WHAT IS INFORMATION ANYWAY?

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What is Information Anyway?

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'If you can't say it in words then you had better not whistle it in mathematics either'

Introduction

In the beginning there was information, later there was probability, and very much later there was logic. Information is and always has been an elusive concept, nevertheless many philosophers, mathematicians, logicians and computer scientists have felt that it is fundamental. Many attempts have been made to come up with some sensible and intuitively acceptable defintion of information, up to now none of these have succeeded. There have been successful definitions of a restrictive kind for the Shannon-Weaver concept, for the various kinds of statistical information, and for the semantic information pioneered by Carnap, Bar-Hillel and Hintikka; the last is a misnomer since it reduces to a purely syntactical definition. It is interesting that all these attempts have involved using Probability.

More recently it has come to pass that authors such as Dretske, Barwise and Devlin have claimed that there is a primitive notion of information in terms of which a logic can be (and perhaps should be) defined. Although I must emphasise that Dretske's notion again involves probability in an esssential way. The notion of information addressed by these authors is of a simpler kind than that addressed by earlier researchers. It starts from the position that given an ontology of objects individuated by a cognitive agent it makes sense to speak of *the information contained in one object about another*. Indeed we can talk of an information flow existing between two objects.

This idea that one object may have an informational link with another is implicit in the earlier work on information theory too. For example, in the Shannon-Weaver theory the receiver contains information about the source. In statistics one probability distribution contains information about another, often measured by the expected mutual information measure or some other variant. What is new and different about the

DBD[1] approach is that information is seen to be dependent on a context and is taken to have a level of intentionality, that is information is *about* something and as we all know aboutness is an intentional notion. Information also dependes on their being a cognitive agent to classify it.

It may help in understanding this notion of information to consider some examples. In a game of bridge a 2 Clubs bid by one of the players has a conventional meaning but the information it contains depends on what the other player already knows. A situation showing smoke contains information that there is a fire because of the nomic constraint that smoke usually means fire[2]. An image showing Robin and Brian contains the information that Robin is taller than Brian. Of course the image contains vastly more information which a cognitive agent could extract (or digitalise as Dretske would put it). Squareness for an object contains the information that the object is a rectangle relative to an analytic constraint. A document about ML contains information about programming languages. All these examples show that we are quite familiar with a notion of information. The big question is whether it makes sense to take it as a fundamental notion in terms of which other notions such as logic and probability are defined. I share the view with DBD that information comes first and probability and logic come second.

Information and IR

In the early days of IR people used to qualify their statements about information retrieval by saying that really they were working on document retrieval, in fact, all that was retrieved was a reference to a document. It was denied strenuously that *information* was being retrieved, e.g. 'An information retrieval system does not inform (i.e. change the knowledge of) the user on the subject of his inquiry. It merely informs on the existence (or non-existence) and whereabouts of documents relating to his request" (Thus wrote Lancaster in 1968). The situation has changed. I believe that the purpose of an information retrieval system is to provide information about a request. That a request is a representation of an information need which an IR system attempts to satisfy. Hence a fundamental problem is how to compute the information contained in one object (e.g. a document) about another (e.g. a query). Thus if a user states a query then it behoves the IR system to find the objects which contain information about that query. Let us see how this was done in the past and what role information played , if any.

Conventially IR systems attempt to retrieve relevant documents: documents relevant to the information need of the user. The usual way of

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1 My abbreviation for approach to information based on the work of Dretske, Barwise, and Devlin.

2 "There are inviolable patterns in nature beyond those which arise out of the individuating process, patterns that areusually called natural laws. We call these patters nomic structural constraints." according to Barwise and Perry.

accomplishing this is to match a query against each document in a large store. The underlying assumption is that closely matching documents are likely to be relevant. These matching strategies make extremely simple assumptions about the relationships between the index terms appearing in both queries and documents. Attempts to improve upon this were typically based on some hypothesis like the following:

> If an index term is good at discriminating relevant documents from non-relevant documents then any closely associated index term is likely to be good at this.

