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Representing and Acquiring Teleological Descriptions*

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Abstract

Teleological descriptions capture the *purpose* of an entity, mechanism, or activity with which they are associated. These descriptions can be utilized in diagnostic reasoning by providing focus in hypothesis generation and selection. Teleological descriptions can also be utilized in design to index existing designs for reuse and to express design rationale.

While a teleological description of a mechanism is distinct from any structural and behavioral descriptions, it is claimed that a teleological description is constructed with references to elements of structural and behavioral descriptions. In particular, the purpose of a component or activity can be expressed in terms of the behaviors it *prevents* or *guarantees*. While these teleological descriptions reference elements of behavioral descriptions, they are independent of any particular behavioral language or model domain. Higher level operators can be constructed from these primitive operators. A technique for deriving teleological descriptions is described, along with its relationship to design requirements and constraints.

1 Introduction

Teleological descriptions capture the *purpose* of an entity, mechanism, or activity with which they are associated. While a teleological description of a mechanism is distinct from the structural and behavioral descriptions of that mechanism [Kuipers 1985], it is claimed that a teleological description is constructed with references to elements of structural and behavioral descriptions, just as behavioral descriptions reference elements of the structural description. To further elucidate the distinction between behavior and function (teleology), consider the steam-release valve in a boiler example in [Kuipers 1985] and the functional (teleological) and behavioral descriptions given there. The function (teleology) of the steam-release value is to prevent an explosion, while the behavior is that the pressure does not exceed a certain value.

The goal of this work is to study the nature of teleological descriptions and their (domain-independent) representation. We describe 1) applications of teleological knowledge, 2) a language for teleological descriptions, and 3) a technique for deriving teleological descriptions.

2 Using Teleological Descriptions

In the following sections we examine the need for teleological descriptions in the task domains of explanation of mechanisms, diagnosis of mechanisms, and the design and redesign of mechanisms.

2.1 Teleological Descriptions in Explanation and Diagnosis

Deriving and utilizing causal relationships in mechanisms is an approach currently used in many explanation systems and diagnosis systems. As stated in [Steinberg, Mitchell 1984],

> The resulting focus [of causal reasoning] is generally broader than that determined from [the representation of purpose] because out of the many places in the circuit that can impact any given output specification, only a small proportion of these involve circuitry whose main purpose is to implement that specification.

If an observed symptom of a mechanism is considered either as an unwanted behavior (or a missing behavior), then a teleological description which relates a component of the mechanism with the prevention (introduction or guarantee) of that behavior provides a heuristic for selection among potential causes. Hence, teleological descriptions provide a more productive focus of attention for diagnosis.

As exhibited in [de Kleer 1985], it is useful to identify the purpose of components when attempting to understand the design of a mechanism. In [Scarl, Jamieson, Delaune 1985], the need for such a description (i.e. the purpose of a command to a control system) is identified and proposed as an area of future work.

2.2 Teleological Descriptions in Design

Design reuse is an area of current research in both CAE environments and CASE environments. A problem in these environments is 1) capturing and representing information by which a design component should be classified for subsequent

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retrieval, and 2) a language for describing the characteristics of the design component the designer wishes to examine as a candidate for reuse. As stated in [Mostow, Barley 1987],

> For design by analogy, finding a suitable design to retrieve from a repository of previous designs requires knowing where to look. How can designers avoid a time-consuming search through such a repository when they've never seen the relevant entry or can't remember where to find it? As we develop a larger database of design plans, we expect the process of finding relevant ones to become a bottleneck ...

Teleological descriptions add another dimension by which designs can be classified and retrieved. In the absence of a description of purpose, designers must rely on their mental inventory of likely components, structural features of likely components, or specific behaviors of likely components in order to construct a query for the search. In reusing an existing design, if the design does not match the current requirements exactly, it will require some modification. As this design is being modified, knowledge of the purpose of components will benefit the (reusing) designer in much the same way a teleological descriptions aids the diagnosis task.

