A Charge-Carrier Ontology for Reasoning about Electronics

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ABSTRACT: Hayes's [1985] *contained-stuff* and *piece-of-stuff* ontologies for liquids show that it is often desirable or necessary to shift to a proper ontological abstraction in reasoning about complex physical systems. The importance of such an ontological shift becomes clear in the resulting explanation of why the system has the manifested behavior. In this paper, we identify a charge-carrier (CC) ontology as a specialization of Hayes's piece-of-stuff ontology for reasoning about electronics and show that the ability to reason with multi-ontological perspectives of a problem domain provides significant advantages over using a single ontology.

1 Introduction

Many AI systems, for use in design and tutoring, need to generate explanations to answer questions from proper ontological abstractions that capture the breadth and depth of human knowledge of the physical world [Collins and Forbus 1987; Falkenhainer and Forbus 1988]. Often, several distinctive but interrelated views of an object or system are necessary for explanation purposes. This paper presents a new ontology, from the charge carrier perspective, for explaining the behavior of electronic devices.

We begin by reviewing the current state of the art in qualitative physics work on electronic circuit analysis. Drawing on the rich literature from qualitative analysis of electronic circuits [de Kleer 1984; Williams 1984; White and Frederiksen 1986], we find that most work has focused on the device ontology. An important assumption made by this ontology is that flow of information in the model of the system directly mirrors flow of causality in the real world. The approach is to model a system in terms of its component devices and their interconnections with qualitative equations ("confluences"). These often decompose into distinct states or operating regions. For example, a diode can be modeled as follows:

ON-STATE: $(V_{a,c} > V_T)$, $\quad \partial V_{a,c} - \partial I_{a \to c} = 0$.
OFF-STATE: $(V_{a,c} \le V_T)$, $\quad [I_{a \to c}] = 0$.

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Models of component devices alone do not carry sufficient domain knowledge to carry out causal analyses of a circuit. Additional network rules and heuristics such as Kirchoff Laws (KVL, KCL) [de Kleer 1984] are required as constraints at connection points to reason about the circuit.

The device ontology models can generate a wide range of causal explanations. Typically, a conclusion that can be reached is how a system might respond to a change in input. Among other things, de Kleer and Brown (1984) showed that incremental qualitative (IQ) analysis of the system's intrastate behaviors can be carried out by local propagation within the model in mythical time. Williams (1986) demonstrated that temporal qualitative (TQ) analysis can be performed with regard to the state transitions of system parameters. Feedback analysis can also be carried out [de Kleer 1984; Williams 1984]. We have also applied the device ontology in generating "first-order"[1] causal explanations in a constructive simulation of cardiovascular models [Douglas and Liu 1989].

Unfortunately, the device ontology models of electronics cannot answer some basic questions that relate structures to behaviors, such as:

1. Why does a diode conduct current only in one direction?

2. Why do resistors in series or parallel affect the current differently?

One major complaint about the device ontology is that it provides no guidance for the construction of the device model itself. While device descriptions suit seasoned experts, such descriptions "leap over" basic knowledge elements crucial for explaining the device behavior. Although a device model correctly describes what the device's behavior is, it typically cannot explain why it behaves the way it does. It represents "compiled knowledge" about the components' behavior.

Much of this situation, however, is not the fault of the device ontology: device ontology mirrors the engineering paradigm of system dynamics. The process of mapping from a real world scenario to a device model lies outside the theory. It appears that a thorough understanding of device models requires an appreciation of the forces that act upon charge carriers inside the devices and effects on charge carrier movements from externally applied bias voltages. The explanation process should have the alternative of shifting to these primitives which reflect our reserve of common-sense (tacit) knowledge.

What is this knowledge? How is it to be organized to facilitate generation of causal explanations? The CC (charge-carrier) ontology is designed with just such questions in mind. In the remaining sections of this paper, a structural abstraction technique for describing electronic devices is first introduced. Then the CC ontology is discussed. Given the device ontology as an "off-the-shelf" representation, bridging relations between the CC ontology and the device ontology are developed, allowing ontological shifts from one to the other. Finally, we show examples of reasoning about electronics in the CC ontology, and discuss some open problems.

