Revisiting the Role of Abductive Inference in Fusion Domain

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Abstract – *Abductive inference plays a very important role in the fusion domain, seen as a "conceptual framework" driving the conjecturing and hypothesizing process mainly aimed to discover relationships. Unfortunately, despite the recent gained attention in several fields as philosophy of science and logic, and the ongoing debate, in the fusion domain almost only one kind of abductive inference is taken under consideration with the aim of developing successful tools to be deployed within a fusion process, namely "Inference to the Best Explanation". The issues faced in the domain of intelligence and information fusion, dealing with the real world, imply processes which follow the sequences of scientific discovery and proof. Therefore a survey of some key concepts around abductive inference in the domain of epistmology can reveal some principles to be directly applied to the Fusion domain.*

Keywords: Abduction, hypothesis creation, information fusion.

1 Introduction

In recent decades abduction has gained attention in several fields as philosophy of science, logic and artificial intelligence. It has been widely recognized that the abductive style of reasoning is in fact inherent in many different tasks, from problem-solving to knowledge acquisition.

Much research has been devoted to elaborating a better understanding of the theoretical grounds underlying abductive reasoning, the purpose being the implementation of a vast scope of applications from language and multimedia interpretation, through design problems, to planning and many others.

The importance of abductive inference has been recognised also by the fusion community, for example in [9] and [12] where it is defined as the process of reasoning about a specific target, conjecturing and hypothesizing to discover best explanation of relationships to describe target, that is the "Hypothesis creation" process within the "Discovery" step.

As a result of such a widespread application interest quite different approaches to abduction have been investigated and employed [10] [4] [1].

Philosophers and logicians often disagree about the status of abduction, having different things in mind, and the discussion is particularly extended also in contemporary works. The same is not happening in other domains where abduction play a very important if not vital role, within which, usually, the only definition and structure of abduciton as "Inference to the Best Explanation". For example in Linguistics, in Mathematics, in AI, generally speaking, as well as in Fusion.

The problematic issues faced in the technological domain of intelligence and information fusion, which deals with real world, imply processes which follow the sequences of scientific discovery and proof as well as our everyday life experience. In the field of our ordinary perception, abductive inference clearly shows to apply to fusion processes. Within the human system of visual perceptions, for example, unconscious abduction processes perform the identification of three-dimensional objects based upon many two-dimensional projective images and the completion of objects partly concealed behind others. A fusion task can be also recognized in the inter-sensual correlation between visual perceptions and tactile perceptions: when the visual appearance of an object, for example, is not enough to build a satisfying knowledge, we will probably go to the object and try touch it to get more information about it. In our paper, after a brief remainder of its origin, we will survey some key concepts around abductive inference in the domain of epistmology, mainly following the analysis worked out in [18], and we will show how some principles which can be found within the epistemological debate, can be borrowed to be directly applied to the Fusion domain.

2 The first ideas: Charles S. Peirce

Charles S. Peirce, the 18th Century American pragmatist philosopher, in his writings talks several times about abduction and gives to the reader a number of slightly different definitions (for a complete review see [15]).

Studying Aristotle's doctrine of induction, which is con-

sidered the inference of the major premise of a syllogism, Peirce observed that there is "a large class of reasonings" that are neither deductive nor inductive: for example reasoning *a posteriori* to infer a cause from its effect. Peirce called *Hypothesis* this kind of reasoning, which can be represented as the inference of the minor premise of a syllogism. In a 1878 article, "Deduction, Induction, and Hypothesis", Peirce reports ([16] CP 2.623) the two ways of permuting the arguments of a deductive inference using the following example with a syllogism. The example is still in use to point out these different forms of inference.

Deduction is an inference of a result from a rule and a case:

(1) *Rule.* - All the beans from this bag are white.
Case. - These beans are from this bag.
$\therefore$ *Result.* - These beans are white.

Induction is the inference of the rule from the case and result:

(2) These beans are from this bag.
These beans are white.
$\therefore$ All the beans from this bag are white.

