Structural Aggregation in Common-Sense Reasoning

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Abstract

Structural aggregation is an inherent aspect of our ability in reasoning about the real-world. In this paper, we present our investigation of structural aggregation to simplify domain models and suppress irrelevant details of complex physical systems. We address the role of clustering, cluster-orientation and creation of black boxes in qualitative causal reasoning. We describe algorithms that automate structural aggregation to achieve efficiency and clarity in planning and explanation of physical system behaviors.

Introduction

To cope with the complexity of the real world, we critically depend upon our ability to abstract and see the "big picture" embedded in a complex situation. When reasoning about real-world systems, mapping from a given structural description to an appropriate structural abstraction is often the most critical step. This paper discusses our work using structural aggregation in qualitative reasoning about complex physical systems. We will emphasize two complementary roles of structural aggregation: (i) suppression of unnecessary details, and (ii) selection of relevant elements.

Structural aggregation is a modeling technique that transforms a given structural description into a simpler one that best fits a task at hand. Such aggregation is readily observable in everyday life. When we look at a world map, we notice that cities become dots. When planning a route from one city to another, this description is adequate and efficient. Only when we want to know how to get around in a city do we need its street map. We switch between these two maps as our needs dictate.

In engineering problems, experts often use "black boxes" to suppress uninteresting detail. Figure 1 shows a black-box description of a circuit by Rusgrove, et al. (1977), where the black box is viewed as a single "resistor". It could be that upon opening the black box one would find that it actually contained a radio transmitter that was converting the *dc* power from the battery into radio-frequency power which in turn was being radiated off into space. The transmitter is certainly not designed as a resistor. But if the task at hand was to find out the total current through the circuit, as measured at ammeter *A*, then the transmitter does act as a resistor. Thus, by aggregating the circuit as a black box and viewing it as a single equivalent resistor, the circuit description is simplified to reflect the task at hand. The primary function here is to suppress unnecessary details.

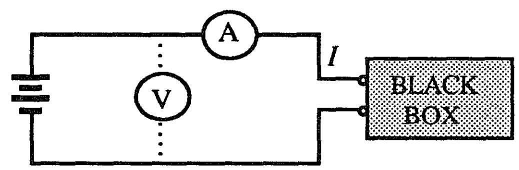

Figure 1: A Circuit Viewed as a Black Box

Structural aggregation can also focus attention on the most relevant elements of a situation. Study indicates that master chess players not only see individual chess pieces but also focus on useful patterns of pieces for planning their winning strategies [Hofstadter 1980]. These patterns focus attention on critical pieces that lie at points of interaction between patterns. We will see below how structural aggregation similarly focuses attention in the domain of hydraulic systems.

Structural aggregation introduces different granularities of modeling. Clearly, an advantage of using structural aggregation in automated reasoning is that reasoning can become more efficient. But only part of the motivation here is efficiency. Even if our computers could run programs ever faster to handle increasing complexity, for many purposes of prediction and explanation of the behavior of physical systems, we simply do not need or want information of great detail. When we do need detail, it is typically about a very narrow range of behaviors [Falkenhainer & Forbus 1988].

To date, the bulk of qualitative modeling techniques have focussed on various means for abstracting the value spaces of variables and parameters that are used to represent qualitative states and for simplifying the constraints that must hold among those values, thereby describing possible behaviors. Some researchers [Sussman & Steele 1980, Davis 1984] have attempted to use hierarchical descriptions

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of the organizations of physical systems to advantage. But, these approaches have relied on pre-defined structural hierarchies or "slices".

Our effort has been to *automate* the selection of structural aggregation for qualitative causal reasoning as driven by the task at hand. We have applied our initial ideas to reasoning about pressurized hydraulic systems and about electronic circuits for tasks of operation, diagnosis, and explanation. Section 2 introduces our approach to cluster-based reasoning in the context of pressurized hydraulic systems. Section 3 presents our definition of oriented clusters and their role in efficiently identifying active configurations in electronic circuits. Section 4 describes a technique for creating black boxes. Finally, we discuss related work and outline future research.

