Special States in Goal-Orientated and Adaptive Systems: Base for a Definition of Information

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Abstract

The paper analyzes the process of decision-making in its most elementary form as occurring in simple feedback systems. Investigating such elementary decisions it is shown that decision-making is a goal-orientated activity, requiring the comparison of incoming sensor data with an a priori given goal-value. Under certain conditions the result of such a comparison can enable a system to make a goal-orientated action. We propose a definition of information based on such results of comparisons. And we discuss the properties of information so defined and the general validity of this approach.

1. Introduction

Decisions are usually superficially understood as if - then rules, without any further consideration of the necessary content of either the if - or the when - term. We could quote many examples for that, starting in literature with Pavlov's famous experiments with dogs and stimulus - response psychology and continuing to authors dealing with artificial intelligence. Here we can just mention two:

Newell and Simon [Newell et al., 1972] speak about decisions within an "information processing system" - not further specified - that carries out „productions" of the form „condition - process", which obviously are a form of if - then rules.

But to illustrate our point in that paper we take a quote out of Holland's influential work on adaptive systems. Holland [1995] proposes, that adaptive systems must contain a "performance system" - not further specified - that is able to make decisions in the form of if - then rules. For such decisions he gives the example of a frog using the following rule for trying to catch a fly:

> "if" [object] "(moving), (small), (near),
> then (approach)".

We suggest that such descriptions of decisions as if - then rules may be a valid for many applications. But we suggest they are not sufficient to get to an in depth understanding of *how* decisions are made by deciding systems, what internal states are necessary so that a deciding system can make a decision and what kind of epistemological implications can be derived form such an understanding.

2. Goal-orientated Systems are Deciding Systems

2.1. The Course of Argumentation

Newell and Simon [Newell et al., 1972], as well as Holland [1995] place the process of decision-making into *unopened* black boxes, like many other thinkers. Newell and Simon [Newell et al., 1972] call it an "information processing system", Holland [1995] calls it a "performance system". In the following we want to introduce our approach to open such black boxes to get to an in depth understanding of decision-making. Our arguments are:

(1) There is a class of systems - i.e. goal-orientated systems - that *has to be able* to make decisions to select for any given situation a situation-specific, goal-orientated action.

(2) The most simple system of this class is arguable a feedback system like a simple regulator. So we propose that such simple goal-orientated system can reveal the process of decision-making in its most elementary form.

(3) And we propose furthermore, that all prerequisites for decision-making can be studied in its most simple form in the prerequisites that enable simple feedback systems to decide and that these prerequisites are necessary, too, for more complex goal-orientated systems to make their decisions.

Let us start to develop our argument by defining goal-orientated systems.

2.2. A Pragmatic Definition of Goal-orientated Systems

Starting point for our approach to decision-making is a very general and pragmatic definition of goal orientated systems:

A goal-orientated system is a system that has

(1) an *internally defined goal*,

(2) the *ability to observe* the actual state of a part of its environment and

(3) the *ability to act* on that part of its environment, so that certain properties of that part can at least be changed in the direction towards the goal or, ideally, correspond with the goal.

We demand (1) the goal to be *internally* defined, because we think for pragmatic reasons that the goal should be always present within the system, so that it is able to pursue that goal independently. Otherwise the system would depend on some external source to provide that goal. This would raise the question, if we could call such system to be goal-orientated by itself.

There may be goal-orientated systems that have properties (1) and (2), but not property (3). Such systems cannot make any changes in their environment towards their goal, so they will not be able to actively achieve their objective, nor will any observer of such systems ever be able to recognize them as goal-orientated. Such systems are therefore not of any practical interest.

Furthermore a goal-orientated system may have properties (1) and (3), but not property (2). These two properties will not be sufficient for the system to actively realize its goal, for it lacks any representation of the actual situation in its environment. So such a system may act on its environment, but does not "know" in any form, if its actions are appropriate for the given situation, i.e. if they have a goal-orientated effect.

For these pragmatic reasons we will focus on goal-orientated systems that have these three basic properties. So for our investigation we can say:

A goal-orientated system is an observing system and an acting system.

Our decisive point to deal with goal-orientated systems is that we propose that there are necessary relations between these three properties, i.e. how observations have to be related to goals so that a goal-orientated system can actually realize goal-orientated actions. And we propose that these necessary relations characterize the process of *decision-making*.