3 Teleological Descriptions

The goal of this work is to study the nature of teleological descriptions and their (domain-independent) representation. A particular language for teleological descriptions is proposed with the goal of demonstrating its:

- Breadth of application to different domains (e.g. electrical, mechanical) of mechanisms
- Breadth of application to different behavioral description languages
- Formal foundation

Given this language, we claim that components can be characterized (with respect to their purpose) without prescribing the teleological descriptions.

3.1 Representation

The teleological description language proposed here involves teleological operators which reference descriptions of behavior, modifications to mechanisms, and other teleological operators. Since the teleological description of an entity is in general context dependent, the teleological description of an entity is not meaningful independent of a context. In this work, the behavior of the system in which a component is embedded provides the context in which teleological descriptions of the component are developed or evaluated.

3.1.1 Definitions

Where possible, existing terminology of qualitative behavioral descriptions has been adopted (*cf.* [de Kleer, Brown 1985], [Forbus 1985], [Kuipers 1985], [Williams 1985]). To this terminology we add the terms ***partial state*** and ***scenario***. A partial state is a subset of a state, possibly equal to the state. Hence, a partial state describes the values of a subset of model variables. A scenario is a time-ordered sequence of partial states in which the subset of variables is the same in all partial states in the sequence. A scenario also contains a Boolean expression whose truth value is determined by a mapping which associates the scenario with a behavior. In addition to ignoring variables of the model, a scenario may also generalize a sequence of states by eliminating certain states in the sequence. To demonstrate this point, consider the scenario

$$\langle \{(x,(0,\mathrm{dec}))\}, \{(x,(0,\mathrm{inc}))\}, Bexp \rangle.$$

The states which are abstracted in this scenario cannot be adjacent in a behavior of the model (in QSIM), but are allowed as an abstraction of the behavior in the form of a scenario. In particular, the scenario says that x at some time had the qualitative value (0,dec), and at some later time (with an unspecified number of intervening values) had the value (0,inc).

3.1.2 Mapping Scenarios to Behaviors

A scenario is said to *occur-in* a behavior if there exists a mapping from the scenario into the behavior such that

1. a partial state is mapped to a state which it abstracts (i.e. is a subset of),
2. the order of states implied by the scenario is preserved in the behavior, and
3. the truth value of *Bexp* is TRUE.

A scenario is said to *occur-in* an envisionment if it occurs-in at least one behavior of the envisionment. For scenarios σ_1, σ_2, the relationships σ_2 *occurs-after* σ_1 and σ_1, σ_2 *occurs-synchronously* are defined in the straightforward manner, and the corresponding composed scenarios are denoted by $[\sigma_1; \sigma_2]$ and $[\sigma_1 \parallel \sigma_2]$, respectively.

3.1.3 Teleological Operators

Teleological operators are the language primitives for teleological descriptions. In the context of a modification to a model (change in the structural description), a single teleological operator relates the envisionment of the unmodified model to the envisionment of the modified model in terms of scenarios. In the following definitions, σ_i are scenarios, M represents the original model, M' represents the modified model, δ represents the modification made to M to achieve M', E is the envisionment of M, and E' is the envisionment of M'. It is important to note that a teleological operator makes a statement about both the modified and the unmodified model.

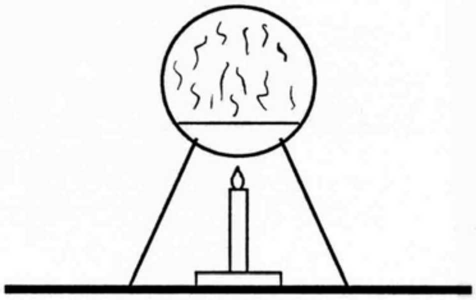

Figure 1: Double Heat Flow Behavior

Teleological Primitives

1. δ **Guarantees** σ - σ occurs-in all behaviors of E', and there is at least one behavior of E in which σ does not occur.
2. δ **Prevents** σ - σ does not occur-in any behavior of E', and σ occurs-in at least one behavior of E.

The third primitive operator provides a means for creating teleological descriptions which involve preconditions. This precondition references a set of scenarios upon which a sentence (a single teleological operator or a sentence constructed from teleological operators and logical connectives) depends. In the following definition, **T** is a teleological sentence.

