# THE DECLARATIVE REPRESENTATION AND PROCEDURAL SIMULA!LOU OF CAUSALITY IN PHYSICAL MECHANISMS

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Abstract:

A theory of cause-effect representation is used to describe man-made mechanisms and natural laws. The representation, consisting of 10 link types that interconnect events into large declarative patterns, is illustrated on a relatively sophisticated device, the home gas forced air furnace. Next, a procedure and framework for translating the declarative description of a mechanism into a population of associatively triggerable computation units is described. The associative, or procedural, form can then be used to perform a discrete cause-effect simulation of the device. The delcarative to procedural translation, including a simulation trace, is shown for the furnace. Topics of mechanism abstraction and mechanism invention are discussed, and the entire "Mechanisms Laboratory" is placed in the larger perspective of our research into human problem solving.

Keywords:

declarative-procedural correspondence, simulation of physical systems, spontaneous computation, cause-effect representation, mechanisms invention

## 1. Introduction

Man-made physical mechanisms provide an interesting domain in which to study human problem solving and cause-effect knowledge representation. In this paper, we describe and illustrate a representation framework which permits us to express and simulate the commonsense internal cause-effect structure of a variety of man-made mechanisms (both mechanical and electronic), as well as a variety of natural mechanisms (laws of physics, physiological mechanisms, etc).

Since our strategy has been to use the mechanisms domain as a medium for investigating human problem solving and cause-effect knowledge representation, we have developed our "Mechanisms Lab" within the existing framework of our Commonsense Algorithm (CSA) Project, a broader investigation of cognitive mechanisms. Following this strategy has lead us to a mechanisms theory in which the base representation of a mechanism is a declarative, cause-effect graph, but in which simulation is accomplished by transforming such a representation into procedural form, then executing it. Thus, in addition to the theory of representation and simulation, we feel the technique provides an interesting case study in declarative-procedural correspondence.

The discussion of our Mechanisms Laboratory is divided into five main parts: (1) background and theoretical framework of the mechanisms research, (2) cause-effect representation and example, (3) background and strategy for the simulation aspects of the project, (4) a simulation example, and (5) philosophy of the approach.

## 2. Motivation

Our motive in this mechanisms research is to understand human problem solving and cause-effect knowledge representation. Man-made mechanisms provide an excellent medium for carrying out such research because mechanisms are in a sense final snapshots of the human problem solving process. By developing representations for the cause-effect notions inherent to all mechanisms as humans perceive them, we stand a good chance of also gaining insight into how humans encode the various principles and physical laws that are evoked during the mechanism's invention or design.

Besides this theoretical relevance of studying mechanisms, there are some interesting practical applications of a cognitive theory of mechanisms representation and simulation. For example, a mechanisms theory can provide the basis of a potentially powerful CAI facility in which a mechanisms-naive user could interactively explore the design principles and behavior of a device. Provided the system is conversant in the same terms as the user (i.e. higher-level, symbolic terms, rather than lower-level numerical or parametric terms), such interaction can communicate concepts rather than details.

Many other specific applications exist. In one, the theory could provide the basis for medical applications, through the modeling of, e.g., human physiological mechanisms. In a second, the theory could be applied to provide a self-model in systems with a self-maintenance capabilities (martian rovers, 2001 vacuum cleaners?). In a third, the theory could provide the basis of interactive design systems in which engineers specify high level goals to the system, which then does the design. Completely automatic "mechanisms invention" is within the realm of possibility and, we feel, would closely resemble the behavior of current-day problem solving and program synthesis theories. Finally, a future application might be to use the representation as a sort of Dewey Decimal System of cause-effect pattern classification.

## J. Background and Related Work

There are many ways to approach the description of a mechanism. Most in the. past (e.g. [Jwl], [LBIU], [RJS1], [SL1J, and [WBL1J) have tended to be more analytical in their approach. In analytical simulations, the mechanism is typically described by parameterizing it in a form suitable for a numerical simulator. The problem with this approach is that, the representation of a mechanism is very different from the human cause and effect knowledge of the mechanism.

We are by no means the only ones addressing the issues of symbolic modeling or simulation of physical systems. Two other notable examples are the MYCIN project and an MIT electronic circuit analysis program (EL). The MYCIN medical diagnosis project at Stanford [D1] has been constructing models of the techniques clinical pathologists presumably apply when attempting to make sense out of the raw data which describes some possible pathology or set of pathologies. In this sense they too are symbolically modeling cause-effect mechanisms. EL, Sussman's and Stallman's electronic circuit analysis program ([SS1] and [SS2]), is both an application program and a theory of circuit design. The main concerns of the project are: how are laws of electronics expressed in a way that is of use both to the analysis of a given circuit; e.g. the user specifies the starting states of all "active" components such as transistors, then asks the program to analyze the circuit's behavior, or the user requests the system itself to derive the various modes of operation of the active devices in the circuit and to the design of a circuit from descriptions of what it should accomplish.

## 4. Theoretical Framework

We have approached the representation and simulation of mechanisms from within the framework of our larger Commonsense Algorithms Project. Since one main purpose of the project has been to understand more about how humans might represent and use all sorts of causal knowledge, we have explicitly chosen to develop the mechanisms theory in the context of the larger CSA theory, drawing upon existing CSA mechanisms which themselves seem to be broadly applicable in all aspects of cognitive modeling. Specifically, this has resulted in (1) adopting as the mechanisms representation the same representation that is used in the other two phases of the project, namely, the plan synthesizer [R1] and the language comprehender [R1] and [R2], and (2) applying our notions of "spontaneous computation" [R3] to simulation. Although the running LISP Mechanisms Laboratory which has resulted is not efficiency-wise competitive with applications simulators, this is of little concern, since efficiency considerations are not relevant to our current goals.

In summary, then, we want to be able to express and simulate mechanisms (and hence, also the physical principles upon which they are founded) in ways that might approximate how humans do these tasks. To accomplish this, we have chosen to embed the simulator in the same framework as the plan synthesis and language comprehension components of our project.

