Flach, J. M. and Bennett, K. B. (1996). Graphical interfaces to complex systems: Separating the wheat from the chaff. In G. Perlman, G.K. Green, & M. S. Wogalter (Eds.) Human factors perspectives on Human-Computer Interaction: Selections from Human Factors and Ergonomics Society Annual Meetings Proceedings, 1983-1994. (pp. 301-305). Santa Monica, CA: Human Factors Society. Reprinted from Proceedings of the Human Factors Society 36th Annual Meeting. Santa Monica, CA: Human Factors Society (pp. 470-474).

PROCEEDINGS of the HUMAN FACTORS SOCIETY 36th ANNUAL MEETING—1992

GRAPHICAL INTERFACES TO COMPLEX SYSTEMS: SEPARATING THE WHEAT FROM THE CHAFF

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There seems to be a clear consensus that graphical interfaces provide an opportunity to integrate data from complex process in a way that can greatly enhance the problem solving ability of human operators in the future. However, this consensus is maske by a proliferation of terms to express this position in the basic and applied research literatures (e.g., "integrality," "configurality," "proximity-compatibility," "visual momentum," "direct manipulation," and "ecological interface"). While the subtle nuances that distinguish among these terms are of academic interest, designers have greater concern for the general principles that might be gleaned from across the subtle distinctions. Base on a thorough review of the basic and applied literature (Bennett & Flach, In press), we argue that there is one basic characteristic of graphical representations that is critical for supporting problem solving. A good graphical display is one whose geometric (space/time) constraints reflect the functional constraints in the proess being represented. In this presentation, we will demonstrate what we mean by a "functional constraint" in a process and a "geometric constraint" in a display. We will demonstrate alternative mappings from "functional constraints" to "geometric constraints." We will also discuss the implications of these mappings for the type of processing (cognitive versus perceptual) required of the human operator.

Woods (1991) discusses three types of mappings from a work domain process to a display: elemental, analogical, and computational. In elemental mappings each sensor reading has an individual indicator within the display. This approach is often referred to as the "single-sensor/single-indicator" approach. In analogical mappings, the display is designed as a spatial analog to the process. This analog can emphasize the physical layout of the process (i.e., mimic displays) or it can emphasize functional constraints within the process (i.e., configural displays or ecological interfaces). Finally, in computational mappings, data is integrated by computational algorithms and the results of these computations which integrate data from multiple sensors is displayed to the operator.

In this paper, we will use a simple process to illustrate these three alternative mappings. We will illustrate why we believe that analogical mappings offer the strongest support for problem solving. In particular we will demonstrate how configural display geometries can be constructed so that "geometric constraints" reveal "process constraints."

A simple process

The process is a generic one that might be found in process control, and it is represented graphically in the lower portion of Figure 1. There is a reservoir (or tank, represented by the large rectangle in the middle of the figure) that is filled with a fluid (for example, coolant). The volume, or level, of the reservoir (R) is represented by the portion of the rectangle that contains cross-hatching. Fluid can enter the reservoir through the two pipes and valves located above the reservoir; fluid can leave the reservoir through the pipe and valve located below the reservoir.

To complete tasks in complex, dynamic domains observers must consider information regarding both "higher-level properties" (e.g., status of processes) and "lower-level data" (e.g., output of sensors). The term low-level data refers to the measured values of individual process variables. In contrast, the term higher-level properties refers to relations that exist between these process variables. For example, a simple relationship might be the measured value of a variable compared to the goal for that variable. A more complex relation might require a number of variables to be considered (e.g., mass balance). In any complex system there will be a continuum of increasingly complex relations (properties, or constraints) that, by definition, will characterize alternative system states. We use the terms high-level properties and low-level data as endpoint labels that refer to this continuum.

Low level data (process variables). There are two goals associated with this simple process. First, there is a goal (G1) associated with R, the level of the reservoir. The reservoir should be maintained at a relatively high level to ensure that increases in demand (the required output flow rate, O) can be met. The second goal (G2) refers to the output flow rate that must be maintained in order to meet an external demand. These goals are achieved and maintained by adjusting three valves (V1, V2, & V3) that regulate flow through the system (I1, I2, & O). Thus, this simple process is associated with a

Sample Process

Low Level Data
(Process variables)

T = Time
V_1 = Setting for Valve 1
V_2 = Setting for Valve 2
V_3 = Setting for Valve 3
I_1 = Flow rate through Valve 1
I_2 = Flow rate through Valve 2
O = Flow rate through Valve 3
R = Volume of reservoir

G_1 = Volume goal
G_2 = Output goal (demand)

High Level Properties
(Process constraints)

$K_1 = I_1 / V_1$, $K_2 = I_2 / V_2$, $K_3 = O / V_3$: Relation between commanded flow (V) and actual flow (I or O)

$K_4 = \Delta R / (I_1 + I_2) - O$: Relation between reservoir volume (R), mass in ($I_1 + I_2$), and mass out (O).

