# Designing Transitions in Multi-Region Devices

**Prasanta Bose** and **Shankar A. Rajamoney**
Computer Science Department
University of Southern California
Los Angeles, CA 90089-0781
Email: pbose, rajamone@pollux.usc.edu

**Abstract**

Generative, model-based design of physical devices with multiple operating regions poses challenging problems. We present an approach for establishing region transitions of multi-operating region devices based on an analysis of the more basic shifts of the qualitative regions of quantities and their synchronization.

The method takes as input design fragments, constructed by model-based design methods, which establish desired qualitative behaviors specific to a region. A design fragment is an intermediate representation that makes explicit the causal relation network and the operating assumptions under which the qualitative behavior in a region is established. The method identifies the quantity shifts to be established and the synchronization constraints that must be satisfied by the design fragment for a region if the device is to transition to the adjacent region. It revises the design fragment and the initial design to establish such shifts. We present the theoretical basis of the method, and show how the method may be used for the conceptual design of a steam engine.

## 1 Introduction

The design of physical devices such as pressure regulators and steam engines is a difficult task. Generative, model-based methods [Williams, 1989; Neville and Weld, 1992; Ulrich, 1988; Joskowicz, 1989; Bose and Rajamoney, 1993], design such devices by using a domain model to build a causal network that entails the desired device behavior, and by selecting and configuring device components such that the assembly imposes the causal relations of the network. Model-based design offers several benefits: 1) By using the domain model and the intermediate causal network, the method generates and investigates only those designs that may potentially produce the desired behavior. 2) An explanation for how the device works can be easily constructed from the causal network. 3) Novel configurations of device components can yield innovative designs.

Previous model-based design approaches have primarily focused on devices with single operating regions, or devices with multiple operating regions but which automatically transition into an adjacent region when the behavior hits the current region's boundary.

Model-based design of devices with multiple operating regions that do not automatically transition is a difficult problem. Such devices require the design of mechanisms that specifically establish the region transitions. As an example of such a device, consider the design of a steam engine [Cummins, 1989] with two operating regions (Figure 1a). In region $R_1$, piston $p_1$ makes an upward stroke while $p_2$ makes a downward stroke[1]. In region $R_2$, the behaviors of $p_1$ and $p_2$ are reversed. The engine is required to shift between these two regions of behavior when the pistons reach the top and bottom of their respective cylinders. Figure 1b shows a candidate design from [Cummins, 1989] which works as follows:

> When piston $p_1$ is at the bottom of cylinder $c_1$ and piston $p_2$ is at the top of cylinder $c_2$, the piston strokes are triggered by the opening of valve $v_1$ and the closing of $v_2$. When valve $v_1$ opens, steam flows from the boiler to the lower compartment of $c_1$ causing the steam pressure to increase. The increasing upward force due to the build up of the steam pressure overcomes the atmospheric pressure and the gravitational force to produce an upward stroke of $p_1$. At the same time, a flow of cold water into the condenser $CD$, causes the steam in the lower compartment of $c_2$ to condense. The residual gas pressure falls, and the atmospheric pressure and gravitational force push down the piston, resulting in the downward stroke of $p_2$. When $p_1$ reaches the top of $c_1$ and $p_2$ reaches the bottom of $c_2$, valve $v_1$ closes and $v_2$ opens. The vacuum left by condensing steam in $c_2$ causes the steam from $c_1$ to flow into the lower part of $c_2$. Thus, the force due to steam pressure causes $p_2$ to move up. Decreasing steam pressure in $c_1$ causes $p_1$ to move down. The cycle repeats when $p_1$ and $p_2$ reach the bottom and top of their respective cylinders.

For simplicity, we focus only on the region transition for a single cylinder ($c_1$) piston motion. Figure 1c shows a design which achieves each of the region behaviors independently, under different operating assumptions, for the piston motion in $c_1$. For example, if the force on the piston $p_1$ due to the pressure of steam inflowing into cylinder $c_1$ is greater than the forces due to the atmospheric pressure and gravity, and the steam outflow to the steam sink $s$ is zero, then $p_1$ is pushed upwards as required in region $R_1$. If the steam inflow from the source,

[1] Throughout the paper, we will use a simple notation for describing quantities: the first few letters describe the quantity and the subscript describes the object. For example, $V_{p1}$ denotes the velocity of piston $p_1$.

