Shifting Ontological Perspectives in Reasoning about Physical Systems

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Abstract

Commitment to an ontological perspective is a primary aspect of reasoning about the physical world. For complex analytic tasks, the ability to switch between different ontologies to represent the same target system can be critical. Supplementing the standard device ontology for electronic circuits, we outline elements of a charge-carrier (CC) ontology for reasoning about electronics. Having two ontologies extends our range of reasoning, but raises the issue of how to control their application. We propose a set of ontological-choice rules to govern the process of ontological shift and demonstrate its effectiveness with examples involving the two ontologies in reasoning about electronic circuits.

Introduction

In order to reason about a physical system, we must be able to describe the structure and behavior of the system within some representational language. Such a description is generally called a model of the system (de Kleer & Brown 1984, Davis & Hamscher 1988). Whatever representational language we use, a model embodies separate entities which we use to designate the "things" in the world, the conceptions which we have about them, and the interrelationships that exist among them. We refer to the individual entities - terms, predicates, and axioms - as organized in the representational language as an ontology. An ontology determines "what there is" in the world (Munitz 1974). The world is initially unlabeled. Division into conceptual entities is made by us with respect to specific ontological choices.

It follows that a physical system can be described from several, distinct ontological perspectives. For example, Hayes (1985) identifies two distinct ontologies for reasoning about liquids. He notices that sometimes an engineer thinks of "the liquid in the container" as an object (the contained-stuff ontology) while at other times thinking about a hypothetical collection of molecules traveling together through the system as an object (the piece-of-stuff ontology). Consequently, the two ontologies involve different language forms as terms, predicates, and axioms. When one uses the contained-stuff ontology for liquids, the terms available include "volume", "pressure" and so on. These terms are not applicable to the piece-of-stuff ontology for liquids, which refers to "fixed mass", "spatiotemporal position", "velocity", etc.

Employing a particular language form to describe a physical object is equivalent to committing to a particular ontological choice (Munitz 1974, Hayes 1985). If we require a term as an important means for reasoning, then whatever type of universe is needed to define this term is the universe to which we are committed. For example, as soon as we use the term "pressure" to describe a liquid, we have committed to the contained-stuff ontology for liquids with "pressure" defined by the set of predicates and axioms therein. Such an ontological commitment leads to a particular perspective for modeling and subsequent analysis of the real world systems. We just cannot analyze a physical system in the world without committing ourselves to an ontological choice. This is an inherent fact of reasoning: true for us and true for artificial systems.

The purpose of this paper is to present an outline of a theory for ontological shift in reasoning about the physical world. While the theory we develop is domain-independent, the discussion here focuses on reasoning about electronic circuits. Below, we first introduce a charge-carrier (CC) ontology that supplements the standard device ontology for modeling and reasoning about electronic circuits. We then discuss how ontological shift is made possible through bridging relations. Finally, we present ontological-choice rules that guide the selection of proper ontological perspectives when generating qualitative causal explanations of circuit behavior in an automated qualitative simulation environment.

Two Ontological Choices for Circuits

Drawing on the rich literature from qualitative physics of electronic circuits, we find that most work has focused on the device ontology (de Kleer & Brown 1984). This is largely due to the need to describe each individual device and its connections with other devices in the circuit. Mirroring the engineering paradigm of system dynamics (Shearer, et al. 1971), the approach is to model a system in terms of its component devices and their interconnections with qualitative differential equations (confluences) involving macroscopic concepts such as "voltage", "current", and "resistance". The axioms at this level essentially represent aspects of Ohm's Law and Kirchoff's Laws.

The device ontology of electronic circuits can generate a wide range of causal explanations. We do not cover details of this ontology here. They are well discussed in (de Kleer & Brown 1984, de Kleer 1984, Williams 1984, White & Frederiksen 1986, Douglas & Liu 1989).

Unfortunately, device-ontology models of electronic circuits cannot answer some basic questions that relate structures to behaviors, such as "Why does the current through a resistor increase when the voltage across it increases?" or "Why changing the length or cross-sectional area of a resistor affect the current through it, even if the voltage across it remain constant?" Although a device-ontology model correctly describes what the device's behavior is, it typically cannot explain why it behaves the way it does. In short, it represents "compiled knowledge" about the circuit components' behaviors.