### 4.1. CSA Cause-Effect Representation

The declarative representation of a mechanism is a cause-effect graph whose nodes are events and whose links are drawn from a set of the ten theoretical forms of inter-event causal interaction. Each event falls into one of four categories: action, tendency, state or statechange. With the exception of "tendency", these terms are intended to reflect their standard connotations. We use the term "tendency" to describe action-like events in which there is an absence of intention. Gravity, for example, is a tendency, since it is a force generator, but has no choice about, or reasons for, acting.

The links of our theory are intended to reflect what we believe to be necessary (and close to sufficient) underlying human concepts relating to causality in physical mechanisms. (These same links are also the basis of the plan synthesizer s representation.) We arrived at several of the ten by obvious intuitive reasoning, and at the remaining ones by considering many mechanisms and attempting to capture the recurring concepts. None of the links by itself is particularly novel to us, or individually provocative; yet, taken as a set, we believe these links are both theoretically significant, and convenient to use in practice.

### 4.2. Representation Example: Forced-Air Furnace

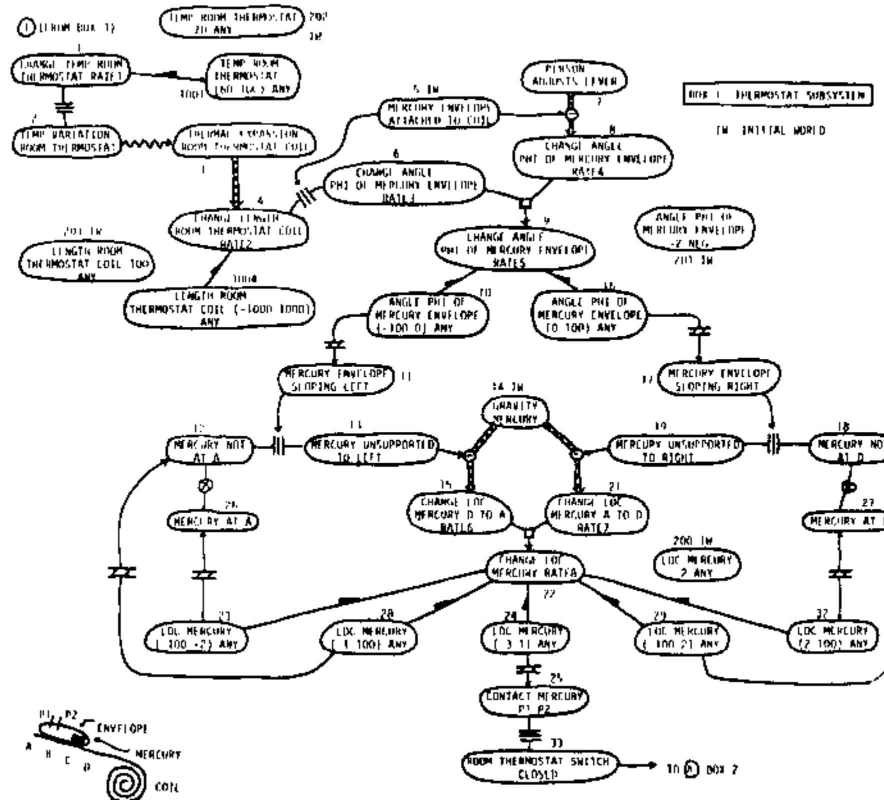
We introduce the CSA mechanisms representation first via an example that illustrates both the individual links and the general size and complexity of mechanisms we are currently representing and simulating. The example is the Home Gas Forced-Air Furnace, and reflects our understanding of this relatively sophisticated device.

For convenience in the presentation, we have segmented the example into three boxes: (1) thermostatie control, (2) heat generation, and (3) heat delivery. Interconnections A through G between boxes are indicated in circles. We have provided an event-wise cross-indexed English description ot BOX 1 to accompany its schematic representation, but have omitted the English descriptions of BOXes 2 and 3 (see [RGI] for more details).

BOX 1 (Control Subsystem)

We assume that the system heats a single room, and that this room contains a mercury-filled, glass envelope style thermostat. A temperature change of the thermostat (1) is equivalent to a state of temperature fluctuation (2). Such fluctuation continuously enables the tendency THERMAL EXPANSION (3) to produce a continuous change in the length of the thermostat strip (4). Provided the glass envelope is attached to thus is coil (5), this length change is equivalent to a change in the angle (phi) of the glass envelope (6) angle of the glass envelope can also be Influenced by an external adjusting action (7,8). At any moment, the net change (9) of this angle is governed by these two causal sources.

As phi changes, there are two points of interest: when phi is below zero (10), i.e. the envelope begins tilting to the left (11), and one when it is above zero (16), i.e. begins tilting to the right (17). When the envelope is tilting, left (11), and the left edge of the mercury is not already at the extreme left end of the envelope (12), the mercury is in a condition of being unsupported to the left (13). This allows the tendency GRAVITY (14) to manifest itself and to begin continuously changing the mercury's location toward the left (15). Returning to the other threshold point for phi (when phi is above zero), a symmetric system of unsupportedness pertains (16,17, 18, 19,14, 21), influencing the mercury to move toward the right. At any moment, the net change in the mercury's location (22) is governed by these two systems.



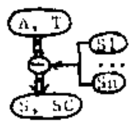

There are five points of interest (23, 24, 28, 29, 32) along the mercury's path of travel (lower part of BOX 1). When the left edge of the mercury reaches point A (less than or equal to -2) (23), the mercury will cease being unsupported, and GRAVITY's influence will be severed (i.e. the mercury will stop moving left). While the mercury is between points B and C (i.e. between -3 and 1) (24) there will be physical contact at the mercury and the electrical contact pins P1 and P2 (25). This amounts to the thermostat having closed the furnace's control circuit (33). This condition feeds into BOX 2 via tie point A, serving as one precondition for the main supply gas valve opening. Conversely, contact between the mercury and P1 and P2 ceases at points less than -3 or greater than 1.