2 Structural Abstraction

Causal reasoning entails relating structures to behaviors. The structural descriptions in qualitative models thus play a critical role in generating causal explanations [Farley 1988]. Traditional qualitative modeling techniques are usually centered around abstracting the value spaces of parameters that are

[1] [White and Frederiksen 1986] distinguish models that reason on the basis of the mere presence or absence of current, resistance, voltage, which are called "zero-order" models, from those that reason on the basis of changes in current, resistance, and voltage, which are called "first-order" models.

used to represent system states and for simplifying the constraints that hold among those parameter values. To supplement these techniques, this paper proposes an approach of structural abstraction to describe electronic devices.

A *region* refers to a dynamic structural unit between two chosen poles through which the movement of electric charge is being analyzed. As a structural abstraction, a region may consists of any number of sub-regions, connected either in series, or parallel, or in mixed ways. The behavior of a region is compositional of the behaviors of its sub-regions.

A region is denoted as $\mathcal{R}(p_1, p_2, t)$, where p_1 and p_2 stand for the positive and the negative poles, respectively, and t indicates the time when the region exists. Two regions are in series when they share a common pole, which one uses as its positive pole and the other uses as its negative pole. Two regions are in parallel when they share the same two poles. Formally,

$$\text{Serial}(A, B, t) \equiv A = \mathcal{R}(p, n, t) \ \wedge \ B = \mathcal{R}(p', n', t) \ \wedge \ n = p'.$$
$$\text{Serial}(A, B, t) \equiv \text{Serial}(A, X, t) \wedge \ \text{Serial}(X, B, t).$$

$$\text{Parallel}(A, B, t) \equiv A = \mathcal{R}(p, n, t) \ \wedge \ B = \mathcal{R}(p', n', t) \ \wedge \ p = p' \wedge n = n'.$$

Some basic descriptions about a region are as follows:

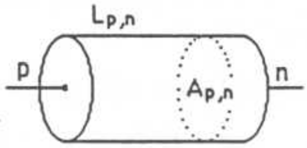
- The direction for a region's linear path is specified by its two poles. For example, given a region's two poles p and n, $p_{\rightharpoonup}n$ denotes the direction along the axis from p to n. We specify $p_{\leftharpoonup}n = rev(p_{\rightharpoonup}n)$ and $p_{\rightharpoonup}n = rev(p_{\leftharpoonup}n)$, where $rev()$ stands for 'reverse'.

- $neighbor(r, dir)$ is a function that returns the neighboring region on the dir side of region r, i.e., $neighbor(\mathcal{R}(p, n, t), p_{\leftharpoonup}n) = \mathcal{R}(x, p, t)$; $\quad neighbor(\mathcal{R}(p, n, t), p_{\rightharpoonup}n) = \mathcal{R}(n, y, t)$.

- One region r_1 may be inside another region r_2, denoted as $\text{Within}(r_1, r_2)$. Clearly, $\text{Within}(r_1, r_2) \wedge \text{Within}(r_2, r_3) \Rightarrow \text{Within}(r_1, r_3)$.

We say a region is 1.5-dimensional because each region not only specifies a linear path for reasoning about charge movement but also has a cross-sectional area, which can affect charge flow. When considered as occupying a cylindrical space, a region $\mathcal{R}(p, n, t)$ has the following two quantities capturing its physical shape:[2]

1. Region's length, $L_{p,n}$, and
2. Region's cross-sectional area, $A_{p,n}$.



Likewise, a pole p, when considered as a plate, has a quantity to describe its surface area, S_p. A pole thus is "0.5" dimensional.

This structural abstraction technique is applicable to both the device ontology and the CC ontology. In this paper, we will mainly discuss its application in the CC ontology.

[2]It is assumed that the length refers to the shortest path and the cross-sectional area refers to the smallest cross section of the region.

3 CC Ontology

The basic function of electronic devices is to control the movement of electric charge carriers, such as free electrons (or holes), through *regions*. In order to be able to reason about an electronic device, it is essential to acquire a qualitative understanding of the electric charge carrier, or what it is believed to be, and describe how it moves in the region(s) of the device. The primitives for the CC ontology include concepts such as 'length', 'area', 'force', and 'velocity', which we assume are intuitively understandable.