To explain why an electronic device behaves in a certain way requires an appreciation of the forces that act upon charge carriers inside the device and the effects on charge-carrier movements from externally applied bias voltages. The explanation process of a qualitative and causal analysis program should have the alternative of shifting to this form of reasoning. Below, we introduce a charge-carrier ontology to reason about electronics to address these issues.

In the charge-carrier (CC) ontology, the basic function of an electronic device is viewed as that of controlling the movement of electric charge carriers, such as electrons (or holes). The primitives for the CC ontology include concepts such as "field", "force", "velocity", "charge-flow", etc. The central notion in the CC ontology is the charge-carrier collection. Considering individual charge carriers would be prohibitive and unnecessary since all positive or negative charge carriers act alike. Considering an anonymous collection of charge carriers as one individual greatly reduces the complexity of modeling their behavior. Thus, a CC collection is similar in spirit to Collins and Forbus's (1987) molecular collection (MC).

We introduce the notion of *region* as a common level of structural description for both the device ontology and the CC ontology. Being a conceptual structural unit, a region is denoted as $\mathbb{R}(p,n)$, where p and n stand for the positive and negative poles of the region, respectively. Structural aggregation can be performed over regions as needed. Specifically, two regions are in series when they share a common pole, one using it as its positive pole and the other as its negative pole. Two regions are in parallel if they share the same two poles. Thus, a region may consist of any number of sub-regions, connected either in series, or parallel, or in mixed ways. By definition, the behavior of a region is a composition of the behaviors of its sub-regions.

When considered as occupying a cylindrical piece of space, a region $\mathbb{R}(p,n)$ has two features that capture its physical shape: length, $L(p,n)$, and cross-sectional area, $A(p,n)$. Likewise, a pole, p, when considered as a two-dimensional surface, has two features: surface area, Sp, and unit charge, Qp. Figure 1 shows a region's field description. A subset of the axioms of the CC ontology is presented as follows (a more detailed description of the CC ontology is available in (Liu 1989)):

CC-Axiom 1: (Field, Charge, and Region's length)

$$\partial E(p,n) = \partial Qp - \partial L(p,n).$$

CC-Axiom 2: (Electric force and Field)

$$\partial F(p,n) = \partial E(p,n).$$

CC-Axiom 3: (CC motion velocity and Electric force)

$$\partial v(p,n) = \partial F(p,n).$$

CC-Axiom 4: (Charge flow, Region's cross-section, and CC Velocity)

$$\partial C(p,n) = \partial A(p,n) + \partial v(p,n).$$

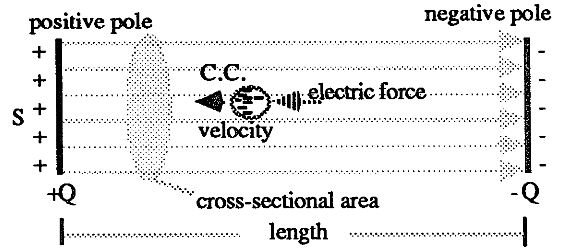

Figure 1: A Region's Electric Field.

Qualitative and causal reasoning about circuits can be carried out in the CC ontology. As a simple example, the following derivation explains why increasing the length of a resistor causes the charge-flow through it to decrease (Figure 2):

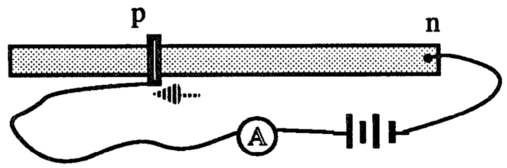

Figure 2: Changing the length of a resistor.

Precondition:	Derivation:	Justification:
	$\partial L(p,n) = +$	Given.
$\partial Qp=0,$	$\Rightarrow \partial E(p,n) = -$	CC-Axiom 1.
	$\Rightarrow \partial F(p,n) = -$	CC-Axiom 2.
	$\Rightarrow \partial v(p,n) = -$	CC-Axiom 3.
$\partial A(p,n)=0,$	$\Rightarrow \partial C(p,n) = -$	CC-Axiom 4.

"When the length of the resistor increases, the electric field of its region decreases, causing the electric force on the charge carriers inside the region to decrease. The decrease of the force causes the velocity of the charge carriers to decrease. As a result, the charge flow through the resistor decreases."