The Control Subsystem participates in a large feedback loop via tie point F from BOX 3. The descriptions of BOXes 2 and 3 are similar (see [RGI]). BOX 1 Introduces all the link concepts in the representation.

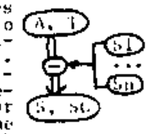
### 4.3. Mechanisms Cause-Effect Links

With this example in mind, we now give a very brief description of the ten links. See [RG1] and [R2] for more detailed discussions.

Continuous and One-Shot Causal



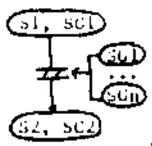
Action A or tendency T causes state S or statechange SC to exist, providing gating conditions S1,...,Sn are in effect. For the continuous form, the action's continued presence is required to sustain the state or statechange (i.e. there is some other unspecified force which would annihilate S or SC if A or T were removed). For the one-shot form, A or T is required only momentarily. The gates govern the effects the action or tendency will have on its environment, in that their continued and simultaneous presence during the action is required for the indicated causality "to flow" from the action or tendency to the state or statechange. These gates are distinct from A or T's enablements; enablements govern the execution of the action itself, independently from any effects it may produce.



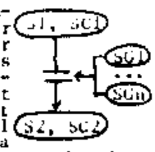
Continuous and One-shot Enablement

State S enables action A or tendency T. For the continuous form, S's continued presence is required in order to begin and sustain A or T. For the one-shot form, S's presence is required only momentarily to allow the action to begin. (Semantically, one-shot enablement occurs when the performance of A or T modifies its environment in a way which liberates the action from the influence of the original enabling condition.)

Continuous and One-Shot State Coupling



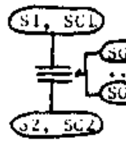
State S1 or statechange SC1 indirectly produces S2 or SC2. For the continuous form, S2's or SC2's continued existence is coupled to S1's or SC1's continued existence. For the one-shot form, S2 or SC2 is independent of S1 or SC1 after the initial coupling. These links provide a means of expressing implicit intervening causal relations which are either unknown or irrelevant to some description (i.e. states do not directly cause states). They accept gating states in the same manner as the



causal links.

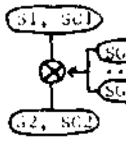
State Equivalence

State S1 or statechange SC1 is an equivalent formulation of state S2 or statechange SC2, providing gating conditions SG1,...,SGn are present. "Equivalent formulation" means that the two states are paraphrases - syntactically different expressions of the same underlying event. Equivalences, we feel, will always be present in any representation, and hence ought to be dealt with explicitly.




Most frequently, an equivalence plays the role of buffering two different points of view of the same event (e.g., the output of one mechanism is "photons exist", the input to another mechanism is "light present", and say, during mechanisms invention, we wish to join the two mechanisms). The existence or non-existence of either equivalenced event implies the existence or non-existence of the other.

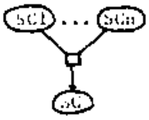
State Antagonism




State S1 or statechange SC1 is antagonistic to state S2 or statechange SC2 (i.e. the two events are mutually exclusive), providing gating conditions SG1,...,SGn are in effect. This link is the companion of the state equivalence link.

Rate Confluence

Statechanges SC1,...,SCn represent the culminations of multiple causal sources for a net statechange of some entity with respect to some feature. The net statechange, SC, specifies the composite rate as a symbolic expression which can be dynamically evaluated during a simulation. Syntactically, all contributory statechanges, and the net statechange must reference the same entity, and the same varying feature of that entity (e.g. change in temperature of the heat exchanger).




Threshold

Net statechange, SC, reaches a threshold, S, of interest to the description of the mechanism. S is an instantaneous description of an entity with respect to the feature which is varying in the statechange, e.g. the temperature of the heat exchanger is 400 degrees. We distinguish positive and negative thresholds graphically and in the internal representation and simulation so as to provide for hysteresis.


This concludes the discussion of the CSA cause-effect links relating to mechanisms description. There are several other links relating to motivation and intentionality of human actors. These other links permit us to explore the areas of plan synthesis and language comprehension in the social as well as physical domain within the same representational framework.

We have represented a number of other physical, electrical and electronic mechanisms in these same terms, including (1) a computer flip-flop, (2) a "drinking duck" novelty toy, (3) an incandescent light bulb, (4) a mechanical oscillator, (5) a reverse-trap flush toilet, and (6) descriptions of composite events involving the Bernoulli effect, gravity and momentum. Additionally, we have used the representation to describe a computer algorithm for computing the average of a table of integers, and feel that the CSA links will provide a good language for programming concepts as well as physical laws. These and other examples appear in [RG1], [R1] and [R4].

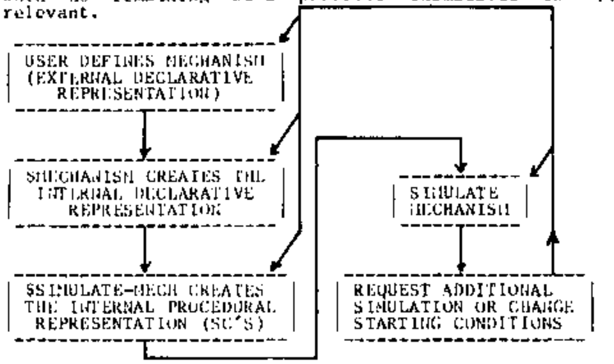
## 5. Simulation Strategy

As we pointed out earlier, our purpose has not been merely to build a mechanisms description and simulation laboratory, but to build one upon concepts which are generally applicable to a wide spectrum of other types of cognitive modeling as well. We feel that we have succeeded in the description aspect by embedding the mechanisms description language in the same framework as our problem solving and language comprehension languages, namely these CSA links just covered.

For the simulation strategy, we have drawn upon another aspect of the CSA system that we call the "spontaneous computation" component. This is a generalized implementation of pattern-directed inference, wherein computations occur spontaneously, rather than on demand from another computation.