A central concept in the CC ontology is the *charge-carrier-collection*, a spatiotemporal entity carrying electric charge, which is either positive or negative. Considering individual charge carriers would be prohibitive and unnecessary, since all the positive (or negative) carriers act alike. Considering an anonymous collection of them as one individual can greatly reduce the complexity for modeling their behaviors. Thus, a CC collection is similar in spirit to Collins and Forbus's MC [Collins and Forbus 1987] as pieces of stuff.

With respect to charge carriers, a region, r, may have the following properties:

- $\mathcal{C}(r)$ — a function that returns a collection of the majority charge carriers in region r.
- $\mathcal{W}(c,t)$ — a function that returns the region where charge carrier collection c is located, at time t. Clearly, $\mathcal{C}(\mathcal{W}(c,t)) = c$ and $\mathcal{W}(\mathcal{C}(r),t) = r$.
- Q_p — a quantity that stands for the net charge at pole p with respect to Φ (a chosen "zero" point). Q_p^σ denotes the magnitude (absolute value) of Q_p. A pole can be electrically biased in the following ways:

  $Q_p > \Phi \equiv [Q_p] = + \equiv$ Positively-biased(p),
  $Q_p < \Phi \equiv [Q_p] = - \equiv$ Negatively-biased(p),
  $Q_p = \Phi \equiv [Q_p] = 0 \equiv$ Neutral(p).

3.1 "Zero-order" Modeling

Now let us formalize some "zero-order" axioms in the CC ontology. From the charge carrier's perspective, $\mathcal{R}(p,n,t)$ is best viewed as a *uniform electric field*, which is a region between poles p and n at time t. The field's intensity, denoted as $E_{\mathcal{R}(p,n,t)}$, is defined as the force exerted on a positive unit charge in the field.

Axiom 1: (Uniform field)

$$[E_{\mathcal{R}(p,n,t)}] = + \wedge dir(E_{\mathcal{R}(p,n,t)}) = (p_{\rightarrow}n) \equiv [Q_p] = + \wedge [Q_n] = -.$$

For any CC collection c inside a field α, there is an electric force exerted on c (denoted F_α^c). The direction of F_α^c is determined by the type of electric charges involved. It is either the same as the field's direction, or the opposite to it.

Axiom 2: (Existence of force)

$$\begin{aligned}&[E_{\mathcal{R}(p,n,t)}] = + \wedge \text{Within}(\mathcal{W}(c,t), \mathcal{R}(p,n,t)) \equiv [F^c_{\mathcal{R}(p,n,t)}] = + \wedge \\ &((\text{Positive}(c) \Rightarrow dir(F^c_{\mathcal{R}(p,n,t)}) = dir(E_{\mathcal{R}(p,n,t)})) \vee \\ &(\text{Negative}(c) \Rightarrow dir(F^c_{\mathcal{R}(p,n,t)}) = rev(dir(E_{\mathcal{R}(p,n,t)})))).\end{aligned}$$

The net force of a group of component forces whose directions are along an axis one way or the other is determined qualitatively by comparing the quantities and directions of the component forces.

Axiom 3: (Formation of Net force)

$\forall f, g \in forces, f = F^c_{\alpha 1}, g = F^c_{\alpha 2}, dir(f) = rev(dir(g)) \wedge f \neq g \Rightarrow$
$\exists \mathcal{F} \in forces, \mathcal{F} = f + g = F^c_{\alpha 1+\alpha 2}, [\mathcal{F}] = + \wedge$
$(f > g \Rightarrow dir(\mathcal{F}) = dir(f) \vee f < g \Rightarrow dir(\mathcal{F}) = dir(g)).$

$\forall f, g \in forces, f = F^c_{\alpha 1}, g = F^c_{\alpha 2}, dir(f) = dir(g) \Rightarrow$
$\exists \mathcal{F} \in forces, \mathcal{F} = f + g = F^c_{\alpha 1+\alpha 2}, [\mathcal{F}] = + \wedge dir(\mathcal{F}) = dir(f).$

If the net force on a CC collection is non-zero, then the charge carriers will move in the direction of the force.

