

# The Qualitative Criticism of Circulatory Models Via Bipartite Teleological Analysis

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## Abstract

This research presents a dual-perspective, or *bipartite* view of *teleology* (i.e. purpose) and uses it to criticize qualitative models of cardiovascular systems in a manner that highlights the relationships between circulatory topology, behavior and function. The Bipartite Teleology Model (BTM) attributes 'purposefulness' to both steady-state and regulatory behavior - thereby providing a split-level bias for evaluating teleological fulfillment in circulatory systems. The Biology Critic (BIOTIC) incorporates BTM to automatically generate circulatory critiques similar to those published by physiologists. In general, this work contributes an operational model of bipartite teleology to qualitative physics, while clarifying the teleological and environmental context necessary to extend qualitative physics into biology.

**Key Words:** teleology, criticism, qualitative physics, circulatory system

## I. Introduction

This research investigates the role of qualitative and teleological techniques during the evaluation and explanation of physiological systems. Specifically, I employ qualitative simulation and teleological reasoning to automate the criticism of circulatory systems. Since expert physiologists tend to rely on qualitative and teleological concepts in their published critiques of circulatory systems, the obvious question from the qualitative physics standpoint is whether the simulation and reasoning behind these criticisms can proceed without detailed quantitative information. I hypothesize that qualitative simulation and teleological reasoning are sufficient to produce circulatory criticisms similar to those proposed by the physiologists.

To test this claim, I have implemented BIOTIC, The Biology Critic. Given a qualitative circulatory model, environmental constraints, and a teleology, BIOTIC produces an evaluation of the model and an explanation of the contribution of its structure to its function. More concretely, it qualitatively evaluates a circulatory system's ability to satisfy *teleologies* (i.e. purposes) such as oxygen transport, carbon-dioxide dissipation or heat conservation while the organism performs activities such as running, swimming, or diving in diverse environments such as a hot desert, a cold ocean or a high mountain. In so doing, BIOTIC illustrates the importance of a properly defined context for physical-system criticism, and, more generally, the vital role of teleology in scaling up qualitative physics to complex domains and tasks.

This work presents a bipartite view of teleology that facilitates the criticism of circulatory systems from two angles: the static and the dynamic. These perspectives embody two ways in which physiological systems go about achieving teleologies: via steady-state behavior, and via regulatory mechanisms when externally perturbed. Modeled after the dual perspectives of teleology evident in both philosophical and physiological interpretations of 'purposeful' behavior, this bipartite teleological theory further clarifies the role of functional knowledge in the qualitative analysis of physical systems.

## II. The 'What' and 'Why' of Physiological Criticism

### II.1 The Problem: Physiological Criticism

For the purposes of this research, physiological criticism is a combination of the evaluation of a system's behavior relative to an environmental and teleological context, and the explanation of those behaviors in terms of the systems global structure. The evaluation phase is the same as the data-analysis phase of diagnosis, in which behaviors are classified as 'normal' or 'abnormal'/symptomatic'. But, whereas diagnosis generally seeks to explain the symptoms in terms of malfunctioning components (or local mechanisms), the physiology critic assumes the proper functioning of local structures while searching for aspects of the global structure that might justify the behaviors.

For instance, in the reptilean circulatory model of Figure 1, notice that oxygenated pulmonary (i.e. pertaining to the lungs) blood mixes with deoxygenated systemic (i.e. pertaining to the body) blood just prior to entering the ventricle. This delivers oxygen concentrations to both lungs and body that are suboptimal relative to the teleology of oxygen transport. The recognition and classification of these behavioral problems constitutes evaluation. These behaviors are then explained by the

structural relationship between the lungs and body: they lie in parallel to one another along the circulatory loop, which causes the mixing, which creates the inefficient oxygen gradients.

## II.2 The Significance of Physiological Criticism

The problem of physiological criticism is interesting for a variety of reasons. For one thing, physiology lies at the heart of many taxonomic controversies over the form and semantics of the evolutionary tree. Physiological structures and behaviors often provide supporting evidence in the classification of various organisms; but even when a taxonomic tree is complete, physiologists still argue over the meaning of "dominance" in that evolutionary partial order. Some view mammals as the state of the art in evolutionary design. To these biologists, natural selection has been a lengthy optimization process culminating with humans. Hence, the semantics of the evolutionary tree involves not just a time order of emergence, but a sophistication ranking as well. Since mammals dominate, their anatomical and physiological structures may serve as "gold standards" for critiquing all extant and extinct organisms. Thus, reptiles, amphibians, and fishes all receive mediocre evaluations, since they just do not make very good mammals!

A more recent line of biological analysis cuts through the anthropocentric bias by examining organisms within the contexts of their environments. There, optimality entails the proper adaptation to a particular habitat, and not the similarity to some gold-standard organism who occupies an entirely different niche. Under this more context-sensitive and objective view of evolutionary prowess, many reptiles, amphibians, birds, fishes and insects receive marks equal to or above those of mammals. However, the objectivity of this adaptation-based criticism does not parlay into a concrete and objective formalism for systematic and automatable evaluation. By foregoing the mammalian gold standard, physiologists clear the way for new debates over the proper criteria for judging a physiological system's survival potential within a given environment. These disagreements often center around the choice of the most-relevant teleology - a critical issue in the formalization of any critiquing process.

Unlike man-made artifacts, which were presumably designed to fulfill a small set of explicit and well-formed purposes, living organisms have only implicit teleologies that are open to human interpretation and debate. And as the physiology literature indicates, the disagreements in evaluations of circulatory systems, such as that of the reptile (Burggren, 1987), have little to do with discrepancies in empirical data but a great deal to do with differences in popular teleologies.

Thus, contemporary physiological criticism is a task without gold standards or design goals. Biologists may know the environment in which an organism lives and the macro-level tasks that it performs, but under the skin, bark or scales, the physiological functions that significantly contribute to survival are not always lucid. The only obvious fact is that the vital physiological teleologies vary with the organism and environment. Hence, criticism in the physiological domain requires a thorough consideration of a context composed of both an environment and a set of teleologies. For qualitative physics, the task of physiological criticism thus presents an interesting challenge for automating the evaluation of physical systems and for investigating the role of environmental and teleological context in this critical analysis.

## III. Teleology

By 'teleology', I mean the desired global behavior of a system. In this research, a teleology embodies a goal, not a constraint, since a teleology may provide a

framework for analyzing a system without necessarily being satisfied by that system. In fact, critical analyses of systems are often more enlightening when a system violates a teleology.

In BIOTIC, teleologies are goals at the level of circulatory physiology. They represent global behaviors such as oxygen transport: the transfer of oxygen from producers, which put oxygen into the blood, to consumers, which take it out. This compiles into the subgoals of local production, local consumption, and producer-to-consumer blood flow. BIOTIC employs teleologies and their concomitant subgoals as the basis for evaluating, explaining, and (to a small degree) simulating circulatory systems.

### III.1 The Bipartite Teleological Model

Via circulatory criticism, BIOTIC makes its fundamental contribution to qualitative physics: the clarification of a bipartite teleological model and a formalization of its role in the analysis of complex systems. Once again, bipartite teleology refers to a system's ability to behave purposefully under both steady-state and dynamic conditions. In this paper, I will synonymously refer to the static perspective as the 'zero-order' perspective, while the dynamic view is also referred to as the 'regulatory' or 'first-order' perspective. BIOTIC critiques circulatory systems from both perspectives.