The simulation strategy (see flow diagram below) is this: convert the declarative (CSA) cause-effect representation of the mechanism to a population of autonomous computation units, each of which models one event in the declarative representation. If each unit in this population of spontaneous computations (SC's) contains a model of all other event schemata that can influence it, (both within, and external to, the particular mechanism in which the event participates) then the modeling SC can be caused to run when all influences are just right by including all those influences in its (potentially complex) invocation pattern. Thus, our strategy is to model each declarative event by an SC whose trigger pattern is sensitive to other prerequisite events in the mechanism.

A simulation will amount to embedding the reactive SC population modeling the events in the mechanism in an environment in which static conditions are appropriate for triggering the mechanism. The environment, as well as all instantaneous states during the simulation, are modeled as a collection of database assertions. Triggering of the mechanism will lead to a conceptually parallel avalanche of activity wherein the running of one or more SC units can prompt the running of one or more other units, and so on. The simulation becomes quiescent when no remaining SC's perceive themselves to be relevant.




There are some important issues relating to why we have chosen this strategy for simulation rather than a more straightforward strategy that manipulates the declarative representation directly. We will discuss the philosophy behind this approach to simulation later. We now describe the CSA system's spontaneous computation component which provides the substrate for the simulator.

### 5.1. Spontaneous Computation and Channels

Our implementation of spontaneous computation is a generalization of the pattern-directed invocation notions embodied in MICRO-PLANNER [SWCI] and CONNiVER [MSI], By "generalization", we mean specifically that we have provided for the specification and organization of more complex invocation patterns, and for more complex hierarchical organizations of SC populations.

The invocation (trigger) pattern of an SC in the CSA system is constructed from nested n-tuples composed in virtually any degree of complexity using the logical relations AND, OR and AnY. Each component of the trigger can be one of the following types: (1) associative, (2) non-associative, or (3) computable. Associative trigger components come to be organized into a reactive data structure we call a "trigger tree"; these are the components which can react to passing stimuli (to be defined) and cause the entire pattern to be tested (polled). Non-associative trigger components represent aspects of the trigger's environment that must be true (when explicitly polled) in order for the SC to fire fully. but which themselves are incapable of initiating the firing. Computables are any EVALable LISP forms other than (1) or (2), and must evaluate non-NIL for full triggering of the pattern to occur.

An SC body is an arbitrary EVALable LISP expression. Each SC is context sensitive, in that it can be masked and unmasked independently within its trigger tree. (The simulator relies on this feature to prevent looping in certain cases.) Entire trigger trees are also context sensitive, as will be described.

Beyond this organization of complex trigger patterns into trigger trees, the CSA SC component provides for the higher-level hierarchical organization of trigger trees around constructions called channels". An SC channel (see [R3]) is intended to be the analog of a hardware channel, and a generalization of the PLANNER/CONNIVER pattern-directed invocation scheme.

The SC's that the mechanisms simulator creates as the procedural representation of a mechanism all exist in two trees attached to two channels. The passing signals on these channels will be the symbolic descriptions of changing events in the simulation, entering and exiting the database via these channels. When it runs, a fully-triggered SC will place a new event description on one of these channels, and possibly mask or unmask itself and/or other SC's in the population, as we will describe.

We feel the trigger tree/channel paradigm is a powerful one. Currently. the mechanisms simulator employs only these two relatively simple channels in performing Its tasks, (analogous to the store and erase channels of PLANNER and C0NN1VER) but we expect it to utilize the full potentials of this system in future phases of the project, especially when we address the topic of mechanisms invention.

This concludes our brief sketch of the CSA SC component insofar as it relates to our purposes here. For a more complete- discussion, including several other theoretical applications of the SC system in the areas of inference, problem solving and language comprehension, see [R3],

b. The Mechanisms Simulator

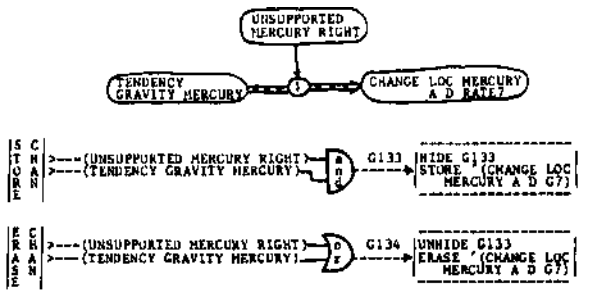
The simulation subsystem Is a collection of LISP functions that take the internal declarative representation of a mechanism, convert it to a population of spontaneous computations, then awaken a subset of the population via a triggering assertion. A subsat of the awakened SC's will request that their bodies be run. The evaluation of the bodies will cause other SC's to awakened. This will constitute an execution of the mechanism. In the execution, events will be automatically asserted and duasserted in the database and states which are changing with time will be updated. The status of an event is determined by Its causal relationships to other events as they become, asserted and deasserted.

The initiation of the simulator is caused by the assertion of some event: semant ical ly, e ittier an action performed by an external actor, a tendency relating to a natural force, or a state, as derived, e.g., as an output from the simulation *of* another mechanism. This latter initiating event wi 1 L provide tor mechanisms interaction where several mechanisms have a common event and t tie assertion oi that event in one mechanism will initiate (or contribute to the initiation of) execution of the other mechanism.

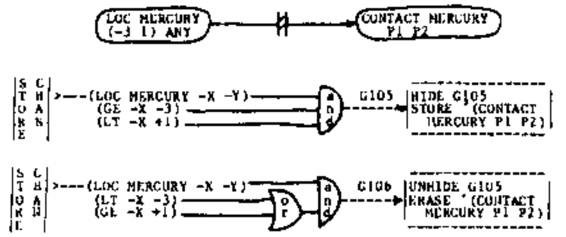
Each link in the internal declarative representation of a mechanism has a set of SC's automatically created for it according to a set *of* rules for each theoretical Link type. An SC is activated when its preconditions have been satisfied. The running of an SC will generally cau.se a database modification or a masking or unmasking of another SC.

b. 1. Declarative to Procedural Conversion

We now give two examples to illustrate the process of decLarative-procedural conversion. The SC's are displayed with the following conventions. Lach SC representing some potential event is Imagined to be watelling a path to the database (channel). The path type (STORE or ERASE) is located between the double bars on the leit side of the display. The logical connectives in the created SC's trigger pattern are to the right ot the triggering events and the arrows out of the .triggering events flow into these connectors. On the far right side of the figure is the body of the SC. These are the activities which will be oerformed when the SC is run. A reference name for the SC is located on the arrow into the body of the SC.