Hence to enhance the retrieval performance it became necessary to identify closely associated index terms. Such associations were frequently measured in terms of some kind of information measure: the idea being that if two terms were linked closely in an information-theoretic sense then this indicated a close semantic association from the point of view of establishing relevance. This is similar to claiming that a high correlation between variables implies a causal link, which is manifestly false. Measuring associations through the strenghth of their statistical association (even in terms of information) is like measuring the extent to which terms are co-extensive. The association hypothesis implies that if terms are strongly co-extensive then they are about the same thing. In general this is false and demonstrates once again that 'aboutness' or 'information content' has first order intentionality as Dretske would put it. So where does that leave us with regard to using associations to enhance retrieval? In my opinion to base associations purely on statistical considerations is doomed to fail, or at least to only lead to marginal improvement in retrieval effectiveness. What is needed is a semantic approach (perhaps in conjunction with a statistical approach) to establishing these associations.

Another area of information retrieval that was based on using informational links between objects to enhance retrieval was document clustering. This approach took its cue from Numerical Taxonomy[3]. In this latter area many techniques had been invented to measure similarity between objects on which to base a classification of these objects[4]. Towards the end of its heyday I think it was agreed that a 'universal' way of measuring similarity could be based on an information measure. In this context objects are described by attributes each of which could be as complex as a probability function, the similarity between two objects is then a function of *the extent to which one attribute contains information about another*. The information from different attributes is agregated. Thus a new information for measuring similarity was born. Many of the

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[3] See for example the book by Sneath and Sokal.

[4] It would seem that this connection between classification and information has been picked up again by Seligman.

previous similarity measures used in numerical taxonomy and in IR were special cases of this more general information theoretic one.

In IR this measurement of similarity between documents led to document clustering. Again it was based on some hypothesis such as:

> closely associated documents tend to be relevant to the same requests.

Associations were used to get at 'aboutness' through an informational link. Although experiments showed great promise actual retrieval enhancement was relatively small. It would seem that statistical connections between documents is not enough.

Conditionality

The most popular commercial IR systems are based on what is called Boolean Retrieval. This form of retrieval assumes that a user is able to express a query in Boolean logic and that the system can identify those documents which satisfy the query. The process of satisfaction is similar to that in formal logic, if a document is assumed to be an interpretation then we seek all the models of the query; a very attractive approach indeed, unfortunately most systems will either retrieve a set much too large, or nothing at all. So here we have a situation where a two-valued logic just will not work.

It is often the case that although a document is not a model of a query it nevertheless has some relevance to the user need and indeed is about the query. The difficulty is how to extend the Boolean logic without at the same time losing its advantages[5]

Another way of analysing the above situation is as follows. Let documents be individuated as objects in their own right, and let us assume that s is a partial description of such an object. Partiality here means that in principle the description may be extended. (For the moment I take no view on whether every extension is decidable). Now Boolean retrieval with respect to a query q is simply establishing whether $s \rightarrow q$ is a tautology, or whether $D \vdash s \rightarrow q$ (we usually ignore D); equivalently we test for $s \vdash q$. If $s \vdash q$ then retrieve D, otherwise do nothing. Of course this raises the question as to what to do in the case when s is false which we will ignore for the moment[6]. There is a slight of hand here because s has a very simple semantics, viz. each component of s is assumed true simply by membership of the description, and $s \rightarrow q$ is established by interpreting q in s.

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[5] The same problem arises in Quantum Mechanics.

[6] The whole issue as to whether to interpret the implication as a material one or in some other way is bound up with the kind of logic we wish to use; this has no easy solution.

The question we must now adress is what to do when s -> q cannot be established? (Give up I hear you cry!)

One approach is to attempt a calculation of P(s -> q) along Bayesian lines ignoring the semantics and once again using statistical information to estimate P(s -> q). Another approach is to look at the evaluation of s -> q as the evaluation of a conditional. This latter approach has a much debated history, for example Ramsey in the 1930's already stated:

> To evaluate a conditional, first hypothetically make the minimum revision of your stock of beliefs required to assume the antecedent. Then evaluate the acceptability of the consequent on the basis of this revised body of beliefs.'