A First Step

Initially, we considered structural aggregation in reasoning about hydraulic systems [Farley 1988]. Such systems may consist of hundreds of pumps, tanks, valves, and gauges. Our primary goal in this research was to generate and explain plans for the operation and troubleshooting of hydraulic systems based on qualitative models of these systems.

The key element of our approach was the notion of cluster. A *cluster* consisted of a maximal, connected subset of system devices not including a closed valve. By this definition, each pair of adjacent clusters is separated by one or more closed valves, constituting a *boundary*. A set of boundaries partitions a complex system into one or more, behaviorally independent clusters or sub-systems. A set of closed valves determines a *cluster graph*, where vertices represent clusters and edges are boundaries, captures the structure of a hydraulic system based upon the states (open or closed) of its valves.

A cluster can either be *stable*, where flow equals zero (i.e., no flow occurs), or *unstable*, where flow is directed along one or more flow-path(s). A *flow-path* is a sequence of devices and device ports, beginning with a tank or pump as source of high pressure and ending with a tank or pump as sink of low(er) pressure.

How can cluster-based aggregation assist in planning and troubleshooting? To raise (or lower) the pressure at some location, one can merge its cluster with one of higher (or lower) pressure. To merge adjacent clusters, we merely open a valve on the boundary between them. To merge non-adjacent clusters, we must find a sequence of merges that connects them. Search is conducted in the cluster graph, which can be expected to be at a lesser order of magnitude in complexity than the original device graph.

As for troubleshooting, cluster-based aggregation allows us to select likely candidates during diagnosis [Farley 1989]. Suppose higher than expected pressure is reported by a pressure gauge. If the gauge is in a stable cluster, we can attempt to place another gauge in the same cluster and check if it reports the same high reading, thereby evaluating our initial suspicion that the gauge is faulty. Or, if pressure is high and continuing to increase in what was thought to be a stable cluster, we suspect a leaking valve on the boundary between that cluster and a neighbor of higher pressure.

In both cases, we see that clustering reduces complexity while focusing attention on relevant components, i.e., those on boundaries and active flow paths.

Oriented Clusters in Electronic Circuits

Structural aggregation plays a critical role in circuit analysis. This section addresses its use in identifying *active configurations* of a circuit under analysis. By *active configuration* is meant a subset of the system components in the system topology which are on the active flow path in a particular qualitative state of the system. Figure 2 shows three distinct active configurations of a half-wave rectifier.

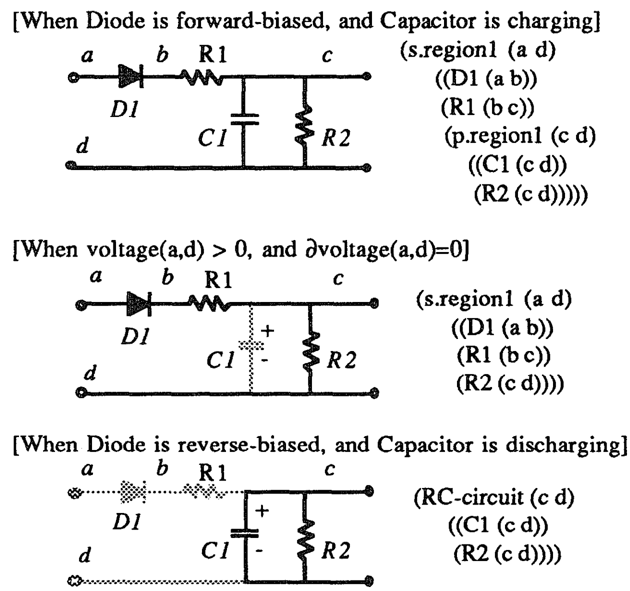

Figure 2: Multiple Topological Configurations

Human engineers formulate local models for each active configuration and switch between these local models when the qualitative state changes. This enables us to keep attention focused on the simplest model possible. When reasoning about a particular configuration, we can temporally shut off or "forget" about the models of the other configurations. Such a local model is based on a subset of the topology of the entire system, facilitating efficient problem-solving and analysis. More importantly, the process of identifying active configurations offers a linearization scheme for analyzing the behavior of non-linear circuits in terms of a series of linear circuits as determined by device states. In an active configuration, the impedance of each device to the current flow follows Ohm's Law.