2.3. Turning to the Most Simple Goal-orientated Systems

To start analyzing this process of decision-making in its most elementary form, i.e. how goal-orientated systems actually relate observations to goals so that they can cause goal-orientated actions, we turn to the most simple goal-orientated systems. These are arguable simple feedback systems, like a temperature regulator.

An analysis how feedback systems make decisions can reveal *functional and structural prerequisites* for decision-making and the *necessary content* of decisions. In this paper we can just focus on this necessary content.

3. Elementary Decisions of Simple Feedback Systems

Best known examples for simple feedback systems are temperature regulators. They are available in many technical forms, measuring and processing temperature data e.g. mechanically or electronically. But whatever the technique used, the system must be able to make two decisions using two decision-rules of the following form:

> if {(actual temperature) < (set point)},
> then {trigger heater on},
>
> if {(actual temperature) ≥ (set point)},
> then {trigger heater off}.

We propose that such decision-rules, so easily revealed by analyzing feedback systems, are the most simple decisions that can be made. Therefore we propose to call them elementary decisions. In the following we will start an in depth analysis of such elementary decisions and the far-reaching epistemological consequences thereof.

4. Content and Basic Properties of Elementary Decisions

We will now generalize what we have found in temperature regulators about elementary decisions, and discuss their content and some basic properties:

(1) Elementary decisions require decision-rules that compare actual sensor data with goal-values and relate the result to triggers for goal-orientated actions. They have the general form:

> if {(data) (relation) (goal-value)},
> then {trigger for a goal-orientated action}.

The possible relations between data and goal-values are relations of order (like <, ≤, =, ≥, > or ≠) or some system-specifically defined, maybe fuzzy or rough, form of equivalence (≈).

So we can now say, what is missing in the if - then rule we quoted above from Holland [1995]:

> “if [object] “(moving), (small), (near),
> then (approach)”.

Holland [1995], like many other thinkers, overlooks the decisive point that all the qualities checked in this decision rule require a comparison with some standard or goal-value. “Moving” as well as “small” and “near” require some point of reference within the deciding system to distinguish them form “not yet moving”, “big” and “far away”. So we can say, that Holland’s “performance system” controlling an adaptive system like a frog must be a form of a goal-orientated system.

(2) Decisions are goal-orientated and require a predetermined, a priori given goal-value.

The first important point in our analysis of decisions is that elementary decisions are goal-orientated acts. As a prerequisite they need *predetermined, a priori given goal-values*, that must be already *available at the point of time when the decision is made*. Observations, delivered in the form of incoming sensor data, cannot be used by the system for any decision for acting until compared with such goal-values.

(3) A priori given goal-values are necessary to *fragment* a range of sensor data.

A range of sensor data, available from some sensor requires at least one goal-value to divide that range into two *fragments*. Without such fragments the system would have just one undivided field of observations. Then it could not *decide* anything. To decide it needs at least two fragments, to relate to every fragment a trigger for a different action.

(4) A decision rule of a simple regulator only *triggers* an action, but does not contain any kind of “knowledge” how that action comes about.

The processing of the sensor data of a simple regulator leads only to triggering an action, and does not and need not contain any data *how* this action is performed. There are two reasons for this:

First, a regulator only needs the ability to observe the *effect* of a triggered action, to sense *what* he controls; *how* this effect is achieved is absolutely unimportant.

And second, any representation *how* the action is achieved would require a much more complicated structure of the system.

Let us illustrate that with an example: What a temperature regulator has to “know” is the actual temperature, to compare it to the set point and to decide to turn on and off the heater. It need not know anything else about the heater. The heater is nevertheless an essential part of the device, without which no control would be possible. If we would like the temperature regulator to “know” something about the heater we would need *additional* and *different* sensors, than just for observing the actual temperature. These sensors would have to be able to observe states of the heater, additionally to observing the room temperature. This would probably require an observation of *other* physical quantities. And to deal with these data we would need some additional, more complex structure for data processing, too.

(5) In goal-orientated systems *one specific* decision-rule is needed for *every* action triggered.

