# Generating Causal Explanation from a Cardio-Vascular Simulation

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## Abstract

In this paper, we present QUALEX, a system and algorithm for generating first-order qualitative causal graphs for tutorial purposes based on de Kleer and Brown's qualitative modeling theory. QUALEX is embedded in a constructive simulation environment called Heart Works which teaches hydraulics principles about the cardio-vascular system to first year college biology students.

## 1 Introduction

Drawing on the rich literature from mental models and qualitative physics, we find that qualitative causal reasoning is not only a central and coherent aspect of human mental life [Forbus and Gentner, 1986a; Pearl, 1987], but also expertise. Problem-solving within physical domains typically begins with a qualitative causal analysis of the problem [deKleer and Brown, 1981; Forbus, 1984; Larkin, 1983; Williams *et al.*, 1983]. Educational research has built on this evidence with both detailed studies of scientific concept acquisition [diSessa, 1983; Clement, 1983; Forbus and Gentner, 1986b; White and Horwitz, 1987] and pedagogical design with a qualitative causal emphasis [Brown *et al.*, 1982; Reif, 1987; White and Frederiksen, 1986a and b; White and Horwitz, 1987].

In elementary physics education the pedagogical issues relate to whether, when and how to introduce qualitative reasoning into a predominate emphasis on quantitative methods. In contrast, elementary biology education, e.g. a first-year college for non-majors, tends to an entirely qualitative approach that can best be described as contrastive classification. The students' primary learning task is to absorb facts and causal relations as facts about a particular type, system, structure or function. Students are rarely expected to problem-solve and the laboratory is intended to give the student experience with real entities and procedural operation of equipment. Thus, although the student is given qualitative explanations, they are rarely sufficiently formal and robust to allow her or him to learn underlying principles and predict behavior. Most biology students do not come with sufficient background in physics. The following quote is typical of the standard textbook treatment of the cardio-vascular system.

> Even though the total cross-sectional area increases in the terminal arteries, arterioles, and capillaries and even though the rate of blood flow through individual vessels decreases in tandem, these vessels, because of their small diameter, are the major sites of resistance in the circulation. This is reflected in precipitous drops in blood pressure.

Much of this situation is not the fault of biology educators: biological systems are exceedingly complex and comparatively unknown. However, the cardio-vascular system is one of the few systems which is well-enough understood in terms of hydraulic principles to give us the rare opportunity to introduce to biology students through simulation these pedagogical objectives: (1) teach general scientific principles that underlie the operation of complex biological systems, (2) develop skills for integrating knowledge about complex systems, and (3) make lab experience more accessible.

For the past two years we have been engaged in an intelligent tutoring system research project called Heart Works. Heart Works explores the above pedagogical objectives through two innovations. Firstly, it makes the reactive learning environment for simulations more reactive by introducing the notion of a constructive simulation. Secondly, it unabashedly believes that teaching dynamic physical system behavior should be based on qualitative causal explanations generated from first principles. To these ends, Heart Works creates a constructive simulation of the cardio-vascular system that is capable of explaining its own behavior in terms of qualitative causal hydraulic principles.

This paper will focus almost entirely on the issue of generating explanations from the simulation, however, a brief understanding of the constructive simulation environment will aid in general comprehension. By constructive simulation we mean that students build circulatory models from a set of cardio-vascular components such as valves and vessels. They may also manipulate

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the simulation through more traditional means such as parameter setting. Whenever a change to the system is made, the components dynamically evaluate producing a new state(s) of the system. To achieve this functionality, each component is modeled as a constraint-based numerical simulation and programmed in an object-oriented methodology. Heart Works was prototyped in KEE running on a Symbolics 3645. A production version is currently implemented in Allegro Common LISP on the Mac II.