One may suggest that the CC-ontology axioms could be simply lumped into the device-ontology models for modeling and reasoning. However, there is ample evidence that models embodying a jumble of interrelated ontologies produce more harm than good (Winograd & Flores 1987). An ontologically consistent model of a physical system is the basis for the kind of simplicity and understandability that makes our analytic program robust and usable.

Bridging Relations

The CC ontology is at a microscopic level when compared to the device ontology. For circuit analysis, the CC ontology supplements the device ontology, but is not "parasitic" to it, as the above example has shown. Causal reasoning can be carried out independently in either ontology. To enable ontological shift between the two, we introduce the notion of bridging relations that link elements from the two ontologies.

Notice that the basic structural elements in the device ontology are the component devices and their interconnections in the system topology of a circuit. In contrast, the basic structural elements in the CC ontology are electric fields. For coherence of causal explanation, we argue that ontological shift must preserve the spatiotemporal continuity of causal propagation. This requires that both the device ontology and the CC ontology have compatible structural views of electronic circuits. The notion of *region* provides this common view. This observation is expressed in the following principle:

Structural Compatibility Principle: In order to preserve spatiotemporal continuity during ontological shift, multi-ontological perspectives of a target physical system must be compatible to a common structural view of the system.

The importance of this principle is two folds. First, bridging relations between distinct ontologies can be formulated with respect to the common structural view. Second, spatiotemporal continuity of causal propagation is maintained when different aggregated constructs are involved in causal reasoning. As the compatible structural view between the device ontology and the CC ontology, a region refers to a structural entity between two chosen poles through which the current or the movement of electric charge is of interest.

Macroscopic concepts and microscopic concepts can relate to each other through regions via bridging relations. Three sample bridging relations are shown as follows:

DC-Bridge 1: (Voltage, Field, and Length)

$$\partial Vp,n = \partial E(p,n) + \partial L(p,n).$$

DC-Bridge 2: (Resistance and Field's physical features)

$$\partial Rp,n = \partial L(p,n) - \partial A(p,n).$$

DC-Bridge 3: (Current and Charge flow)

$$\partial Ip,n = \partial C(p,n).$$

Bridging two different ontologies, these relations provide a simple means for shifting ontological perspective during causal reasoning about the physical world while maintaining the spatiotemporal continuity of causal propagation from one ontological perspective to another.

Now, since an analytic task can often be carried out in or require more than one ontological perspective, how do we control their applications? In the next section, we show that selection of ontological choices is task-dependent, i.e., the decision as to which ontology to use and when to shift perspective depends on the specific analytic task at hand.

Shifting Ontological Perspective

Our interest in qualitative analysis of a physical system is to be able to generate causal explanations for behavior resulting from input perturbations to the system. This reasoning process follows a specific analytic task defined by specifying the input and desired output of the task with respect to a specific target system under analysis.

We have designed a task definition language (TDL). Three parts comprises a task definition: the target system topology, the specification of input perturbation, and the specification of output desired. Using TDL, one can manipulate the circuit at some equilibrium state through either *parameter perturbation* or *structural perturbation.* The former means changing the value of a system parameter to cause change. The latter means adding a new device either in series or parallel with an existing construct in the system topology to cause change. In either case, we ask for causal explanations of related system variables' behavior as a result. A complete discussion of TDL is beyond the scope of this paper. Instead, we will present task definitions in English. Based on a given specific task, proper ontological perspectives are selected using the ontological-choice rules.

Ontological choice rule 1: If the input is a parameter perturbation, then if the output variable is of the same ontology and the analysis requires justification for one of the axioms of the ontology, then shift to a related ontology for explanation.

Consider the analytic task: "Why does the current through a resistor increase when the voltage across it increases?" This task directly questions the component model of the resistor in the device ontology. Since a component model contains primitive axioms of the ontology, which cannot be derived in the same ontology, we shift between the device ontology and the CC ontology, generating the following explanation of why "$\partial Vp,n \Rightarrow \partial Ip,n$".