In the previous points we have shown, that a comparison of incoming sensor data and goal-value is needed, so that the system can choose a goal-orientated action. Expanding on that, we can say, that *every* goal-orientated action of a goal-orientated system requires such a comparison as input in a decision rule. And furthermore *every* goal-orientated action of a goal-orientated system requires exactly *one* specific decision-rule.

Without such decision-rules a system may be able to observe and may be able to act in some arbitrary way. But unless it has not only sensor data, but *additionally* goal-values to compare the two and thus generate fragments of the range of sensor data *and additionally* can *connect* the results of these comparisons with triggers for goal-orientated actions, it will not be able to influence a given situation towards a goal.

We propose that the statements (1) to (5) derived from the analysis of simple feedback systems hold in principle for all decisions, even when more complex than elementary, and for all goal-orientated systems - from regulators to computers and from the first forms of life to human brains. We will touch that point in the discussion below.

5. Prerequisites for the Comparison of Data

We suggest that the term {(data) (relation) (goal-value)} is usually totally overlooked when decisions are analyzed just as if - then rules. So we will focus here on that term.

We begin with the prerequisites that have to fulfilled so that a comparison of data and goal-values becomes possible and leads to results that can be used for *feedback* control:

(1) Sensor data and goal must be available as physical states of the *same physical nature.*

To all our knowledge it is only possible to process together and compare data that are provided in the same physical states. (E.g. we can only compare temperature data represented electrically, e.g. in mV, with each other; we cannot compare them directly with data represented mechanically, e.g. in mm Quicksilver column.)

(2) Sensor data and goal must be available as same physical states mapped in the same way in the same range of magnitude, i.e. in the *same data format.*

Given two data as physical states of the same nature we are able to compare them. But they have to have the same mapping and the same order of magnitude, so that a comparison delivers undistorted results. (E.g. if some set point for a temperature is represented electrically in the V range, but all sensor data are represented in the mV range, a comparison is physically possible. But it will deliver the systematically distorted result, that all sensor data, whatever temperatures they stand for, are smaller than the goal-value.)

(3) Sensor data and goal must be a *representation of the same external state* of a controlled system so that the result of the comparison has a relation to the external world.

For example if we have temperature and humidity data represented in the same data format in an air conditioning system, we could easily compare them. But what kind of advantage could result out of a comparison that a datum for temperature is greater than one for humidity? A system trying to *use* this kind of comparisons for actions is simply *mad*. (Of course the same holds for man: We cannot and need not compare if the red of the flower is more intense than the sound of the wind.)

We call the first two properties *uniform representation* and the third *corresponding representation*. And we propose that these are the general minimal requirements that two sets of data are comparable. (Let us mention here, that there are more criteria for corresponding representation for systems more complex than simple feedback systems.)

6. A Definition of Information

We propose that the importance of the term {(data) (relation) (goal-value)} for decision-making justifies to use it for defining information. We will elaborate our arguments for that in the next section. Here we want to introduce our cybernetic definition of information:

Information results from the comparison of two comparable sets of data. Therefore information has the general form

{(data set 1) (relation) (data set 2)}.

Two data sets are comparable if they are available in uniform and corresponding representation.

The requirements of uniform and corresponding representation for simple feedback systems, as discussed above, are that (1) sensor data and goal must be available as physical states of the same physical nature, (2) that sensor data and goal must be available as same physical states mapped in the same way in the same range of magnitude (i.e. in the same data format) and (3) that sensor data and goal must be a representation of the same external state of a controlled system. (The requirements for corresponding representation have to be expanded for more complex systems.)

Only if uniform and corresponding representation are maintained in a system (1) a comparison of sensor data and goal is physically possible, (2) such comparison will be undistorted and (3) the result of such comparison will have a meaningful relationship with an external controlled system.

The possible relations between data sets, that constitute information, are relations of order (like $<$, $\leq$, $=$, $\geq$, $>$ or $\neq$) or some system-specifically defined, maybe fuzzy or rough, form of equivalence ($\approx$).

Data sets that lead to information can be single data or signs, or sets, patterns or even sequences of signs. Data sets that are hold constant over some period of time we call *goal-values* or *standards*.

7. Properties of Information

The results of comparisons {(data) (relation) (goal-value)} are delivered within a goal-orientated system as special states that represent some external state and are necessary to trigger goal-orientated actions. We continue now discussing some properties of these internal states. These properties seem us to justify calling these states information. Yet we want to emphasize that these properties exist independently if one wants to follow our definition of information or not.