In contrast to simulation systems teaching diagnostic skills such as SOPHIE [Brown *et al.*, 1982] and STEAMER [Hollan *et al.*, 1984], as a constructive simulation Heart Works is an experiment in teaching scientific principles and methods by a design approach. The student is presented with a system design problem that must be solved by an understanding of the function and structure of the components and their interacting behaviors. For example: Given a pulsatile pressure source and using one-way valves create a counterclockwise blood flow loop from the pressure source through vessels to muscle and back through vessels. The solution to this problem requires that the student understand the relationship of pressure difference to flow and the structure and function of one-way valves. Given that the simulation is highly reactive and uses a direct manipulation, graphic animation interface, it clearly falls into the class of intelligent tutoring systems that Wenger [1987] calls *knowledge presentation systems.*

## 2 What is Qualitative Causal Explanation?

However, we were not satisfied with a system that offered no direct causal explanation of its behavior to the student. For example, given the question, "What is the effect of cholesterol deposits in the arteries on blood pressure, and why?", generating an explanation requires understanding the implications of the fundamental tenets and principles of the underlying causal mechanics with regard to the topological structure of a cardiovascular system.

### 2.1 Extension to Confluence Theories

In developing the explanation system for Heart Works we need a language that is sensitive to the causal mechanisms, the directionality from causes to effects, and the sequential dependency of causal chains. Following the taxonomy of White and Frederiksen [1986b], Heart Works requires explanations that are primarily first-order. Models that reason on the basis of changes in system properties are called "first-order" because they are based on the first order derivative, as in "If the pressure difference increases, then the flow increases."

Because of its constructive simulation approach and thus the necessity to model individual components, Heart Works is based primarily on the de Kleer-Brown model [1984], In this model equations constructed from the basic arithmetic operations, but using only sign values, are called confluences. Confluences are solved by propagation of constraints, using generate and test when unresolvable simultaneities occur. However, de Kleer and Brown's confluence notations are borrowed and extended to introduce the notion of global concepts, like system flow and total pressure difference. At first glance, the introduction of these global features may seem to violate the "no-function-in-structure" principle, for it goes beyond the original confluence theory. But, if one views the whole target system as a single device, then those global features will be "local" to the system. This view, in fact, corresponds to the notion of decomposable mental models discussed by Williams *et al.* [1981]. That is, a model consists of a set of mental objects, each of which can be further decomposed.

Note that confluences as constraint equations do not distinguish causes and effects. In particular, de Kleer and Brown's theory does not have any principled way of distinguishing between possible causal factors in an intrastate. For example, if one needs to represent the relationship of "the change of a valve's opening area can cause the flow through the valve to change, but not vice versa," the formalism of confluence $dP + dA — dF = 0$ alone would not suffice.

We approach this problem by classifying the qualitative variables in the system model into two types, system parameters (exogenous variables) and system properties (endogeous variables). The system parameters in a qualitative model correspond to those features which can be directly manipulated to cause changes in the system, e.g., a valve's opening area. They always stand for the root causes whenever the system behavior changes. By contrast, the system properties are those whose changes are caused by either a system parameter or a system property, e.g., the flow through the valve. From a pragmatic standpoint of troubleshooting, for example, faults would fall into the system parameters and symptoms into the system properties. This strong typing is required for reasoning about what cause can bring about what effects.

Though the qualitative model extends the original intention of the confluence theories, the three characteristics of de Kleer and Brown's notations still hold:

1. A qualitative variable can appear in more than one confluence, and thus can be affected in different ways simultaneously;
2. A confluence in a qualitative model must be individually satisfied no matter what the other effects on the same variable in different confluences are;
3. A system component may have a different set of confluences in a different state. For example, when a vessel is closed, the system enters a new qualitative state and the above confluences would not apply.

## 3 Generating Causal Explanation

The previous discussion of causal explanation represents a general orientation to the issues of causal explanation and the desiderata chosen for Heart Works. It points out the necessity to develop a system for reasoning through causalities in order to explain dynamic system behavior. However, most of the previous research literature, with a few exceptions, is descriptive and does not yield much specific guidance about how to automate the generation of qualitative causal explanations. To transcend the limitations of past work, this section will focus exclusively on developing a formalism and implementation for a causal reasoning explanation process. This reasoner is called QUALEX. Since Heart Works is a constructive simulation environment which we hope to use for systems other than the cardio-vascular, the QUALEX design should be dynamic, robust and domain-independent.