This statement has become widely known as the Ramsey test (e.g Gardenfors, 1988) My application of it is slightly different. Perhaps an example will help. Given a query about 'Programming Languages' (=q) and a document described by 'Fortran' (=s), then the document would be considered relevant because s -> q . On the other hand consider q = 'Reasoning under uncertainty' and a document s = 'probabilistic logic'. Here it is not obvious that s -> q , what to do? The Ramsey test motivates the following, augment s in some minimal way until $s + \Delta s$ -> q . The measure of Δs can then be used to give a measure of s -> q .

This modification of Ramsey can be summarised as follows:

> Given any two sentences s and q; a measure of the uncertainty of s -> q relative to a given data set is determined by the minimal extent to which we have to add information to the data set to establish the truth of s -> q .

This principle, if I may call it that, is not as unusual as one would think. For example, if you have (in propositional logic) A and B and you wish to derive B from A, then B $\supset$ A is the logically *weakest* information you can add to A to derive B: A, B $\supset$ A |- B; and modus ponens is a well accepted rule of inference. Of course logically weakest is not the same as minimal in information-theroretic terms[7].

Another analogy that can be made is with a Kripke semantics for modal logic. let us assume an accessibility relation between worlds, then to evaluate a statement such as possibly p or necessarily p at a world one considers the truth value of p at all the worlds accessible from the initial

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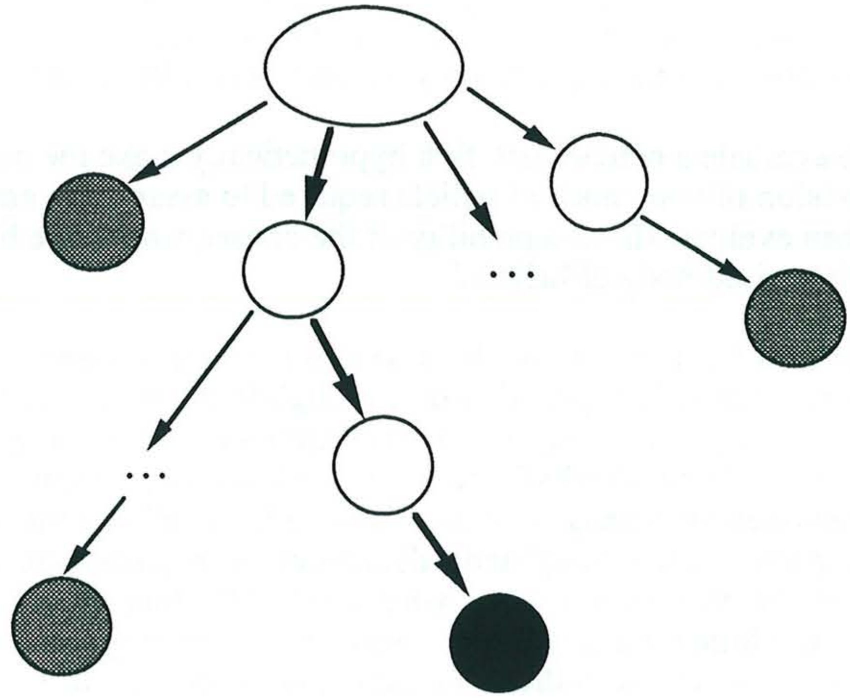
[7] But see Sober for a closely allied concept of minimimum extra information.

world. Possibly p evaluates to true if p is true in at least one accessible world, and necessarily p is true if p is true at all accessible worlds.

INITIAL WORLD



- **a possible final world**

- **a transition to a possible world**

- **the possible final world and transition chosen by the measure of certainty**

Whereas in modal logic the worlds are assumed fixed and given in advance endowed with a binary accessibility relation, our version of this in IR is to assume, in general, that the worlds are created by adding information to an initial world. This process of addition will be interpreted formally as one of transformation. The other difference is that in IR the accessibilty relation is dynamic and real valued, and the propositions are evaluated to a degreee not simply to 'true' or 'false'[8]. The termination conditions for these transformations are that the propositions evaluate to true but this too can be relaxed. The above diagram illustrates the point.