Qualitative physicists have not formalized these dual teleological modes, but philosophers have. Dennett (1978) contrasts the 'design stance' with the 'intentional stance' as two methods of teleologically predicting and interpreting device behavior. From the design perspective, a device acts purposefully; but from the intentional angle, the system's most prominent characteristic is its ability to react to a host of perturbations in order to continue progressing toward its goal. The difference between action and reaction also comes forth in the teleological theories of Rosenblueth, Wiener and Bigelow (1966). In their classic paper, they differentiate artifacts such as guns and clocks, which are designed for a purpose but whose behavior is not goal-directed, with 'servomechanisms' such as temperature regulators and heat-seeking missiles, whose abilities to react to change suggest an active awareness of their goals. These regulating systems possess 'intrinsic' purposefulness, since they have an internal penchant toward goal attainment, while artifacts such as clocks exhibit only 'extrinsic' purposefulness.

These philosophical theories hold relevance for qualitative physics, since both static and dynamic behaviors of qualitative models often have teleological interpretations. During static operation, the basic actions have teleological import, while in more dynamic contexts, systems display purposefulness by reacting to perturbations. The most noteworthy exploration of teleology's role in qualitative physics is de Kleer's QUAL system (1979), which focuses on the dynamic aspects of electrical behavior in recognizing complex circuits. De Kleer admits that QUAL cannot perform steady-state analysis but that an extension to the static perspective would open the way for teleological analyses of other systems such as logical circuits and mechanical devices. Since de Kleer seeks to model electrical engineers, who rely primarily upon perturbation analysis, the first-order perspective is of exclusive importance to QUAL. However, physiologists appear to use both perspectives in circulatory criticism; and, as the examples below illustrate, both vantage points highlight interesting connections between teleology, behavior and structure. Thus, physiological criticism provides an excellent arena for an investigation into bipartite teleology.



### III.2 The Bipartite Teleological Model in Circulatory Criticism

Physiological systems satisfy a variety of purposes from both a static and dynamic perspective. These multiple teleologies and perspectives, in combination with the wealth of external environments, provide many diverse contexts for physiological criticism. In the physiological literature, no circulatory critiques better illustrate this diversity than those of the reptile.

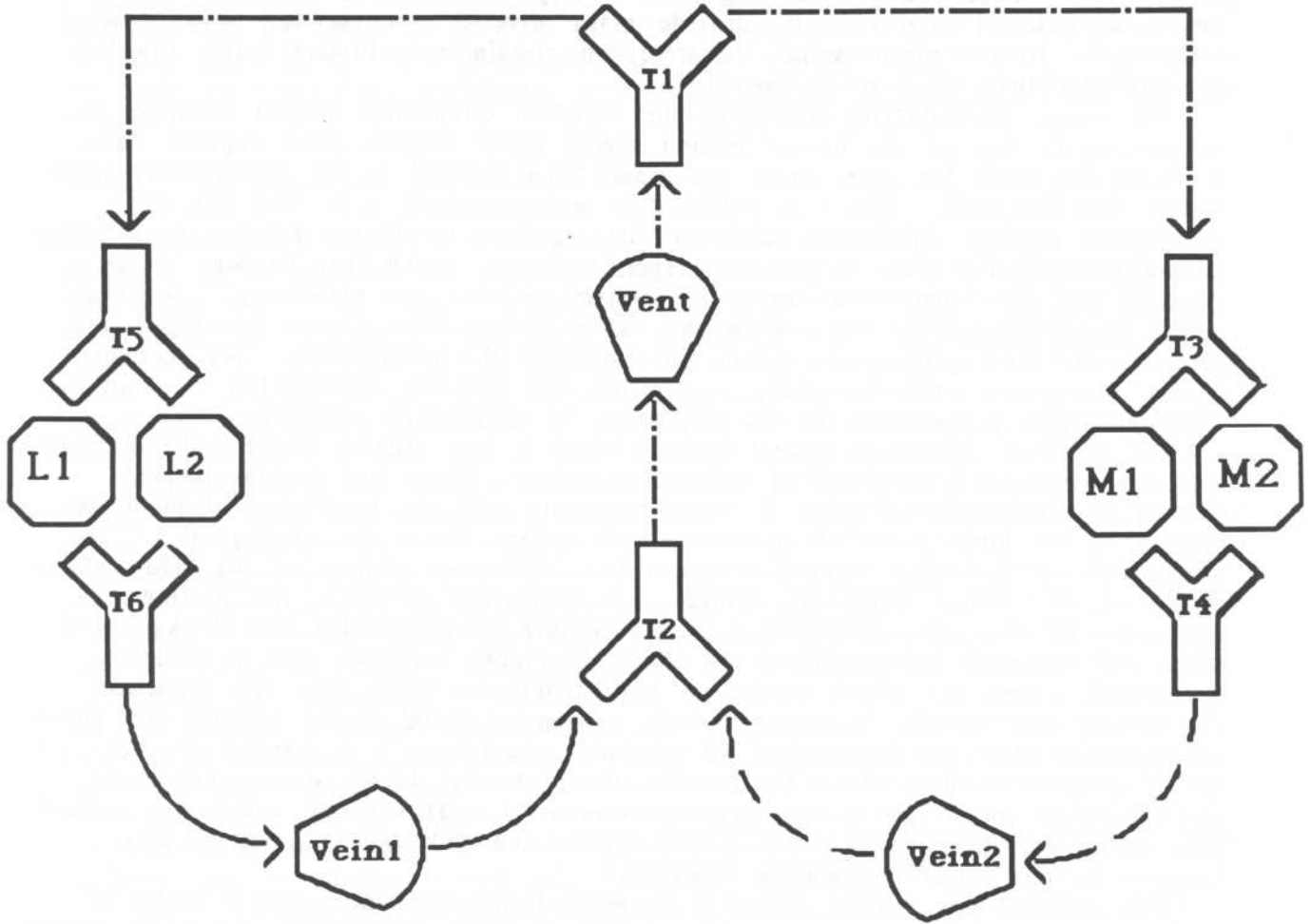
For years, physiologists considered the reptilean circulatory system primitive in comparison to that of the human (which seems rather absurd, since reptiles have inhabited the earth for many more years and have evolved to fill considerably more niches than humans!). The bias behind this anthropocentric view was one of teleological rigidity. Scientists criticized the reptilean circulation relative to a single teleology and perspective: zero-order oxygen transport, which just happens to be a standard that the mammalian circulatory system satisfies par excellence. However, recent studies (Burggren, 1987) show that when viewed from other teleologies and perspectives, the reptilean circulation far outshines the mammalian. As recounted below, Burggren's study colorfully exemplifies the sizeable contribution of multiple teleologies and perspectives to the robustness of circulatory criticism.

The reptilean circulatory system delivers blood to two primary regions: the body or systemic region, and the lungs or pulmonary region. These two regions lie in parallel to one another (Figure 1), which contrasts with the topologies of mammals (Figure 2) and birds, where those areas are in series. From the teleological perspective of zero-order oxygen transport (i.e. delivering oxygen to the body under conditions of normal metabolic, cardiac and respiratory activity), the glaring deficiency of a parallel arrangement is the mixing of oxygenated and deoxygenated blood that occurs in the ventricle. As shown in Figure 1 (which, due to modeling constraints, shows the blood mixing as immediately upstream from the ventricle), this mixing leads to the delivery of poorly oxygenated blood to the muscles and poorly deoxygenated blood to the lungs. To maximize the lung-to-body oxygen transfer during a cycle of blood flow, the muscles should receive highly oxygenated blood, and the lungs should get a low-oxygen concentration. This would enable the highest rates of oxygen diffusion to occur at both source and sink and is precisely what happens in the serial mammalian topology.

This criticism has assisted biologists in neatly fitting the reptile into a ladder of evolutionary sophistication at a point midway between amphibians and homeotherms (i.e. warm-blooded animals). However, this nearsighted view fails to recognize the environmental differences between reptiles and homeotherms. An analysis of the reptile's regulatory responses to these environmental factors attests to the reptilean circulatory efficiency from a first-order teleological perspective.