Precondition:	Derivation:	Justification:
	$\partial Vp,n = +$	Given.
$\partial L(p,n)=0,$	$\Rightarrow \partial E(p,n) = +$	*DC-Bridge 1.*
	$\Rightarrow \partial F(p,n) = +$	CC-Axiom 2.
	$\Rightarrow \partial v(p,n) = +$	CC-Axiom 3.
$\partial A(p,n)=0,$	$\Rightarrow \partial C(p,n) = +$	CC-Axiom 4.
	$\Rightarrow \partial Ip,n = +$	*DC-Bridge 3.*

"When the voltage across the resistor increases, (shifting to the CC ontology) the resistor's region, with its length and cross-sectional area unchanged, experiences a stronger electric field than before. This increases the electric force on the charge carriers in the field and speeds up their movement. As a result, more charge carriers move through the field in unit time. The increased charge-carrier movement in the region (shifting back to the device ontology) reflects the current increase through the resistor." Figure 3 illustrates the ontological shifts involved.

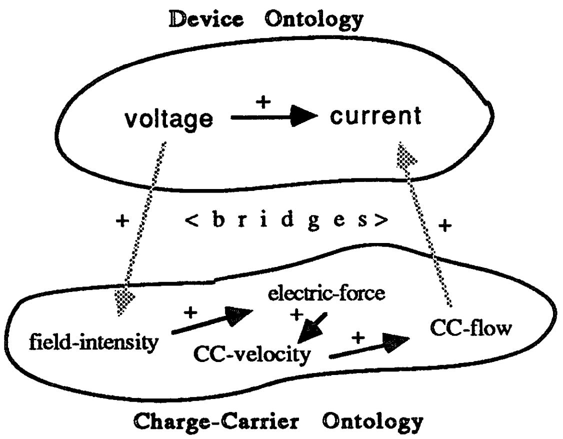

Figure 3: Ontological Shift.

Ontological Choice Rule 2: If the input is a parameter perturbation, then if the output variable is of the same ontology and the analysis does not require justification of any of the axioms in the ontology, then select that ontology.

For example, "Given the circuit in Figure 4, when the voltage between *a* and *d* decreases, what happens to the voltage between *b* and *c*?"

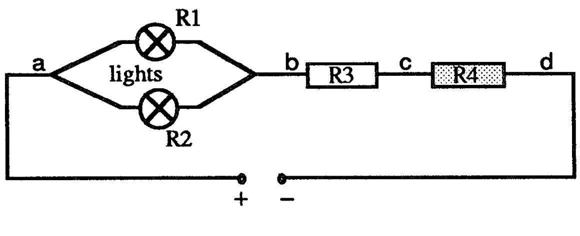

Figure 4: Light-bulb Circuit.

In this task, both the input and output variables are in the device ontology and the question does not directly concern a specific axiom in the ontology. The explanation thus stays in the device ontology.

Precondition:	Derivation:	Justification:
	$\partial Va,d = -$	Given.
$\partial Ra,d = 0,$	$=> \partial Ia,d = -$	Ohm's Law.
$Ia,d = Ib,c,$	$=> \partial Ib,c = -$	(KCL).
$\partial Rb,c = 0,$	$=> \partial Vb,c = -$	Ohm's Law.

"When the voltage between *a* and *d* decreases, the current between *a* and *d* decreases. As a result the current through *b* and *c* (R3) decreases. This causes the voltage across *b* and *c* to decrease."

Ontological Choice Rule 3: If the input is a parameter perturbation, then if the output variable is from a different ontology, proceed with the input ontology until causal propagation comes to the region of the output variable and then shift to the output ontology to complete the reasoning.

For example, "Given the light-bulb circuit in Figure 4, when the voltage between nodes *a* and *d* increases, what happens to the charge flow between nodes *b* and *d*?" For this task, the following explanation is generated:

Precondition:	Derivation:	Justification:
	$\partial Va,d = +$	Given.
$\partial Ra,d = 0,$	$=> \partial Ia,d = +$	Ohm's Law.
$Ia,d = Ib,d,$	$=> \partial Ib,d = +$	(KCL).
$\partial Rb,d = 0,$	$=> \partial Vb,d = +$	Ohm's Law.
$\partial L(b,d) = 0,$	$=> \partial E(b,d) = +$	*DC-Bridge 1.*
	$=> \partial F(b,d) = +$	CC-Axiom 2.
	$=> \partial v(b,d) = +$	CC-Axiom 3.
$\partial A(b,d) = 0,$	$=> \partial C(b,d) = +$	CC-Axiom 4.