To illustrate, in the example of the SC'_ ___________ the continuous causal (C-CAUSE) link governing the movement of the mercury in the furnace s thermostat, when the tendency GRAVITY or the state "mercury unsupported on the right is asserted and the other event is currently in the database (i.e., also present), then the state-change of the location of the mercury is stored (i.e. asserted) in the database. If either the tendency GRAVITY or mercury unsupported on the right is deasserted (i.e. erased) from the database, then the state-change of the location of the mercury is erased from the database.




The second example is the SC's created tor the continuous coupling (C-COUPLE) link which watches for the mercury to enter the region between Pl and P2. When the location of the mercury is between -3 and 1 there is contact between the mercury, Pl, and P2 (i.e the contact event is asserted in the database). When the location of the mercury moves above or below the given range, the contact event is erased from the database.

This illustrates the conversion process on two of the simpler link types. More complex processing may be required for other links. For example, the rate confluence (R-CONFL) link requires symbolic rate computations to be performed. Details of the conversion process appear in 1RC1],

° • 2. Simu lat. i on Kxample

We have successfully simulated the entire furnace, illustrated earlier in its declarative form, although the simulation must be done in three pieces (because of memory limitations). The furnace cuts on, heats the room up, then cuts oft, providing a trace of all events in the sequence. To convey a picture of the simulator's operation, we include an excerpted and annotated sequence showing the simulation of the thermostatic control portion of the furnace.

Input Syntax for BOX J_

The Mechanisms Lab requires that each mechanism's CSA description be coded into a machine readable form. This form is the external declarative CSA representation and is used as input to a mechanisms defining function called SMLCUAN1SM. This function generates the internal declarative representation of the median ism from the external declarative representation. Below is the call on SMLCHAiNSM in the external declarative form for the thermostatic control section of the furnace.

```
(SMECHANISM '(
(NAME BOX1)
(EVENTS
    (1 SC (CHANGE TEMP ROOM-THERMOSTAT P1 P2 RATE1))
    (2 S (VARIATION TEMP ROOM-THERMOSTAT))
    (3 T (TENDENCY THERMAL-EXPANSION R-T-COIL))
    (4 SC (CHANGE LENGTH-MM R-T-COIL P3 P4 RATE2))
    (5 S (ATTACHED MERCURY-ENVELOPE R-T-COIL))
    (6 SC (CHANGE ANGLE-PHI MERCURY-ENVELOPE P5 P6 RATE3))
    (7 A (ADJUST LEVER))
    (8 SC (CHANGE ANGLE-PHI MERCURY-ENVELOPE P7 P8 RATE4))
    (9 SC (CHANGE ANGLE-PHI MERCURY-ENVELOPE P9 P10 RATE5))
    (10 S (ANGLE-PHI MERCURY-ENVELOPE (#-100 #0) ANY))
    (11 S (SLOPING MERCURY-ENVELOPE LEFT))
    (12 S (NOT LOCA MERCURY A))
    (13 S (UNSUPPORTED MERCURY LEFT))
    (14 T (TENDENCY GRAVITY MERCURY))
    (15 SC (CHANGE LOC MERCURY D A RATE6))
    (16 S (ANGLE-PHI MERCURY-ENVELOPE (#0#1 #100) ANY))
    (17 S (SLOPING MERCURY-ENVELOPE RIGHT))
    (18 S (NOT LOCA MERCURY D))
    (19 S (UNSUPPORTED MERCURY RIGHT))
    (21 SC (CHANGE LOC MERCURY A D RATE7))
    (22 SC (CHANGE LOC MERCURY P11 P12 RATE8))
    (23 S (LOC MERCURY (#-100 #-2) ANY))
    (24 S (LOC MERCURY (#-3 #1) ANY))
    (25 S (CONTACT MERCURY P1 P2))
    (26 S (LOCA MERCURY A))
    (27 S (LOCA MERCURY D))
    (28 S (LOC MERCURY (#-1 #100) ANY))
    (29 S (LOC MERCURY (#-100 #2) ANY))
    (32 S (LOC MERCURY (#2 #100) ANY))
    (33 S (CLOSED ROOM-THERMOSTAT))
    (200 S (LOC MERCURY #2 ANY))
    (201 S (ANGLE-PHI MERCURY-ENVELOPE #-2 NEG))
    (202 S (TEMP ROOM-THERMOSTAT #70 ANY))
    (203 S (LENGTH-MM R-T-COIL #100 ANY))
    (1004 S (LENGTH-MM R-T-COIL (#-1000 #1000) ANY))
    (1001 S (TEMP ROOM-THERMOSTAT (#60 #100) ANY))    )
(LINKS
    (S-EQUIV (1 2))
    (C-ENABLE (2 3))
    (C-CAUSE (3 4))
    (S-EQUIV (4 6) (5))
    (C-CAUSE (7 8) (5))
    (RATE-CONFL ((6 8) 9) )
    (THRESH (9 (10 16)))
    (C-COUPLE (10 11))
    (S-EQUIV (12 13) (11))
    (C-CAUSE (14 15) (13))
    (ANTAG (12 26))
    (C-COUPLE (23 26))
    (C-COUPLE (32 27))
    (RATE-CONFL ((15 21) 22))
    (THRESH (22 (23 24 32 28 29)))
    (C-COUPLE (28 12))
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        (C-COUPLE (29 18))
        (C-COUPLE (24 25))
        (S-EQUIV (25 33))
        (ANTAG (27 18))
        (C-CAUSE (14 21) (19))
        (C-COUPLE (16 17))
        (S-EQUIV (18 19) (17))
        (THRESH (4 (1004)))
        (THRESH (1 (1001)))   )
    (INITIAL-WORLD 14 5 200 201 202 203)
    (TRIGGER 1)
    (RATES
        (RATE1 RATE59)
        (RATE2 (#QUOTIENT RATE1 #2#0))
        (RATE3 RATE2)
        (RATE4 #1)
        (RATE5 (#PLUS RATE3 RATE4))
        (RATE6 #-4)
        (RATE7 #4)
        (RATE8 (#PLUS RATE7 RATE6))
        (RATE59 #1)   )
    ))
```