As pointed out by Burggren, many reptiles such as turtles, snakes and crocodiles spend a good deal of time in the water - often submerged for long periods of time. During diving, the lungs are not ventilated with oxygen. From the oxygen-transport perspective, it therefore make little sense to perfuse them with blood. The beauty of the parallel pulmonary and systemic circulation is that blood distributions between the two regions can change according to their comparative resistances. During diving, the resistance rises in the reptile's pulmonary region, thus "shunting" more blood into the systemic portion. After diving, when the animal needs to quickly rid its system of carbon dioxide, blood shunts the other direction: the majority goes to the lungs. Mammals, with their dual-ventricle hearts, cannot perform this dynamic redistribution; since their two regions are in series, each receives essentially the same blood flow under all conditions. Thus, reptiles but not homeotherms achieve an optimal ventilation-perfusion match during apnea (non-breathing periods).

Figure 1 : Reptilean Directed Flow Network



Legend

**Components:**



**Pump**



**Tissue**



**Vessel**

**Oxygen Concentrations:**

**High**      \_\_\_\_\_

**Medium**    - · - · - ·

**Low**        - - - - -

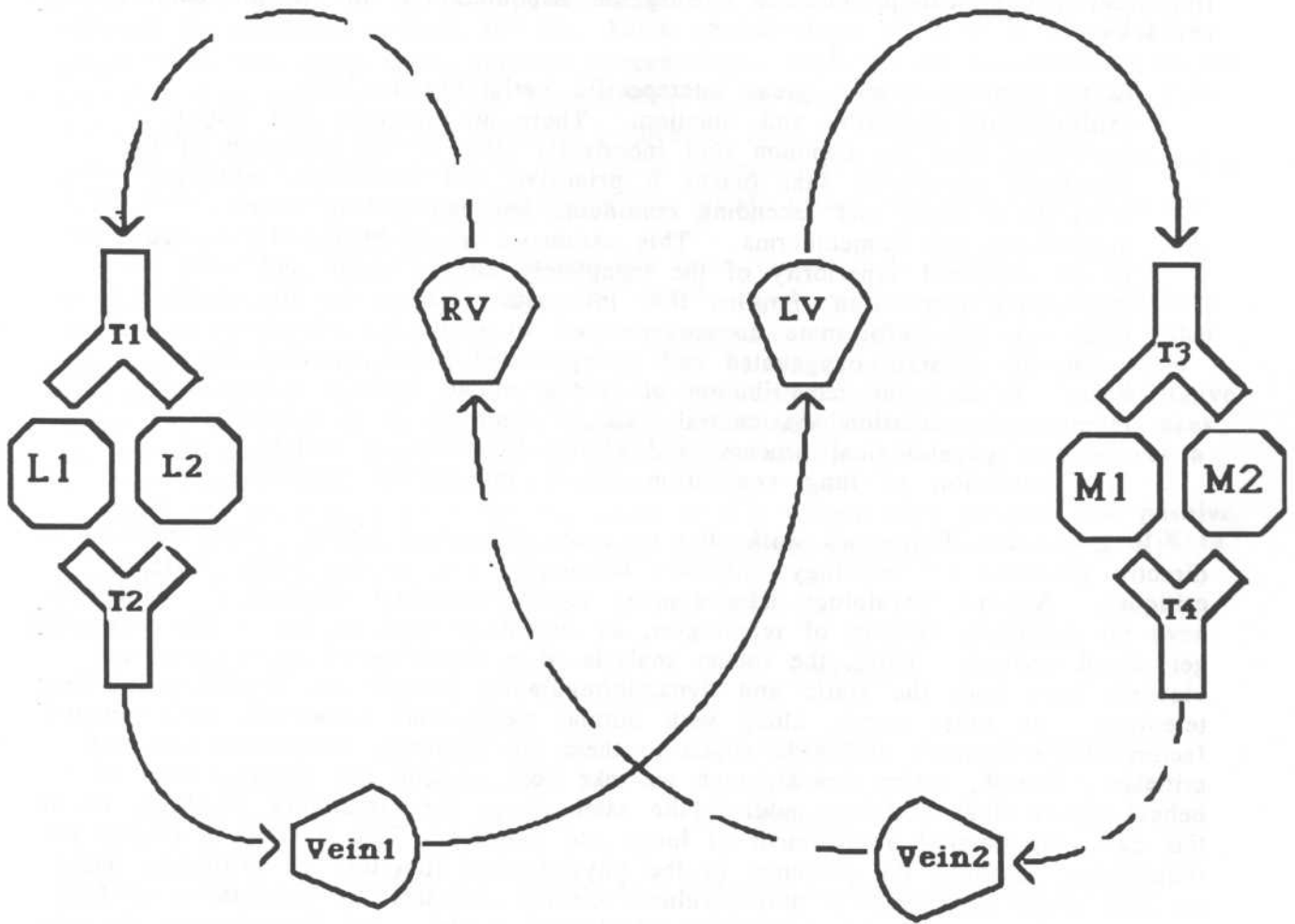
**Abbreviations:**

**Ventricle - Vent**

**Muscles - M1, M2**

**Lungs - L1, L2**

Figure 2: Mammalian Directed Flow Network

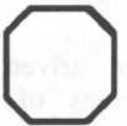


Legend

**Components:**



**Pump**



**Tissue**



**Vessel**

**Oxygen Concentrations:**

**High**      —————

**Low**        - - - - -

**Abbreviations:**

**Right Ventricle - RV**

**Left Ventricle - LV**

**Muscles - M1, M2**

**Lungs - L1, L2**

Burggren's research clearly illustrates the importance of multiple teleologies and perspectives in the criticism of circulatory systems. From the zero-order perspective, the reptilean circulation seems lacking; but from a broader view encompassing the animals environment and physical activity, the reptile displays first-order teleological prominence. Burggren expounds on this in his summarizing remarks:

Extant reptiles exhibit great interspecific variability in both cardiovascular structure and function. There are frequent and major departures from the common (but incorrect!) view of the evolution of the vertebrate circulation that places a primitive and inefficient reptilean heart on a direct and ascending continuum between that of extant amphibians and homeotherms. This erroneous view, historically rooted in the supposed superiority of the completely divided avian and mammalian circulation, implies that intracardiac shunts in the reptilian heart are the unfortunate consequence of an undivided circulation unable to separate oxygenated and deoxygenated blood entering the heart. In fact, the redistribution of cardiac output between systemic and pulmonary circulation via central vascular shunting is a carefully regulated physiological process, and allows for effective matching of lung perfusion to lung ventilation during intermittent breathing.

In conclusion, Burggren's work stirs up many interesting points. First, criticism is directly governed by teleology; different teleologies can inspire vastly different critiques. Second, physiology admits many equally-important teleologies. Scientists have no definitive ranking of teleologies, so organisms such as the reptile frequently get mixed reviews. Third, the robust analysis of a physiological system requires viewing from both the static and dynamic/regulatory perspective, regardless of the teleology. In other words, along with normal steady-state behaviors, environmental factors and a system's ability to adjust to them are important factors for structural criticism. Fourth, notice that although we take both a static and dynamic view of behavior, our final criticisms address the same thing: the circulatory topology, or, in this case, the parallel arrangement of lungs and muscles. This overlap is crucial for robustness. Finally, the presence in the physiological literature of criticisms based on both static and dynamic purposefulness clearly indicates the importance of both computationally formalizing a bipartite teleological model and investigating its role in physiological criticism.

#### IV. Formalizing The Bipartite Teleological Model

This work formalizes The Bipartite Teleological Model (BTM) for a certain class of systems, although the fundamental concept should apply to many other classes. The relevant systems are composed of components and a medium for transporting entities to and from the components. The medium circulates by being transferred between a series of pump components interspersed throughout the system. Typical entities include heat, ions, and chemicals, while standard mediums include air, water, and blood. The entity exchanges occurring between mediums and components are driven by concentration gradients, with entities always passively diffusing from regions of denser to regions of sparser concentration. A component 'produces' some entity X if X diffuses from the component into the medium, it 'consumes' X if diffusion goes the



other direction. Thus, the relevant systems for bipartite teleological analysis can be viewed as networks of producers and consumers.