Although this logical model of IR is highly abstract it can be related to some older models which can be shown to be special cases of the logical one[9]. For example the vector space, Boolean, and probabilistic model can be interpreted within the logical model. This interpretation is only syntactic, the strenght of the logical approach is that it opens the door to incorporating semantic information through the transformations. The process of progressive transformation has a mathematical formulations and makes intuitive sense. The older models do not allow the incorporation of such semantics.

Situation theory for information retrieval

The objective of Situation Theory is the development of a mathematical framework for *information* which is considered fundamental in the same way that energy and momentum are considered fundamental in Chemistry and Physics. It is widely recognised that the development of any new scientific tool is better carried out in the abstract. Thus a science of information should follow a mathematical approach even though the definition of information itself is still problematic. In the past this has not stopped scientist from speculating about the nature of such objects as electrons, nor mathematicians about the concept of number. We may not be able to define them but we admit them to our ontology because we know how to use them.

In Situation Theory two concepts are primordial: *situation* and *infon*. A situation is where information resides and an infon is the representation of some of the information. To illustrate these notions, suppose we have a situation about an office. Let us denote this situation with *s*. Any person entering the office is able to extract information about it, such as. *"Who is there? What pictures are hanging on the wall? What is the size of the window?"* The person can also deduce other information. For example, from the fact that it is 12.30 and the person Mounia is not in the office, she can infer that *"Mounia might be having her lunch"*. The information that a person, called a cognitive agent, perceives depends strongly on her focus of attention and her perception capability. The information that the person infers also depends on her knowledge of the environment.

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[8] See Nie's thesis for this.

[9] Nie has spelt this out in great detail in his thesis

We can identify a document as a situation since a document contains the information written in its text, or contained in its images. The information that is based on the words used in the text is *explicit*. The information that can be derived with respect to semantics and pragmatics of natural language is *implicit*.

How is the information represented? If we go back to the example above, let us suppose that the information a cognitive agent gets is that *"Mounia is working"*. Situation Theory considers this information as a basic entity and models it by the infon:

« Working, Mounia, Office F101; 1»

The object '1' represents the *polarity* of the infon and signifies that the information is *positive*. If the cognitive agent does not observe the fact that *"Mounia is working"* (for example, she explicitly sees that *"Mounia is discussing"*), the infon is *«Working, Mounia, Office F101; 0»*. Information is not represented by its truth value anymore but by its content and *what makes the information true is the situation where it has been extracted.* Indeed, there might be several situations that make an item of information true. Situation Theory model this notion of "make true" by the support relation, denoted ⊨. If σ is an infon and s a situation,then

$$s \models \sigma$$

read *s supports* σ, means that s makes σ true. Applied to IR, the document, which is a situation, supports the infons that represent the information in its text.

Situation Theory introduces a level of abstraction that generalises infons into types. Let us introduce this notion through an example. Consider the three infons: *« Working, Mounia, Office F101, 11am; 1»*, *« Working, Mounia, Office F101, 3pm; 1»* and *« Working, Mounia, Home, 11am; 1»*. These infons provide the common information *"Mounia is working"*. What differs is the place and the time where the action takes place. This similarity is represented in the theory by *types of situation* or simply *types* . In the example above, the appropriate type would be:

$$\varphi = \left[\dot{s} \mid \dot{s} \models «Working, Mounia, \dot{p}, \dot{t}; 1» \right]$$

The type φ *classifies* all the situations where *"Mounia is working"*, at a certain time and a certain place. Here, $\dot{s}$, $\dot{p}$ and $\dot{t}$ are parameters; $\dot{s}$ is bound and represents a situation in general; $\dot{p}$ and $\dot{t}$ are free and represent respectively a place and a time. Any situation that supports the fact *"Mounia is working at a given time and a given place"* is said to be of the type φ. This is also denoted $s \models \varphi$, read s supports φ. A type can be constituted of several infons as the example below shows:[10]

$$\psi = \left[\dot{s} \,|\, \dot{s} \models \left\{ \begin{matrix} «Working, Mounia; 1», «Writing, Mounia, Paper; 1», \\ «Topic, Paper, Meditation; 0» \end{matrix} \right\} \right]$$

So a document and the information it contains are modelled by a situation and type. A query is a type and represents the information sought. Let d and φ be respectively the document and the information in the query. If $d \models \varphi$,that is the document supports the query then the document is relevant with respect to the query. However, a negative answer does not entail that the document is not relevant to the query because it might be the case that there is not enough explicit information to show the relevance. This is where the flow of information comes in. There might be a flow that conveys additional or related information in the document that concerns the query.