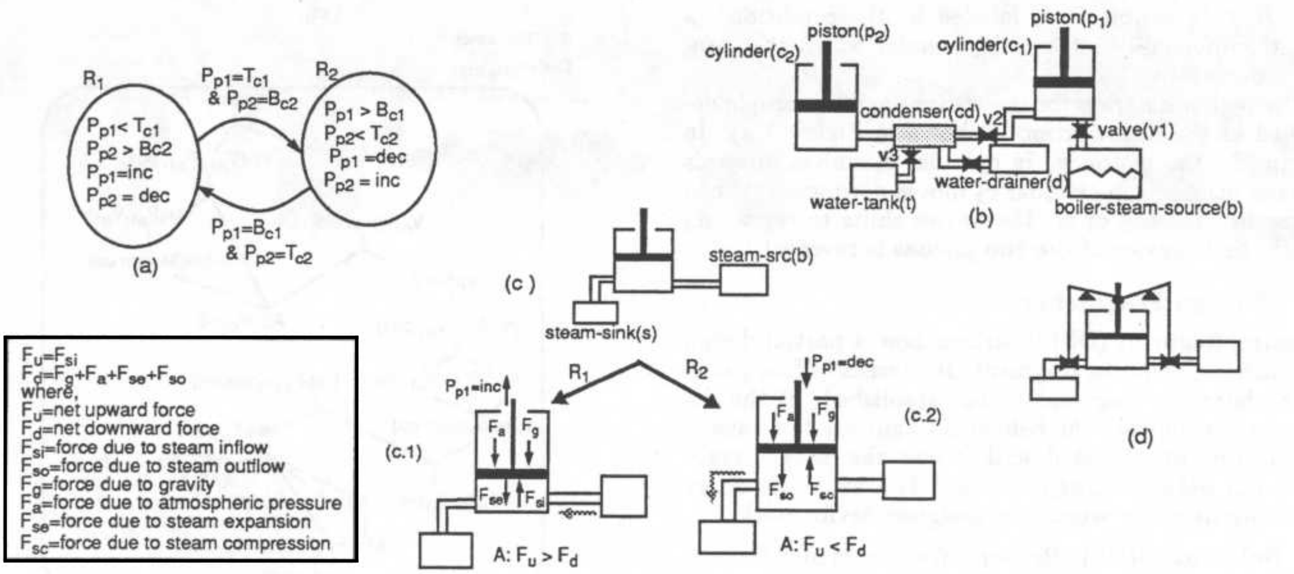


Figure 1: a) A region diagram for a steam engine. b) A schematic design of a double-acting compound steam-engine. c) A design which under different operating assumptions establishes the device behavior in each region, but does not automatically transition between regions. d) A revised design that includes mechanisms for explicitly effecting the transitions.

$b$, is assumed to be zero, and if the forces due to atmospheric pressure, gravity, and steam outflow are stronger than the steam pressure due to compression, then piston $p_1$ is pushed down, as required in region $R_2$. However, each behavior persists since the operating assumptions do not change; hence, the steam engine will not automatically transition between the two regions. Consequently, additional mechanisms such as valves and linkages must be incorporated into the design to accomplish the transition (Figure 1d).

In this paper, we present a method for designing transitions between the regions of a device. The method takes as input, initial partial designs, called *design-fragments*, that accomplishes the behavior of each region (under different operating assumptions[2]). It divides the problem into three subproblems: 1) Which quantities must be changing to accomplish a transition? 2) To which quantities must these quantities be causally linked to make them change as required and in synchronization with other changes? 3) What mechanisms should be added to the design to produce the required causal links? Briefly, the answers to these questions for the above example are: 1) the steam inflow and outflow rates must be changing to switch the operating assumption that the upward force, $F_u$, be greater than the downward force, $F_d$, in region $R_1$, to the operating assumption that $F_u$ be less than $F_d$ in region $R_2$, 2) the rates of the steam inflow and outflow must be causally linked to the piston's position to achieve the proper synchronization, and 3) the causal link between the inflow and outflow rates and the piston's position must be established through an appropriate configuration of valves, levers, and linkages.

[2]The initial design may be produced by generative, model-based methods [Williams, 1989; Neville and Weld, 1992; Bose and Rajamoney, 1993]

The remainder of the paper is organized as follows. Section 2 describes the inputs to the design method. Section 3 analyzes region transitions and, based on the analysis, presents a set of axioms for a region transition to occur. Section 4 derives a set of revision operators for establishing the transitions from an examination of the conditions under which the axioms fail. Section 5 presents the algorithm for extending an initial design to make region transitions and illustrates the method with a trace of how a portion of the system shown in Figure 1a is designed. Finally, Section 6 discusses some of the limitations of our method, related work, and conclusions.

## 2 Inputs

The inputs to the method are a domain model, a region diagram and design fragments for each region. We adopt Forbus' Qualitative Process (QP) theory [Forbus, 1984] to represent domain models.

### 2.1 Region Diagrams

The desired device behavior is specified by a *region diagram* [Williams, 1990; Joskowicz, 1989] consisting of a set of non-overlapping regions and a set of transitions between the regions. Each region is described by a set of inequalities between quantities and qualitative changes (inc, dec, std) to quantities.[3] Each transition from a re-

[3]Note that though a qualitative change may be specified in a region, it need not necessarily hold in all the states represented by the region. For example, in regulatory devices, the quantity to be regulated may be specified to be steady in a region. The intention is to design a device that will attempt to maintain it steady in the region by sensing and compensating for disturbances. Since there may be a delay,

gion $R_i$ to a region $R_j$ is labeled by the condition[4] (a quantity inequality relationship) under which the transition occurs.

The region diagram for the steam-engine example described in the introduction is shown in Figure 1(a). In region $R_1$, the piston $p_1$ in cylinder $c_1$ moves upwards and the piston $p_2$ in cylinder $c_2$ moves downward. When $p_1$ reaches the top of $c_1$, the device shifts to region $R_2$ where the behavior of the two pistons is reversed.

### 2.2 Design Fragments

A design fragment (DF) describes how a partial design establishes a behavior fragment. It consists of four parts: 1) the behavior fragment to be established, 2) the design that establishes the behavior fragment, 3) a causal-relations network that describes how the design establishes the behavior fragment, and 4) a set of auxiliary assumptions under which the designed device works.

1. **Behavior** B(DF). Behavior fragments may be simple (e.g. a qualitative change to a quantity in a region) or complex (e.g. a collection of qualitative changes constituting a region, or a collection of regions and transitions between them). Apart from fragments of the input behavior, auxiliary behavior fragments deemed necessary by the design method may also be included. Figure 2 shows a design fragment, $df_u$, for the upward stroke[5] of piston, $p_1$, in cylinder, $c_1$.
2. **Design** D(DF). The design is specified by a set of design components (e.g. steam-source($s_1$)) and structural relations describing how they are assembled (e.g. connects($bot(c_1), s, p_1$)). Figure 2 shows a portion of the design stating that the cylinder, $c_1$ and steam sink, $s$, must be containers with steam as the working fluid, and $sp_1$ must be a path connecting the bottom of the cylinder $c_1$ to the sink $s$.
3. **Causal-relations network** CRN(DF). The causal-relations network is a data-dependency graph [de Kleer, 1986]. The nodes of the graph may be: a) qualitative changes, b) quantity inequalities, c) partial influences on a quantity, d) causal relations, e) activity status of model fragment instances, f) existence of model fragment instances, g) design components and structural relations, and h) assumptions.