Hypothesis is the inference of the case from the rule and result:

(3) All the beans from this bag are white.
These beans are white.
$\therefore$ These beans are from this bag.

A typical example of *Hypothesis* in the sense of (3) has thus the following logical form:

(4) Given the law $\forall$ x(Fx $\rightarrow$ Gx),
from Ga infer Fa.

Soon it became perfectly clear to Peirce that *Hypothesis* is an inference to an *explanation*:

> "We find that light gives certain peculiar fringes. Required an explanation of the fact. We reflect that ether waves would give the same fringes. We have therefore only to suppose that light is ether waves and the marvel is explained." ([17], 1:267)

and in 1866, the philosopher says that *Hypothesis* is the inversion of the explaining syllogism which has the typical structure (1) ([17], 1:428, 425, 440, 452).

3 Key concepts around Abduction

3.1 Abuction vs Induction

Deductions are certain: given true premises, the conclusion must be true, but non-ampliative. It is commonly recognised the tautological nature of deductions. In contrast, inductions and abductions are ampliative, their conclusions enrich knowledge but in uncertain way: even if the truth of the premises is taken for granted, the conclusion may be false, so further testing is necessary.

Many epistemologists have been using the term "induction" do denotate all kinds of ampliative (non-deductive) inferences since the 19th century when John Stuart Mill despite "several methods for discovery and demonstration of causal relationship" had been recognized.

Nowadays philosophers and logicians argue (see [18] and [1]) that induction and abduction are two distinct families of reasoning not reducible to each other. Both of them have the purpose of extending knowledge beyond observation but in rather different respects. The goal of inductions consists in inferring something about the future course of events. On the other hand, the goal of abductions consists in inferring something about the unobserved (or unobservable) causes or explanatory reasons of the observed events.

The main reason according to which abductions cannot be reduced to inductions consists in that inductions cannot introduce new concepts or conceptual models in the inferential process; their "ampliative power" is confined to merely transferring new concepts to new instances. Some kinds of abductions, istead, can introduce new concepts or models. Following [13] they are called *creative*, in contrast to *selective* abductions whose goal is to choose the best candidate among a given number of possible explanations.

3.2 Inference to the Best Explanation

Besides a "Peircean" use of the term *abduction*, basically seen as "the third" mode of inference and further studied by Norwood Russell Hanson [6] who investigated the logic of discovery in the 1950s, another way of using it considers it a synonym for the Inference to the Best Explanation model (IBE). Such a model, which has a great diffusion in the technological domains, from multimedia automated analysis (see [14]) to the fusion domain itself (see [2] and [9]) is based on the studies of Gilbert Harman's, who formulated the idea in the 1960s [7].

Most of the authors working on explanation agree that nobody can know all possible explanations for a given phenomenon, therefore IBE needs to be modified: what can be really reach is an inference to the best *available* explanation, a so called IBAE. However, as some philosophers have pointed out, the best available explanation within an inference is not always good enough to be acceptable from a rational point of view. If we come across some new and not well understood phenomenon, then our best available explanation is usually a mere speculation. Speculative explanations, not meeting important methodological criteria, like animistic explanations of natural phenomena involving intentional agents (like personified Sun and Planets), are not acceptable in science. The rule IBE is therefore not always viable, and the rule IBAE is not generally acceptable.

More satisfying versions of abduction rules are needed which satisfy both minimal criteria for the acceptability of scientific abductions and, above all, some comparative criteria for testing the quality of the abduced explanations.

Also about the preferability of the quality criteria some debate is still going on. Some authors (like [15]) deny the very existence of an unique criterion talking about several criteria which may also come in mutual conflict. Talking about scientific abductions, some epistemologists argue about supremacy of *loveliest* explanations (i.e., the hypothesis which offers the best potential explanation as to explanatory strength, precision, simplicity, etc.) over *likeliest* explanations (i.e., the most probable hypothesis), while others argue that in some cases loveliness of the explanation converges with its likeliness, while in those cases in which loveliness and likeness offer different results, it is usually preferred the likeliest explanation.

