A Computational Model for Information Value

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Abstract

The estimation of information value will be a key issue for upcoming intelligent information systems, that not only provide information on request but deal with time-dependently varying information needs. Due to its subjective nature, information value cannot be computed and each individual has a different perception of what exactly is relevant to him.

However, we propose a concept of information value and a computational model for its estimation. Our model is based upon the observation that information concerning the future can easily be divided into relevant and irrelevant information as long as the future is deterministic and well known.

We use a network representation of uncertain quantities to model the uncertainty of the future. Information value is introduced as the likelihood of reaching a situation in the future where the information is relevant. The approach is demonstrated for the modelling of individual travel planning.

keywords: network representation, uncertain quantities, information value

1 Introduction

The term *Intelligent Information System* has been widely used to refer to information systems, that exhibit intelligent or user-friendly behaviour. However, *intelligence* can be understood in many different ways. Our concern is the timing of information flow. The following categories of information systems can be distinguished with respect to this aspect:

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Conventional Information Systems Conventional information systems typically provide information, that is already available at the moment of request. Thus, requests are posed when the value of information is sufficient to the user and will be answered by the system as soon as possible. The user is responsible for regulating the information flow.

Alerting Systems Recently, alerting mechanisms and formalisms have been introduced to enable information systems to actively deliver new information to those users that will consider such information to be of high value. A general overview of alerting systems is given in [HF99].

Proactive Information Systems While the notion of proactive information systems is not established yet, it can be thought of as a more complex form of an alerting system, where the information value and its dynamics will be observed and can be used to find the optimal point in time for information delivery.

Intuitively, we judge an information to be right in time, if it is useful for some task at hand. If information is not right in time, it can be irrelevant (wrong content), too late or too early (wrong time). One of the major reasons for information to be too early is due to plan changes. If scheduled tasks of the future are replaced due to plan changes, early information may turn out to have wrong content in the end.

We are well aware, that the goal of providing information right in time is complex and has been tackled by the artificial intelligence community for more than two decades. Therefore, we spezialize our research question to a very specific partial problem that has received few attention and may serve as a brick in building an intelligent digital world.

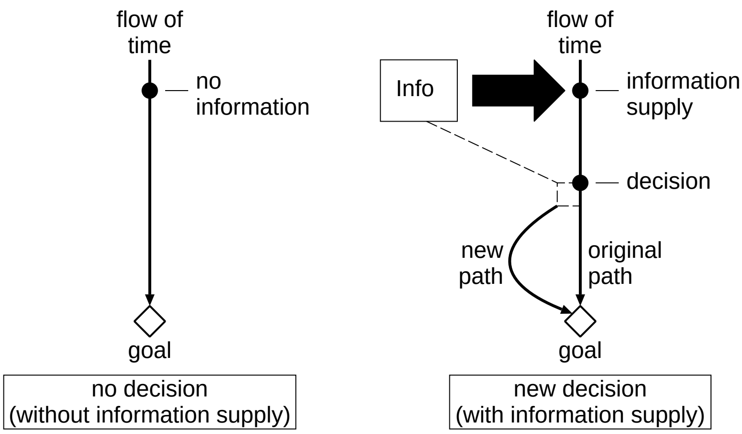


Figure 1: Information for planning

Figure 1 sketches the basic idea of our notion of information value. We regard information for planning and assume that the supply of additional information results in additional plan alternatives (or decisions). Decision support is clearly an issue but will not considered here.

The information value of additional information is to be used in the decision about information supply and should cover the following intuitive aspects, whose evalution we try to achieve.

Information Applicability as being a measure for the applicability of the information. (Question: Is it possible to apply the information?)

Information Goal-Orientation as being a measure for the benefit of information application with respect to a given objective. (Question: Is the application of the information useful?)

Regarding figure 1 again, *information applicability* translates into the likelihood of the decision to occur and *information goal-orientation* translates into the likelihood of achieving the goal after information application.

The rest of the proposal will focus on a computational model for the maintenance and analysis of temporal uncertainty in plans. Even though our approach applies generally to plan-related information, our ideas presented here are concretized for the modelling of individual travel planning.

The paper is structured as follows. In section 2 a terminology is introduced. Based on that, we present our preliminary ideas on

- the relevant temporal and structural aspects to be modeled,
- the network representation for dynamic update of temporal uncertainty and
- the application of the model

in section 3. Section 4 gives a short overview on other approaches to the modeling an application of *information value*. Finally (section 5), we present a sketch of further research plans.