   The links of the graph are justifications supporting the nodes. In general, qualitative changes to a quantity are justified by a collection of partial influences on the quantity; partial influences are justified by causal relations (direct influences and qualitative proportionalities) and quantity inequalities or qualitative changes; causal relations (and some quantity inequalities) are supported by the activity of the model fragment instances to which they belong; activity of a model fragment instance is supported by the activity of its constituent model fragment instances and its operating conditions; and, finally, existence of a model fragment instance is supported by the existence of its constituent model fragments, design components and their structural relations.

Figure 2 illustrates the causal-relations network that establishes the upward motion of the piston $p_1$ in cylinder $c_1$. The piston's position, $P_{p1}$, is established to be increasing by assuming that its velocity, $V_{p1}$, is greater than zero. However, based just on this assumption, the behavior may transition prematurely before the piston reaches the top, since the piston's velocity is decreasing due to the net downward force (and, hence, acceleration) from the atmospheric pressure, steam expansion and gravity, and may eventually hit zero. This premature transition is prevented in the design fragment shown in Figure 2 by introducing a steam inflow such that the net force on the piston is upward and increasing, thereby, ensuring that the piston's acceleration and velocity will also be positive and increasing.

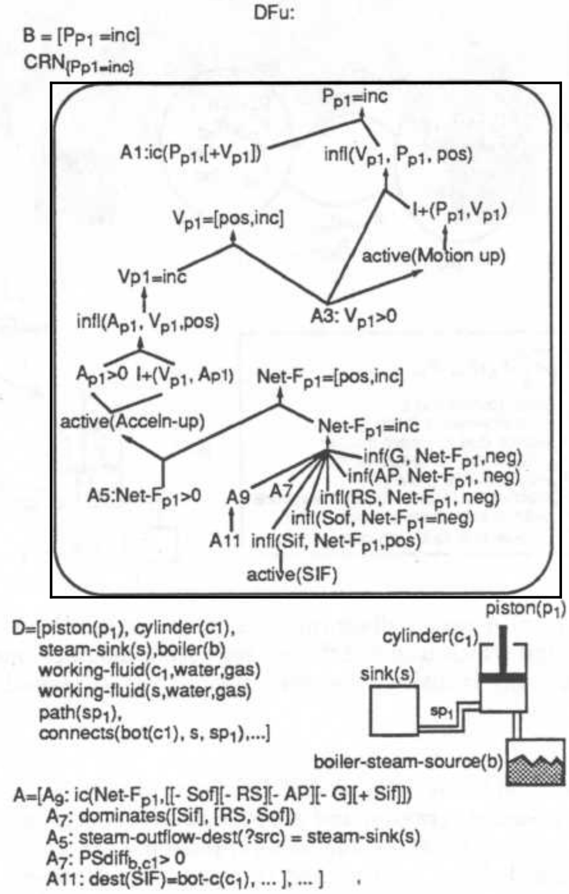


Figure 2: A design fragment for the upward stroke (region $R_1$) of a single piston engine.

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the quantity could be disturbed from its value temporarily.

[4] In this paper, we consider only single conditions (the piston $p_1$ reaches the top of cylinder $c_1$). Extending our method to cover transitions under compound conditions (e.g. Figure 1a) is an area of future work.

[5] The design fragment, $df_d$, for the downward stroke is similar.

4. **Assumptions** A(DF). There are four types of assumptions under which the design may establish a behavior fragment:

   (a) *Codesignation assumptions.* In extending a partial design, additional objects may be required. Often, instead of considering new objects, some of the existing objects may fulfill the role (a form of function-sharing). Codesignation [Chapman, 1988] explicitly considers the possibility that two objects may be identical. The causal-relations network in Figure 2 is based on the assumption, $A_{11}$, that the destination of the steam-inflow codesignates with the lower-chamber of the cylinder.

   (b) *Influence closure assumptions.* To determine the qualitative change to a quantity, the partial influences on the quantity (from direct influences or qualitative proportionalities) must be combined to determine the net influence. The computed qualitative change is valid only under the closed-world assumption [Forbus, 1990] that all the partial influences on the quantity are known. This assumption is explicitly represented by listing all the known partial influences on the quantity. For example, in the causal-relations network shown in Figure 2, assumption $A_1$ is an influence closure assumption specifying that the only known partial influence on the piston's position is a positive influence due to the piston's velocity.

   (c) *Influence dominance/ cancellation assumptions.* When there are opposing partial influences on a quantity, the qualitative change to it may be ambiguous. Influence dominance/cancellation assumptions specify whether one set of partial influences dominates or cancels the other, thereby, permitting unambiguous computation of qualitative changes.[6] In Figure 2, the net upward force is increasing based on an influence dominance assumption $A_7$ which states that the partial influence due to the inflow rate of steam from the boiler is greater than the partial influences due to the outflow rate of steam to the condenser and the steam expansion due to the piston's upward motion.

   (d) *Quantity inequality assumptions.* Quantity inequalities that are not justified by the model fragment instances must be assumed as initial conditions or region boundary conditions. For example, the inequality assumption $A_3$ specifies an initial condition: the velocity, $V_{p1}$, of the piston $p_1$ is greater than zero.