$K_5 = R / G_1$, $K_6 = O / G_2$: Relation between actual states (R, O) and goal states (G_1,G_2)

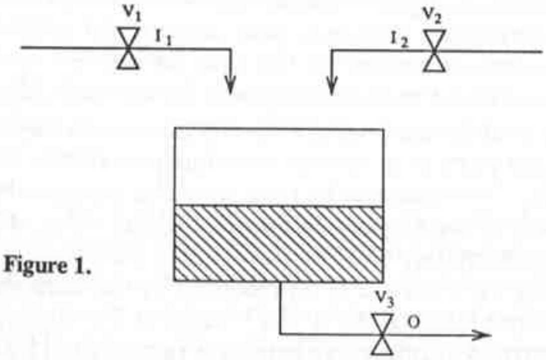

Figure 1.

number of process variables that can be measured directly: these low-level data are listed in the upper, left-hand portion of Figure 1 (V1, V2, V3, I1, I2, O, G1, G2, & R).

High-level properties (process constraints). In addition, there are relationships between these process variables that must be considered when controlling the process. The most important high-level properties are goal-related: Does the actual reservoir volume level (R) match the goal of the system (G1)? Does the actual system flow rate (O) match the flow rate that is required (G2)? An alternative way of conceptualizing these high-level properties is as "process constraints." For example, consider the relationship between R and G1. When the actual reservoir volume (R) equals the goal reservoir volume (G1) the ratio of these two values will assume a constant value (1.00). This process constraint is represented by the equation associated with the higher-level property K5 in Figure 1. All the constraints will be satisfied if the process is being controlled in a proper fashion.

Even for this simple process some of the constraints or (high-level properties) are fairly complex. For example, an important property of the system is mass balance. The mass balance is determined by comparing the mass leaving the reservoir (O, the output flow rate) to mass entering the reservoir (the input flow rates of I1 & I2). This relationship determines the direction and the rate of change for the volume inside the reservoir (ΔR). For example, if mass in and mass out are equal then mass is balanced, then ΔR will equal 0.00 and R will remain constant.

Controlling even this simple process will depend upon a consideration of both high-level properties and low-level data. As the previous example indicates, decisions about process goals (e.g., maintaining a sufficient level of reservoir volume) generally require consideration of relationships between variables (is there a net inflow, net outflow, or is mass balanced?), as well as the values of the individual variables themselves (what is the current reservoir volume?).

Mapping: Elemental, Analogical, Computational

Figure 2 shows six different graphic displays that represent alternative mappings for the process shown in Figure 1. At the right of each display is a listing of the process information which is placed into two categories (P & D). Variables and relationships that are directly represented in the display (that is, which can be "seen") have been placed in the P category (Perceived). If the information is not directly represented, and must be computed or inferred, it is placed in the D category (Derived). Information about physical structure is represented by the theta symbol (ø). Information about functional structure is represented by the symbol (∫).

Elemental mappings. Figure 2(a) illustrates a simple elemental mapping in which there is a single display for each individual process variable present. Each display is represented in the figure by a circle, but no special significance should be attached to the symbology: the circles could represent digital displays, bar graphs, etc. In this display there is not likely to be a selective attention cost for low-level data: individual variables are directly represented in the display. However, there is likely to be a divided attention cost. Although the low-level data has been provided, it is up to the observer to derive the high-level properties. For example, to determine the direction (and cause) of ΔR would require detailed internal knowledge about the process, since no information about physical relationships (ø) or functional properties (∫) are available in the display.

Simply adding information about high-level properties does not change the separable nature of the display. In Figure 2(b) a second elemental mappng has been illustrated. In this display the high level properties (constraints) have been calculated and are displayed directly (e.g., K1 through K6) This does off-load some of the computational