Axiom 4: (Force and motion)

$[F^c_{\mathcal{R}(p,n,t)}] = + \Rightarrow \text{Move}(c, dir(F^c_{\mathcal{R}(p,n,t)})).$

Consequently, the motion implies a relocation of the CC collection.

Axiom 5: (Motion and spatial relocation)

$\text{Move}(c, dir(F^c_{\mathcal{R}(p,n,t)})) \Rightarrow \exists t', t' > t,$
$\mathcal{W}(c, t') = neighbor(\mathcal{R}(p, n, t), dir(F^c_{\mathcal{R}(p,n,t)})).$

A charge flow exists between two poles ($M_{\mathcal{R}(p,n,t)}$) if the charge carriers inside all the (sub) regions in between p and n move in the direction of the electric force from the field $\mathcal{R}(p, n, t)$.

Theorem 1: (Electric-charge flow)

$[M_{\mathcal{R}(p,n,t)}] = + \equiv \forall \alpha \in \mathcal{R}, \text{Within}(\alpha, \mathcal{R}(p, n, t)), \forall c \in \mathcal{C}, \text{Within}(\mathcal{W}(c, t), \alpha),$
$\text{Move}(c, dir(F^c_{\mathcal{R}(p,n,t)})).$

The above axioms are "zero-order" because they can be used to reason about the existence of the basic model parameters. The following "first-order" knowledge in the CC ontology is presented for reasoning about their changes.

3.2 "First-order" Modeling

The change in field intensity, $E_{\mathcal{R}(p,n,t)}$, is directly proportional to the change in the net charge in the poles of the region but inversely proportional to the change of their surface areas.

Confluence 1: (Field, charge and pole's surface-area)

$\partial E_{\mathcal{R}(p,n,t)} = \partial Q^\sigma_p - \partial S_p.$

Subsequently, the change of magnitude of the force on a CC collection is directly proportional to the change of the field intensity:

Confluence 2: (Force and field)

$\partial F^c_\alpha = \partial E_\alpha.$

Like any object in our universe, the movement of charge carriers is subject to the influence of force. The average velocity of the CC collection in region α, v^c_α, is directly proportional to the net force, F^c_α, exerted on it[3]. So,

Confluence 3: (Motion and velocity)

$$\partial v^c_\alpha = \partial F^c_\alpha.$$

With different conductivities σ_m (or resistivities ρ_m) of different materials in a region, the movement of electric charge through the region ($M_{\mathcal{R}(p,n,t)}$) is constrained by the conductivity and the cross-sectional area of the region as well as the velocity of the carriers moving through the region.

Confluence 4: (Charge flow and carrier movement)

$$\partial M_{\mathcal{R}(p,n,t)} = \partial \sigma_m + \partial A_{p,n} + \partial v^c_{\mathcal{R}(p,n,t)}.$$

3.3 Bridging Device Ontology and CC Ontology

The CC ontology is at a microscopic level when compared to the device ontology. These two ontologies can be related by defining "bridging" confluences, so that ontological shifts are possible from one to the other. We believe that such ontological shifts in general require a common structural description of the target system. Furthermore, if two ontologies share a common structural description, then there are comparable elements from each that can be related. For example, a region is such a common structural abstraction to bridge the CC ontology and the device ontology to describe electronic devices.

In the following bridging confluences, the concepts in the device ontology are on the left-hand side of the equality sign, and the concepts in the CC ontology on the right-hand side.

Macroscopic concept "capacitance" $C_{p,n}$ describes the region's ability to store electric charge. It does not say how much charge is already stored, but rather how much can be stored. Thus, only the quantities of the region's physical shape are of relevance to the capacitance.

Confluence 5: (Capacitance and spatial shape)

$$\partial C_{p,n} = \partial S_p - \partial L_{p,n}.$$

Macroscopic concept "voltage" $V_{p,n}$ is an alternative to field intensity in describing a field. The field intensity describes a field from the perspective of force, while the voltage describes a field from the perspective of the ability to do work with that force.

Confluence 6: (Voltage and field)

$$\partial V_{p,n} = \partial E_{\mathcal{R}(p,n,t)} + \partial L_{p,n}.$$

Macroscopic concept "resistance" $R_{p,n}$ typically can be described in terms of the physical characteristics of a conducting material, that is, its physical features (length and cross-sectional area) and description the material's resistivity.