A design fragment is locally correct if, based upon its design and auxiliary assumptions, its causal-relations network can be constructed (using the domain model axioms and qualitative inference rules) and if its causal-relations network entails all the behavior fragments specified in its behavior.

## 3 Axioms for Region Transitions

Two qualitative regions $R_i$ and $R_j$ can differ in qualitative values of quantities or in quantity inequalities. Since qualitative values of quantities are ultimately due to quantity inequalities too (e.g. the increasing of the piston's position is due to its velocity being greater than zero), the differences in two regions can be reduced to a core set of quantity inequality differences. If region $R_i$ is to transition to region $R_j$, quantity inequalities underlying the design fragment $df_i$ for $R_i$ must be dynamically transformed to the quantity inequalities underlying the design fragment $df_j$ for $R_j$.

The dynamic transformation involves: a) Identifying the quantity shift (termed q-shift) basis, that is, the conjunction of quantity shifts that must necessarily occur if the device is to transition from region $R_i$ to $R_j$. In a quantity shift, an inequality is transformed into another. For example, in Figure 2, the design fragment $df_u$ establishes the upward motion of the piston $P_1$ by ensuring that its velocity, $V_{p1}$, is maintained greater than zero. For $df_u$ to transition to the design fragment $df_d$ for the downward motion, the velocity must undergo a shift from $V_{p1} > 0$ to $V_{p1} < 0$. In this example, the q-shift basis for the transition from region $R_1$ to region $R_2$ includes shifts in velocity, acceleration, net-force and steam flow rates. b) Synchronizing and ordering quantity shifts. The quantity shifts must be synchronized with the shift in the transition condition, so that the designed device transitions between regions only when the transition condition is reached. For example, the q-shift of the piston's velocity from $V_{p1} > 0$ to $V_{p1} < 0$ must be synchronized with the piston's position reaching the top of cylinder $c_1$. c) Establishing a set of quantity shifts. The quantity shifts must be established by ensuring that one or more of the quantities involved in the inequalities are changing appropriately. For example, to establish a q-shift in the piston's velocity from $V_{p1} > 0$ to $V_{p1} < 0$, the velocity must be made to be decreasing in region $R_1$.

To address the dynamic transformation of design fragments systematically, we first declaratively specify the necessary and sufficient conditions for consistent region transitions. We define region transition axioms in terms of sq-shift, a more compact representation capturing both the quantity shift and its associated synchronization. An sq-shift specifies a shift of the qualitative region of a quantity in synchronization with the shift of a reference quantity.

Table 1 shows some of the axioms for region transition.[7] Axiom 1 describes the necessary and sufficient conditions for region $R_i$ in which quantity $q$ is increasing to transition to a region $R_j$ in which $q$ is steady, when the transition condition $T_c$ is $q = c$. Consider two simple cases [8]: (i) The influence closure of $q$ consists of

[6] This assumption may be refined to determine how the cancellation or dominance is achieved when the preliminary qualitative design is analyzed with quantitative information or exact equations.

[7] Space restrictions prevent us from discussing the remaining.

[8] More general cases may be similarly formulated.

Table 1: Axioms specifying the synchronized quantity shifts that must occur if the device is to transition from region $\mathsf{R}_i$ to $\mathsf{R}_j$.

Let,

holds$(P, R)$ denote that literal $P$ is true in the interval defined by region $R$

$P_{i+}(q)$ denote the set of positive influences on a quantity $q$ in some region $R_i$,

$P_{i-}(q)$ denote the set of negative influences on a quantity $q$ in some region $R_i$

i_inf$(p, q)$ denote $p$ is an indirect influence (Q+ or Q-) on $q$

d_inf$(p, q)$ denote $p$ is a direct influence (I+ or I-) on $q$

co-occurs$(rel_1(p), rel_2(q))$ denote the co-occurence of inequality $rel_1(p)$ and the inequality $rel_2(q)$

correspondence$(rel_1(p), rel_2(q))$ denote the co-occurence of inequality $rel_1(p)$ and the inequality $rel_2(q)$ where a qualitative proportionality imposes a direct causal link between $p$ and $q$

sq-shift$(rel_1(q)\xrightarrow{T}rel_2(q),\ rel_3(p)\xrightarrow{T}rel_r(p), R_i)$ denote the synchronized q-shift of quantity $q$ from $rel_1$ to $rel_2$, and the q-shift of quantity $p$ from $rel_3$ to $rel_4$.

All unquantified variables are universally quantified.

All quantities are denoted by the symbol letters $p, q, r, s$.

All constants values are denoted by the symbol letters $c, c_1, c_2, c', c''$.

r-transition$(q, R_i, R_j, Tc) \Leftrightarrow$

$\mathrm{Tc}=[q = c] \wedge [[\mathrm{holds}(q < c, R_i) \wedge \mathrm{holds}(q = inc, R_i)] \vee [\mathrm{holds}(q > c, R_i) \wedge \mathrm{holds}(q = dec, R_i)]]$ [1.0]

$\wedge\ \mathrm{holds}(q = std, R_j) \Rightarrow$

$[\ [\exists c_1 < c, \exists R_{i1} = q < c_1\ P_{i1+}(q) = \{p\} \wedge \mathrm{dinf}(p, q) \wedge P_{i-}(q) = P_{j+}(q) = P_{j-}(q) = \{\}$

$\wedge\ \text{sq-shift}(q \geq c_1 \xrightarrow{T} q = c, p > 0 \xrightarrow{T} p = 0)\ ]$ [1.1]