The flow of information

Flow of information carries the implicit information in a document[11]. Basically, a flow can be viewed as "if we know that a fact is present in a given context, we can infer other facts". Situation Theory models this phenomena via constraints. Let us define the concept through an example by considering the following types:

$$\varphi_1 = \left[\dot{s} \,|\, \dot{s} \models «Smoke, \dot{p}_1, \dot{t}_1; 1»\right] \quad \text{and} \quad \varphi_2 = \left[\dot{s} \,|\, \dot{s} \models «Fire, \dot{p}_2, \dot{t}_2; 1»\right]$$

These two types are not independent. The information they represent is semantically and pragmatically related in people's mind. Indeed, most human beings know that if they see smoke in a place, there is a high probability that there was (or is) a fire nearby. Situation Theory captures the link through *constraint* which is a relation between types. The constraint for the example above is denoted $\varphi_1 \rightarrow \varphi_2$ and indicates that the *existence* of a situation of type φ_1 implies the *realisation* of a situation (may be the same) of type φ_2. We call φ_1 and φ_2.respectively the *antecedent* and the *consequent* of the constraint.

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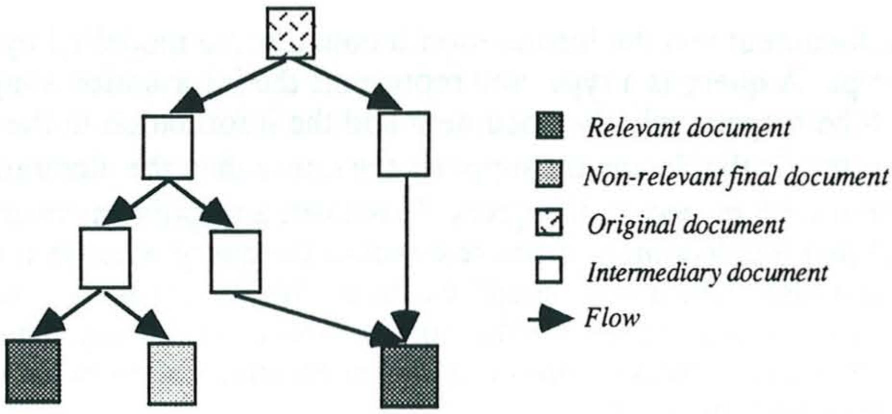
10 The comma between infons can be read as a conjunction.

11 Many flows exist. For example, there is the flow that conveys the information we are reading from what we are actually reading in term of words, letters. Here, we only consider flows that cater for the semantics and the pragmatics of natural language.

The nature of a flow of information is determined both by where it arises and by what is delivered. The former corresponds to the antecedent of the constraint and the latter to its consequent. To relate this to the Transformation Principle[12], the process of transforming a document consists of first finding the constraints that give rise to flows, then letting the flows happen and finally constructing *fictive* documents where the carried information is delivered. The following Figure illustrates how the flow of information transforms an intial document.



You will see that several fictive documents are built in sequence. This happens when the information that is generated through a first flow is delivered in a document which gives rise to a second flow. Furthermore, several divergent flows can arise from a document because very often there are several ways to interpret and transform a document. What we need now is to represent the combination of constraints in sequence and in parallel . Unfortunately Situation Theory does not propose a framework for the combination of constraints.Instead a development called Channel Theory has been suggested, which in addition to modelling the flow of information, provides a tool that manipulates flows. In this theory the definitions of infon, situation, type and constraint remain the same.

Channel Theory for Information Retrieval

The purpose of Channel Theory is to model conditional sentences of the form '*If S_1 then S_2*' because it is believed that an adequate model of conditional sentences will lead to a model of the flow of information. Moreover, Channel Theory attempts to provide a uniform framework for any kind of sentence (declarative, imperative, conditional and so forth).