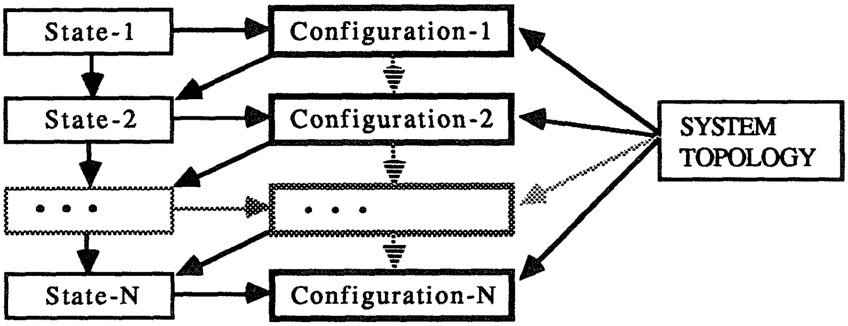

Figure 3: Configuration-wise Simulation

Figure 3 represents our configuration-wise scheme capable of reasoning about nonlinear systems in terms of linear configurations. We identify the active configuration of the circuit under analysis by examining the state of each component to decide whether it is on the current flow path. The subsequent qualitative reasoning to determine the next state of each device is based only on this active configuration. New states of component devices, together with the system topology, determine the next configuration, and so on.

In the standard qualitative simulation framework, the intermediate level of configuration determination is missing. Most previous systems represent the structure of a physical system as a set of parameters and constraints holding among them [Kuipers 1986]. Such a description does not directly represent the physical organization of the system. As such, previous systems could not address this important structure issue.

To automate the process of formulating a configuration model for a circuit in a specific qualitative state, we must identify the current flow path in the model of system topology of a circuit. One way to decide whether a device is on the current flow path is by checking whether there is a voltage difference across the device and, if so, whether the device allows current to flow across it. At first glance, the process of identifying active configurations based on checking voltages at individual devices seems fairly straightforward. But the complexity of a brute-force search algorithm turns out to be exponential. For example, Figure 4 shows a ladder circuit. Initially, all the nodes' voltages are zero. Given a non-zero voltage applied between nodes *a* and *h*, we start the search from node *a*, the positive pole. The problem is that when the search comes to a node whose degree is greater than two, the node becomes a potential backtracking point.

We call nodes of degree greater than two *fan-out nodes.* Nodes *b, c, f, g* are fan-out nodes. For lack of knowledge other than local voltage difference, the choice of which path to take at a fan-out node can only be arbitrary. For example, the program may try the path *a, b, g, f, c, ...* until it discovers a conflict. It then backtracks to the nearest fan-out-node and tries a different choice. The complexity of this search algorithm is $O(D^n)$, where D stands for the average degree of fan-out nodes and n for the number of such nodes in the system topology of the circuit.

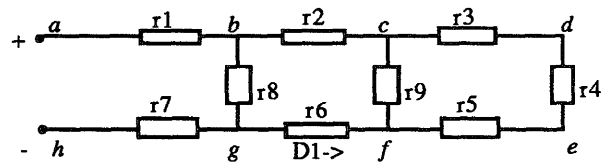

Figure 4: A Ladder Circuit

We developed two techniques that reveal the "big picture" of a circuit under analysis without this exponential complexity. The first is cluster determination; the second is cluster orientation.

Cluster determination, as used here, is the process that makes explicit the implicit structural hierarchy in the system topology of a circuit by aggregating parallel and serial sub-graphs in the system topology of a given circuit. *Cluster orientation* gives each cluster a "road sign" for signals travelling inside the system topology of the circuit. First, we discuss cluster determination. The rules used to identify parallel-serial constructs are as follows:

Serial Clustering: If there is a degree-two node (except the pole nodes) in the system topology, then the two constructs connected to the node are merged into one serial construct.

Parallel Clustering: If two constructs are connected to the same two nodes in the system topology, then the two constructs are merged into one parallel construct.