$\vee\ [P_{i+}(q)=P_{j+}(q) = \{p\},\ P_{i-}(q)=P_{j-}(q) = \{p'\} \wedge \mathrm{holds}(p > p', R_i) \wedge \mathrm{holds}(p = p', R_j)$

$\wedge\ \text{sq-shift}([q < c \xrightarrow{T} q = c, p > p' \xrightarrow{T} p = p', R_i)]\ ]$ [1.2]

$\text{sq-shift}(c_1 \leq q < c \xrightarrow{T} q = c, p > c' \xrightarrow{T} p = c', R_i) \Leftrightarrow$

$\mathrm{holds}(p > 0, q < c_1) \wedge \mathrm{holds}(p = dec, c_1 < q < c) \wedge \mathrm{holds}(q = inc, R_i) \wedge \text{co-occurs}(q = c, p = c', R_i)]$ [2.0]

$\wedge\ [\ [P_{i+}(p) = \{\} \wedge P_{i-}(p) = \{q\} \wedge \text{Q-}(p, q) \wedge \text{correspondence}(q = c, p = c')]$ [2.1]

$\vee\ [P_{i+}(\mathrm{p})=\{p'\} \wedge \text{Q+}(p, p') \wedge \text{sq-shift}(c_1 \leq q < c \xrightarrow{T} q = c, p' > c'' \xrightarrow{T} p' = c'') \wedge \text{correspondence}(p = c', p' = c'')]$ [2.2]

$\vee\ [P_{i-}(\mathrm{p})=\{p'\} \wedge \text{Q-}(p, p') \wedge \text{sq-shift}(c_1 \leq q < c \xrightarrow{T} q = c, p' < c'' \xrightarrow{T} p' = c'') \wedge \text{correspondence}(p' = c'', p = c')]$ [2.3]

$\vee[\exists c_{12}, c1 < c_{12} < c, \exists R_{i1} = c_1 \leq q < c_{12}, \mathrm{holds}(\text{I+}(p, p'), R_i) \wedge P_{i1+}(p) = \{p'\} \wedge P_{i1-}(p) = \{\}$

$\wedge\ \text{sq-shift}(c_1 \leq q < c_{12} \xrightarrow{T} q = c_{12},\ p' > 0 \xrightarrow{T} p' = 0, R_i)$

$\wedge\ \text{sq-shift}(c_{12} < q < c \xrightarrow{T} q = c,\ p' = 0 \xrightarrow{T} p' \leq c'' < 0, R_i) \wedge \text{co-occurs}(p = c', p' \leq c'')\ ]$ [2.4]

$\vee\ [\exists c_{12}, c1 < c_{12} < c, \exists R_{i1} = c_1 \leq q < c_{12},\ P_{i+}(p) = \{p'\} \wedge P_{i-}(p) = \{p''\}$

$\wedge\ \mathrm{dinf}(p', p) \wedge \mathrm{dinfl}(p'', p) \wedge \mathrm{holds}(p' > p'', R_{i1})$

$\wedge\ \text{sq-shift}(c_1 \leq q < c_{12} \xrightarrow{T} q = c_{12}, p' > p'' \xrightarrow{T} p' = p'', R_i)$

$\wedge\ \text{sq-shift}(c_{12} < q < c_2 \xrightarrow{T} q = c_2, p' = p'' \xrightarrow{T} p' \leq c' < p'', R_i)$

$\wedge\ \text{co-occurs}(q = c_2, p' = c'' < p'') \wedge \text{co-occurs}(p' \leq c'', p = c')]\ ]$ [2.5]

a single direct positive influence ($p$) in region $\mathsf{R}_i$ and no influences in $\mathsf{R}_j$. The transition of $q$ must be accompanied by a disabling of the direct influence $p$ (Axiom 1.1), that is, the quantity $p$ must shift from $p > 0$ to $p = 0$. (ii) The influence closure of $q$ consists of a direct positive influence $p$ and a direct negative influence $p'$, such that, in region $R_i$, $p$ dominates $p'$ and, in region $R_j$, $p$ cancels $p'$. The transition of $q$ must be accompanied by a shift from $p > p'$ to $p = p'$ (Axiom 1.2).

Axiom 2 in Table 1 specifies the conditions for the shift of a quantity $p$ from $p > 0$ to $p = 0$, synchronized with the shift of the reference quantity $q$ from $q < c$ to $q = c$. The necessary condition specifies that $p$ must decrease (Axiom 2.0). The sufficiency conditions are specified in Axioms 2.1-2.5 and depend on the influences on $p$. We describe three cases of interest: i) The influence closure of $p$ consists of only one indirect negative influence $q$, the reference quantity with which the q-shift of $p$ is to be synchronized (the base case). In this case, the shift in $p$ is synchronized to the shift in $q$ if, from the domain model fragments, $p$ is established to be negatively qualitatively proportional to $q$, and if $q = c$ corresponds to $p = c'$ (Axiom 2.1). ii) The influence closure of $p$ consists of only one indirect positive influence $p'$ (which does not co-designate with $q$). In this case, the shift in $p$ is synchronized with the shift in $q$ if, from the domain model fragments, $p'$ is established to be positively qualitative proportional to $p$, if $p = c'$ corresponds to $p' = c''$, and if the shift in $p'$ is recursively established to synchronize with $q$ (Axiom 2.2). iii) The influence closure of $p$ consists of only one direct positive influence $p'$ (which does not co-designate with $q$). In this case, the region $R_i$ is divided into two subregions $R_{i1}$ and $R_{i2}$. In region $R_{i2}$, immediately preceding region $R_j$, $p$ must be decreasing and, hence, $p'$ must be less than zero. In region $R_{i1}$, $p$ may be increasing. Consequently, two synchronized shifts are required: 1) $R_{i1}$ to $R_{i2}$. $p'$ shifts from positive to zero as $q$ shifts to the boundary between the two subregions, $c_{12}$. 2) $R_{i2}$ to $R_j$. $p'$ shifts from zero to negative as $q$ shifts to $c$.