In [18] Gerhard Schurz shows how the evaluation criteria for abductions are different for different kinds of abductions, negating a general answer to the question.

3.3 Ignorance Problems

In [5] can be found an insightful analysis of abduction from a logical point of view, and, as declared by authors a very prudent one indeed. Among the other key concepts exposed in the book, very important for our sake are some definitions, which we are quoting here preserving the original enumeration, covering the concept of "Ignorance Problem" which somehow triggers and drives an abduction process.

> **Definition 3.2 (Ignorance Problems - IP)** An IP exists for a cognitive agent X iff X has a cognitive target T that cannot be attained from what he currently knows (or equivalently from K, his current knowledge base).

The cognitive agent, who faces the problem, has two possible options: acquiring new information with the purpose of enabling T to be attained, or acknowledge that T is not attainable from K, constituing the pair $\{K, T\}$ an *insolubilium*.

> *IP-option (1)* (X overcomes his ignorance) X extends K to some successor knowledge base K^* such that K^* attains T.
>
> *IP-option (2)* (X's ignorance overcomes him) Unable to succeed with option (1), X capitulates.

The proposed pair of option have, nevertheless, a dynamic character: the agent X might try and fail to perform *option (1)* at time t_1, at time t_2 he might accept *option (2)*, but at a subsequent time t_3 the agent might recur one more time to *option (1)* with a good result. An interpretation of these options in the fusion domain can be depicted by Figures (1) and (2): if the fusion process leads to a negative response, the system can stop just failing its task or look for other available data from previously not considered sensors.

Options (1) and (2) are usually considered the only available to an agent confronted with an ignorance problem. In fact the agent has a third option which represents, according to Gabbay and Woods, "the founding datum of abduction".

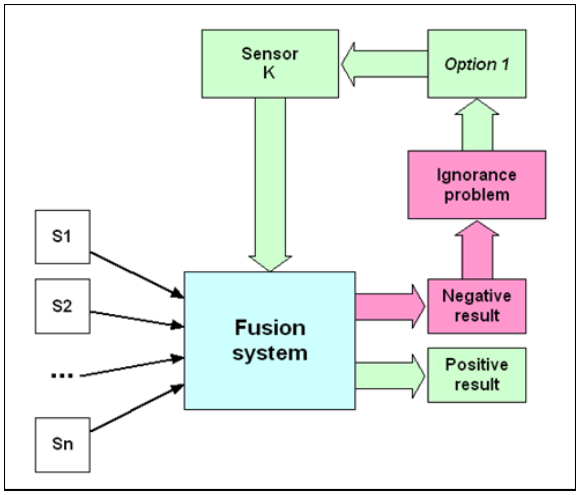

Figure 1: *Option 1* - The system works out the ignorance problem using a new sensor.

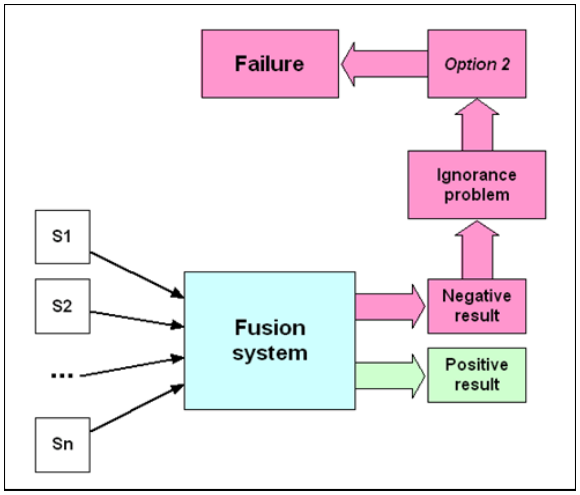

Figure 2: *Option 2* - The system fails its task and stops.

> *IP-option (3)* (Presumptive attainment) X finds an H which, if he knew it, together with K would solve his IP; and from that fact he conjectures H.