7.1. The Enabling of Decisions

The following properties of information follow immediately from our analysis of elementary decisions above:

(1) Comparisons {(data) (relation) (goal-value)} mark a *fragment of the range of sensor data*. So here we deal not any longer with data, as delivered by a sensor (e.g. mapping external temperature in “mV”). The result of such a comparison (e.g. of two data in “mV”) is a special internal state within the goal-orientated system that characterizes a current *state* of an *external* system. E.g. in a temperature regulator the range of sensor data is divided into the two fragments representing “cold” and “hot”.

Now we propose to call such internal states representing external *states* (like “cold” or “hot”): information.

(2) Such fragmentation of the range of sensor data is necessary, so that the system can relate to every fragment a different goal-orientated action.

Just let us consider briefly, what would happen without such fragmentation: Then the system would have to work like a channel, and relate to every input datum an output action. And it would lack any point of reference when to cause actions with *opposed* effects as necessary for control (e.g. like “heater on” respectively “heater off” in temperature control).

Therefore we can say: *Information enables decisions for goal-orientated actions - but data don’t.*

7.2. The Impossibility of Transmission to Different Physical Carriers

Now we come to an important and really surprising property of that internal state resulting from a comparison of data. This state is definitely only available internally, within a system, as a special state of a certain physical nature within a certain structural context. It cannot be transmitted to another system by transformation into only one state of another physical nature. What we say is: *Information - according to our definition - cannot be transmitted when a change of the physical carrier is necessary.*

Let us try to explain this point in detail:

(1) The result of a comparison of two data can be used in a decision rule to select and trigger some action. It is not the condition of the physical state itself that makes up an information, but the physical state within the structure of a system and within a decision rule in that system. When the triggered action has been carried out, the result is an external change of some state of a controlled system - an external difference or an external datum - but not an external information.

Observing this external action respectively change is not enough, to know the internal information causing it. E.g. a temperature controller heats as long as it generates internally the information "cold" (i.e. actual temperature < set point). To find out what such system internally considers as "cold" it is necessary to observe, too, when it starts and / or ends that external action.

So a *single external observation* - one single datum - is not enough to find out what single state another system uses internally as information: We need observations of actions and changes of actions for that.

(2) A *single internal measurement* is not sufficient, too, to characterize a state of information in another system:

For example in a bimetal temperature regulator a bimetal disc pops up in a defined direction, if the temperature falls below the set point. So in this simple system the information "cold" (i.e. actual temperature < set point) is represented *mechanically*.

Let us suppose we want to use this information to *electrically* turn on or off a heater. We can achieve that for example by electrically measuring the position of the bimetal disc. But this electrical measurement delivers only *data* of the current position of the disc but *not the information* if this position stands for "hot" or "cold" within the mechanical system. To get from these electrical data to the electrical information "cold" we need of course some electrical goal-value and a comparison of the two. So we need an electrical regulator to determine the relation between the position of the bimetal sheet represented in a signal in mV and the goal-value in mV to electrically operate the heater accordingly.

The same holds for much more complex systems like neural nets: In neural nets incoming data are fed into an input layer and are *compared* with some trained standards - a form of necessary, a priory given goal-values - in a hidden layer. The comparison of input data with the standards delivers some system-specific output, either as a signal at one of various output lines in the net, or as signal of a certain strength in a single output line. Again just the measurement of such output signal alone, i.e. measuring a change at one certain location or some certain value in an output line, delivers only data. These data alone are not enough to reconstruct the information these changes in a location or an output line represent for the system, e.g. if they represent (input data = standard) or (input data ≠ standard).

These two points with the related examples may suffice to illustrate that information, as we define it, cannot simply be transmitted to another physical carrier. So to find out from the outside, what kind of information a system uses internally to cause its actions, requires a lot of observation and data:

(1) Either we can observe the behavior and changes in behavior and conclude that the system has reached a goal-value when a change occurs. Than we can conclude furthermore that any observable constant behavior from start to end is caused by some internally constant state, i.e. an information representing a constant relation of sensor data to a goal-value.

(2) Or we have to open up the system and have to find out how its input data are processed internally, to which goal-values they are compared and how the results are used in decision-rules to trigger certain actions.