The approach is to break the process into three steps, ensuring reasoning from structures to functions [deKleer and Brown, 1984):

- Gather the information about the topology of the target system, including the types of the devices and their interconnections;
- Generate the component models of the individual devices and integrate them according to the system's topological information gathered above. The integration includes the qualitative descriptions of the system's continuity and compatibility conditions and results in a qualitative model of the target system. (For the hydraulics domain, compatibility conditions are (1) the total pressure drop in a passage equals the sum of all the sub-pressure drops along the way of the passage, and (2) the total resistance in a passage equals the sum of all the sub-resistances along the way of the passage. A continuity condition is that the total liquid flowing out of the passage equals the total liquid entering the passage.)
- Use qualitative techniques to reason about the system model generated above to derive the first-order causal chains in the form of an intrastate causal graph.

### 3.1 A Qualitative Inference Engine

The task now is to derive causal graphs directly from the topology of the target system. Causal graphs are directed, acyclic graphs whose nodes represent variables and whose arcs represent first-order cause-effect relations. These relations are typed as either directly proportional or inversely proportional. For example, the relations "A is inversely proportioned to B; B is directly proportional to C; B is directly proportional to D." allow an instantiated representation such as "When A increases B decreases which in turn decreases C and D." In order to derive the graphs the only information that QUALEX requires is the topological structure of the lab simulation, including the devices and their interconnections. All the other information about the underlying causalities of the system's first-order behaviors can be derived by a qualitative inference engine as described below.

Deriving a causal graph is analogous to reasoning through the qualitative model in confluences to update the status of the qualitative variables, while observing the extensions introduced above. Though they are a type of equation, confluences do not obey the available quantitative mathematical principles. A new causal reasoning framework must be developed. First, some key concepts for this formalism need to be defined.

Besides its symbolic name and type, each qualitative variable in the model has two additional facets. The first is its qualitative value that indicates its state change. For example, if the quantitative value of a variable is increasing, then its qualitative value would be "+", and vice versa. The second is its sign in the confluence that indicates its relationship with other variables. The product of these two values determines the role played by that variable in a confluence. It is not surprising to see that a variable can play different roles in different confluences due to the signs preceding the variable, even though its qualitative value is always unique in the model.

Now, in order to find the qualitative value, *qv,* of a variable that appears in several confluences, any one of the confluences can be a candidate relation to derive *qv.* The roles of the variables in a confluence may be used to deduce the roles of other variables in the confluence. For instance, given a confluence $dY - dX = 0$, if the quantity of $X$ is decreasing, then its qualitative value (derivative) $dX$ is negative. Because a "—" precedes $dX$ in this confluence, and $dX$ is negative, then $X$ plays a positive role due to the interaction of the two "—" 's. *X's* positive role determines that the role of Y must be negative so that the equation will balance. Consequently, from the role and the sign of a qualitative variable, the qualitative value can be deduced. In the above case, the qualitative value of $Y$ is "—".

The motivation in defining the term role is to introduce the qualitative value (QV) theorem for reasoning through the confluences to generate causal chains.

**QV Theorem:** *Suppose a confluence has N variables in the form*

$$\partial X_1 \pm \partial X_2 \pm \ldots \pm \partial X_n = 0.$$

*In order to find the qualitative value of variable* $X_i$ *in the confluence, the other variables* $(X_1, \ldots, X_{i-1}, X_{i+1}, \ldots, X_n)$ *must all play an identical role* $\hat{R}$*. If such an* $\hat{R}$ *exists, then the qualitative value of* $X_i$ *equals* $(sign(X_i) \times \hat{R} \times (-))$.

In the expression $(sign(X_i) \times \hat{R} \times (-))$, $sign(X_i)$ stands for the sign preceding $X_i$ in the confluence, and $(\hat{R} \times (-))$ stands for $X_i$'s role which is always opposite of $\hat{R}$ in the confluence. The product of the sign and the role give the qualitative value of the variable.

To illustrate this, consider confluence $\partial A + \partial B - \partial C = 0$. Suppose we want to find the qualitative value of $A$, and we know that $\partial B = +$ and $\partial C = +$, we simply cannot use this confluence to find $\partial A$, because $\partial B$ and $\partial C$ do not play an identical role: $\partial B$ is playing a positive role, while $\partial C$ is playing a negative role. However, if $\partial B = +$ and $\partial C = -$, then both of them are playing the positive role. To keep the equation balanced, $\partial A$ thus must play an inverse role, i.e., negative, which leads to $\partial A = -$, since $sign(A) = +$, and $\hat{R} = +$ in $(sign(A) \times \hat{R} \times (-))$.