Arnborg and Proskurowski (1989) have shown that this clustering algorithm can be implemented in $O(n)$ time with canonical partial k-tree representation for the topology of a circuit. When the serial clustering rule is applied, the number of nodes and the number of edges in the graph decrease by one because two constructs merge into one. When the parallel clustering rule is applied, the number of nodes remains the same, but the degree of each of the two nodes connected by the two merging constructs decreases by one. Thus, the structure is reduced by clustering all possible parallel and serial constructs.

After reformulating a given system topology into clusters, the complexity of search for active configurations becomes polynomial. For the ladder circuit example, when search comes to node b, it has come to a parallel construct having two branches: a single resistor *R8*, and a construct which involves serial and parallel connections. The search can proceed in parallel. Backtracking in this case is avoided.

For cluster orientation, suppose in the ladder circuit, *R6* is replaced by a diode, *D1*, with its anode connected to *g* and its cathode to *f*. The road sign for the cluster connected to *b* and *g* (involving *R2, R3, R4, R5, R9 & D1*) is that a signal can only travel from *g* to *b*, not vice versa. Thus, when search for the active configuration comes to node *b*, it can know that the cluster is a one-way lane from *g* to *b*. By the same token, for the half-wave rectifier shown in Figure 2, when the input sine wave becomes negative, we know that it is not possible for current to flow from node *d* to *a*. Thus, cluster orientation eliminate consideration for impossible flow paths.

Devices, such as resistors, diodes, capacitors, etc, have their own primitive orientations. A diode's orientation is from its anode to its cathode, i.e., current can only flow from the node connected to the anode to that connected to the cathode. The other direction constitutes an impasse. A resistor's orientation is more flexible because it allows current to flow in either direction. A capacitor's orientation is different. Only when *dV/dt* is not zero is the capacitor considered to conduct current. When two constructs are merged into a cluster through the parallel and serial clustering, the orientations are propagated to the resulting cluster following simple orientation rules.

Figure 5 shows some orientation rules. An arrow indicates the orientation of a construct with respect to the two nodes to which it is connected. An X means it is an impasse. A straight line means it is bi-directional.

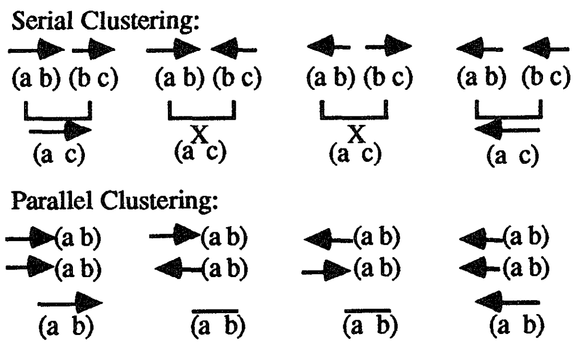

Figure 5: Orientation Propagation in Clustering

When building a series cluster out of two constructs, if one is bi-directional, then the new s-cluster takes the orientation of the other construct. When building a parallel cluster out of two constructs, if one construct's orientation is bi-directional, then the new p-cluster is bi-directional. A bi-directional orientation thus yields in a series clustering but dominates in a parallel clustering.

When building a series cluster out of two constructs, if one construct's orientation is an impasse, then the new s-cluster is an impasse. When building a parallel cluster out of two constructs, if one construct's orientation is impasse, then the new p-cluster takes the orientation of the other construct. Contrary to the bi-directional orientation, an impasse orientation dominates in a series clustering but yields in a parallel clustering.

When a capacitive construct is involved, it always adds its capacitive properties to the other construct's orientation in the resulting cluster's orientation like forward-capacitive and backward-capacitive.

Orientation assignment during the clustering process does not affect the complexity of the clustering algorithm since it takes constant time as each cluster is formed. As noted early, when based upon an *oriented-cluster representation* of the target circuit, the process to find the active configurations becomes efficient.

Black-Boxing to Avoid Detail

In this section, we present a different aspect of structural aggregation - the creation of black boxes that suppress details that are irrelevant to the task at hand. The use of black boxes in circuit analysis follows the "equivalent circuit" concept, as illustrated in Figure 1. A task definition specifies an input perturbation and the behavior to be observed. When a task asks about the behavior of voltage or current between two nodes in a circuit, the devices between those two nodes comprise what we call the *output structural unit*.