2 Definitions

2.1 Modeling of Processes

From a human modelers perspective, processes may be described in a number of application-oriented concepts such as *departure from* ... , *arrival at* ... and *riding train no.* ... . A variety of abstract representations of such concepts and their temporal relationships have been developed in many different research communities such as *(object-oriented) modeling* (comp. cf. State Charts [Har87]), *simulation* (comp. [Fis73]) or *artificial intelligence* (comp. [HHP93] for an overview).

We will base our model upon the notion of events. An *event* is a occurence of something at some point in time and space. An event does not have a duration. Events are not restricted to state changes. That is, an event may serve as an anchor in time and space and it is well possible that no state change is involved with the occurence of an event, even though this seems to be counterintuitive.

Movement is modelled as a sequence of event's such as *arrival*, *departure* or *entering a vehicle*. Every movement is associated to a physical object of interest.

Adopted from the abovementioned research areas, we will use the following temporal concepts throughout this article.

Event An event is a primitive without duration. It is used to model real-world actions or events, that do not consume time or where time consumption is not relevant. In a model of movement, events may be used to represent *departure*, *arrival* or *enter vehicle* resp. *leave vehicle*.

Location in time and space An event can be located in time and space by mapping it to an point in time and to a place.

Epoch An epoch represents the interval between two events. Thus, an epoch has a duration. Epochs are not located in time and space. Concepts like *movement* or *waiting* adhere to epochs between events.

Location in time and space An event can be located in time and space by mapping it to an point in time and to a place.

Process A process is a collection of events that are possibly ordered and located or constrained in time and space.

Movement Movement is a special process, consisting of events located in time and space and bound to a specific object.

Plan A plan is a specification of a future process.

2.2 Uncertain Quantities

Plans are never certain or completely specified. This is partly due to the uncertain nature of human plans and partly due to the unpredictable nature of external events. The following types of uncertain quantities seem to be relevant.

Uncertainty of occurence will be used for the modeling of alternatives. In plans, different possible movements are represented by a tree structure (left-linear *next*-relation). Uncertainty of occurence reflects the likelihood of an event to occur. Subsequent events have the same likelihood of occurence unless alternatives (branching) or uncertain dependence is to be modelled.

Uncertainty in timing reflects the timing of an event or, alternatively, a duration. We distinguish bounds, discrete distributions and density functions for timings and durations. However, bounds will not be modelled explicitly. Instead, we assume equal distribution over the temporal interval given by bounds.

Clearly, there is a number of relationships between uncertainty in timing and uncertainty of occurence, especially when more than one physical object of interest is involved into a plan. This will be discussed in section 3.2.

3 Our Approach

Both the basic idea and methodology of our work is sketched in figure 2. We want to use expert knowledge on *uncertainty in plans* in order to derive knowledge on *information value*. Intelligence is brought to our approach by an appropriate computational model.

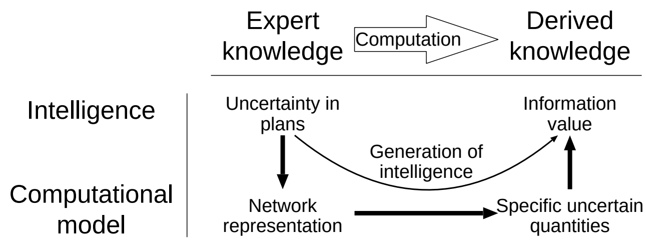


Figure 2: Intelligence through computation

In the sequel, we

1. model the plans of our application domain with a graph notation,
2. represent knowledge on *uncertainty in plans* in a *network representation*, expressing also the computational relationships between uncertain quantities and
3. develop a metric for the indication of *information value*.

3.1 Graph Notation

For the representation of plans and their interaction, a graph notation will be employed. Events are represented by nodes and their temporal or causal order is represented by arcs. An example is given in Figure 3.

Events are uniquely identified by their name, incorporating also the place of occurrence. The point of time at which an event occurs is not shown and regarded as a uncertain quantity. However, an event is optionally labelled with time bounds to constrain the desired range of time.

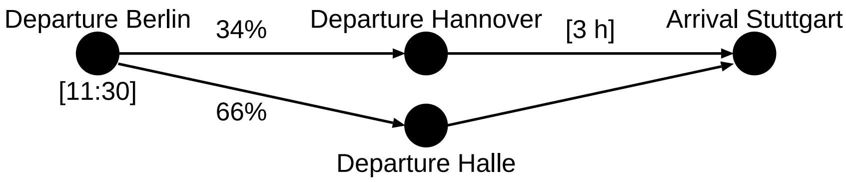


Figure 3: Event structure

Constraints on the relative temporal distance between two events are written as durations in square brackets.