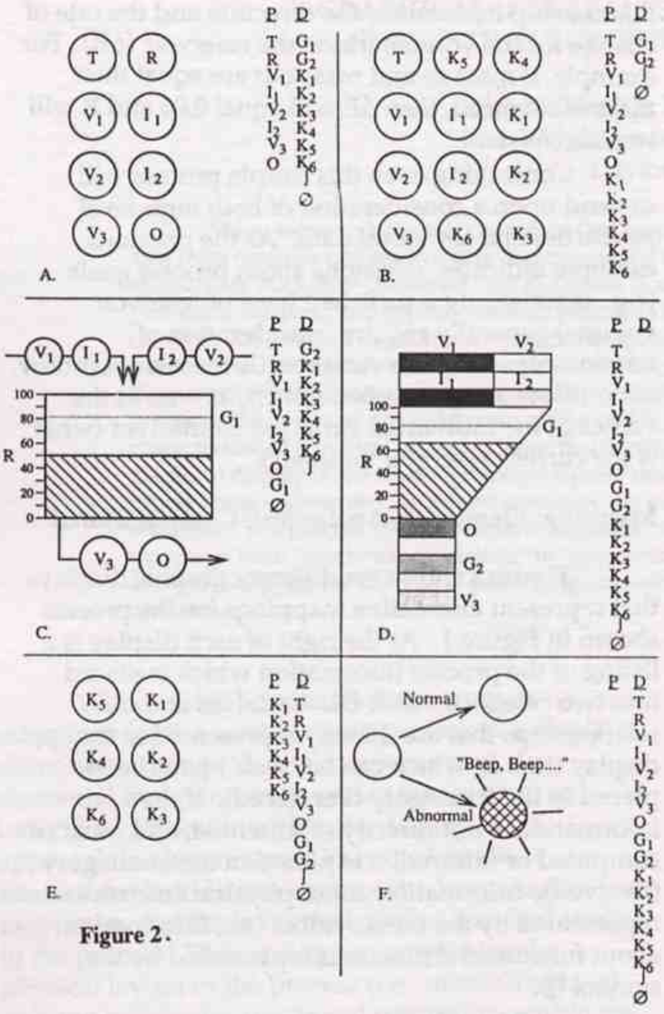

Figure 2.

requirements (e.g., ΔR). However, there is still a divided attention cost. Even though the high-level properties have been calculated and incorporated into the display the relationships among and between the information is still not visible. The underlying cause of a particular system state still must be derived from the separate information that is displayed. Thus, while some low level integration is accomplished in the display, the burden for understanding the causal structure rests in the observer's stored knowledge.

Analogical mappings. The first analogical mapping, illustrated in Figure 2(c), provides a direct representation of much of the low-level data that is present in the display in Figure 2(a). However, it also provides additional information that is critical to completing domain tasks: information about the physical structure of the system (ø). This "mimic" display format has been used successfully in STEAMER (Hollan, Hutchins, & Weitzman, 1984). This visual model of the physical structure allows the observer to "see" some of the logical constraints that link the low-level data. Just as in the displays listed in Figures 2a and 2b, there is not likely to be a cost in selective attention with respect to the lower-level data. However, although information about physical structure illustrates the logic of higher-level properties or system constraints, the burden of computation (e.g., determining mass balance) rests with the observer.

The second anological mapping, illustrated in Figure 2(d), is slightly more complex (the logic is similar to Vicente, 1991). The valve settings V1 and V2 are represented as back-to-back horizontal bar graphs that increase in width with increases in the valve settings. The measured flow rates have the same configuration of graphical elements and are located below the valve settings in the display. The horizontal bar graphs depicting valve settings and flow rates for a particular pipe (e.g., V1 & I1) are connected with a line (in this case the line is perpendicular to the settings and flow rates). The volume of the reservoir (R) is represented as the stippled portion of the intermediate part of the display. Its value can be read from the scale on the left side of the display; in Figure 2(d) the value of R is approximately 68. The flow rate of the mass leaving the reservoir is represented by the horizontal bar graph labelled "O" at the bottom of the display; the corresponding valve setting is represented by the bar graph labelled "V3." The mass output goal (G2) is represented by an additional horizontal bar graph. All three of these bar graphs are connected by vertical lines as in the case of the mass input settings and flow rates. The relationship between mass in (I1 + I2) and mass out (O) is highlighted by connecting the horizontal bar graphs corresponding to these data. In effect, the orientation of the line represents the mass balance of the process. In Figure 2(d) the line is oriented at approximately 45 degree angle. This orientation would indicate that there was a net inflow. This configural display, while not a direct physical analog, preserves important physical relations from the process (e.g., volume & filling). In addition, it provides a direct visual representation of the process constraints and connects these constraints in a way to make the "functional" logic of the process visible (∫). In addition, all of the low level data is available as well defined elements within the geometric form. This display will be discussed further in a subsequent section.

Computational mappings. Figure 2(e) shows a computational mapping in which each of the process constraints are precomputed and shown directly. However, with this representation, low-level data must be derived. Finally, Figure 2(f) shows the logical extreme of this continuum. In this display, the process variables and constraints are integrated into a single "bit" of information, that indicates whether the process is working properly (all constraints are at their designed value) or not. It should be obvious that while this display has no divided attention costs, it provides little support for problem solving when the system fails.

Functional & Geometric Constraints

In the following section we will attempt to define and illustrate the concepts of "functional" and "geometric" constraints in terms of the simple process illustrated in Figure 1.