Within these networks, bipartite teleological analysis relies on a fairly simple qualitative representation of concentrations, gradients and exchange rates. The production or consumption level of an entity X at a component K depends upon two factors: the amount of medium perfusing K, and the concentration gradient of X between the incoming medium and K. Three concentrations of X in K are relevant:  $[X]^{K\text{-state}}$ , the component's internal concentration,  $[X]^{K\text{-in}}$ , the concentration in the incoming flow, and  $[X]^{K\text{-out}}$ , the concentration in the outgoing flow.  $G(X,K) = ([X]^{K\text{-state}} - [X]^{K\text{-in}})$  represents the diffusion gradient of X in K. When it is positive, K produces X; when negative, K consumes. BTM assumes that for any X and K,  $[X]^{K\text{-out}} = [X]^{K\text{-state}}$ , that is, relative to X, the medium always comes into equilibrium with the component before flowing out.

The quantity space for concentrations has three values: high, medium and low. A producer of X, P, will generally have  $[X]^{P\text{-state}} = \text{high}$ , while a consumer C will have  $[X]^{C\text{-state}} = \text{low}$ . Besides *exchange sites* (i.e. producers or consumers) the only other components where concentration gradients have relevance are flow mixers. The zero-order mixing rule is quite simple: the output concentration takes the qualitative value of the input concentrations if they are qualitatively equal; otherwise, it takes the value 'medium'. Hence, the mixing of a high and low concentration produces a medium concentration (as shown in Figure 1).

Diffusion gradients have a quantity space of five values: high positive, low positive, zero, low negative, and high negative. They are derived from  $[X]^{K\text{-state}}$  and  $[X]^{K\text{-in}}$  according to Table I:

|        |  | [X]-state     |              |               |
|--------|--|---------------|--------------|---------------|
| [X]-in |  | High          | Medium       | Low           |
| High   |  | Zero          | Low Negative | High Negative |
| Medium |  | Low Positive  | Zero         | Low Negative  |
| Low    |  | High Positive | Low Positive | Zero          |

Table I: Qualitative Diffusion Gradients As a Function of Input and State Concs.

A high positive gradient indicates the high production of X, while a low positive gradient signals a low production level. Similarly, a high negative gradient entails high consumption, and so on. During zero-order analysis, the gradients solely determine the consumption and production levels. As long as flow exists, it is assumed adequate for the component's needs.

For any entity, X, BTM recognizes four basic teleologies: *transport*, *conservation*, *accumulation* and *dissipation*. A system transports X if there are active producers and consumers of X, while it conserves X if there are neither. Accumulation entails a buildup of X in the medium (i.e. X's concentration,  $[X]$ , is high and/or rising - depending upon the perspective), while dissipation denotes a low or declining  $[X]$ .

Teleologies guide the evaluation of producer-consumer networks. For a given teleology, the criteria vary between the static and dynamic perspectives. From the zero-order perspective, the salient behaviors of any producer or consumer are 1) whether or not the medium flows through them, and 2) the qualitative diffusion gradients of various entities between that component and the medium. Different teleologies will recommend different values for the flow and gradient parameters.

From the static perspective, the 'recommended' behaviors of the four basic teleologies are as follows\*:

| Teleologies | Parameters    |               |                   |                   |
|-------------|---------------|---------------|-------------------|-------------------|
|             | Producer Flow | Consumer Flow | Producer Gradient | Consumer Gradient |
| Transport   | Yes           | Yes           | High              | High              |
| Conserve    | No            | No            | Zero, Low         | Zero, Low         |
| Dissipate   | No            | Yes           | High              | Zero, Low         |
| Accumulate  | Yes           | No            | Zero, Low         | High              |

Table II: Teleology-Recommended Flows and Gradients at Exchange Sites

In Table II, the absence of flow obviously precludes a diffusion gradient, so according to conservation, for instance, the optimal situation involves no flow to any exchange sites, but if there is flow, the gradients should be low. Similarly, accumulation favors no flow to consumers, but if flow exists, a high gradient is preferred, since it suggests a high steady-state concentration in some portion of the medium.

From the dynamic/first-order perspective, producer-consumer networks are evaluated according to their ability to adjust to perturbations in a manner advocated by the teleology. In this mode, external perturbations cause producers and consumers to exhibit certain *tendencies*, such as increasing or decreasing their exchange rates. For example, at high altitude, the oxygen concentration within the lungs will decrease to show a tendency of decreased oxygen production. Teleologies

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\* The first two teleologies are fairly straightforward, but the latter two run contrary to intuition: accumulation would seem to require high production and low consumption, and dissipation the opposite. The problem is that these two processes have strong first-order connotations. Accumulation entails an increase or positive *derivative* (with respect to time), but the static perspective involves steady-state analysis. Hence, from a static view, accumulation means 'high' not 'rising'. Similarly, dissipation means 'low' not 'falling'. Remember, by assumption, producers always have a high internal concentration, and consumers a low one. If the gradient at a producer is low, then the incoming concentration must be fairly high, and only a low amount of production will occur (per unit of perfusing medium); in other words, little production is needed to maintain the already-high steady-state concentration. Thus, from the steady-state perspective, accumulation has occurred in a diffusion-driven environment when producers have small gradients but consumers have large ones. Similarly, low consumption and high production (per unit of perfusion) hint of dissipation.

The cardiovascular abnormality in human infants known as 'Tetralogy of Fallot' (Guyton, 1986) clearly illustrates this conception of steady-state dissipative behavior. In Tetralogy of Fallot, various structural defects within the heart cause a 'right-to-left shunt' in which blood from the right heart is recirculated through the body instead of being passed to the lungs. As a result, less blood gets reoxygenated than normal, but the blood that does make it to the lungs is very low in oxygen and hence forms a high gradient for oxygen diffusion. However, systemic (i.e. bodily) flow contains a mixture of oxygenated and deoxygenated blood and therefore forms a small gradient for oxygen consumption in the muscles. In sum, the oxygen producer has a large gradient, while the consumer has a small one; but oxygen has dissipated from the blood to cause the 'blue baby' condition symptomatic of Tetralogy of Fallot.

determine the behavioral changes that should occur in response to those tendencies, and first-order evaluation compares those prescriptions to the actual behaviors.

The Bipartite Teleology Model assumes that the producer-consumer network has a single mechanism for reacting to the first-order tendencies: changing the resistance to medium flow of the producers and consumers. These changes can modify flow levels throughout the network, which in turn will alter exchange rates either in accordance or in conflict with the tendencies. The following Table III indicates the local qualitative flow changes recommended by the four teleologies in response to the six qualitative tendencies exhibited by exchange sites:

| Teleo  | Tend                     |                          |                          |                          |                          |                          |
|--------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
|        | $\partial$ Produc<br>[-] | $\partial$ ConsmP<br>[-] | $\partial$ Produc<br>[+] | $\partial$ ConsmP<br>[+] | $\partial$ Produc<br>[0] | $\partial$ ConsmP<br>[0] |
| Trans  | [-]                      | [-]                      | [+]                      | [+]                      | [0]                      | [0]                      |
| Cons   | ---                      | ---                      | [-]                      | [-]                      | ---                      | ---                      |
| Diss   | ---                      | [-]                      | [-]                      | [+]                      | [-]                      | [+]                      |
| Accum. | [-]                      | ---                      | [+]                      | [-]                      | [+]                      | [-]                      |

Table III: Teleology-Recommended Flow-Change Responses to Exchange Tendencies

So, from the dynamic perspective, each teleology advocates a different reaction to the exchange tendencies. For transport, the flow changes should vary in direct proportion to the exchange tendencies\*\*. Alternatively, conservation dictates a decrease in flow to all increasingly active exchange sites. Dissipation seeks to flood the stable and potentially hyper-active consumers but starve the producers, while accumulation has the opposite desires. These recommendations represent local attempts to continue pursuing the teleology in the face of perturbations. However, the global network topology may or may not permit the mutual satisfaction of these local goals. The resulting interactions between topology and local flow-change goals form the basis for first-order criticism of the network.