### 3.2 A Derivation Process

As a case study, let us use the above formalism to answer the question raised at the beginning of this paper: "What is the effect of cholesterol deposits in the artery on the blood pressure in the heart, and why?" We will use the steady state cardiovascular model [Peterson and Campbell, 1985] to conduct the causal reasoning for this problem.

The hydraulic behavior can be modeled qualitatively by the confluences that consist of the descriptions of the components and the continuity and compatibility conditions in the system. In this formalism, P, A, F, J?, and *K* stand for Pressure-drop, cross-sectioned Area, Flow, Resistance, and coefficient of heart strength and conductivity, respectively. The subscripts indicate the particular components being modeled, with *c* for capillaries, *a* for artery, *h* for heart, and *sys* for system, "in/out" attached to pressure-drop stands for input/output pressure to the component.

**HEART :**

$$\partial P_h - \partial F_h + \partial K_h = 0 \qquad (1)$$

$$\partial P_{heart} - \partial P_{h_{out}} - \partial K_h = 0 \qquad (2)$$

$$\partial P_h + \partial P_{h_{out}} - \partial P_{h_{in}} = 0 \qquad (3)$$

**ARTERY :**

$$\partial P_a + \partial A_a - \partial F_a = 0 \qquad (4)$$

$$\partial P_a + \partial P_{a_{out}} - \partial P_{a_{in}} = 0 \qquad (5)$$

**CAPILLARYBED :**

$$\partial P_c + \partial A_c - \partial F_c = 0 \qquad (6)$$

$$\partial P_c + \partial P_{c_{out}} - \partial P_{c_{in}} = 0 \qquad (7)$$

**CONTINUITY CONDITIONS :**

$$\partial F_{sys} = \partial F_h = \partial F_a = \partial F_c \qquad (8)$$

**COMPATIBILITY CONDITIONS :**

$$\partial P_{sys} - \partial P_h - \partial P_a - \partial P_c = 0 \qquad (9)$$

$$\partial R_{sys} + \partial K_h + \partial A_c + \partial A_a = 0 \qquad (10)$$

**SYSTEM :**

$$\partial P_{sys} - \partial R_{sys} - \partial F_{sys} = 0 \qquad (11)$$

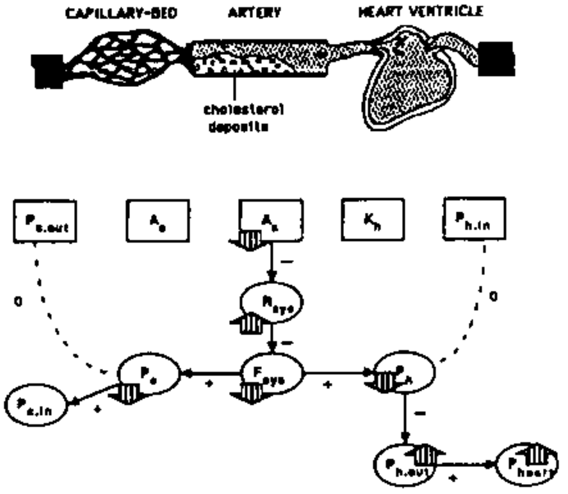
$$\partial P_{sys} - \partial P_{h_{in}} + \partial P_{c_{out}} = 0 \qquad (12)$$

When the cholesterol deposits increase in the artery, the cross-section of the artery decreases. Let us see how the causal chains from the decrease of the cross-sectional area $A_a$ to the increase of the heart pressure $P_{heart}$ and other changes in the system are generated. Below, notations ft, JJ-, © attached to a variable, *X,* means that the quantitative value of the variable is increasing *(dX* = +), decreasing *(dX* = —), or remains constant *(dX* = 0), respectively.

