explicit representation of its problem-solving context.

Our approach explicitly represents problem-solving contexts as contextual schemas. A contextual schema provides the reasoner with information it can use to respond appropriately to changes in a context represented by the schema. Specifically, a contextual schema provides: (1) predictions about changes likely to occur and that should be responded to; (2) goals that should be activated in response to changes in the situation; (3) actions that are useful for goals occurring in that context; and (4) strategies and other information the reasoner can use to assess the relative worth of goals in its current context, allowing it to focus on appropriate goals during problem solving.

Our approach is currently being tested by the MEDIC program in the domain of medical diagnostic consultations. However, we believe our approach is more general than this. It should be useful in any task in which the appropriate response to a change depends on the

problem-solving context. This will include most real-world problem-solving tasks.

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