Confluence 7: (Resistance and physical features)

$$\partial R_{p,n} = \partial \rho_m + \partial L_{p,n} - \partial A_{p,n}.$$

[3]Newton's second law $f = ma$ describes an ideal situation whereby the confluence should be $[f] = \partial v$. However, considering the charge carriers bumping into atomic nuclei during motion, $\partial f = \partial v$ is an approximation about the average speed of the charge carrier movement.

Macroscopic concept "current" $I_{p \rightarrow n}$ summarizes the descriptions of the charge carrier movement, that is, how much charge flows through the region.

Confluence 8: (Current and charge flow)

$\partial I_{p \rightarrow n} = \partial M_{\mathcal{R}(p,n,t)}$. $([I_{p \rightarrow n}] = [M_{\mathcal{R}(p,n,t)}])$

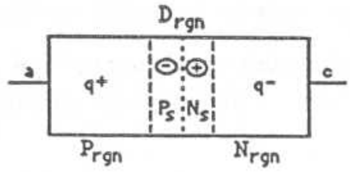
The microscopic concepts in the CC ontology can help justify the macroscopic knowledge in the device ontology. In the next section, we will show examples of the CC ontology applications to answer some of the questions raised at the beginning of this paper.

4 Examples

"Why is a Diode a One-way Device?"

To answer this type of questions entails constructing a causal justification involving the structure of the devices and the underlying causal mechanisms. Topologically, a diode is a pn-junction[4] consisting of three regions, namely P_{rgn}, D_{rgn} (depletion region), and N_{rgn}. The depletion region initially has a potential difference V_T from n-side N_s to p-side P_s. The state of the pn-junction has the following specification:

$\mathcal{C}(N_{rgn}) = q^-$, Negative$(q^-)$,
$\mathcal{C}(P_{rgn}) = q^+$, Positive$(q^+)$,
$[E_{\mathcal{R}(N_s,P_s,t)}] = +$.



When an external voltage is applied to the diode, positive to the anode terminal (a) and negative to the cathode terminal (c) at time t, $\mathcal{R}(a,c,t)$ is created with $E_{\mathcal{R}(a,c,t)} = +$. Below, the derivation will only trace the movement of the electrons (Negative(q^-)) from the N_{rgn} since the movement of the holes (Positive(q^+)) from the P_{rgn} follows exactly the same pattern in the opposite direction. Assuming a time line: $t_1 < t_2 < \ldots < t_i < \ldots$:

$$
\begin{array}{lll}
 & [Q_a] = +, [Q_c] = -, & \text{Given} \\
 & \Rightarrow [E_{\mathcal{R}(a,c,t_1)}] = +,\ dir(E_{\mathcal{R}(a,c,t_1)}) = a_{\rightarrow}c, & \text{Axiom 1} \\
\mathcal{W}(q^-, t_1) = N_{rgn},\ \text{Within}(N_{rgn}, \mathcal{R}(a,c,t_1)), & \Rightarrow [F^{q^-}_{\mathcal{R}(a,c,t_1)}] = +,\ dir(F^{q^-}_{\mathcal{R}(a,c,t_1)}) = a_{\leftarrow}c, & \text{Axiom 2} \\
 & \Rightarrow \text{Move}(q^-, a_{\leftarrow}c), & \text{Axiom 4} \\
neighbor(N_{rgn}, a_{\leftarrow}c) = D_{rgn}, & \Rightarrow \mathcal{W}(q^-, t_2) = D_{rgn}, & \text{Axiom 5} \\
\mathcal{W}(q^-, t_2) = D_{rgn},\ \text{Within}(D_{rgn}, \mathcal{R}(a,c,t_2)), & \Rightarrow [F^{q^-}_{\mathcal{R}(N_s,P_s,t_2)}] = +, & \\
 & \quad dir(F^{q^-}_{\mathcal{R}(N_s,P_s,t_2)}) = a_{\rightarrow}c, & \text{Axiom 2} \\
[F^{q^-}_{\mathcal{R}(a,c,t_2)}] = +, dir(F^{q^-}_{\mathcal{R}(a,c,t_2)}) = a_{\leftarrow}c, & \Rightarrow F^{q^-}_{\mathcal{R}(a,c,t_2)} > F^{q^-}_{\mathcal{R}(N_s,P_s,t_2)}, & \text{Assumed} \\
 & \Rightarrow [F^{q^-}_{\mathcal{R}(a,c,t_2)+\mathcal{R}(N_s,P_s,t_2)}] = +, & \\
 & \quad dir(F^{q^-}_{\mathcal{R}(a,c,t_2)+\mathcal{R}(N_s,P_s,t_2)}) = a_{\leftarrow}c, & \text{Axiom 3} \\
 & \Rightarrow \text{Move}(q^-, a_{\leftarrow}c), & \text{Axiom 4}
\end{array}
$$