In the fusion domain, as it is shown in Figure (3), the hypothesis H generated by an abductive inference can be considered as an input to the fusion process, just like any other sensor.

Option (3) essentially incorporates the element of conjecture. But the critical point is that this does not solve the original problem. The agent's problem is that T is attainable only on the basis of what he knows (K) or can manage to know (K^*). After turnign to option (3) his situation is that T cannot be attained either way. Selecting an H such that the truth of K revised by H would hit T, then conjecturing H does not produce K^*; K together with H ($K(H)$ for now on) is not a knowledge base for the agent. $K(H)$ does not solve X's ignorance problem. This highlights a second unavoidable element of conjecture embedded in option (3).

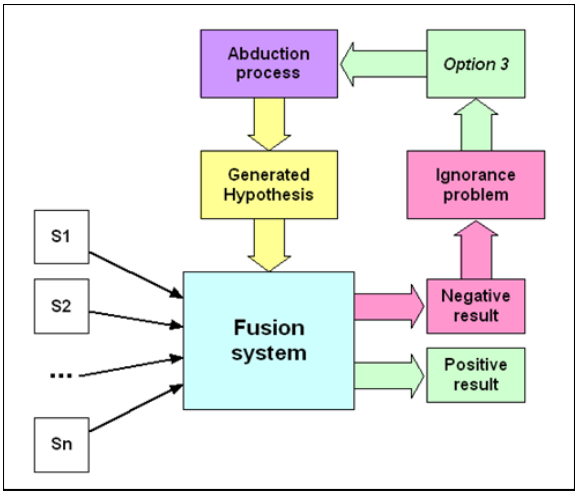

Figure 3: *Option 3* - The system tries to overcome the ignorance problem abductively conjecturing an hypothesis.

$K(H)$ doesn't directly hit T, but it does it *presumptively*. Accordingly, option (3) doesn't offer the agent a solution of his ignorance problem, but an attainment of a minor target. It proposes a conjectural variant of a target which admits of only *epistemic* attainment: a target that provides *presumptive* attainment.

> **Proposition 3.3 (Ignorance Preservation)** Whereas deduction is truth-preserving and induction is probability-enhancing, abduction is ignorance-preserving.

This proposition states an *ignorance condition* on abduction. As seen before, option (3) is not a solution of an IP, it is a transformation of an IP into a problem that can be solved by conjecture. It is a response to an IP that requires the agent to "lower his aim" with respect to T. It turns on X's disposition to satisface rather than maximize.

Once again IPs and the response they induce show a dynamic character. A cognitive agent might try and fail with option (1), and then move to option (3). If that failed too, option (2) is the last chance. If option (3) succeeded, the agent might persist with it until he succeeded also in knowing better about the problem; in which case he might move to option (1). So in the beginning X might try to overcome his ignorance, and, failing that, might try to conjecture to a minor target. If it fails, he might acknowledge his ignorance and stop. Yet even if he succeeded conjecturally, he might later have the chance to solve, with new knowledge, the original problem. Accordingly a new proposition can be stated

> **Proposition 3.4 (IP-relativities)** IP arise in relation to targets in play at a time and resources then available. Responses to IPs retain those targets and proceed in ways permitted by subsequent resources.

Peirce and others have emphasized that it is a condition on the *scientific* admissibility of an abductive conjecture H that it be testable, at least in principle. A solution to an abduction problem is therefore also a step in a process that may eventually solve the originating ignorance problem. So, for the class of cases that Peirce probably had in mind,

> **Proposition 3.5 (Ignorance mitigation)** Although a solution to an abduction problem preserves the ignorance that gave rise to it, it may also contribute to the solution of the originating problem by identifying candidates for the status of new knowledge.

3.4 Strategical role of abduction

All considered authors agree upon the fact that all inferences have, to a different degree, an *justificational* (or "inferential") and a *strategical* (or "discovery") function. The justificational function consists in the justification of the conclusion, under condition of the justification of the premises. The strategical function consists in finding a most promising conjecture (conclusion) which stimulates further empirical tests, or new questions according to [8].