Structural aggregation centers around the output structural unit. The procedure for creating black boxes takes two items as input: (i) an active configuration, and (ii) the two nodes that delimit the output structural unit. The outcome of this procedure is the active configuration with black boxes replacing irrelevant structural details for the task at hand.

Take the circuit in Figure 6 for example. Suppose one asks the question: "Will the light (*b1*) become brighter or dimmer if the resistance in *R4* increases?"

Here the brightness of the light is directly related to the level of current flowing through the bulb. Our system aggregates the individual devices uninteresting to this task as black boxes, as shown in Figure 6. In an active configuration, a black box acts as a resistor. Furthermore, its resistance qualitatively equals the sum of all the resistances of its substructures. The resulting aggregated structural description of the circuit with the black boxes is equivalent to, but much simpler than, the original one given.

The challenge for creating black boxes is to search for the set of individual devices that are to be boxed in a given configuration and to determine other regions irrelevant to the task at hand which can also be boxed. The primary set of individual devices to be identified is the output structural unit. The aggregation algorithm is recursively applied to the hierarchical structure of the active configuration. It first checks to see if the region is the output structural unit. If it is, it boxes this region and the aggregation process is complete. Otherwise, it checks if the region is serial or parallel and continues search inside

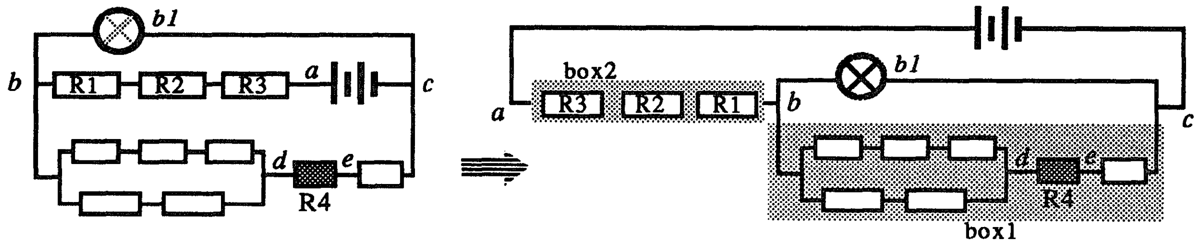

Figure 6: Creation of Black Boxes to Simplify Causal Analysis

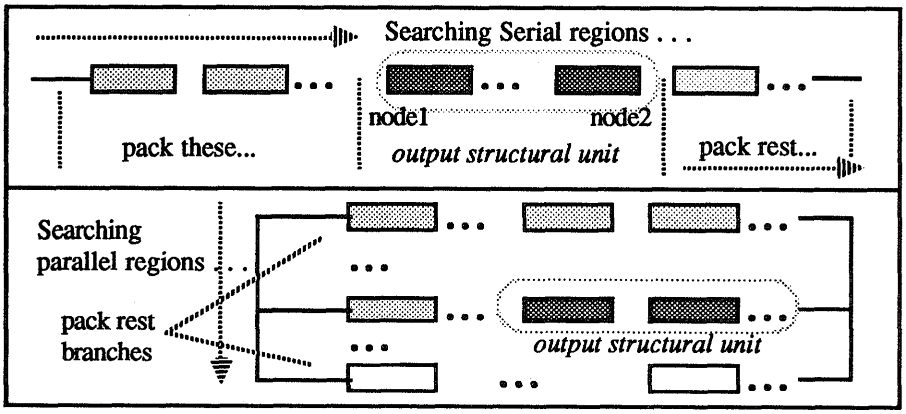

Figure 7: Black Boxing in Serial and Parallel Regions

the region as appropriate. Figure 7 shows how these regions are searched. The algorithm is linear in time complexity with the size of the series-parallel structure representing the active configuration.

Returning to the circuit in Figure 6, the following derivation generated by our system shows why the lights become brighter when the resistance in R4 increases.