## 4 Failure Conditions and Operators

By examining the axioms, we determine the basic types of *sq-shift failure conditions*—violations of the necessary and sufficient conditions that may prevent the design fragment $df_i$ for region $R_i$ to transition to the design fragment $df_j$ for region $R_j$. For each failure condition, we devise operators that revise the design fragment to satisfy the region transition axioms.

For example, if a design fragment $df_i$ which establishes an increase to a quantity $q$ in $R_i$ fails to transition to $df_j$ which establishes $q = std$, from the transition axioms, the failure must be due to one of the following failure conditions:

1. $df_i$ establishes an increase to $q$ based on a direct positive influence $p$ on $q$ in $R_i$ , but fails to shift $p$ from $p > 0$ to $p = 0$ as $q$ shifts from $q < c$ to $q = c$, the transition condition. This failure can be revised in two ways: a) By introducing new influences and sq-shift constraints. b) By modifying the persistence of existing influences and adding sq-shift constraints on them.
2. $df_i$ establishes an increase to $q$ based on a direct positive influence $p$ dominating a direct negative influence $p'$, but fails to shift $p > p'$ to $p = p'$ as $q$ shifts from $q < c$ to $q = c$. This failure is revised by introducing the negative influence, the domination constraint and an sq-shift of the domination relation in $df_i$.

Failure conditions may be classified into two broad categories: persistence conflicts and causal synchronization failures. Persistence conflicts are characteristic of design fragments in which the quantity that is to be shifted in an sq-shift is causally dependent on existing quantities in the design fragment. Causal synchronization failures are characteristic of design fragments in which no such causal dependencies exist, and hence must be newly created. Accordingly, we describe two basic revision operators: i) shift-reduce operators for persistence failures which, given an sq-shift to be established, revises existing causal relations to establish the synchronized shift, and ii) shift-establish operators for causal synchronization failures which, given an sq-shift to be established, introduces causal relations with additional correspondence constraints to ensure that the shift in the reference quantity produces a shift of the required quantity.

### 4.1 The Shift-Reduce Operator

A required sq-shift for DF transition may lead to inconsistent persistences of existing quantity changes and relations in the design fragment. The shift-reduce operator consist of two parts: i) Applicability conditions determine the applicability of the operator. They specify the failure conditions in terms of the presence of persistences that are inconsistent with the persistences required to justify a given shift. ii) Revision action which revises the design fragment by deriving new sq-shift, if necessary, and by backpropagating the behavior persistences across the causal links, and making changes to existing persistences.

Figure 3(a) illustrates the use of a shift-reduce operator in the steam engine example. The required shift specifies an sq-shift of the velocity of the piston $p_1$ from $V_{p1} > 0$ to $V_{p1} = 0$ as the piston moves from some position greater than the bottom to the top. Velocity is increasing, since the acceleration is maintained greater than zero, in the design fragment $df_u$. The increasing velocity conflicts with the requirements of a decreasing velocity for the synchronized shift with the position. Hence, region $R_1$ is divided into two adjacent subintervals, one in which the velocity is positive and increasing and the other in which it is positive and decreasing (from Axiom 2.4). The operator changes the design fragment by, adding the sq-shift requirement on acceleration and correspondence constraints.

### 4.2 The Shift-Establish Operator

The shift-establish operator extends the design fragment by adding mechanisms to establish a given sq-shift. The operator has an applicability condition part and an action part. The applicability conditions model failure conditions to establish a shift. The action part searches the domain model to instantiate model fragments from the domain model, which introduce new causal relations to the *df* and backward chain the required shift over the causal relations to derive new shifts and correspondences, such that the derived relations support the required shift.

Figure 3(b) illustrates the establishment of the shift of the steam inflow rate from $Sif > 0$ to $Sif = 0$ as the piston $p_1$ moves from some position less than $t_2$ to $t_2$, where $t_2$ is less than $Top_{c1}$. The failure condition corresponds to the behavior $Sif = dec$ when the position of the piston is less than $Top$. The revision action corresponds to introducing a negative influence on $Sif$ due to path resistance, $PR$. The influence due to the path resistance on $Sif$ is used to backward chain the required shift of $Sif$ to generate a new shift in terms of $PR$.

## 5 Method

Table 2 presents the algorithm for design changes required to meet pairwise region transition constraints. The algorithm accepts as input the operating regions that involve a transition, the design fragments which establish the behaviors in each region, the design basis for the fragments and a domain model.

In step 0, it initializes $SQS$ to the set of sq-shifts to be established by $df_i$ for transition to $df_j$ based on comparing the desired behaviors of $df_i$ with that of $df_j$. The main body of the method is an iterative process with two main steps. Step 1.1 tests for applicable shift reduce or shift establish operators. If there are no failure conditions then the applicable operator set Ops is empty. Step 1.2 applies a chosen operator. Application of an operator may lead to introducing new sq-shift to $SQS$. The