In deductive inferences the justificational function is maximal, because the premises guarantee the truth of the conclusion. Deductive inferences may have also non trivial strategical functions, because many different conclusions can be derived from given premises. Inductive inferences do not invlove much search strategy, because the inductive conclusions of a premise set are narrowly defined by the operations of generalization over instances. So the major function of inductive inferences is justificational, but, by nature of induction, their justificational value is not certain. In abductive inferences the strategical function appears to be crucial. In abduction problems cognitive agents are often confronted with thousands of possible explanatory conjectures (or conclusions). Abductions essentially play the role of search strategies which tell the agent which explanatory conjecture should be chosen first to further inquiry or which suggest the agent a short and promising (not necessarily successful) path through the exponentially complex search space of possible explanatory reasons.

However the justificational function of abductions is minor. Peirce himself pointed out that abductive hypotheses are not even probable, like inductive hypotheses, but merely possible ([16] CP 5.171). An abductive hypothesis may become probable only after being further confirmed.

A good search strategy leading an agent to an optimal conjecture must give results in a finite and possibly reasonable time. In this respect, the rules of IBE or IBAE fail. IBE or IBAE can tell the agent which is the best available conjecture only after evaluating them all, IBE merely reflects the justificational but misses the strategical function of abductions which is their essential function. The rule of IB(A)E is therefore epistemically rather uninformative and definitely not creative.

Peirce himself remarked there are myriads of possible hypotheses which would explain the experimental phenomena, nevertheless scientists have usually found the correct explanations after only a relatively small number of *guesses* ([16] CP 6.5000). But Peirce did not write a line about any abductive rules for conjecturing new theories; he rather explained the ability of human minds talking about abductive *instincts*.

The crucial question seems to be whether there can exist any "logic" underlying explanation processes. According to [18] such rules exist and every kind of abduction pattern constitutes such a rule, each pattern fitting to a particular kind of conjectural situation.

4 Patterns of abduction: a classification

Patterns of abduction can be classified along three dimensions:

- the kind of hypothesis which is abduced, that is the kind of conjecture which gets produced
- the kind of evidence which the abduction intends to explain
- the cognitive mechanisms (beliefs) which drive the abduction.

three dimensions which are not independent: the properties of an abduction pattern in the second and third dimension are in characteristic covariance with its status in the first dimension. Moreover, the way according to which the evidence, together with the background knowledge, conveys epistemic support to the abduced hypothesis, and the typical follow-up procedures used to further test abduced hypotheses, deeply depend on the kind of abduced hypothesis. We will not review the whole classification kinds of Figure (4), which can be found in [18], but we will limit ourselves to some paradigmatic kinds od abduction which can be immediately recognized in a fusion process.

4.1 Factual abduction

In factual abductions, both the evidence to be explained and the abduced hypothesis are singular facts. Factual abductions are always driven by known (causal) laws, and the abduced hypotheses are found by backward reasoning. This kind of abduction is also called "retroduction", or "the official Peirce abduction schema". Its structure is as follows:

(5) (Factual Abduction):
Known Law: If Cx, then Ex
Known Evidence: Ea has occurred
==========
Abduced Conjecture: Ca could be the reason.

Detective stories are prototypical examples as well as all causal interpretations of traces. Factual abductions are omnipresent in common sense reasoning, and contemporary AI-literature is focused almost exclusively on factual abductions. Depending on the nature of the abduced fact, three subpatterns can be distinguished.