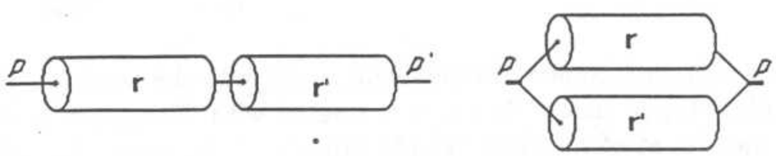
[4]The limitation of not going into the atomic structure level prevents us from describing the formation of a pn-junction and the size change of the depletion region as a result of the charge-carrier movement.

$$
\begin{array}{lll}
neighbor(D_{rgn}, a_{\leftarrow}c) = P_{rgn}, & \Rightarrow \mathcal{W}(q^-, t_3) = P_{rgn}, & \text{Axiom 5} \\
\mathcal{W}(q^-, t_3) = P_{rgn},\ \text{Within}(P_{rgn}, \mathcal{R}(a,c,t_3)), & \Rightarrow [F^{q^-}_{\mathcal{R}(a,c,t_3)}] = +, dir(F^{q^-}_{\mathcal{R}(a,c,t_3)}) = a_{\leftarrow}c, & \text{Axiom 2} \\
 & \Rightarrow \text{Move}(q^-, a_{\leftarrow}c), & \text{Axiom 4} \\
 & \Rightarrow [M_{\mathcal{R}(a,c,t_i)}] = +, & \text{Thm 1} \\
 & \Rightarrow [I_{a \to c}] = +. & \text{Confl 8} \\
 & \Box &
\end{array}
$$

This is a "zero-order" causal explanation about the existence of the current $I_{a \to c}$. Of course, this explanation only holds if the assumption, $F^{q^-}_{\mathcal{R}(a,c,t_2)} > F^{q^-}_{\mathcal{R}(N_s,P_s,t_2)}$, is true. Under this assumption, the charge carriers can cross the depletion region, because the opposing force of the depletion region, $F^{q^-}_{\mathcal{R}(N_s,P_s,t_2)}$, is weaker than the external force, $F^{q^-}_{\mathcal{R}(a,c,t_2)}$. This agrees with the diode's ON-state specification $V_{a,c} > V_T$ where V_T is the threshold voltage to current flow. If the assumption is false, then the charge carriers will be repelled back by the net force in the depletion region and hence cannot cross the depletion region. In this case, there will be no current flow[5]. By the same token, one can also derive that there is no current when an external voltage is applied to the diode, positive to the cathode (c) and negative to the anode (a) (reverse-biased).

"Why Do Resistors in Parallel or Series Affect Current Differently?"

When a region is connected to another region either in series or parallel, the following causal heuristics[6] are used to describe the effects:



- **The series-heuristic:** When a new region is constructed from two sub-regions in series, its length is greater than that of any of the two sub-regions, and its (smallest) cross-sectional area cannot get any greater than that of any of the two sub-regions. Assuming the change of its cross-sectional area insignificant, we have

  $$\forall r, r',\ r = \mathcal{R}(x,y,t),\ r' = \mathcal{R}(x',y',t),\ \text{to-serialize}(r,r',t)$$
  $$\Rightarrow \exists \mathcal{R}(p,p',t),\ p = x, p' = y',\ \partial L_{p,p'} = +, \partial A_{p,p'} = 0.$$

- **The parallel-heuristic:** When a new region is constructed from two (sub) regions in parallel, its cross-sectional area is greater than that of any of the two sub-regions, and its (shortest) length cannot get any greater than that of either one of the two sub-regions. Assuming the change of its length insignificant, we have

  $$\forall r, r',\ r = \mathcal{R}(x,y,t),\ r' = \mathcal{R}(x',y',t),\ \text{to-parallel}(r,r',t)$$
  $$\Rightarrow \exists \mathcal{R}(p,p',t),\ p = x = x',\ p' = y = y',\ \partial L_{p,p'} = 0, \partial A_{p,p'} = +.$$

[5]This argument only considers the movement of the majority charge carriers in the semiconductor materials.
[6]These heuristics assume the same conductivity (same materials) for the two sub-regions.