## Simulation Trace

The following illustrates the output of the simulator. There are 72 SC's created for this section of the furnace. For space reasons, only a small portion of the trace has been left intact to convey the flavor of the simulation. For clarity, the edited trace has all database activities removed except those which affect the location of the mercury and those events directly linked to them. The right-hand side of the trace is an English description of the simulation.

```
(SIMULATE-MECH 'BOX1)
 MAX TICK COUNT (T = INFINITY) 7

 ** INITIAL WORLD EVENTS **

(TENDENCY GRAVITY MERCURY) STORED G143 BY                 GRAVITY always in effect.
(ATTACHED MERCURY-ENVELOPE R-T-COIL) STORED G144 BY IW    envelope and coil attached.
(LOC MERCURY #2 ANY) STORED G145 BY IW                    initial location of mercury is 2.
(ANGLE-PHI MERCURY-ENVELOPE #-2 NEG) STORED G146 BY IW    initial angle is -2.
(TEMP ROOM-THERMOSTAT #70 ANY) STORED G147 BY IW          initial room temperature is 70.
(LENGTH-MM R-T-COIL #100 ANY) STORED G148 BY IW           initial length of coil is 100 mm.

 ** END INITIAL WORLD **

(SLOPING MERCURY-ENVELOPE LEFT) STORED G149 BY G111       sloping left since angle is -2.
(NOT LOCA MERCURY A) STORED G150 BY G103                  mercury not at A since at 2.

  **** unedited trace begins  ****

(UNSUPPORTED MERCURY LEFT) STORED G151 BY G121            mercury unsupported at left since at 2.
   G135 HIDDEN BY G135                                    c-causal SC hidden.
(CHANGE LOC MERCURY D A G6) STORED G152 BY G135           mercury moving to A since left sloping and unsupp.
(CHANGE LOC MERCURY P11 P12 G8) STORED G153 BY G75        net state-change to mercury.
   G98 HIDDEN BY G95
   G99 HIDDEN BY G99
(LOCA MERCURY D) STORED G154 BY G99                       location of mercury is D since at 2.
   G94 HIDDEN BY G91

(CHANGE TEMP R-T P1 P2 G1) STORED G155 BY TRIGGER         temp change to thermostat is trigger for mechanism.

TICK 0 REAL TIME 26487

   G129 HIDDEN BY G129
   G130 HIDDEN BY G129
(VARIATION TEMP ROOM-THERMOSTAT) STORED G156 BY G129      temp variation caused by trigger.
   G141 HIDDEN BY G141
(TENDENCY THERMAL-EXPANSION R-T-COIL) STORED G157 BY G141 enabled by temp variation.
   G139 HIDDEN BY G139
(CHANGE LENGTH-MM R-T-COIL P3 P4 G2) STORED G158 BY G139  changing coil length caused by thermal-exp.

    **** end of unedited trace.  ****

(LOC MERCURY #-2 NEG) CHANGED G145 BY G87                 mercury moves to -2.
(CONTACT MERCURY P1 P2) STORED G161 BY G107               contact between mercury-P1-P2 since location is -2.
(CLOSED ROOM-THERMOSTAT) STORED G162 BY G113              thermo closed because of contact of mercury-P1-P2.
(UNSUPPORTED MERCURY LEFT) ERASED G151 BY G123            mercury now supported on left.
(CHANGE LOC MERCURY D A G6) ERASED G152 BY G136           loc of mercury no longer changing due to left slope.
(CHANGE LOC MERCURY P11 P12 G8) ERASED G153 BY G76        net change to location of mercury no longer occuring.
(LOCA MERCURY A) STORED G153 BY G96                       mercury now at A.
(NOT LOCA MERCURY D) STORED G152 BY G101                  mercury not at D.

TICK 1 REAL TIME 35956

(CHANGE LOC MERCURY -B -E G8) NO LONGER CHANGING          mercury no longer moving.

TICK 5 REAL TIME 50528

(UNSUPPORTED MERCURY RIGHT) STORED G154 BY G117           mercury becomes unsupported on right.
(CHANGE LOC MERCURY A D G7) STORED G151 BY G133           mercury start moving toward D.
(CHANGE LOC MERCURY P11 P12 G8) STORED G150 BY G75        net location of mercury now changing.

TICK 6 REAL TIME 55813

(LOC MERCURY #2 POS) CHANGED G145 BY G87                  new mercury position is 2.
(CONTACT MERCURY P1 P2) ERASED G161 BY G108               mercury no longer in contact with P1-P2 since at 2.
(CLOSED ROOM-THERMOSTAT) ERASED G162 BY G115              thermostat no longer closed.
(NOT LOCA MERCURY A) STORED G153 BY G98
(UNSUPPORTED MERCURY RIGHT) ERASED G154 BY G119           mercury supported on right since at D.
(LOCA MERCURY D) STORED G150 BY G94

LIST ADDITIONAL ACTIVITIES: NIL

** FINAL WORLD **
(TEMP ROOM-THERMOSTAT #79 POS)                            current room temperature is 79.
(ANGLE-PHI MERCURY-ENVELOPE #2#0 POS)                     current angle is 2.
(LENGTH-MM R-T-COIL #1#04E2 POS)                          current coil length is 104 mm.
(LOCA MERCURY D)                                          current mercury location is D.
(LOC MERCURY #2 POS)                                      mercury located at 2.
(SLOPING MERCURY-ENVELOPE RIGHT)                          envelope sloping right.
(TENDENCY THERMAL-EXPANSION R-T-COIL)                     thermal expansion still occuring.
(VARIATION TEMP ROOM-THERMOSTAT)                          variation in temperature of thermostat.
(CHANGE TEMP ROOM-THERMOSTAT P1 P2 G1)                    temp of thermostat still changing.
(ATTACHED MERCURY-ENVELOPE R-T-COIL)                      envelope still attached to coil.
(TENDENCY GRAVITY MERCURY)                                gravity still affecting the mercury.

BOX1 SIMULATED
```