"When the voltage *Va,d* increases, the current *Ia,d* increases, which causes current *Ib,d* to increase. This causes the voltage across *b* and *d* to increase. (shifting to the CC ontology) This voltage increase causes the field between *b* and *d* to increase, resulting in more force pushing the charge carriers in the region to move. Therefore, the charge carriers' velocity increases, causing the charge-flow between nodes *b* and *d* to increase."

Ontological Choice Rule 4: If the input is a structural perturbation, then select the ontology of the output variable specification.

When a resistor is added to an existing construct in the target system, either in series or parallel, a new region is created. The following two heuristics are used to account for the underlying structural perturbation to the system:

P-Heuristic (parallel-heuristic):
For all R and R', R(x, y), R'(x', y'), **to-parallel!**(R, R')
=> there exists $\mathbb{R}$(p, p'), p=x=x', p'=y=y',
$\partial L(p,p') \leq 0, \partial A(p,p') = +$.
S-heuristic (series-heuristic):
For all R and R', R(x, y), R'(x', y'), **to-serialize!**(R, R')
=> there exists $\mathbb{R}$(p, p'), p=x, p'=y',
$\partial L(p,p') = +, \partial A(p,p') \leq 0$.

When a structural perturbation is made to the target circuit in the simulation, the change can be viewed in either the device ontology or the CC ontology, as illustrated in Figure 5. The selection of an ontology depends on the specification of the output desired.

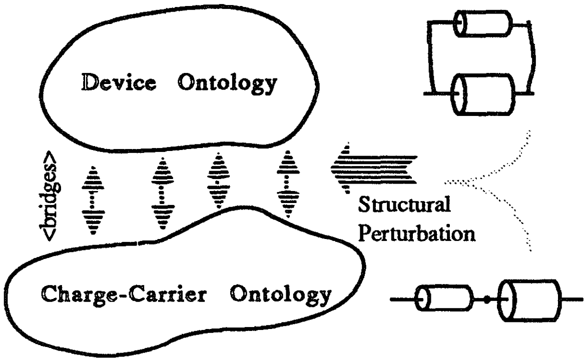

Figure 5: Structural Perturbations.

For example, "Given the light-bulb circuit in Figure 4, will the current through the two lights (R1, R2) increase or decrease when one adds a new resistor R5 to the circuit as shown in Figure 6?"

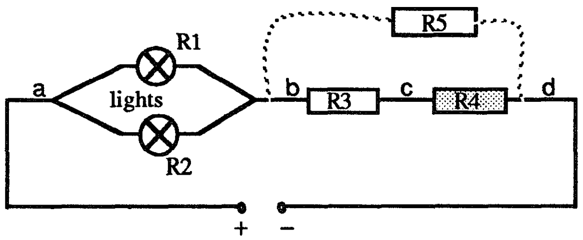

Figure 6: Structural Perturbation by Adding a Device.

In this example, since the output specification is of the device ontology, the following explanation is generated:

Precondition:	Derivation:	Justification:
	to-parallel!$(R5, \mathbb{R}(b,d))$	Given.
	$\Rightarrow \partial L(b,d) \leq 0, \partial A(b,d)=+$	P-Heuristic.
	$\Rightarrow \partial R_{b,d} = -$	*DC-Bridge* 2.
$\partial R_{a,b} = 0,$	$\Rightarrow \partial R_{a,d} = -$	Compatibility.
$\partial V_{a,d} = 0,$	$\Rightarrow \partial I_{a,d} = +$	Ohm's Law.
$I_{a,d} = I_{a,b},$	$\Rightarrow \partial I_{a,b} = +$	(KCL).
$\partial R_{a,b} = 0,$	$\Rightarrow \partial V_{a,b} = +$	Ohm's Law.
$\partial R1 = 0,$	$\Rightarrow \partial I(R1) = +$	Model of R1.
$\partial R2 = 0,$	$\Rightarrow \partial I(R2) = +$	Model of R2.