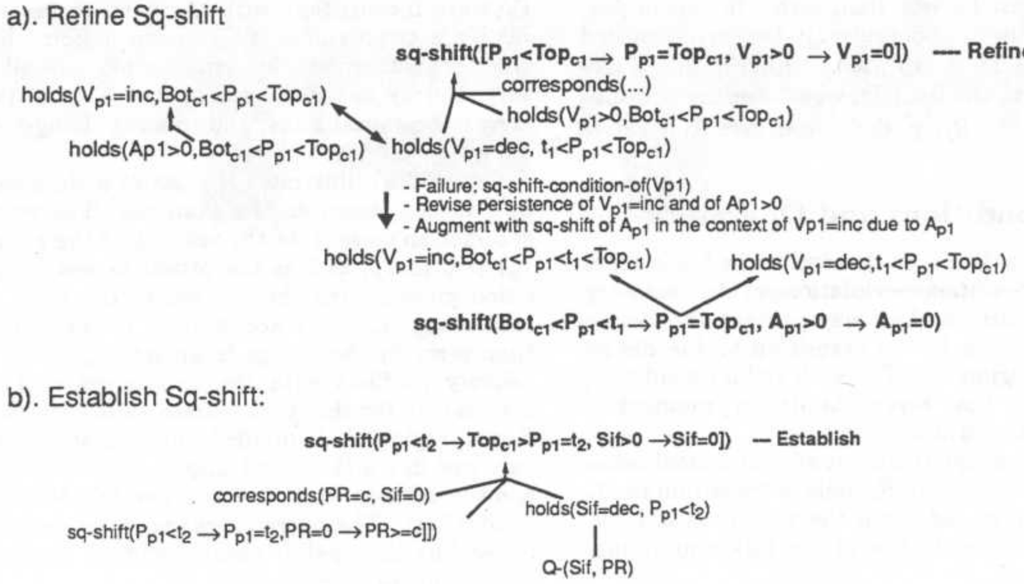


Figure 3: The shift-reduce and shift-establish operations.

Table 2: The method for the design of transitions.

Method: DT($R_1$, $R_2$, Tc, $df_1$, $df_2$, DS, $\mathcal{DM}$)
- Given:
  $R_i$= an operating-region with transition to $R_j$ under transition condition Tc,
  $df_i$ = design fragment for $R_i$
  $\mathcal{DM}$ = Domain Model
- Output: Design solutions which are augmentations of DS

Let,
  SQS be a working set of sq-shifts to establish
- Steps:

0. Initialize.
   SQS = { sqs | Established(sqs) → transition($df_1$ , $df_2$ ) }
   $df_i^{'}$ = $df_i$ augmented with all sqs∈ SQS
1. Do *Forall* sqx ∈ SQS, *do*:
   1.1. Find applicable shift reduce/ shift establish Ops.
   1.2. *If* empty($Ops$)
   *Then* continue
   *Else* Choose($Opx$, $Ops$); Apply($Opx$, $df_i^{'}$).
2. Output design solution D($df_i^{'}$).

loop terminates when $SQS$ is empty.

## 5.1 An Example Trace

We illustrate how the method works in the context of establishing the region transitions for a single cylinder piston motion. The design fragments for this example are as shown in Figure 4. In the trace, we show only the choices made by the method that lead to the design shown in Figure 1; if it were to make alternative choices, it would lead to a different design.

The transition requires that $df_u$ establish the sq-shift of velocity $V_{p1}$ of piston $p_1$, from $V_{p1} > 0$ to $V_{p1} = 0$ as the piston moves upward towards the region boundary of $P_{p1} = top$. From the necessary conditions of sq-shift, the velocity must decrease over the region while remaining greater than zero until the boundary is reached. This condition is violated due to the consequence of the operating assumption on the piston acceleration, $A_{p1}$, which is the only positive influence on $V_{p1}$. The effect of the assumption that $A_{p1} > 0$ in the initial *df* holds throughout the region, is that the velocity of $p_1$ increases in the region. Figure 4(b) shows the application of a reduce operator to establish the shift of the velocity: the persistence of $V_{p1} = inc$ is clipped by revising the persistence of $A_{p1} > 0$ and augmenting the $df_u$ with the sq-shift of $A_{p1}$. Figure 4(c) shows the result of iteratively applying reduce operators, where the two basic sq-shifts must be established are: i) the steam inflow rate, $Sif$ must be shifted from $Sif > 0$ to $Sif = 0$ and, ii) the steam outflow rate $Sof$ must be shifted from $Sof = 0$ to $Sof > 0$.

Figure 4(d) shows the application of an establish operator to satisfy the failure condition for the sq-shift involving $Sif$. The necessary behavior, $Sif = dec$, required for the shift is established by an increase to the steam path resistance. Figure 4(e) shows the result of repeated applications of establish operators which establish sq-shifts of steam-inflow path resistance ($PR$), valve opening, and lever-arm position. The composition is such that the shift of piston position from the bottom to the top of the cylinder when forward propagated through a set of causal relations produces the sequence of shifts (assumed instantaneous) of the lever-arm position, valvel opening, etc., to finally lead to the desired shift of $S_{if}$. Figure 4(f) shows the design resulting from the components introduced by the establish operators.

# 6 Discussion

Previous work on design has primarily focused on designing single operating region devices. Some previous work