In sum, The Bipartite Teleology Model provides a standard/bias for the evaluation of producer-consumer networks during both steady-state and dynamic behavior. The orthogonality of the four teleologies and two perspectives yields eight different angles for critiquing a network's behavior (relative to any entity). Once the interesting behaviors have been identified, a structure critic can use them to discern the network's salient topological formations.

## V. The Contribution of Topology to Behavior and Teleology

In producer-consumer networks, the spatial relationships between exchange sites are major determinants of behavior and teleological fulfillment. The exchange of entities at any given site vitally depends upon the exchange sites upstream, downstream and in parallel to it. I will refer to these relationships as *topological*. When viewed from this spatial angle, the producer-consumer network becomes the

\*\* This characterization of transport generalizes the well-known physiological concept of ventilation-perfusion matching, which demands a direct proportionality between the amount of air that ventilates the lung and the amount of blood that perfuses the alveolar capillaries. Physiologists consider this matching (along with the dual match of perfusion to metabolism in other tissues) critical to the efficient transfer of oxygen and carbon dioxide between the lungs, muscles and organs.

*producer-consumer (PC) topology.* In the circulatory analysis performed by BIOTIC, topological relationships are the cornerstones of causal activity and the focal points of structural criticism.

Two types of relationships characterize the PC topology: *communication* and *flowpath*. A communication relationship between two components implies that the concentrations of various entities within one component will affect the exchange rates of those entities at the other component. A flowpath relationship describes the relative spatial orientations of components along a flow or flow series, where a *flow* denotes a one-way transfer of blood from a sending pump to one or more receiving pumps.

Communication relationships are easy to spot, since BTM relies on the assumption that an incoming flow achieves equilibrium (relative to all critical entities) with an exchange site before exiting. Hence, the effects of an upstream site's state concentrations are only felt by the nearest downstream sites, which in turn put their state concentrations into the passing medium and effectively 'overwrite the concentration message' sent by the original upstream site,  $S_{U1}$ . From the concentration standpoint, all of  $S_{U1}$ 's causal efficacy gets absorbed in the entity-exchange rates of the immediate downstream sites. Conversely, mixers do not absorb this efficacy, but combine it with another site's (or mixer's) message and pass on the conjunctive effect.

To continue this message-passing metaphor,  $S_{U1}$  *signals* another component (relative to some entity X) iff that component receives  $S_{U1}$ 's concentration-of-X ([X]) message. For a given entity, the collection of signals/messages that an exchange site receives constitute its *feed*. A *unique* feed contains a single signal, while a *non-unique* feed contains multiple signals and indicates that the site lies immediately downstream (i.e. no intervening exchange sites) from a mixer. Furthermore, a feed is *pure* iff all of its signals come from sites of the same exchange type. A *pure-p* feed has only producers as signal senders, while a *pure-c* feed comes from consumers. Finally, an exchange site exhibits *feedback* iff it signals itself; i.e., its outgoing concentration flows past no other exchange sites (although mixers may intervene) before looping back to the sender.

The communication relationships within a PC topology indicate groups of exchange sites with co-dependent diffusion behaviors. For instance, if a consumer lies immediately downstream from a producer, then a rise in the producer's state concentration (of some entity X) will increase both production and the consumer's incoming concentration - thereby raising consumption also. Intertwined producer-consumer behaviors of this sort form critical pieces of a global understanding of system behavior and function.

*Flowpath* relationships also contribute to this gestalt understanding. Along a *flow*, two exchange sites lie in *direct series* iff the same portion of the medium (i.e. the exact same medium molecules) flows through each site. The sites are *directly parallel* iff they lie along opposite branches of a flow-splitting component. Two sites are *indirectly* serial or parallel if either or both sites reside within an aggregate of parallel or serial sites, and that aggregate is parallel or serial to the other site (or its aggregate). Furthermore, under the assumption that no system components have capacitance, serial relationships may extend across flows, since the medium molecules that enter a receiving pump will all leave when that pump becomes a flow sender.

The flowpath relationship between two sites indicates the degree to which they can affect one another's perfusion rates. For instance, if two sites are directly serial and one raises its resistance to flow, the other site will also experience a flow decrease. However, if the sites are directly parallel, the resistance increase should redistribute flow away from the increase and toward the other site. For *indirect* flowpath



relationships, the coupling of the two perfusion rates weakens, since the behaviors of other sites within the aggregate(s) also come into play.

The communication and flowpath relationships highlight salient aspects of the network's global structure. This helps link topology to teleology, because the satisfaction of a teleology often requires a particular topological arrangement. Within The Bipartite Teleology Model, these requirements vary with the perspective. Specifically, the zero-order viewpoint focuses on the communication relationships between sites, while the first-order perspective deals primarily with flowpath concerns.

From the static perspective, the four teleologies recommend the following communication relations (relative to some entity):

| Teleology  | Communicate Relations |                    |                   |                   |
|------------|-----------------------|--------------------|-------------------|-------------------|
|            | Producer Feed         | Consumer Feed      | Producer Feedback | Consumer Feedback |
| Transport  | <u>Pure-c</u>         | <u>Pure-p</u>      | No                | No                |
| Conserve   | <u>Pure-p</u>         | <u>Pure-c</u>      | ---               | ---               |
| Dissipate  | Pure-c                | Pure-c<br>or Mixed | <u>No</u>         | <u>Yes</u>        |
| Accumulate | Pure-p<br>or Mixed    | Pure-p             | <u>Yes</u>        | <u>No</u>         |

Table IV: Teleology-Recommended Communication Relations

In Table IV, underlined parameter settings represent the most salient prerequisites for each teleology. Hence, the critical aspect of zero-order transport is the existence of pure feed lines between producers and consumers, while conservation recommends no such feed lines (whether pure or mixed). The keys to static dissipation and accumulation are feedback. When a consumer feeds back on itself, a propensity for dissipation exists, while producer feedback inspires static accumulation.

From the first-order perspective, the correlations between topology and teleology are too context-sensitive to lay out in two-dimensional tabular form. As shown in Table III, the 'success' of first-order behavior (relative to a teleology) relates to the ability to achieve certain perfusion changes in response to various exchange tendencies. Flowpath relations constrain those changes by requiring all directly serial sites to have equivalent qualitative perfusion derivatives. On the other hand, parallel relationships frequently permit the mutual satisfaction of different perfusion-change requests. In short, the significance of a flowpath relationship will depend upon the teleology and the comparative tendencies of the two sites. Future examples will illustrate this point.

Looking back, this section has shown the importance of the producer-consumer topology in determining both exchange behavior and teleological satisfiability (from the static and dynamic perspective). These topological relationships enable us to ground the explanations of teleologically-relevant producer-consumer behaviors in the global structure of the network - thus integrating structure, behavior and function into a coherent picture of the gestalt system.



## VI. Circulatory Criticism in BIOTIC

Having formalized The Bipartite Teleology Model and discussed the manner in which topology, teleology and behavior intertwine, I will now describe BIOTIC's application of these concepts to circulatory criticism.

BIOTIC inputs a qualitative circulatory model and one or more *critical contexts* in which to criticize that model. It then intermixes qualitative simulation and criticism to analyze the model. Both processes receive varying degrees of guidance from each critical context, which consists of four elements:

- 1) Teleology - A behavioral goal of the physiological system composed of a *critical entity* and a *critical action* (e.g. oxygen transport or heat dissipation).
- 2) Teleological Perspective - steady-state or regulatory.
- 3) Environment - External situation expressed as changes in the internal entity concentrations of various circulatory components; e.g., high altitude entails a lower oxygen concentration in the lungs.
- 4) Task - high-level endeavor such as running or swimming, which translates into activity-level changes of the circulatory components that assist in the performance of that task.