If an ohmic conductor's length increases, as when resistors are put in series, then the current through it decreases. A justification for this behavior can be derived in the CC ontology as follows:

$r = \mathcal{R}(p, x, t),\ r' = \mathcal{R}(y, n, t),$	to-serialize(r, r', t),	Given
$\partial A_{p,n} = 0,$	$\Rightarrow \partial L_{p,n} = +,$	series-heuristic
$\partial V_{p,n} = 0,$	$\Rightarrow \partial E_{\mathcal{R}(p,n,t)} = -,$	Confl 6
	$\Rightarrow \partial F^{c}_{\mathcal{R}(p,n,t)} = -,$	Confl 2
	$\Rightarrow \partial v^{c}_{\mathcal{R}(p,n,t)} = -,$	Confl 3
$\partial \sigma_m = 0, \partial A_{p,n} = 0,$	$\Rightarrow \partial M_{\mathcal{R}(p,n,t)} = -,$	Confl 4
	$\Rightarrow \partial I_{p \to n} = -.$	Confl 8
	$\square$	

This explains why the increase of a region's length causes the current through the region to decrease. It is because the increased distance between the two poles of the region causes the field intensity and the force on charge carriers in the region to decrease. As a result, the velocity of the charge carriers decreases and, hence, less charge flows through the region.

By the same token, one can also derive that when a conductor's cross-sectional area increases, the current through the conductor increases since more charge carriers can move through the region in unit time. Confluence 7 shows that the resistance decreases as the cross-sectional area increases. Confluences 4 and 8 indicate that the current will increase when the cross-sectional area of the conductor increases, and vice versa.

5 Discussion

One of the motivations for looking into the CC ontology is to automate causal reasoning about the behavior of electronic devices at a microscopic level. A qualitative inference engine capable of the kinds of formal reasoning described here would be a useful adjunct to many types of expert systems for design and instruction. The use of *regions* for structural abstraction provides a systematic way of analyzing complex circuits within both the device ontology and the CC ontology. The behavior of a region is compositional of the behaviors of its sub-regions. Using this representation, quantities can only interact if they are spatially local and their changes occur during the same time. The need to describe the movement of charge carriers as pieces of stuff confirms Forbus's speculation [1988] that many new ontological issues revolve around spatial reasoning.

For circuit analysis, the CC ontology supplements the device ontology, but neither is "parasitic" to the other. The notion of "mythical time" [de Kleer and Brown 1984] in the device ontology to describe causal orders can be unfolded to include the microscopic view of the causal behavior. Ontological shifts between the device ontology and the CC ontology are possible through the mutual bridging relations. These bridging relations are formulated via the the common structural description by regions, which are conceptual objects as distinguished from their real world counterparts. In general, we believe that multi-ontological perspectives of a physical system are compatible to a common structural abstraction of the system. In order to make ontological shifts, this structural description must be made explicit for causal reasoning.

We have only begun to explore multiple ontological perspectives of a problem domain for qualitative, causal explanations. While reasoning about electronic devices at the microscopic level is possible, some new problems arise. One is how to map an arbitrary circuit into proper regions for analyses. This mapping directly reflects the way one thinks about the circuit. Also, a region in a circuit may be assigned teleological information of its purpose in the overall function of the system. Such information is important for teleological reasoning of the circuit behavior. Finally, controlling ontological shifts between the CC ontology and the device ontology for explanation purposes entails joint efforts of qualitative physics and other research areas, such as intelligent tutoring systems (ITS). Work is under way to investigate these problems as a next step toward understanding qualitative, causal reasoning of complex physical systems.

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