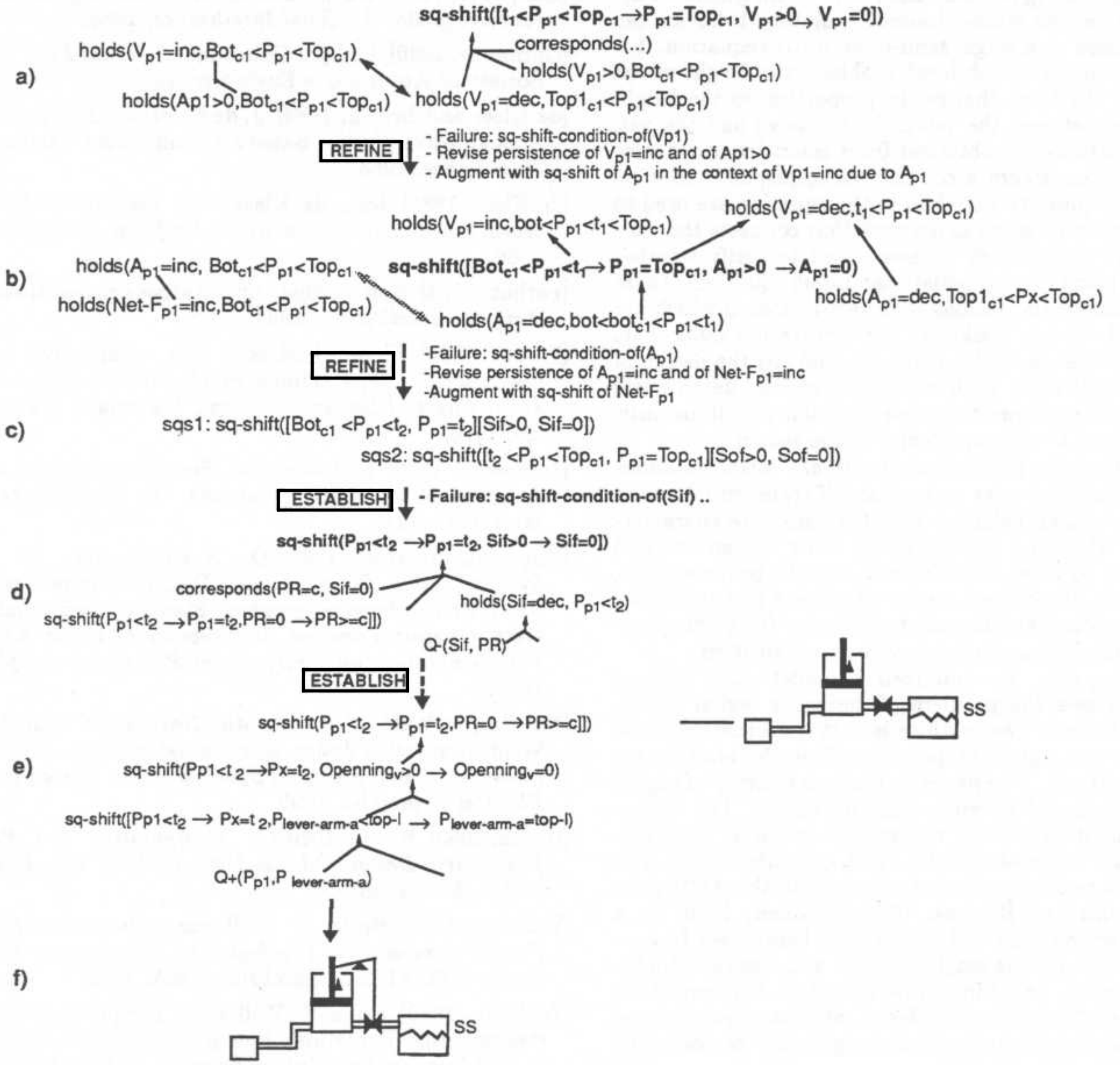


Figure 4: A trace of the method for establishing the transition from the upward stroke to the downward stroke of a single cylinder piston.

has analyzed devices with multiple operating regions [Williams, 1990; de Kleer and Brown, 1984]. Specifically, the work of Williams [Williams, 1990] on qualitative temporal analysis for understanding region transitions is related to our work. The work presented here extends Williams' work and applies it to the design task.

The more recent work of Williams [Williams, 1989] on *Interaction Topology-Based Design* considers the design of regulating devices. His IBIS system generates designs for devices whose desired regulatory behavior can be expressed as a single semi-quantitative equation. For example, in the punch-bowl problem, the height of the punch in the bowl changes in proportion to the height difference between the punch in the bowl and the vat. Such equations are obtained from conditional behavior specifications, where a conditional corresponds to a region. The quantity variables in the equation are used to search for an interaction network that connects the variables and the network is then tested to verify whether the relations imposed satisfy the input equation. There are two major limitations with this approach which are addressed by our work: (i) the verification failures do not guide the search for revisions, and (ii) the design of more complicated, multi-operating region, devices will require solving more than one equation simultaneously, and will add to the complexity of the search.

Navinchandra [Navinchandra *et al.*, 1992] describes an approach that uses a case-base of transformations to elaborate design behavior specifications. He characterizes the triggering conditions for state transitions and uses them to index into the case base to retrieve transformations. In contrast, our work takes a first-principles based approach and formulates a theory for guiding systematic model-based design of region transitions.

In this paper, we described a model-based method that addresses the problem of designing region transitions of devices. The key idea is that synchronized shifts of qualitative regions of quantities form the basis for region transitions. The paper formulates a theory of region transitions based on such quantity shifts. The theory is then used as a basis to develop operators that recognize and establish synchronized quantity shifts. The method is under implementation within the ADB rule-based framework [Forbus, 1990; de Kleer, 1986] on a SPARC workstation and is currently being used to generate designs for the single cylinder and double cylinder steam engines. In addition, we intend to demonstrate it on examples involving the design of control subsystems for chemical reactors and other regulatory devices with multiple operating regions.

Some major limitations of our the approach are: (i) Global interactions. Our method generates designs by analyzing pairwise region transitions. Such localized analysis may not work for some classes of devices which may require more global transition analysis. (ii) Compound transitions and compositional design. For devices with compound transitions, a compositional design approach will have to consider possible interactions between the individual transitions. (iii) Parallel sq-shift. A quantity shift for region transition may depend on a conjunction of synchronized quantity shifts which have to be coordinated simultaneously. Our future work will address some of these limitations.

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