Alternatives are labelled with a constant quantity in $[0, 1]$, representing the likelihood of that path. The sum of the likelihood of all paths emerging from a single event cannot exceed one. Alternatives can meet again at a later point in time, as depicted.

A basic reason for the failure of plans is due to failure of synchronisation. Here, synchronisation is the information process leading to synchronous events, i.e. events of different physical objects with similar temporal and spatial location. Synchronous events of different physical objects do represent physical meeting of objects like individuals or vehicles.

There are different types of synchronisation according to the interaction of the participating objects. So far, we want to distinguish

Balanced synchronisation Here, further processing (resp. action in case of individuals) of both participants strongly depends on whether or not the physical meeting occurs. Therefore, the process of synchronisation is a balanced negotiation. An example is the situation of two people dating for dinner.

Unbalanced synchronisation Here, further processing of one of the participants does not depend on whether or not the physical meeting occurs. Therefore, the process of synchronisation is based upon a unidirectional information flow from the undependent participant to the dependent participant. An example is the situation of an individual that plans to catch a train.

Only the case of unbalanced synchronisation will be considered here and is sketched in Figure 4. Synchronization is provisionally visualized by connecting synchronous events of different objects, namely train and individual, by thick vertical arrows that depict start and end of dependent movement. Departure and arrival times of the train are given in square brackets.

3.2 Computational Network Model

So far, we introduced a graph notation for the study of uncertain movement. Now, we want to introduce a computational network model for the relation-

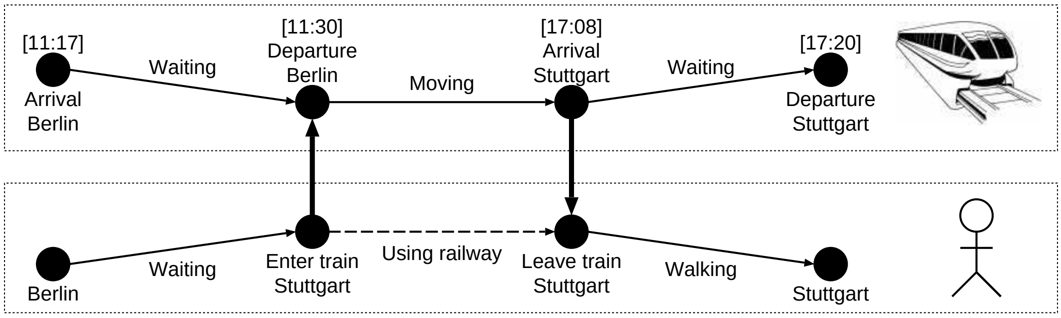


Figure 4: Synchronisation event

ships between uncertain (temporal) quantities. The notation of the network model has been inspired by influence diagrams (comp. cf. [Sha87]).

We distinguish the following types of *nodes*:

Time nodes (T) represent a uncertain timing T.

Likelihood nodes (L) represent a Likelihood L.

Event nodes (T, L) represent an uncertain timing T together with a likelihood (of occurence) L for a specific event. While more than one node may describe a single real-world event representing the fact of alternating path's leading to the same real-world event, the total sum of the likelihood on all path's is always less than or equal to one for a single real-world event.

Duration nodes (L) represent a uncertain duration D for given or known temporal distance between events.

A number of operations have been identified to be useful for the modeling of individual travel plans and will be presented in the sequel.

Figure 5 depicts the operations for the movement of a single physical object. They are discussed from left to right.

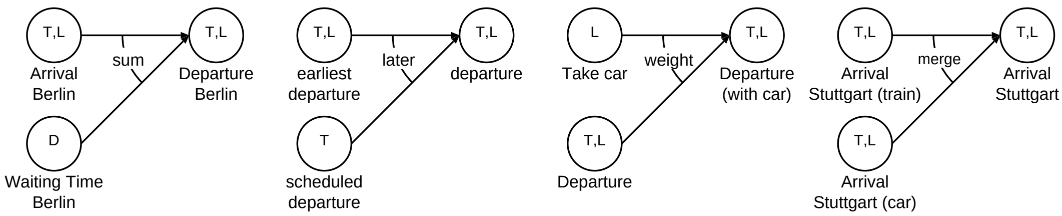


Figure 5: Propagation rules for a single physical object

Sum takes a duration node and an event node, resulting in another event node, whose uncertain timing is the sum of the uncertain timing and the duration on the input nodes and whose likelihood is copied from the input nodes. As an example, *Sum* can be used to calculate departure time from arrival time and waiting time, assuming that waiting time is independent from arrival time.