3. δ **Conditionally** (in $\{\sigma_1, \ldots, \sigma_n\}$) **T** - If $\sigma_1, \ldots, \sigma_n$ all occur-in a behavior of E', then **T** holds in that behavior. Further, there is a behavior b of E such that $\sigma_1, \ldots, \sigma_n$ all occur-in b and **T** does not hold in b.

These three primitive teleological operators form the basis upon which teleological descriptions can be built.

3.2 An Example - Double Heat Flow System

To demonstrate a functional description using a teleological operator, consider the double heat flow system from [Kuipers 1985] (Figure 1). (In this discussion, variable names are italicized and use initial caps, and landmarks are denoted by all caps.) With initial conditions of *InternalTemp* = (AIRTEMP,nil), where *InternalTemp* ranges over the quantity space (0 AIRTEMP FLAMETEMP INF), simulation via QSIM derives a single behavior in which *InternalTemp* reaches a value between the landmarks AIRTEMP and FLAMETEMP at which point the system is in equilibrium.

If the variable *InternalPressure* is added to the model, constrained via the QSIM constraint

(M+ *InternalPressure InternalTemp*)

and ranging over the quantity space (0 AIRPRESSURE MAXPRESSURE INF) with initial value (AIRPRESSURE,NIL), three behaviors are derived (Figure 2). In each, *InternalTemp* reaches an equilibrium value between the landmarks AIRTEMP and FLAMETEMP as before. The three behavioral distinctions are introduced by the fact that when the system reaches equilibrium, *InternalPressure* may be either

((0 MAXPRESSURE),std),

(MAXPRESSURE,std), or

((MAXPRESSURE inf),std).

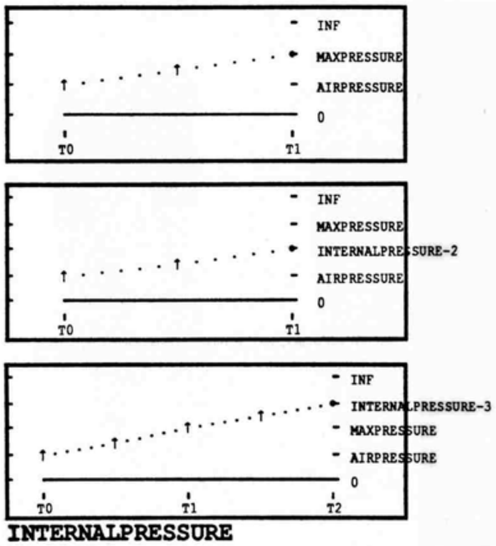

Figure 2: Double Heat Flow with Pressure

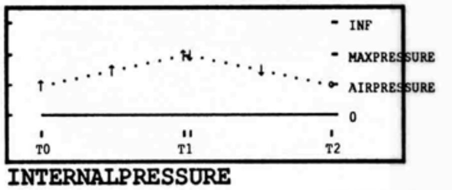

Figure 3: Double Heat Flow with Shutoff

Now consider a modified double heat flow system in which a pressure-sensor and flame shut-off have been added, such that the heat source (flame) is removed from the system if *InternalPressure* assumes the value (MAXPRESSURE,inc). Simulation again derives three behaviors. The behaviors in which *InternalPressure* has value ((0 MAXPRESSURE),std) or (MAXPRESSURE,std) when equilibrium is reached are as before. However, in the third behavior (Figure 3), the value of *InternalPressure* reaches MAXPRESSURE and then returns to (AIRPRESSURE,std).

In this example, the scenario of interest is

$$\sigma = \langle\{(\mathit{InternalPressure},((\text{MAXPRESSURE},\text{inf}),\text{nil}))\}\ \text{TRUE}\rangle.$$

If modification δ represents the addition of the pressure-sensor and flame shut-off, then

δ **Conditionally** (in $\{\sigma_I\}$) **Prevents** σ

where σ_I is a scenario representing the initial state of this example. The value of the qualitative approach is demonstrated here in that all possible behaviors (from a given initial state) are explored, and hence statements involving **Guarantees** and **Prevents** can be made upon examining the envisionments.