1. *Observable fact abduction* - Here the reasoning process follows schema (5) from observed effects (Ea) to non-observed but *observable* causes (Ca) in the background of known and available laws. The follow-up test-procedure consists in the attempt to gain direct evidence for the abduced conjecture. In a murderer case, for example, the direct evidence would be attained by a confession of the murderer to have committed the crime. Probabilistic evaluation of causes and elimination of implausible ones plays a central role in factual abductions. The probabilistic evaluation can provide justification only provided that (a) the assertions are supported by statistical laws, and (b) our knowledge of the causal laws which may lead the agent to the possible causes of the explanandum via "retroduction" is complete or, at least, does not miss some probable cause. As we saw before, in observable fact abduction, the abduced hypothesis may at later stages of inquiry by confirmed by direct observation.

2. *First-order existential abduction* - This subcase occurs when the antecedent of a law contains variables which are not contained in the consequent of the law. The simplest formal structure of first-order existential abduction is the following:

   (6) *Known Law*: $\forall x \forall y(Ryx \rightarrow Hx)$
   Ha
   ==========
   Conjecture: $\exists y$ Rya

   Instantiating the consequent of the law with "a" and backward chaining yields a law-antecedent in which variable "y" remains uninstantiated. In such a case, the safest abductive conjecture consists in existentially quantifying over the variable "y". From a footprint in the sand can be abductively inferred that some man was walking at the beach. It cannot be inferred that some particular person has walked there. Furthermore, only in some cases the existential conjecture will be a satisfying answer. In other cases (in most of the cases, in security domains), finding out which individual is the one whose existence is conjectureed is absolutely necessary. The first-order existential abduction is not satisfying with but a proper fact-abduction (which variables are fully instantiated) is necessary.

3. *Unobservable fact Abduction*- This kind of abduction has the formal structure (5), as observable fact abduction, but in this case the abduced fact is unobservable. Typical case of unobservable fact abductions are historical fact abductions, in which the abduced fact is located in the past, or, in security domain, any case of

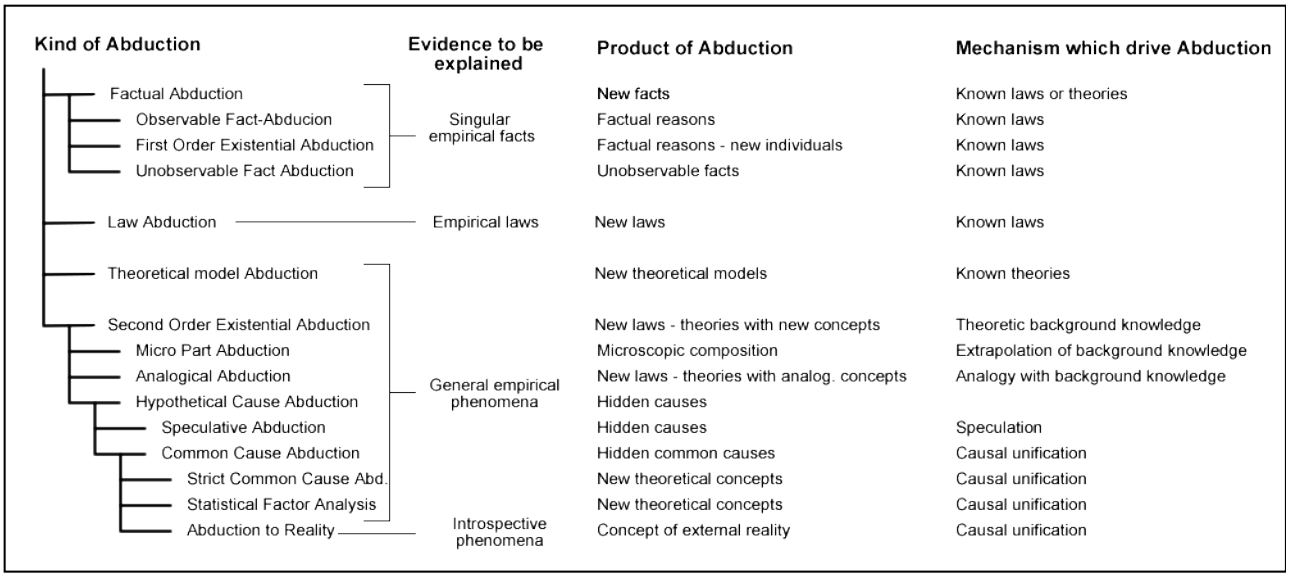

Figure 4: Classification of kinds of abduction according to Schurz.

event not detected, a "hole" in information, due for example to sensor failures. The abduced fact may also be unobservable in principle, because it is a theoretical fact.