| STEP | DERIVATION | JUSTIFICATION |
|---|---|---|
| a. | $\partial A_a \Downarrow,\ \partial A_c \odot,\ \partial K_h \odot,\ \partial P_{h_{in}} \odot,\ \partial P_{c_{out}} \odot$ | Given |
| b. | $\partial A_a \Downarrow,\ \partial K_h \odot,\ \partial A_c \odot \rightarrow \partial R_{sys} \Uparrow$ | a; 10 |
| c. | $\partial P_{h_{in}} \odot,\ \partial P_{c_{out}} \odot \rightarrow \partial P_{sys} \odot$ | a; 12 |
| d. | $\partial R_{sys} \Uparrow,\ P_{sys} \odot \rightarrow \partial F_{sys} \Downarrow,$ | b, c; 11 |
| e. | $\partial F_{sys} \Downarrow \rightarrow \partial F_i \Downarrow,\ \ (i = h, a, c)$ | d; 8 |
| f. | $\partial F_h \Downarrow,\ \partial K_h \odot \rightarrow \partial P_h \Downarrow$ | a, e; 1 |
| g. | $\partial P_h \Downarrow,\ \partial P_{h_{in}} \odot \rightarrow \partial P_{h_{out}} \Uparrow$ | a, f; 3 |
| h. | $\partial P_{h_{out}} \Uparrow,\ \partial K_h \odot \rightarrow \partial P_{heart} \Uparrow$ | a, g, 2 |
| i. | $\partial F_c \Downarrow,\ \partial A_c \odot \rightarrow \partial P_c \Downarrow$ | a, e; 6 |
| j. | $\partial P_c \Downarrow,\ \partial P_{c_{out}} \odot \rightarrow \partial P_{c_{in}} \Downarrow$ | a, i; 7 |

Following the causal chains, either backward or forward, in the causal graph (see Figure 1), an articulation can be rendered in English.

Figure 1: A Derived Causal Graph



Labels on arcs are: + direct; − inverse; 0 constant. Squares are system parameters; circles are properties.

For example, a forward tracing of the causal chain produces the following output:

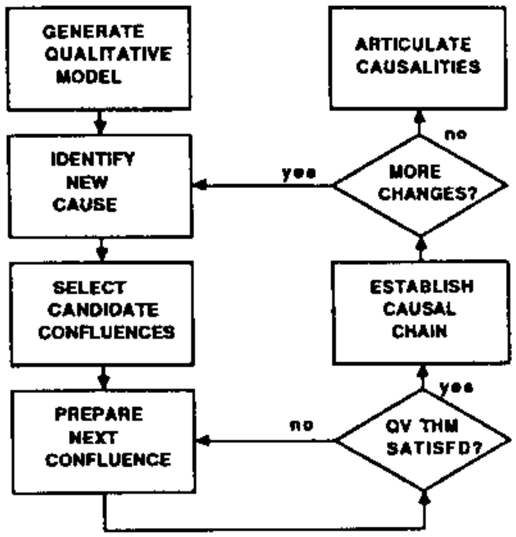
> "The decrease of the artery's cross-sectional area ($A_a \Downarrow$) causes the total resistance in the system to increase ($R_{sys} \Uparrow$) and, as a result, the blood flow in the system will decrease ($F_{sys} \Downarrow$). The decreased flow will cause the pressure-drop across the heart to decrease ($P_h \Downarrow$). Given the pulmonary pressure constant ($P_{h_{in}} \odot$), the decreased pressure-drop ($P_h \Downarrow$) indicates that the arterial pressure has increased ($P_{h_{out}} \Uparrow$), which in turn causes the heart's internal pressure to increase ($P_{heart} \Uparrow$)..."

Giving a full account of the underlying causality from the decrease of the artery's cross-sectional area to the increase of the heart pressure and to the decrease of the blood flow to the capillaries, this explanation clearly spells out the causal relationships in the system.

## 3.3 First-Order Causal Chain Generation

We are now ready to discuss an algorithm of causal reasoning for QUALEX to derive first-order causal chains from the system topology (see Figure 2).

**Figure 2: QUALEX Reasoning Process**



begin CAUSAL-GRAPH-GENERATION:

1. Generate the complete set of confluences, CONFS, from the system topology. CoNFS must capture the component models and the continuity and compatibility conditions in the system.
2. Substitute in CONFS the identical variables in the system with a unique name. For example, if an artery is connected to a capillary bed, then the outcoming pressure from the artery would equal the incoming pressure to the capillary bed. These two names will be substituted with a common internal name chosen by the system.
3. Gather the system parameters from CONFS into SYS-PARAMS. Identify the cause, C, chosen by the user in SYS-PARAMS. Mark the qualitative values of the variables in SYS-PARAMS except *C* as 0 in CONFS.
4. Draw square nodes for the variables in SYS-PARAMS and draw circle nodes for other system properties. The positions of the nodes are chosen to reflect the positions of the corresponding system components' icons in the simulation.
5. Select from CONFS those candidate confluences which involve the cause *C* and put these confluences in CF-SET.
6. For each CF in CF-SET, do:
   - Find those variables in CF whose qualitative value is not known and put them in UNKNOWN. Put the remaining variables into KNOWNS.
   - If UNKNOWN contains only one variable V, and the variables in KNOWNS all play an identical role *R,* then

     Assign *(sign(V)* x *R* x (-)) as the qualitative value for *V.* Note that *sign(V)* is a function returning the sign of variable *V* in CF.