## 7. Simulation Philosophy

Why do simulation this way? Namely, why do it symbolically, and why go through the contortions of converting the declarative form to spontaneous computation units? Clearly, it would be possible to simulate a mechanism by applying relatively simple graph algorithms directly to the declarative representation.

To understand why we have adopted this SC strategy, reflect on the nature of any physical system - a mechanism in particular. A mechanism is built from physical principles and components that act autonomously, in the sense that they are governed by physical laws that "run in parallel". The mechanism just happens to work in desired ways because the inventor has managed to identify, harness, and coordinate a population of autonomous agents. In this setting, very minor or very local alterations to one component or its environment can propagate to all parts of the mechanism in a falling-dominoes fashion. In particular, embedding the mechanism in alien or novel environments can significantly alter the micro and macro behavior of the mechanism in ways that will always relate to the individual components of the mechanism, viewed as autonomous agents, but seldom to the mechanism as a whole. Certainly, the net effect of embedding the mechanism in an environment will be to change the cumulative, overt behavior of the mechanism; but the overt behavior changes will be nothing more that the sum of many smaller, possibly unrelated influences.

By converting the mechanism's declarative form into SC form, we effectively crack the description open, exposing all the invididual cause-effect relationships directly to the environment. Each is free to behave as its trigger pattern dictates. Thus, when we embed the eviscerated form in a new environment, each cause-effect relationship must fend and produce results on its own.

In particular, this makes possible the more detailed study or debugging of the mechanism when placed in an environment where there are other mechanisms, as occurs, say. when a new mechanism is invented out of existing mechanisms and physical laws. For example, suppose that two mechanisms, designed separately, are thrust into the same environment and made to coexist, as happens when the two become part of a larger mechanism. Without cracking each decsription apart and casting the resulting spontaneous units into a large population in which the two mechanism's boundaries are lost, it would not be apparent how the two might interact. But using such a strategy, event-wise crosstalk is more readily discovered.** A case in point was the much publicized glitch in Polaroid's new SX-70 camera, where the sensitive electronics were interfered with by noise spikes produced by the concurrent operation of the picture ejecting motor. The interaction was a simple, but obscure one, and was solved by clever timing of events to remove the concurrency.

** Forcing two independent mechanisms to coexist in one environment is the analogy of forcing brother subgoals to coexist in one environment in plan synthesis; in both domains, there is the possibility of unanticipated interactions. See [RLIJ.

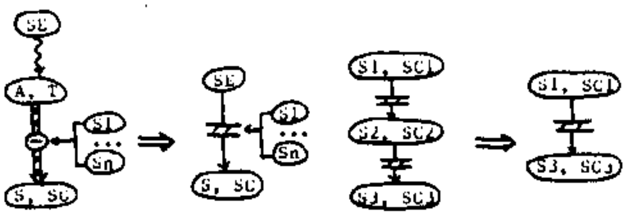
7.1. _A Related Issue: Mechanisms Abstraction

There is quite often a need to suppress much of the representation or simulation detail present in the system s full model of a given mechanism. There would be a need for suppresssion of detail, for example, if we. wished to provide a very high-level overview of a mechanism to serve, say, as a black box in a larger invention effort, or as an introduction of the mechanism to a totally naive CAI user. Since the suppression of mechanism detail is analogous to the suppression of detail in text, we use the term "abstraction'.

One of our current areas of interest is in automating the process of mechanisms abstraction. Note that we already have provisions in the representation tor expressing abstracted forms: the state coupling link. This link allows us the freedom of direct state-state causality. The abstraction technique can therefore be one of syntactically replacing certain patterns in the detailed representation with state coupling links.

It appears that there will be only a small number of syntactic abstraction rules. Two of the most obvious abstracting rules are depicted below. Such rules, applied transitively, could perform both minor and major abstractions. A major abstraction would amount to a simple coupling between the input and output states of a mechanism, e.g. "A falling temperature causes the thermostat to close."

Such abstracting would be applied to the declarative representation before simulation, so that the converted computation units would directly reflect the abstraction. Abstraction could be applied uniformly over an entire mechanism, or locally to excise parts which are not of immediate interest. Non-uniform abstracting, in which all uninteresting sections have been defocussed, would deliver practical advantages by allowing the simulator to devote more time to the relevant aspects of the simulation. This could be important if, for example, we suspect the audio stages of a radio are at fault, but know the power supply is functional. Before simulation, the radio's power supply description could be defocussed before conversion to simulation representation (i.e. population of SC's).



TWO OLFOCUSSING RULES

In addition to simple syntactic defocussing, we will also be exploring more semantic forms. Semantic mechanisms abstraction would be useful if, for example, we wished to know about the gas furnace with respect to a particular aspect of its operation, such as "heat production'. We might scan through the description, assessing each event according to its semantic relevance to the concept of heat production. Then, using the Highly ranked events as milestone events, the syntactic abstraction procedure could be applied to yield an abstraction with respect to the desired point of view, i.e. one which retained only the milestone states.

8. Conclusions

We have presented a theory of mechanism description and simulation which is based on tenets and processes we hypothesize to be applicable to other aspects of human cognition. We feel the theory of cause-effect representation is sound and expressive for a wide variety of mechanisms, and that it bears significance as a theory of human cause-effect knowledge representation.