Factual abduction is definitely the best studied and techically approached kind of abduction. If we leave the epistemology domain, so wide because dealing with the entire existing real world, and we focus on restricted domains like security or narrower ones, we can see that IBE or IBAE, despite the problems of dealing with possible computability complexity, nevertheless can give accettable and satisfying solutions in reasonable time (see the already cited [2] and [9]. Factual abduction doesn't need *creative* solutions, for facts or individuals are already included in the knowledge base together with the candidate connecting laws. A good ontology and some tailored choice criteria can speed up the process.

4.2 Second order existential abductions

The explanandum of a second-order existential abduction consists of one or more empirical phenomena, or laws. What is abduced is a new property or kind concept dependent on a new (at least partly) theoretical law. The inference can be driven by extrapolation, analogy, or by pure unification depending on whether the concept is merely partly or completely new.

A partially new concept and at the same time new laws which connect this concept with given (empirical) concepts, for example, can be inferred by analogical abduction. Analogical abduction is driven by the existence of a (partial) isomorphic or homomorphic mapping between some already possessed concepts and the new observed facts. Every (partial) isomorphism drives a conceptual abstraction by putting together just that parts of both structures which are isomorphically mapped into each other: the resulting structure is interpreted in an abstract system-theoretic sense. So, finding an abductive analogy consists in finding the key features of the source structure which can be generalized to other domains, thus forming the corresponding conceptual abstraction.

The most fundamental kind of conceptually creative abduction seems to be the Hypothetical (common) cause abduction. The explanandum here consists either (a) in one phenomenon or (b) in several mutually intercorrelated phenomena (properties or regularities). The cognitive agent abductively conjectures that the phenomenon is the effect of a hypothetical (unobservable) cause (in case (a)), or that the phenomena under observation are effects of a hypothetical common cause (in case (b)). From an epistemological point of view only case (b) constitutes a scientifically worthwhile abduction, while (a) could be a case of pure speculation. In both cases, the abductive conjecture postulates a new unobservable entity (property or kind) together with new laws connecting it with the observable properties, without taking into consideration analogies to concepts which one is already familiar with. This kind of abduction does not presuppose any background knowledge except knowledge about those phenomena which are in need of explanation. What drives hypothetical cause abduction is the pure search for unification, usually in terms of hidden or common causes. Hypothetical (common) cause abduction is a large family of abduction patterns which embeds inferences over domains ruled by strict causal laws as well as probabilistic patterns of correlation.

The problem of discerning the underlying regularities in the world, despite sparsity and noise in data and information, has been addressed to by recent studies in cognitive sci-

ences and some good results have been achieved by taking into consideration some "library" of structures (see [11]), to fit most of the dataset under investigation. Such ideas have been proposed to the high level fusion community too [3].

5 Conclusions

As presented in this article, abductive inference, whose goal is inferring the unobserved (or unobservable) causes or explanatory reasons of observed events, can be considered from different points of view making emerge many interesting key concepts. Some of them are stuck in the subtleties of philosphy, but most of them are immediately disposable for a necessary theoretical discussion which preludes the development of tools to be used in a fusion process. Inference to the Best Explanation, for example, shoudn't be considered as "the" (almost unique) kind of available concept of abduction to deal with. "Ignorance" related definitions can have great influence on knowledge base upgrade issues: an abduced conjecture H cannot be considered as a candidate to be introduced in the knowledge base itself in its "floating" status waiting to possibly gain existence rights through a follow-up procedure. Strategic role of abduction should also be further investigated in high level fusion matters like, for example, upper levels of the JDL model. To these fields are oriented our next research steps.

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