     Draw a positive arc from *C* to *V* if the qualitative values of V" and *C* are equal, or a negative arc if the qualitative values of *V* and *C* are opposite. Store CF as a justification for the arc just drawn. Identify *V* as a new cause C, and recurse from step 5.

end CAUSAL-GRAPH-GENERATION.

This procedure starts from the root cause, a system parameter, to derive the qualitative values of those system properties whose changes are directly related to the cause. Each variable is assigned a qualitative value only once. These variables in turn become the causes that propagate further changes. Note that a single-perturbation assumption is used (step 3) to reduce the complexity of multiple causalities. This suggests that in order to derive a causal chain, one can hold all but one causal parameter constant so as to create a situation ideal for studying the causal impact of this individual cause on all the system properties. The advantage of this is obvious: when a variable, X, remains constant, *dX* — 0. The zero effects can be ignored during qualitative reasoning.

The key notions used in the algorithm are the roles of qualitative variables in the model and the QV theorem described above. These notions are formed on the basis of mathematical deductive reasoning about the constraint equations. Thus, the correctness of the algorithm for generating the causal chains is entirely dependent on the validity of the qualitative model of confluences. For the model to be valid, it is essential that it is both correct and complete: correct in the sense that it does not violate the underlying causal principles of the domain, and complete in the sense that none of the device descriptions and the system's compatibility and continuity conditions are missing. With a valid qualitative model of the system, this algorithm will always generate the optimal causal graph in the sense that the causal chain does not "leap over" any particular concept underlying the causalities.

## 4 Discussion

One limitation in the current approach is that it does not handle circular topologies with confluences, which only describe changes in an intrastate [deKleer and Brown, 1984]. Adding this extension would allow the representation of feedback.

QUALEX is domain-independent. It is based on *device-ontology* to generate qualitative, causal explanations. QUALEX has been implemented in a version of Heart Works written in KEE (IntelliCorp. Corp.) and Common Lisp on a Symbolics 3645. As a result of a judicious choice of data structures, the algorithm is fairly efficient and runs sufficiently fast for human-computer interaction. For a qualitative model with *q* system components, n confluences, and an average number of *v* variables in a confluence, the computing time is *0(q + nv).* In the CAUSAL-GRAPH-GENERATION algorithm, step 1 takes *0(q)* step 2 takes *0{n)* step 3 takes *0(n):* step 4 takes *0{nv):* step 5 takes O(n); step 6 takes *O(nv).* The total complexity, therefore, is *0(q + nv).*

Once the causal graph is generated the tutoring system can use it for either student modeling purposes or explanation and remediation. If it is used for student modeling, the causal graph can be generated as the expert model of the causality of the system and used in traditional student overlay models. If it is used directly as output, such as in our simulations, the system must integrate the output into the user interface or discourse manager. We have experimented with displaying the causal graph directly as part of the simulation window. The results of extensive protocol studies indicate that after students learn to read the notation, it seems to be an effective addition to animation in explaining the behavior of the system. In addition to a graphic display, we have also converted the causal graph output into synthesized English text. A more sophisticated use of the causal graph could focus on subgraphs of the explanation in response to student modeling concerns.

We should finally point out that the QUALEX algorithm will also work in tutoring systems that aire not simulation based. All that is necessary is provision of the initial system parameter values. These function as the initial causes in the causal chain.

## 5 Conclusion

In this paper, we have presented QUALEX, a system and algorithm for generating first-order qualitative causal graphs for tutorial purposes based on deKleer and Brown's qualitative modeling theory. QUALEX is embedded in a constructive simulation environment called Heart Works which teaches hydraulics knowledge about the cardio-vascular system to first year college biology students.

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