In both cases we need a lot of data to characterize from the outside, what system-internally is just one single state within a certain decision-rule and an unequivocal structure, but can as such represent some external state and cause an action. We propose to call these internal states: information.

8. Discussion

8.1. General Validity

We propose that our statements about decisions and information derived from the analysis of simple feedback systems hold in principle for all goal-orientated systems - from regulators to computers and from the first forms of life to human brains. We can here just outline how these principles build the very core of every decision-making even in complex systems:

(1) A priori given internal goal-values are generally necessary to evaluate incoming sensor data. Here we can just briefly illustrate that point using our above examples of the feedback system, the frog and the neural net:

(1.1) These goal-values can be built into the structure of the system (as "hardware"), as in a mechanical temperature regulator.

(1.2) Or goal-values can be preprogrammed in the memory (as "software"). This seems to be the case in an adaptive system, like the frog. The work of Lettvin et al. [1959] shows how a frog preprocesses the sensor data from its eye to enable especially the detection of small moving objects as points in the visual field and of large objects covering an area of that field. Lettvin et al. [1959] do not deal directly with goal-values nor decisions for actions, i.e. how detected points and detected large objects are finally distinguished to cause different actions. But there work seems to suggest that a preprocessing of sensor data is used to enable a relatively simple definition of goal-values and a simple comparison process to enable fast decisions for crucial actions (like jump for food or jump to flee).

(1.3) Or goal-values can be acquired - learned - by the system and stored in its memory by itself (as “software”). This is the case in neural nets. And it seems to apply to the human brain as well. For illustration we can here just refer to the extensive work of Grossberg (see [Grossberg, 1980] for an introduction). Grossberg shows how a repeated input of the same sensor data leads to traces in long term memory. And with every further input of sensor data corresponding with already stored data occurs an “adaptive resonance”, confirming the *relationship* of identity (“=” or at least “≈”) between the input data and the stored standard and, at the same time, reinforcing the already existing traces in the memory. So here, too, we find a *comparison* of input data with standards yielding states of information as we define it.

(2) So we seem to find generally that incoming sensor-data are compared with appropriate goal-values. We propose that the compared data have to be available in uniform and corresponding representation, so that the results of such comparisons can lead to information that can be used for decisions for goal-orientated actions.

(3) The results of such comparisons - information - are special states, which are necessary as inputs in decision-rules stored in the system.

(4) Decision-rules relate comparisons of sensor data with goal-values - information - to triggers for goal-orientated actions. In complex systems more than one information may enter a decision-rule according to the form (as in our example of the frog)

if {(data 1) (relation 1) (goal-value 1),
(data 2) (relation 2) (goal-value 2), ...},
then {trigger for a goal-orientated action}.

(5) Exactly one stored decision rule is necessary for every single action of a goal-orientated system. Without such decision-rules a system may be able to act in some arbitrary way, but cannot repeatedly and constantly act in a goal-orientated way.

(6) Like the goal- values, decision rules are either built in the structure of the system (as “hardware”) or are pre-programmed in the memory (as “software”) or are acquired - learned - by the system and stored in its memory by itself (as “software”).

8.2. Epistemological Importance

Finally we want to point out the epistemological importance of our analysis of elementary decisions leading us to the insight, that elementary decisions are goal-orientated activities. We found:

(1) Prerequisite for decisions are *internally a priori given goal-values, representing some preferred external state*. These goal-values must be already available at the point in time when a decision is made.

(2) Then incoming sensor data, *mapping* some actual external state, have to be compared with such given goal-values. The result of such a comparison - we propose to call it information - is the necessary input for making a decision.

We consider these statements as statements of utmost epistemological importance: thus decision-making requires a representation, delivered by sensors, mapping actual external states, and internally an a priori given goal-value, for evaluating this representation. We consider these statements as starting point for an epistemology, rooted in science and demanding a position between realism and constructivism. Perceptual realism emphasized the necessity of mapping external states and neglected the internal evaluation of these mappings. Constructivism on the other hand overemphasizes internal constructions and may even tend to neglect the necessity of mappings. Our cybernetic analysis of the necessary content of decisions of goal-orientated systems shows that both - mappings and internal goal-values - are absolutely necessary for decisions for goal-orientated actions.

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