### VI.1 Qualitative Simulation in BIOTIC

Like most qualitative simulators, BIOTIC's circulatory simulator (CIRC-SIM) generates behaviors from a basic structural description and a few initializing behaviors. In this case, the structural description is a connected set of components, of which there are four primitive types:

- 1) Pumps - These propel blood through the system and also receive blood flows from other pumps.
- 2) Vessels - These simply transmit blood, although in some cases they may split one flow into two, or merge two flows into one. These are the only components that can have more than two ports.
- 3) Valves - These block the flow of blood in exactly one direction. In the other direction, they behave as 'straight' (i.e. two-port) vessels.
- 4) Tissues - These are the only components that produce or consume the vital entities (e.g. oxygen, carbon-dioxide, heat), and only tissues have a modeled resistance.

As start-up behaviors, CIRC-SIM requires the pumping patterns of all pumps and their initial binary capacitance states: either empty or full. Also, for every critical entity, CIRC-SIM demands the internal state concentration of that entity in each tissue.

From these simple beginnings, CIRC-SIM computes the pulsatile blood flows throughout the circulatory system. It then abstracts temporally over the pulsatile flow patterns to form the Directed Flow Network (DFN), a steady-state model of blood flow in the form of a directed cyclic graph representing the paths that a piece of blood can take through the system. BIOTIC uses the DFN a) to determine *communication* relationships between tissues/exchange sites, and b) to propagate critical-entity concentrations, their derivatives, and the derivatives of flow amounts.

Orthogonal to the temporal abstractor, a spatial aggregator parses each *flow* into a hierarchy of parallel and serial tissue aggregates. The combination of all such

hierarchies across all flows constitutes the Global Tissue Hierarchy (GTH). From the GTH, BIOTIC discerns *flowpath* relationships between tissues. Furthermore, during dynamic analysis, BIOTIC employs the GTH to propagate changes in tissue' resistances and their concomitant changes in pump outputs and flow distributions. Together, the DFN and GTH comprise the aforementioned *PC Topology* for the circulatory system\*.

After determining flows and abstracting them temporally and spatially, CIRC-SIM looks to the critical contexts for critical entities. Regardless of the teleological perspective, CIRC-SIM propagates each entity's qualitative concentrations throughout the DFN to determine the zero-order exchange behaviors of each tissue. In zero-order simulation, CIRC-SIM ignores the environment and task while assuming 'lab conditions' of negligible external perturbation. If the critical context calls for first-order simulation, CIRC-SIM also propagates qualitative *changes* in entity concentrations, resistances, and flows through the PC Topology. These changes are determined by the environment and task, and by teleology-driven reactions (as dictated by BTM) to the tissue' exchange *tendencies* invoked by the environment and task.

## VI.2. Criticism in BIOTIC

In BIOTIC, criticism consists of two stages. The first, *evaluation*, employs BTM to interpret exchange behaviors relative to the critical teleology. In *explanation*, the second stage, BIOTIC uses behaviors and the teleological bias to identify key properties of the PC Topology that justify the behaviors. The net result is a critique that describes how circulatory topologies contribute, via exchange behaviors, to circulatory teleologies.

Evaluation is fairly straightforward. Given a teleology and a qualitative behavior, BIOTIC merely compares the behavior to the teleology's recommended behavior and assigns an evaluation between -1 and 1 depending upon the difference, where a 1 denotes qualitative equality and a -1 implies that the values are at opposite ends of the quantity space. For instance, a comparison of 'high production' to 'high consumption' yields a -1, while 'zero exchange' versus 'high production' merits a 0. In zero-order evaluation, BIOTIC compares gradients to the recommended gradients of Table II, while first-order evaluation requires a comparison of flow-change behaviors to those of Table III. In either case, the global evaluation is simply the average of the local ratings.

These evaluations connect teleologies to circulatory behaviors, so to complete our desired chain from teleology to topology, we must next connect the behaviors to the global circulatory structure. In BIOTIC, this constitutes *explanation*. In zero-order explanation, BIOTIC searches the *feed* lists of each tissue for the teleology-recommended relationships of Table IV and bases its explanation upon the presence or absence of those *communication* paths. Thus, teleology biases zero-order explanation by providing a schema for behavioral interpretation.

Unfortunately, first-order explanation cannot rely on schema instantiation, since, as pointed out earlier, 'desirable' topologies for first-order teleological prominence are not easily generalizable. Instead, BIOTIC focuses on those tissues whose exchange *tendencies* merit teleology-advocated flow changes (as presented in Table III). It then

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\* Due to ambiguities concerning the relative strengths of circulatory pumps (both hearts and veins are modeled as pumps), CIRC-SIM often produces multiple PC Topologies for a circulatory model. Hence, each critical context contains a fifth element: the topology to be critiqued. Due to space limitations, I will ignore the ambiguities of flow envisionment and concentrate on one topology per circulatory system.

attempts to parse the actual flow changes to those tissues into a concise and comprehensive story of how *flowpath* relationships affect those changes.

### VI.2.1 Zero-Order Criticism

As an illustration of zero-order criticism in BIOTIC, consider the reptilean and mammalian circulatory systems when simulated with oxygen as the critical entity. Figures 1 and 2 show the DFNs (generated by CIRC-SIM) for reptiles and mammals, respectively. Also, Tables V and VI show the exchange behaviors at each tissue along with the zero-order evaluations of those behaviors relative to all four teleologies.

| COMP                | [O <sub>2</sub> ]-IN | [O <sub>2</sub> ]-ST | GRAD       | EXCHG          | TRANS     | CONS      | DISS      | ACCUM     |
|---------------------|----------------------|----------------------|------------|----------------|-----------|-----------|-----------|-----------|
| Lung1               | Medium               | High                 | Low<br>Pos | Low<br>Prod    | .5        | .5        | .5        | .5        |
| Lung2               | Medium               | High                 | Low<br>Pos | Low<br>Prod    | .5        | .5        | .5        | .5        |
| Muscle1             | Medium               | Low                  | Low<br>Neg | Low<br>Consmpt | .5        | .5        | .5        | .5        |
| Muscle2             | Medium               | Low                  | Low<br>Neg | Low<br>Consmpt | .5        | .5        | .5        | .5        |
| <b>Global Eval:</b> |                      |                      |            |                | <b>.5</b> | <b>.5</b> | <b>.5</b> | <b>.5</b> |

Table V: Reptilean Exchange Behaviors and Evaluations

| COMP                | [O <sub>2</sub> ]-IN | [O <sub>2</sub> ]-ST | GRAD        | EXCHG           | TRANS    | CONS     | DISS      | ACCUM     |
|---------------------|----------------------|----------------------|-------------|-----------------|----------|----------|-----------|-----------|
| Lung1               | Low                  | High                 | High<br>Pos | High<br>Prod    | 1        | 0        | 1         | 0         |
| Lung2               | Low                  | High                 | High<br>Pos | High<br>Prod    | 1        | 0        | 1         | 0         |
| Muscle1             | High                 | Low                  | High<br>Neg | High<br>Consmpt | 1        | 0        | 0         | 1         |
| Muscle2             | High                 | Low                  | High<br>Neg | High<br>Consmpt | 1        | 0        | 0         | 1         |
| <b>Global Eval:</b> |                      |                      |             |                 | <b>1</b> | <b>0</b> | <b>.5</b> | <b>.5</b> |

Table VI: Mammalian Exchange Behaviors and Evaluations

The key differences between these tables occur under 'transport' and 'conservation'. The mammal receives a perfect oxygen-transport rating, since high consumption and production occur throughout the PC Topology; but mixing in the reptilean model leads to low exchange rates and hence a sub-optimal evaluation.