"As a result of the parallel construction, the parallel-heuristic indicates that the cross-sectional area of the region $\mathbb{R}(b,d)$ increases, causing the resistance of the region to decrease. As a result, the total resistance of the circuit decreases, causing the current through the whole circuit as well as the region $\mathbb{R}(a,b)$ to increase. This current increase causes the voltage through the region $\mathbb{R}(a,b)$ to increase, which in term causes the current flow through both the light-bulbs (R1, R2) to increase." Therefore, the two lights in the circuit become brighter.

If, instead, the output specification of this task asks about what happens to the "charge flow" from *a* and *b* as a result of the structural change, then the explanation will be generated in the CC ontology because "charge flow" is a concept in the CC ontology. We omit this derivation here.

Discussion

The approach presented here is based on two insights regarding modeling in general and work in qualitative physics in particular. First, all model-based reasoning is only as good as the model and no single model can be adequate for a wide range of tasks (Davis & Hamscher 1988). Second, model generation and selection is an integral part of a human engineer's reasoning process about complex physical systems. The work described here is part of our on-going effort to automate qualitative and causal analysis of physical systems from multiple perspectives, including structural aggregation, dynamic configuration, as well as ontological shift (Farley and Liu 1990). We recognize that ontological perspective is of a more fundamental nature than the other two because it provides the underlying organizing structure of the problem world.

Related work includes Collins and Forbus's (1987) system that reasons about liquids from both a contained-stuff ontology and a molecular-collection (MC) ontology. They state that the MC ontology is parasitic to the contained-stuff ontology. Specifically, the predicates and axioms of the MC ontology itself are not represented. Their bridging relations consist of rules for one-way conversion of process descriptions into MC descriptions. As a result, the overall reasoning is done only in the contained-stuff ontology. The system "peeps" into the MC ontology from active processes through the bridging rules and draws conclusions about the corresponding molecular-collection behaviors.

In contrast, the CC ontology is not parasitic on the device ontology. Instead of one-way conversion, the framework presented in this paper allows two-way conversions during causal analysis. Reasoning can potentially proceed in either ontology. The decision as to which ontology to use and when to shift perspectives is based on the specific analytic task at hand. When a shift is necessary from one ontology to another, reasoning follows one of the bridging relations, formulated according to a common structural view of the world.

The representation of charge carriers as pieces of stuff is rather limited in our system. Complex analytic tasks may require additional spatial and temporal reasoning about the behavior of charge carriers as pieces of stuff. The parallel and series heuristics only cover resistors for structural perturbations. When one adds other types of devices such as a capacitor or a battery as a structural perturbation, the underlying configuration of the circuit may change as a result, triggering generation of a new model of the circuit for analysis.

The ontological choice rules presented in this paper are novel. Exploratory in nature, they provide a way to control ontological choices to carry out an analytic task and generate causal explanations. We assume that a task can be either formulated by the user or generated by another program, such as the tutoring module in an intelligent tutoring system. Based on task specifications in TDL, these rules are straightforward to automate. We are aware that for complex tasks in design, diagnosis, and tutoring, more knowledge will be incorporated into deciding which ontological choice to take.

Other related work on reasoning from multiple perspectives include the paradigm of graph of models (Weld 1989, Addanki, et al. 1989) and query-guided local model generation (Falkenhainer & Forbus 1988). The former use a lattice of predefined models. Each edge connecting two models is labeled with a set of simplifying assumptions for model selection. The latter is to generate models according to the tasks or queries by activating (or deactivating) pertinent pieces of a large-scale model of a complex physical system. Recent progress has been made. However, the bulk of the work in these approaches involves only a single ontology.

Conclusion

We have presented a framework for shifting ontological perspectives in qualitative and causal reasoning about physical systems. We illustrate how reasoning with multi-ontological perspectives provides significant advantages over using a single ontology. The examples presented are implemented, based upon our previous system that generates causal explanations in a constructive simulation environment (Douglas & Liu 1989). Work is in progress to create a framework that generates and selects qualitative models to reason about electronic circuits. Capabilities for ontological shift are combined with means for identifying dynamic configurations to handle nonlinear devices and aggregating structural components for structural abstraction. Although our discussion has focused on electronic circuits, our approach to how and when to shift ontological perspectives is domain-independent. Such a framework that is capable of reasoning from multiple perspectives is essential to many types of application programs that require qualitative analysis, from automated design and diagnosis to intelligent tutoring systems.

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