Schedule takes an event node and an timing node, resulting in another event node, whose uncertain timing is constrained to be after the uncertain timing given by the timing node. As an example, *Schedule* can be used to calculate the actual departure time of a train from the earliest possible departure event and a scheduled departure time.

Weighting takes an event node and a likelihood node resulting in an event node whose likelihood is the product of the likelihoods of the input nodes and whose uncertain timing is copied from the respective input node. *Weighting* is used to incorporate the likelihood of an alternative or a synchronisaton to occur into the dependent plan.

Merging takes two event nodes representing the same real-world event and results into one event node for both. While the path likelihood is simply added, the joint uncertain timing provides a combined picture of the point in time the event occurs. Typically, *Merging* is used when a real-world event (for instance *Arrival in Stuttgart*) can be reached on two alternative paths.

Figure 6 depicts two basic operations for the unbalanced synchronisation of several physical objects.

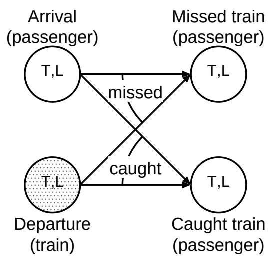


Figure 6: Propagation rules for synchronisation

Caught is a decision on a ordered pair of event nodes resulting in another event node, whose dependent uncertain timing is the uncertain timing of the second event (here: train) for the case that the first one is earlier (here: passenger caught train) and whose dependent likelihood is the product of the likelihood of the first one and the likelihood of the first one to be earlier than the second one.

Missed is a decision on a ordered pair of event nodes resulting in another event node, whose dependent uncertain timing is the uncertain timing of the first event (here: passenger) for the case that the second one is earlier (here: passenger missed train) and whose dependent likelihood is the product of the likelihood of the first one and the likelihood of the second one to be earlier than the first one.

For the scheduled departure of trains, the transformation of the graph notation into a network representation of uncertain quantities is given in Figure 7 for the example of a train arriving to and departing from Berlin. *Earliest departure in Berlin* is introduced as an additional quantity that could not be seen in the graph notation. The *Departure in Berlin* is a result of *Scheduled departure in Berlin* and *Earliest departure in Berlin*.

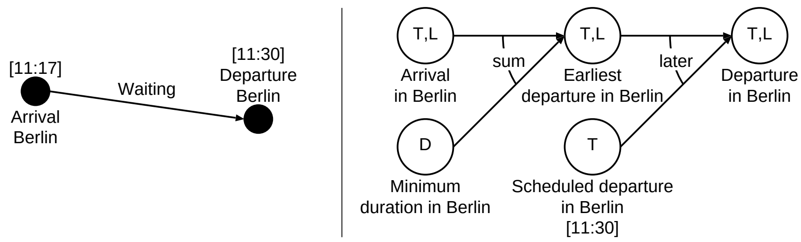


Figure 7: Network representation of scheduled movement

As another example, the transformation of an individual entering a train is depicted in Figure 8. In the case of catching, the uncertain timing of the train departure leads to a uncertain timing of the individual. For the case of missing the train, the uncertain timing of the individuals arrival in Berlin is propagated and can be used as an input for alternative plans.

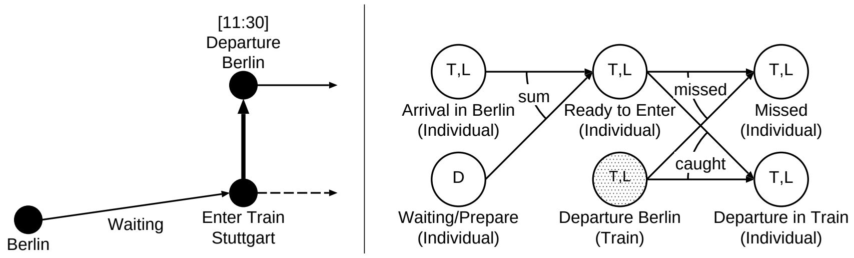


Figure 8: Network representation of unbalanced synchronisation

Other situations are transformed in a similar way. Thus, from our graph notation we receive a computational network model for the analysis of uncertain temporal quantities.