Our next specific goals are threefold: (1) to make the acquisition of new mechanism patterns interactive, having the model prompt the user, and verify that the user s use of the representation coincides with the model's notions of semantic well-formedness, (2) to study the processes of mechanisms abstraction, and (3) to apply the existing CSA plan synthesizer to the task of mechanisms invention, involving the simulator in a debugging loop.

Acknowledgments

We wish to thank the other members of the Maryland CSA group (Phil London, Nache Creeger, John Boose and Ceorgy rekete) for their participation in numerous discussions and for their suggestions. We wish also to thank the Office of Naval Research for its support of this research under Grant NOOOU-76C-047 7.

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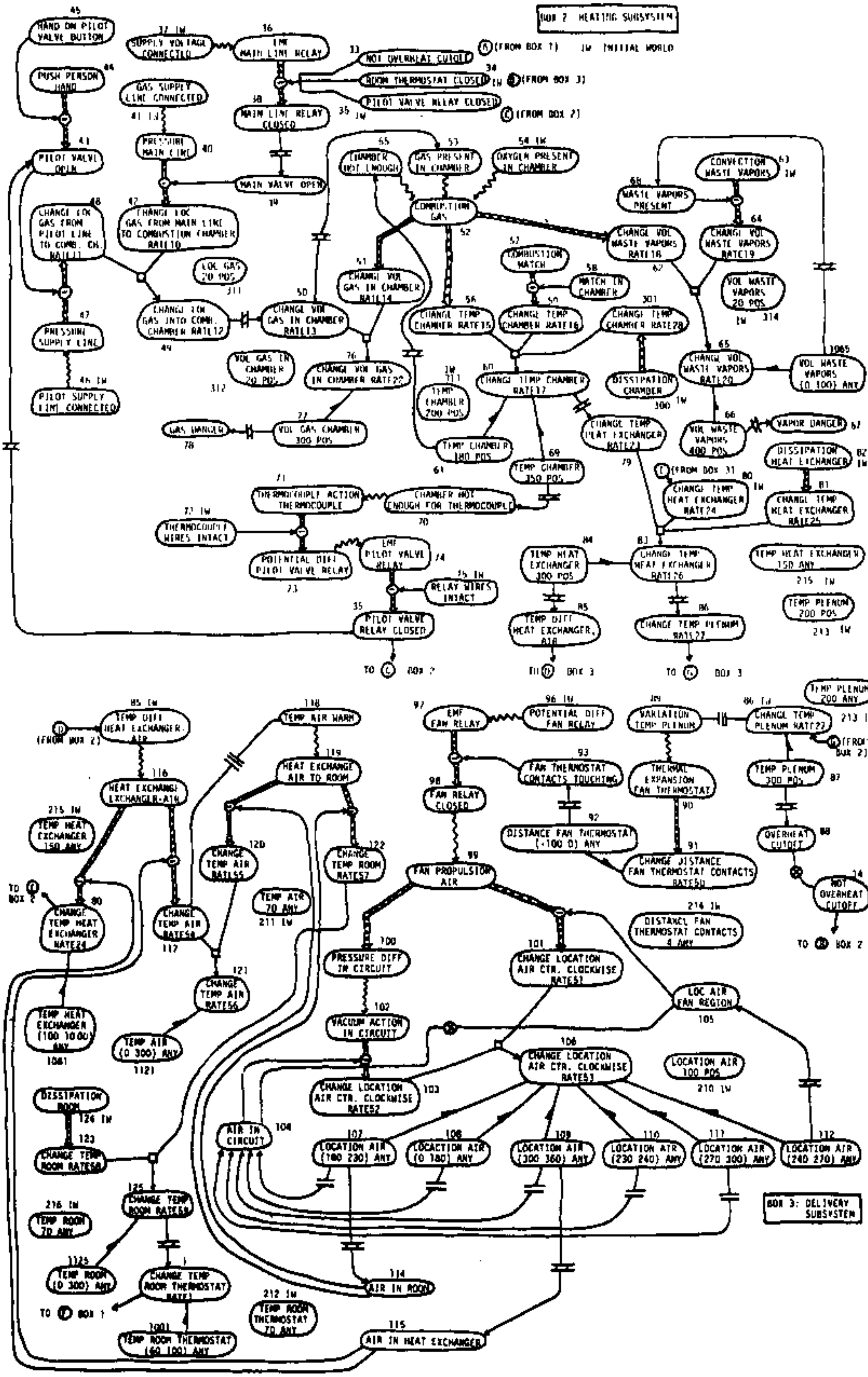
BOX 2 HEATING SUBSYSTEM
IW INITIAL WORLD
HAND ON PILOT VALVE BUTTON
PUSH PERSON HAND
PILOT VALVE OPEN
SUPPLY VOLTAGE CONNECTED
EMF MAIN LINE RELAY
GAS SUPPLY LINE CONNECTED
MAIN LINE RELAY CLOSED
NOT OVERHEAT CUTOFF
ROOM THERMOSTAT CLOSED
PILOT VALVE RELAY CLOSED
MAIN VALVE OPEN
GAS PRESENT IN CHAMBER
OXYGEN PRESENT IN CHAMBER
COMBUSTION GAS
CONVECTION WASTE VAPORS
WASTE VAPORS PRESENT
COMBUSTION MATCH
MATCH IN CHAMBER
GAS DANGER
VAPOR DANGER
THERMOCOUPLE WIRES INTACT
RELAY WIRES INTACT
PILOT VALVE RELAY CLOSED
TEMP AIR WARM
HEAT EXCHANGE AIR TO ROOM
FAN RELAY CLOSED
FAN PROPULSION AIR
PRESSURE DIFF IN CIRCUIT
VACUUM ACTION IN CIRCUIT
AIR IN CIRCUIT
AIR IN ROOM
AIR IN HEAT EXCHANGER
LOC AIR FAN REGION
DISSIPATION ROOM
BOX 3: DELIVERY SUBSYSTEM