3.3 Additional Operators

The operators described here are intended to demonstrate the ability to define semantically richer operators in terms of the three primitive operators (**Guarantees**, **Prevents**, and **Conditionally**) proposed in the previous section. When examining descriptions of purpose generated by designers, verbs such as introduces, controls, regulates, maximizes, reduces or allows occur. In the following definitions verbs will be decomposed into the teleological primitives directly or via previous definitions. The goal is introduce higher level operators (verbs) for generating teleological descriptions which can be transformed into a predetermined, small set of domain independent primitives.

Descriptions of purpose should be able to express constraints on scenarios with respect to the time domain. The first two operators given here describe the manner in which two scenarios may be related in time. These two operators are not concerned with the magnitude of time intervals other than the distinction between 0, finite, and infinite time.[1] The primary point is to demonstrate the expressive power of the primitive teleological operators.

1. δ **Orders** σ_1,σ_2 - If σ_1 and σ_2 both occur-in a behavior of E', then σ_2 occurs-after σ_1. Further, there exists a behavior in E in which both σ_1 and σ_2 occur-in, and σ_2 does not occur-after σ_1. This can be decomposed as δ **Conditionally** (in $\{\sigma_1, \sigma_2\}$) **Guarantees** $[\sigma_1; \sigma_2]$.

2. δ **Synchronizes** σ_1,σ_2 - If σ_1 and σ_2 both occur-in a behavior of E', then σ_1 and σ_2 occur-synchronously. Further, there exists a behavior in E such that σ_1 and σ_2 both occur, but they do not occur-synchronously. This can be decomposed as δ **Conditionally** (in $\{\sigma_1, \sigma_2\}$) **Guarantees** $[\sigma_1 \parallel \sigma_2]$.

3. δ **Introduces** σ - σ occurs-in some behavior of E', and does not occur-in any behavior in E. This can be written as δ **Guarantees** $\neg$ (**Prevents** σ).

4 Acquisition

Two forms of acquisition of teleological descriptions are considered here – human entry and derived. The teleological primitives given here are interesting with respect to human entry of teleological descriptions in that they provide the language in which these descriptions can be expressed. It may be desirable to develop higher level operators such as control or regulate which a designer uses to write a teleological description which can then be transformed into lower level operators if needed. For example, [Abelson, et al. 1989] describes a hypothetical design assistant (program) and a conversation between a designer and the design assistant with the following interaction:

> Begin the design of an active stabilizer to damp the family B motions.

The existing design and a current behavior (*family B motions*) are understood by the assistant, and a design modification has been named and given a description of purpose, namely *to damp the family B motions.* A precise definition of *damp* in terms of teleological operators and behaviors would facilitate further reasoning by the assistant.

To perform automatic derivation of teleological descriptions, a model and a modification to that model must be examined. These modifications may be either structural or simply changes in the value of an independent or exogenous [Iwasaki, Simon 1986] variable.

4.1 Comparative Analysis

Comparative analysis is a technique for examining (comparing) the behaviors of two similar models. Comparative analysis of mechanisms in which the result of varying the value of a variable is examined has been described by [Weld 1988] and [Chiu, Kuipers 1989]. Given a model and a modification to the value of a variable of the model, these systems determine how other variables of the model change with respect to the specified change in the specified variable. In addition to other variables of the model, time intervals between states can also be examined with this technique.

4.2 Deriving Teleological Descriptions for Structural Changes

The derivation technique proposed here compares the behaviors (represented in attainable envisionments) of the unmodified and the modified mechanisms. Consider the double heat flow example discussed earlier. Figure 4 shows abstractions of the attainable envisionments (from the previously specified initial state) of the double heat flow system with pressure and the double heat flow system with shutoff. Behaviors *a* and *b* are the same in both envisionments and hence do not introduce potential scenarios of interest. Behavior *c* of the unmodified system (M) is characterized by the variable *InternalPressure* exceeding the landmark MAXPRESSURE before equilibrium is reached (Figure 2). Behavior *c* of the modified system (M') is characterized by the variable *InternalPressure* reaching the landmark MAXPRESSURE and then returning to landmark AIRPRESSURE (Figure 3). Additionally, the variable *InternalTemp* returns to the landmark AIRTEMP while the variable *TSource* is fixed at AIRTEMP.