3.3 Application

The proposed model can be used for the evaluation of *information value* as being introduced in section 1. In order to demonstrate this, we employ

- An objective function, represented by a basic influence diagram (figure 9) representing the benefit of our plan with respect to the *goal* of arriving at the destination prior to a given deadline. The benefit is the likelihood of arrival at the destination with arrival time being less or equal to the deadline.

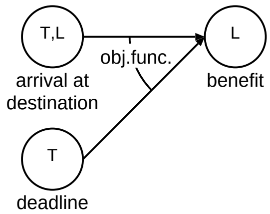


Figure 9: Network representation of objective function

- An information item, represented as a transformation of the original plan as it provides further alternatives. This representation in itself is a complicated task, since it involves a decision theoretic analysis of the decision to be taken by the individual in order to optimize the objective function. However, since our focus here is not the decision support of the individual, we assume this transformation to be given.

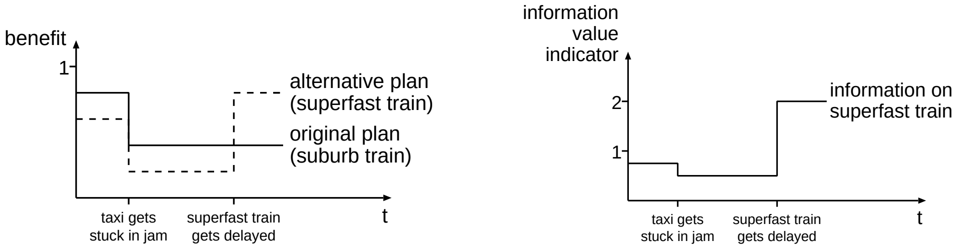
Using our network representation, the benefit of a plan can be computed and updated as the values of some input nodes evolve. For a given information item the benefit of the original plan can be compared to the benefit of the plan being transformed with respect to the additional information item. The ratio of the *benefit with information* versus the *benefit without information* is a good indicator for information value. The indicator covers aspects of

information goal-orientation directly by it's definition.

information applicability implicitly, since any transformation needs to apply the new information item in order to result in an improvement versus the case without new information.

The following szenario illustrates the effects of real-world events to our information value indicator.

> *A business man uses a taxi and is on the way to the railway station. He plans to catch a suburb train in order to get to some town for a presentation. There is also a superfast train going to the same destination, but it will leave earlier than the suburb train. The business man is late for the superfast train, but he will reach the suburb train in time. Suddenly, the taxi get's stuck in a jam (signal $\rightarrow$ likelihood to catch the train is falling). Some minutes later, the superfast train gets delayed. The delay causes the superfast train to*



(a) benefit

(b) information value indicator

Figure 10: Time-dependent information value

> *be scheduled 15 minutes after the suburb train but will still reach the business mans destination in time. (signal → likelihood to catch the superfast train is raising). This causes our intelligent information system to notice, that the indicator value for the information on the superfast train is raising with respect to the original plan of the business man. Therefore, information about the superfast train is supplied to the user.*

The evolution of benefit for both the original plan and the plan alternative is depicted in figure 10(a) while the evolution of the information value indicator is depicted in figure 10(b).

4 Related Work

The presented approach for a computational model for information value can be viewed as a foundation for a decision support model for the timing of information flow.

Information value has been recognized as an important research topic in decision theory. Laux [Lau91] defines *information* value in the context of a decision model, i.e. *information value* is the expected economic gain from additional information in the decision model. In this approach, the result of the information request (the information content) is not known *a priori* when the *information value* is to be computed. Grass and Zilberstein [GZ97] present a system for value-driven information gathering (VDIG) that strives for the best possible information gathering strategy at any moment in time, considering replanning of information gathering as an option. Papadimitriou and Yannakakis [PY91] investigate the information value in distributed systems from a computer science perspective.

In our approach, we implicitly employ a decision model for the plan transformation caused by additional information. However, our concern is the dynamic change of temporal uncertainty, causing information value on alternatives to raise or fall. We do not employ the decision model itself in order to decide upon the value of information.

5 Outlook

The approach of modelling information value based upon a network representation of uncertainty in movement plans may develop into a fundamental concept in intelligent information services. Proof of concept, however, is still missing. Within my PhD-thesis, I intend to investigate the concept of information value as a time-dependent measure, study stochastic processes as a computational model for the investigation of information value and extend the approach to further application examples.

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