Conversely, low exchange outranks high exchange relative to the conservation teleology. Both systems show local signs of dissipation and accumulation, but in each model, the dueling effects essentially cancel.

To explain these behaviors, BIOTIC uses each teleology as an index into Table IV and then applies the relevant schema to the *feeds* of each tissue. Rough summaries of these explanations appear in Table VII.

|                            | Reptile  | Mammal  |
|----------------------------|--|---|
| <b>Oxygen Transport</b>    | Impure feeds to P's and C's (caused by blood mixing) thwarts transport | Pure feeds to P's and C's satisfies transport               |
| <b>Oxygen Conservation</b> | The existence of P->C and C->P signals thwarts conservation            | The existence of P->C and C->P signals thwarts conservation |
| <b>Oxygen Dissipation</b>  | 'Helpful' C feedback counterbalanced by 'harmful' P feedback           | Lack of C feedback precludes dissipation                    |
| <b>Oxygen Accumulation</b> | 'Helpful' P feedback counterbalanced by 'harmful' C feedback           | Lack of P feedback precludes accumulation                   |

\* P = Producer, C = Consumer

Table VII: Explanations Linking Topology to Zero-Order Teleology

If necessary, BIOTIC can elaborate these explanations by pinpointing the exact producers and consumers involved in the communication relationships, along with the flows that connect them.

### VI.2.2. First-Order Criticism

As shown above, the mammalian circulation clearly dominates the reptilean model relative to zero-order oxygen transport. However, from the first-order perspective, and within the context of certain environments and tasks, the reptile outperforms the mammal. Returning to Burggren's (1987) example of the diving reptile, consider the following critical context:

(Oxygen-Transport First-Order Underwater Swimming)

This combination of environment and task incurs the following tendencies within the tissues: first, both lungs will show strong signs of decreased oxygen production due to the unavailability (for an organism without gills) of underwater oxygen. Furthermore, let us assume that M1 represents a tail muscle, and M2 a leg. Then, M1's oxygen consumption will tend to increase, while M2's will decrease (since, in reptiles, the tail is often the primary swimming muscle, while other appendages perform much less work than on land). Thus, according to Table III, the oxygen-transport

teleology recommends an increase in flow to M1, and a decrease to L1, L2 and M2. To attempt to achieve these flow changes, BIOTIC decreases M1's resistance and increases all other tissue' resistances.

BIOTIC propagates these resistance changes throughout the Global Tissue Hierarchy (GTH). This causes a slight decrease in the flow out of the reptile's ventricle\*, and it also produces significant redistribution(at T1) of blood away from the lungs and toward the muscles. In physiological terminology, this constitutes a 'right-to-left shunt'\*\*. At T1, BIOTIC qualitatively combines the redistribution influences with the decreased-ventricular-flow influence to yield a net decrease in flow to the lungs and a steady flow to T3. However, at T3, the incoming blood redistributes toward M1 and away from M2. These flow behaviors lead to the first-order evaluation of Table VIII.

| Tissue       | Tendency   | Teleo-Desired Flow Change | Actual Flow Change | Teleo-Based Rating |
|--------------|------------|---------------------------|--------------------|--------------------|
| Lung1        | Decr. Prod | Decr                      | Decr               | 1                  |
| Lung2        | Decr Prod  | Decr                      | Decr               | 1                  |
| Muscle1      | Incr Consm | Incr                      | Incr               | 1                  |
| Muscle2      | Decr Consm | Decr                      | Decr               | 1                  |
| Global Eval: |            |                           |                    | 1                  |

Table VIII: Evaluation of Diving Reptile According to First-Order Oxygen Transport

BIOTIC then forms groups of tissues that have common superior aggregates within the GTH and common a) tendencies, b) recommended flow changes, and/or c) actual flow changes. The flow-change behaviors of these groups then serve as primitives for first-order explanation. In addition, basic tissue aggregates of the GTH are employed during explanation. In the case of the diving reptile, L1 and L2 unify into a group,  $G_L$ , while the GTH aggregate,  $A_M$ , comprised of M1 and M2 also supports the following (paraphrased) explanation:

The decrease in ventricular output along with the parallelism of  $G_L$  and  $A_M$  permits  $G_L$ 's flow to decrease while  $A_M$ 's flow remains relatively constant. Then, the steady flow to  $A_M$  combines with the parallelism of M1 and M2 to enable the desired increase in M1's flow and decrease in M2's flow.

This explanation captures the salient topological relationships that contribute to teleological satisfaction.

\* Pump outputs change under the assumption that the systolic (contracted) and diastolic (relaxed) pressures of all pumps remain constant. Under the opposite assumption (i.e. pump outputs hold steady while their pressures change), resistance changes in tissues can cause changes in the relationships between pump pressures; and this may cause a shift to a completely different flow topology. As shown in Burggren (1987) and as simulated in BIOTIC (Downing, 1990), the circulatory system of the crocodile clearly illustrates the utility of flow-topology shifting during first-order behavior.

\*\* This terminology stems from the fact that the pulmonary aorta branches to the right upon leaving the vicinity of the heart, while the systemic aorta branches to the left. In physiology, 'right' and 'left' are always relative to the organism, not to an observer facing the organism.



Returning to the mammal, BIOTIC critiques it within the same critical context, but the tissue components need a slight reinterpretation: assume M1 is an arm and that the mammal primarily uses its arms for swimming. M2 remains a leg. Now, when swimming underwater, the same tendencies and teleological flow recommendations occur within the mammalian circulation as in the reptile. However, the diverse flow demands between the lungs and muscles lead to a dilemma in the first-order simulation: the overall resistance to the left ventricle's flow remains qualitatively constant, while the right ventricle's resistance goes up. Hence, RV's flow should increase, while LV's flow should remain constant. Since these two flows lie in series (when connected via the flows from Vein1 to LV and Vein2 to RV), the circulation cannot sustain an increase in one coupled with a steadiness in the other. CIRC-SIM signals a major conflict. As a result, BIOTIC skips local evaluation and generates the following (paraphrased) explanation:

The different flow demands of AM and GL in combination with the inter-flow serial relationship between the two regions precludes the satisfaction of first-order oxygen transport.

Thus, BIOTIC highlights the critical distinction between the mammalian and reptilian circulatory topologies: serial versus parallel pulmonary and systemic regions. By critiquing both systems from two teleological perspectives (i.e. static and dynamic), the differential functionalities of each topology become evident. These functionalities and their relationships to topology closely mirror those discussed by Burggren (1987).

To complete this comparison of BIOTIC to Burggren, consider the 'left-to-right' shunt that occurs in reptiles during periods of high lung ventilation (e.g. immediately following a lengthy underwater swim). Burggren indicates that this shunt stimulates the dissipation of carbon dioxide from the blood. In BIOTIC, this maps into the following critical context:

(Carbon-Dioxide-Dissipation First-Order Land Heavy-Breathing)

The *task* of heavy breathing indicates that both lungs will have high carbon-dioxide-consumption tendencies, while the production tendencies of the muscles should be normal. As shown in Table III, carbon-dioxide dissipation recommends an increase in pulmonary flow (and hence a decrease in pulmonary resistance) and a decrease in systemic flow (and thus a rise in systemic resistance). CIRC-SIM propagates these resistance changes and produces the resulting flow changes. BIOTIC then forms the evaluation of Table IX.

| Tissue       | Tendency    | Teleo-Desired Flow Change | Actual Flow Change | Teleo-Based Rating |
|--------------|-------------|---------------------------|--------------------|--------------------|
| Lung1        | Incr Consmp | Incr                      | Incr               | 1                  |
| Lung2        | Incr Consmp | Incr                      | Incr               | 1                  |
| Muscle1      | Steady Prod | Decr                      | Decr               | 1                  |
| Muscle2      | Steady Prod | Decr                      | Decr               | 1                  |
| Global Eval: |             |                           |                    | 1                  |

Table IX: Evaluation of Post-Dive Reptile According to First-Order CO<sub>2</sub> Dissipation

BIOTIC treats the muscle and lung groups as primitives:  $G_M$  and  $G_L$ , respectively, due to the similarities within each region. This facilitates the following concise explanation:

The steady ventricular output along with the parallelism of  $G_M$  and  $G_L$  permits the desired a) increase of flow to the consumption region,  $G_L$ , and b) decrease of flow to the production region,  $G_M$ .