Precondition:		Derivation:	Justification:
		$\partial R_{(r4)} = +,$	Given;
	->	$\partial R_{(box1)} = +,$	Σ resistance;
	->	$\partial R_{a,c} = +,$	Σ resistance;
$\partial V_{a,c} = 0,$	->	$\partial I_{a,c} = -,$	Ohm's Law;
	->	$\partial I_{a,b} = -,$	$I_{a,b} = I_{a,c}$;
$\partial R_{a,b} = 0,$	->	$\partial V_{a,b} = -,$	Ohm's Law;
$\partial V_a = 0,$	->	$\partial V_b = +,$	$V_{a,b} = V_a - V_b$;
$\partial V_c = 0,$	->	$\partial V_{b,c} = +,$	$V_{b,c} = V_b - V_c$;
$\partial R_{(b1)} = 0,$	->	$\partial I_{(b1)} = +,$	Ohm's Law.

Note that the derivation mentions only *R4* and *b1* as the individual devices and suppresses the rest. As resistance in *R4* increases, the resistance of box1 increases as a result. This causes the total resistance in the circuit to increase. This chain of causal propagations is possible because our system is able to generate a hierarchical view of the circuit. Imagine answering the same question using only knowledge about individual devices without structural aggregation. The derivation would be more complex, if not intractable. Causal reasoning would have to deal unnecessarily with primitive-level feedback for all the parallel branches [Williams 1984].

Discussion

Aggregation as an abstraction technique for modeling complex physical systems has been studied by a number of researchers. Weld (1986) presented an aggregation technique that detects repeating cycles of processes and dynamically creates a new process description of the cycle's behavior. This allows complex behaviors to be aggregated into higher-level descriptions. Kuipers (1986) introduced a time-scale abstraction method for qualitative simulation. In this approach, a given mechanism views a slower one as being constant, and a faster one as being instantaneous. Although we draw inspiration from these two techniques, we have focused directly on aggregating structural elements in the physical organization of complex physical systems.

Sussman and Steele (1980) introduced a method to express *slices* as structural abstractions in circuit analysis. Slices are defined using a language of hierarchical constraint networks to represent the multiple viewpoints in the synthesis and analysis of electrical networks. They noted that while in principle slices contain no extra information, one point of view may be more useful than another in some given circumstance.

Similarly, Davis (1984) and Genesereth (1984) used structural abstraction to describe the organizations of complex physical systems. The most common application is to use design descriptions for artifacts to control search. A complex device is often described in terms of high-level components, whose internal structural is specified separately. Using this approach, much of the structural detail is suppressed when reasoning only concerns the high-level components.

Our research shares the same motivation as these previous systems. Different from those approaches, which relied on pre-defined constructs, our research extends this work by automating structural aggregation as an integral part of qualitative causal analysis. We believe that in reasoning about a complex physical system, different tasks may entail different structural granularities to best model the system for the task at hand. The task definition embodies necessary information for our automated reasoning systems to take the appropriate perspectives to carry out the task [Liu & Farley 1991].

The techniques described in this paper are based upon the interaction of structure and behavior for qualitative causal analysis. Parallel-serial aggregation is driven by a given perturbation-analysis task. Analyzing circuits that can not be simplified by parallel-serial reduction remains an interesting research problem for structural aggregation. Interestingly, due to cluster orientation, our system can analyze the bridge rectifier circuit. While the circuit topology is not series-parallel, each active configuration is. The Wheatstone Bridge cannot be aggregated even though we intuitively know that the circuit can be viewed as a single resistor where current goes in at one end and comes out at the other end. Electrical engineering provides formal methods to find an equivalent of the Wheatstone Bridge. But the resulting circuit loses the internal characteristics of the Wheatstone Bridge.

One way to cure this limitation to structural aggregation in automated reasoning is to use the functional knowledge of physical systems for structural aggregation. For example, a circuit could also be aggregated as a black box and described as an "adder" or a "multiplexer". As a interesting direction for future work, one feasible way for doing this would be to access the design or teleological knowledge of an artifact to guide structural aggregation.

Conclusion

Our ability to reason about the physical world from different structural granularities and to switch among them as needs dictate is fundamental to our intelligence and flexibility [Hobbs 1985, Hayes 1985]. In this paper, we have described our research on structural aggregation in automated reasoning about complex physical systems. We have described procedures to aggregate individual devices in hydraulic systems and electronic circuits. By focusing on the details required by the task and encapsulating the rest, our systems achieve efficiency and flexibility in qualitative causal analysis.

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