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12 Given two sentences *d* and *q*, an evaluation of *d* -> *q* relative to a given data set is determined by the minimal extent to which we have to transform *d* so that *d* -> *q* becomes true. This is discussed more fully in the paper by Lalamas and Van Rijsbergen.

In Situation Theory, a sentence S is modelled by two entities: a type φ which represents the content of the sentence and a situation s which is the situation described by the sentence. So the utterance of the sentence S is modelled by φ_1 In '*If S1 then S2*', the sentences $S1$ and $S2$ can respectively be represented by two types φ_1 and φ_2 and it seems quite natural to represent the entire sentence by the constraint $\varphi_1 \rightarrow \varphi_2$. But what about the situation that supports the constraint? For this *channels* have been introduced so that two situations can be joined together and thus jointly support the constraint.

A channel is a relationship between two situations. The notation $s_1 \overset{c}{\longmapsto} s_2$ stands for a channel c that links the two situations s_1 and s_2, where s_1 and s_2 are called respectively the *signal situation* and the *target situation* with respect to c. Informally, this means that the *realisation* of the situation s_1 *implies* through the channel c the *existence* of the situation s_2; a *flow of information* circulates in the channel between the two situations. This flow originated from (or part of) the information supported by s_1 and conveys information about the situation s_2 To say it differently, $s_1 \overset{c}{\longmapsto} s_2$ expresses the fact that the realisation of the situation s_1 gives rise to a flow of information, which delivers us the information supported by s_2. The flow, as we will see, is characterised by constraints. What is new with respect to Situation Theory is that now we have a device to describe how the flow propagates. Channel Theory describes this device formally and specifies its mathematically properties.

Let us clarify what a channel is through an example. First, we define the following types related to the atmospheric temperature and the height of the liquid mercury in a thermometer. The two types model the two clauses of the sentence "*If the height of the mercury liquid is 8cm, then the temperature is 40 °F*".

$$\varphi_1 = [\dot{s} \mid \dot{s} \models \langle\langle height\_liq\_cm, 8; 1 \rangle\rangle] \quad \text{and} \quad \varphi_2 = [\dot{s} \mid \dot{s} \models \langle\langle temp\_farh, 40; 1 \rangle\rangle]$$

Let $s_1 \models \varphi_1$ and $s_2 \models \varphi_2$. A flow of information takes place between the two situations which such that a height of *8cm* indicates a temperature of *40 °F* (if the thermometer functions correctly). This is noted $s_1 \overset{c}{\longmapsto} s_2$ where c is the channel between height situations and temperature situations. Consider now the following types related to the two clauses of the sentence "*If the height of the mercury liquid is 10cm, then the temperature is 60 °F*".

$$\varphi_3 = [\dot{s} \mid \dot{s} \models \langle\langle height\_liq\_cm, 10; 1 \rangle\rangle] \quad \text{and} \quad \varphi_4 = [\dot{s} \mid \dot{s} \models \langle\langle temp\_farh, 60; 1 \rangle\rangle].$$

Let $s_3 \models \varphi_3$ and $s_4 \models \varphi_4$. Again, there is a flow of information between the two situations. This flow is borne by the *same* channel c, hence $s_3 \overset{c}{\longmapsto} s_4$. The channel c *supports* the two types $\varphi_1 \rightarrow \varphi_2$ and $\varphi_3 \rightarrow \varphi_4$. However, only one flow can circulate at a time because φ_1 and φ_2 are not compatible since it is not possible that a thermometer shows two different values of the height of its mercury liquid at the same time. If the two types were compatible and were both supported by a situation, then the channel could bear both flows simultaneously.

From the example above, it is clear that information in most cases carries additional information: this corresponds to the flow. People, in their life time, are constantly confronted with flows of information. Many channels exist in their mind which allow them to get more information from what they already have. For example, a typical deduction is "The light is on, Keith must be back". Channel Theory proposes a framework to model the notion of "...carries the information that...". More formally, a channel c supports $\varphi \rightarrow \psi$ means that if $s_1 \models \varphi$, $s_1 \overset{c}{\longmapsto} s_2$ and $\varphi \rightarrow \psi$ then $s_2 \models \psi$ In other words, if s_1 supports φ ,if there is a channel between s_1 and s_2 that supports the constraint $\varphi \rightarrow \psi$, then s_2 supports Ψ.