Given the same context, the mammalian circulation again produces a major conflict that leads to the following explanation:

The different flow demands of  $G_M$  and  $G_L$  in combination with the inter-flow serial relationship between the two regions precludes the satisfaction of first-order carbon-dioxide dissipation.

Once again, the reptile clearly dominates.

In sum, BIOTIC produces critiques similar to those of Burggren and other physiologists (Eckert, Randall and Augustine, 1988) by formalizing (via BTM) and operationalizing (via BIOTIC) the notions of teleology and perspective that are essential, fundamental, yet implicit aspects of these expert' critiques. In so doing, BIOTIC illustrates the utility of the Bipartite Teleological Model in analyzing flow-and-diffusion-based systems. And more generally, it further clarifies the qualitative relationships between structure, behavior and function in physical and biological reasoning.

## VII. Discussion

The BIOTIC project addresses two general research questions, neither of which has received much attention from qualitative physicists:

- 1) What teleological concepts are useful for qualitative physics, and how should they be applied?
- 2) Can qualitative physics be extended to biological domains?

Regarding the 'how' clause of the first question, de Kleer and Brown's (1983) 'No-Function-in-Structure' principle (NFIS) makes significant theoretical headway. In NFIS, they warn that functional assumptions, if embedded in a component's local behavioral model, can greatly undermine the robustness of simulation. Still, they acknowledge the indispensibility of teleology in the interpretation and explanation of *envisionments* (i.e. the traces of an envisioner/qualitative simulator). The ramifications of NFIS are twofold: 1) teleological information should not interfere with the envisioning process but can later be applied to search through the complete envisionment, and 2) if functional assumptions are used to bias the simulation, then the envisioner should have explicit awareness of them.

De Kleer (1979) exemplifies NFIS when introducing teleological knowledge of electrical circuits to help prune complete envisionments during circuit recognition. His system, QUAL, employs teleology to bias reasoning/recognition, but not simulation. Furthermore, QUAL partially answers the 'what' clause of the first question by using standard teleologies of electrical engineering. Unfortunately, these do not apply to all domains. Of course, neither do those of the Bipartite Teleology Model. However, at the abstract level, the BTM provides more breadth than QUAL by encompassing both steady-state and dynamic teleological behavior. It seems clear that any truly general teleological model must span both perspectives.

BIOTIC tackles the 'how' clause by employing teleology as a bias during the evaluation and explanation phases of criticism. The differences between criticism and recognition, and between physiology and electronics, necessitate a different approach in BIOTIC than in QUAL. To wit, recognition demands the matching of teleologies against behaviors in order to eliminate behavioral interpretations. A teleology that matches none of the interpretations is rejected as a possible classification. Conversely, in criticism, a contradiction between system behavior and teleology simply indicates a problem that must be analyzed, explained and possibly corrected. In other words, a critic must deal with 'negative instances' of the teleology, while a recognition system can discard them. Concerning the teleological differences between electronics and physiology, much of electronic teleological analysis appears to be perturbation driven, while physiological purposefulness has strong regulatory and steady-state aspects.

Regarding the extension of qualitative physics to biology, the primary contribution has come from Kuipers, who has run QSIM on various cardiovascular and renal examples. In (Kuipers and Kassirer, 1984), they convert a doctor's qualitative reasoning into a QSIM model of the effects of protein loss on water retention; while in (Kuipers, 1987), he models the related mechanisms of water and salt regulation in the blood. Finally, in (Kuipers, 1987 IEEE), he considers the diagnosis of those same regulatory mechanisms from a first-principle perspective. There, he differentiates medical from electrical domains by contrasting the component-centered electrical models with physiological systems, which are governed by regulatory mechanisms. However, systems in both domains clearly rely on dynamic purposeful behavior, and as evidenced by the critiques of Burggren and others, static teleology is also an important key to understanding physiological systems.

Another critical aspect of physiological behavior is topology: the spatial relationships between components. As the contrast between mammalian and reptilian circulations indicates, the structural topology often determines the efficacy of regulatory and steady-state activity. In QSIM, Kuiper's 'structure' is nothing more than a set of qualitative differential equations (with respect to time). However, Throop (1989) has recently modified QSIM to also simulate change with respect to space. This facilitates causal reasoning (which usually requires some notion of change) about temporally steady-state physiological mechanisms such as countercurrent exchange. Hence, Throop's work helps integrate qualitative physics and biology by formalizing a model of spatial change, which in turn enables him to recognize interesting behaviors in steady-state systems.

BIOTIC continues along the lines of Kuipers and Throop by focusing on spatial relationships from both regulatory and steady-state perspectives. Additionally, BIOTIC injects teleology into physiological reasoning to organize and provide a motivation for the behaviors of these systems - thereby eliciting the functional significance of the structures underlying those behaviors. Furthermore, teleology combines with perspective, environment and task to form BIOTIC's *critical context* for physiological analysis; and a clear, explicit context is an essential ingredient of biological reasoning. As a corollary to the NFIS implication that robust physical reasoning demands an explicit representation of assumptions, biological reasoning requires a thorough characterization of a context composed of environmental, teleological and even historical/evolutionary elements. Without this context, biological evaluation reverts to 'gold-standard' comparison (and the temptation of the anthropocentric bias). One bright prospect for future research is the formalization of biological context within an assumption-management system such as the ATMS (de Kleer, 1986).

To take a wide-angle view of this research, consider the relationships between qualitative physics, qualitative biology and circulatory criticism. Qualitative methods possess great potential in both physics and biology. In the last decade, great strides have been made in qualitative physics, but the contemporary structure-behavior

myopia demands an infusion of teleology to boost qualitative physics above the complexity level of pendulums, springs and bouncing balls. Meanwhile, the successes of qualitative physics: envisioning techniques, various semantics for causality, data interpretation methods, models of naive physics, qualitative mathematics, etc., have yet to find widespread application in biology. Possibly the ambiguities of qualitative simulation prove too risky for medical applications; and maybe first-principle reasoning has little worth to medical practitioners, who often put their trust in empirical data and its compiled abstractions. Still, many biology textbooks teach basic biological principles and the causal interactions of physics and chemistry that determine organic behavior. This importance of basic principles and causal models indicates that, at the very least, biology education could benefit from qualitative simulation and reasoning methodologies.

Now consider circulatory criticism, a biological task that a) seems well grounded in the qualitative first principles of flow and diffusion, and b) demands a clear model of teleology (and environment). These features indicate that circulatory criticism should help link qualitative physics to biology to form a bi-directional pathway for their mutual enrichment. Namely, the application of qualitative physics techniques to circulatory criticism, via BIOTIC, gives some indication of their general use in other biological situations, especially since many biological systems rely on the fundamental processes of flow and diffusion. Furthermore, physiological criticism ties more closely to biology education than to medical diagnosis or therapy. Hence, qualitative techniques applied to criticism pose no threat to lives, but instead help elucidate the fundamental interconnections between structure, behavior and purpose that are so essential to understanding organic systems.

Going the other direction, the Bipartite Teleology Model should point the way to more general teleological models in qualitative physics; since many inorganic systems also rely on flow and diffusion, or, more generally, upon some delivery mechanism routed between components (e.g. a copying machine or a steam-generation plant). In short, the specialized task of circulatory criticism has widespread implications for the integration of two important fields. BIOTIC and BTM hint of the potential fruits of this interdisciplinary pursuit.

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