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[1] The particular operators defined here are not derived from any particular temporal logic, and are merely hypothesized as useful in constructing teleological descriptions.

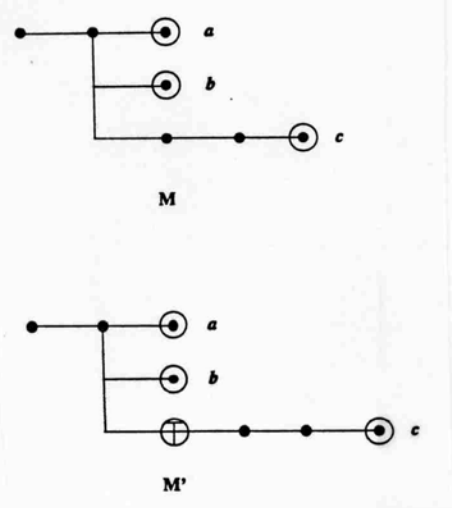

Figure 4: Double Heat Flow Envisionments

In examining these two behaviors, the following two scenarios can be identified as different between the two behaviors:

$$\sigma_1 = \langle\{(\mathit{InternalPressure},((\mathrm{MAXPRESSURE},\mathrm{inf}),\mathrm{nil}))\}, \mathrm{TRUE}\rangle,$$

$$\begin{aligned}\sigma_2 = \langle & \{(\mathit{InternalPressure},(\mathrm{MAXPRESSURE},\mathrm{nil})),\\ & \quad (\mathit{TSource},(\mathrm{AIRTEMP},\mathrm{std})),\\ & \quad (\mathit{InternalTemp},((\mathrm{AIRTEMP},\mathrm{inf}),\mathrm{nil}))\ \},\\ & \{(\mathit{InternalPressure},(\mathrm{AIRPRESSURE},\mathrm{nil})),\\ & \quad (\mathit{TSource},(\mathrm{AIRTEMP},\mathrm{std})),\\ & \quad (\mathit{InternalTemp},(\mathrm{AIRTEMP},\mathrm{nil}))\ \},\\ & \mathrm{TRUE}\rangle,\end{aligned}$$

σ_1 is absent in the modified model (M'), and σ_2 has been introduced in M' (i.e. was absent in M, the unmodified model). At this point, this comparison is unable to distinguish whether both, only one, or neither of the scenarios are of interest with respect to the purpose of the modification.

The Role of Design Requirements and Specifications

Many design requirements and specifications are described in terms of behaviors (required, prohibited, or constrained) and in terms of ranges on physical aspects (variables) of the system. Assuming that the design requirements and specifications for the double heat flow system stated that *InternalPressure* should not exceed MAXPRESSURE and that no statement was made about the behavior characterized by σ_2, it can be determined that the teleological description for the modification δ (addition of the pressure sensor and flame shutoff) is

$$\delta\ \textbf{Conditionally}\ (\text{in}\ \{\sigma_I\})\ \textbf{Prevents}\ \sigma_1.$$

5 Future Work

Work in the immediate future is focused on 1) deriving teleological descriptions for components of nontrivial models (utilizing hierarchical model definitions (*cf.* [Franke, Dvorak 1989])), 2) examining the relationships between the teleological operators defined here and modal and temporal logics ([Turner 1984], [Chellas 1980]), and 3) integrating the use of teleological descriptions into a diagnosis system.

6 Conclusions

Research in the area of qualitative reasoning and model-based reasoning has developed theories and understanding of structural and behavioral descriptions to such a degree that work on understanding, theory, and application of teleological descriptions can begin in earnest.

This work introduces domain-independent techniques for representing and deriving teleological descriptions and is attempting to place them on a formal foundation. With these tools in hand, stronger approaches in the domains of explanation, diagnosis, and design of mechanisms will be realizable.

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