Functional constraints. The fnctional constraints of a process can be characterized using Rasmussen's (1986) abstraction hierarchy. These constraints include the functional purpose or design goals for the system. For our simple process these are constraints K5 and K6. For an actual work domain, the actual value system (costs & benefits) underlying these particular goals might be considered.

The abstract functions or physical laws that govern system behavior are another important source of constraints. In our example, K4 reflects the law of conservation of mass. Change of mass in the reservoir should balance with the residual mass in or out. K1, K2, and K3 represent the mass flow. Flow is proportional to valve setting (this assumes a constant pressure head). Further constraints arise as a result of the generalized function (sources, storage, sink). In our example, there are two sources, a single store, and a single sink. Also, the physical processes behind each general function represents another source of constraint. Two feedwater streams, a single output stream, a reservoir for storage. Finally, the physical form, what's connected to what, length of pipes, position of valves on pipes, size of the reservoir, etc. Also, the moment-to-moment values of each of the variables (T, V1, V2, V3, I1, I2, O, & R) could be considered at the level of physical form.

Display constraints. Constraints in the display geometry will generally take the form of symmetries --- equality (e.g., length, angle, area), parallel lines, colinearity, or reflection. In addition, Gestalt properties of closure and good form are useful. The configural display in Figure 2(d) makes extensive use of equality, parallel lines, and colinearity. The constraint relating output to demand (K6) is represented in terms of the equality of length between the bar labelled O and the bar labelled G2. The constraints on mass flow (K1, K2, K3) are represented in terms of equality of length of the bars labelled V1/I1, V2/I2, and V3/0. Rate of change of volume is represented by the relative position between the length of I1+I2 and the length of O. This relative position is highlighted by the line connecting these bars. This line also creates a closed form creating the metaphor of containment and the shape of the closed form creates a funnel metaphor. The constraint on mass inventory (K5) is shown using relative position between the hatched area representing volume within the containment and the level marked G1.

Mapping process constraints to display constraints. The elemental mapping in Figure 2(a) shows information only at the level of physical value. This display requires the observer to take into account the higher levels of abstraction. That is, the observer must have an internalized model of the functional purpose, the abstract functions, the general functional organization, and the physical process. The elemental mapping in Figure 2(b) includes information on functional purpose (K5 & K6) and on abstract function (K1, K2, K3 & K4). However, the relations across the levels is not represented. Thus, the observer must provide the expertise necessary to integrate these isolated data. The integral display shown in Figure 2(e) has information at the higher levels of abstraction. The display does not aid the observer to relate these high levels to the physical variables. Because there would normally be a many-to-one mapping from physical variables to the higher order constraints it would be impossible for the observer to recover information at lower levels of abstraction from this display. The integral display in Figure 2(f) provides absolutely no information about the functional processes behind the display.

The mimic display shown in Figure 2(c) is an excellent format for representing the generalized functions in the process. This has many of the properties of a functional flow diagram or flow chart The elements can represent physical processes (e.g., feedwater streams) and, by appropriately scaling the diagram, relations at the level of physical form can be represented (e.g., relative positions of valves). Also, the moment-to-moment values of the process variables can easily by integrated within this representation. This display not only includes information with respect to generalized function, physical function, and physical form, but the organization provides a visible model illustrating the relations across these levels of abstraction. Thus, the current value of I2 can be seen in the context of its physical function (feedwater stream 2) and its generalized function (source of mass) and in fact, its relation to the functional purpose in terms of G1 is also readily apparent from the representation. The mimic display is likely to be a very powerful representation for controlling the process during normal operations.

What is missing in the mimic display is information about abstract function. That is, information about the physical laws that govern normal operation. This information becomes critical for detecting faults (e.g., a leak).The configural display in Figure 2(d) is an attempt to integrate information from the abstract function level with information at the other levels. In this display, the values of the process elements are represented as the height of bar graphs and the height of the filled area within the reservoir. The generalized functions are related through a funnel metaphor with input (source) at the top, storage in the center, and output (sink) on the bottom. The abstact functions are related using the equality and the resulting colinearity across the bar graphs. For example, the mass balance is represented by the symmetry between the input bargraphs and the output bargraphs with the slant of the line connecting them being proportional to rate of change of mass in the reservoir. These symmetries within the display geometry can provide a powerful representation for fault detection.

Summary

In conclusion, we would like to offer three principles for constructing analogical representations for representing functional process constraints:

1. Each relevant process variable should be represented by a distinct element within the display. If precise information about this variable is desirable, then a reference scale or supplemental digital information should be provided.
2. The display elements should be organized so that the emergent properties (primarily symmetries that arise from their interaction correspond to higher order constraints within the process.
3. The symmetries within the display should be nested (from global to local) in a way that reflects the hierarchical structure of the process.

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