I will now describe an information theory and show how it could meet some of the requirements for modelling information retrieval. In what follows, I suppose that s_1, s_2 and s_3 are situations and $\varphi, \varphi', \psi, \psi'$ and θ are types. I list the properties expressed as principles, that a model of information flow should satisfy according to Barwise and at the same time I justify their relevance to IR. Remember that we are looking for a formalism that will model sequential and parallel transformations of documents via the concept of information flow.

Principle 1: The Xerox Principle

> If $s_1 \models \varphi$ carries the information that $s_2 \models \psi$ and $s_2 \models \psi$ carries the information that $s_3 \models \theta$, then $s_1 \models \varphi$ carries the information that $s_3 \models \theta$.

This principle applies exactly to our interpretation of sequential transformations; in other words a flow can follow from another flow and the combination of the two flows is a flow.

Principle 2: The Logic as Information Flow

> If the type φ entails ψ then $s \models \varphi$ carries the information that $s \models \psi$

This principle corresponds to the notion of *information containment*. For example, the information item *'deductive database'* contains the information item *'database'* since mentioning the former suggests assuming the latter.

Principle 3: The Addition of Information

If $s_1 \models \varphi$ carries the information that $s_2 \models \psi$ and $s_1 \models \varphi'$ carries the information that $s_2 \models \psi'$, then $s_1 \models (\varphi \wedge \varphi')$ carries the information that $s_2 \models (\psi \wedge \psi')$.

This principle captures the hypothesis that a document can be transformed on the basis of all the information it contains as long as no inconsistency is introduced.

Principle 4: The Exhaustive cases

Suppose that:

$s_1 \models \varphi$ carries the information that $s_2 \models (\psi \vee \psi')$,
$s_2 \models \psi$ carries the information that $s_3 \models \theta$ and
$s_2 \models \psi'$ carries the information that $s_3 \models \theta$.

Then $s_1 \models \varphi$ carries the information that $s_3 \models \theta$.

This principle expresses that it is not always possible to know how to transform a document, however, if whatever alternative is chosen the same information is delivered, then the information contained in the original document is sufficient to convey the delivered information. This principle is important with respect to IR because it takes into account that there may be different ways of obtaining the information sought. One could speculate that the more ways there are of satisfying a query the more relevant the initial document might be. It is like having many independent pieces of evidence for a hypothesis.

Barwise and his co-workers expect a model for the flow of information to respect the four principles, similarly I would expect a model for information retrieval to conform to them. A document is a situation that supports information modelled by types. Constraints model semantic and pragmatic relationships between information items. These are abstract objects which have an effect only when they are related to situations. A channel is what we use to model the transformation of a document into another : a channel bears flows whose nature is determined by constraints.

Conclusion

The above principles give a framework for manipulating constraints which are crucial to the flow of information. There is a paper in preparation (with M. Lalmas) which shows how to construct a 'calculus' of channels to conform to this framework. It is not obvious how to introduce a measure of uncertainty into this calculus as suggested by the above section on conditionality. However, once that has been done this approach to information can be connected with the pevious work on probabilistic retrieval described in my first paper. The calculation of the probability of relevance will be conditioned on the support relationship developed in this paper, that is, the final result will be an algoritm for evaluating $P(relevance | s \models \varphi)$.

Acknowledgement

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DISCUSSION

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Lecture Two

In the context of objects, such as images, which have infinite numbers of items of information, Professor Lincoln, asked how could one handle the infinite information. Professor van Rijsbergen answered that although the information found in the image objects is infinite, the process of extracting a piece of information is finite.

Professor Ercoli asked if one could use fuzzy logic to measure the uncertainty of the transitions to the possible worlds (the links) instead of using the probabilistic-based model. Professor van Rijsbergen answered that it could be used and added that the implementation is quite straightforward although the approach has very conservative combinations.