Diagnostic Reasoning
with
Anaesthesia Knowledge

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Abstract
This paper reports on a collaboration between two research groups. The first group has studied Formalization of ANaesthesia knowledge (FAN). An aim in the knowledge formalization was support of diagnosis, but the diagnostic method to be used was itself not formalized at the time.

The second group has developed a general framework for diagnostic reasoning. The framework is parametrized to account for the variation in diagnostic methods.

In this paper the diagnostic framework is instantiated to describe the FAN diagnostic method. The result of mapping FAN to the framework is twofold: (1) the FAN diagnostic method has been formalized, and (2) it has been proven that the diagnostic framework is general enough to describe a diagnostic method as a generalization of which it was not designed.

Keywords: Diagnosis, Anaesthesia

1 Introduction

This paper reports on a collaboration between two research groups. The first group, has investigated Formalization of knowledge in the ANaesthesia domain. This group will be designated the FAN group. Its members are from the department of Computing Sciences of the University of Groningen and from the Academic Hospital in Groningen.

The second group has developed a general framework for diagnostic reasoning. Its members are from the Social Information Science (SWI) department of the University of Amsterdam. This group will be designated the diagnosis-group.

The aim of the FAN project [5, 6] is to provide support in Anaesthesia. Support includes diagnosis, therapy advice and simulation. In the first phase of the FAN project the kinds of knowledge used in these support tasks were investigated and formalized. Aims in choosing the kinds of knowledge for FAN were minimization of the number of concepts used, adequateness for the different support tasks and restriction to notions used by physicians. The diagnostic method that the knowledge should support was described informally but not formalized before the study reported here.

[3] Currently, she is carrying out her work at Imperial Cancer Research Fund (London) as part of a community training project (TMR) financed by the European Commission. Project: ERBFMBICT961130
The diagnostic framework [1] is a generalization of diagnostic methods reported in the literature. To account for the differences between these methods, the model is parametrized. The conjecture is that the framework captures the essence of diagnostic reasoning such that any concrete method of diagnostic reasoning can be described by instantiating the parameters. In the general nature of the framework a diagnostic problem is defined as a discrepancy between observed and expected behaviour. The systems subject to diagnosis can next to patients also be complex artifacts, e.g., machines or electronic circuits.

The question answered in this paper is whether and how this is possible for the FAN diagnostic method can be described. In other words, the diagnostic framework is instantiated to describe the FAN diagnostic method. The parameters of the model are instantiated such that two requirements are fulfilled. Firstly the object knowledge in the FAN formalization is mapped to particular parameters. Secondly the parameters instantiations are such that the FAN reasoning method is reflected.

The result of mapping FAN to the framework is twofold: (1) the FAN diagnostic method has been formalized, and (2) it has been proven that the diagnostic framework is general enough to describe a diagnostic method as a generalization of which it was not designed.

The structure of this paper is as follows: section 2 describes the FAN structure for anaesthesia knowledge. Section 3 contains an example of domain knowledge that will be used throughout this paper. Section 4 informally describes the FAN diagnostic method in terms of its knowledge structure. Section 5 defines the general framework for diagnostic reasoning. In section 6 the actual mapping of the framework to FAN is reported. The last section contains discussion and conclusions.

2 FAN knowledge structure

In representation of medical knowledge a distinction is often made between nosological and physiological models [9]. Nosological knowledge describes a disease in terms of the symptoms and signs by which it manifests. Viewed from the opposite site, nosological knowledge assigns a label to the simultaneous manifestation of a group of symptoms and signs. Physiological knowledge describes cause-effect relations between physiological phenomena.

In the development of medical knowledge, it is usual that a disease is first described nosologically. Later it is investigated why there is a correlation between the symptoms and signs of the disease. The answer is given in terms of cause-effect relationships.

An intermediate step in the development of knowledge is the distinction of syndromes, symptom complexes and the like. Like diseases, syndromes and symptom complexes are described nosologically by their symptoms and signs. In turn, syndromes and symptom complexes as a whole can be used in the nosological description of diseases.

In the FAN project, nosological and physiological knowledge are represented by means of two link types: has-part links and causal links respectively [6].

The notion of phenomenon comprises anything in the nosological hierarchy ranging from diseases through syndromes, symptom complexes, to symptoms and signs. Phenomena are at the same time physiological phenomena that causal relations can apply to.

With both types of link a strength is associated. For a has-part link its strength expresses the probability that the part is present when the corresponding whole is present. For a causal link its strength expresses the probability that the effect occurs when the cause is present.
Three discrete levels of strength are distinguished: facultative, obligatory and pathognomonic. These strength levels are commonly used in representing nosological knowledge. A facultative symptom/sign of a disease usually manifests when the disease is present but this need not be the case. An obligatory symptom/sign of a disease is a necessary precondition for the presence of the disease; if not present, the disease can be excluded. A pathognomonic sign of a disease is a sufficient precondition for presence of the disease. For example, the presence of cancer cells is a pathognomonic sign of the presence of cancer.

In the FAN structure strength is represented by these three levels in both has-part and causal links. An alternative that has been considered is representation of strength by a continuously variable measure like a probability or a fuzzy membership value. The reason for favouring the discrete representation of strength is that it has a clear meaning to physicians. Therefore it is easier to elicit strengths in knowledge acquisition than it would be for continuous measures.

In diagnostic reasoning has-part and causal links are equivalent. This is because we have chosen the types of entities and the strength measures the same for both link types.

Therefore the distinction between has-part and causal links may seem irrelevant. The distinction is maintained for the following reasons. Firstly, the distinction need not complicate description of the diagnostic reasoning process. Below, the reasoning process is described in terms of links, which can be both has-part and causal links. Secondly an abstraction to link would make formalized knowledge hard to recognize for domain experts, i.e. anaesthetists. Link is too abstract notion to connect it with concepts that they are familiar with. Thirdly, the distinction between nosological and physiological knowledge is so pervasive that it is likely that the conclusions that can be drawn from the two knowledge types differ, also when this is not the case for diagnosis.

3 Example: Anaesthesia Knowledge

The example of Anaesthesia knowledge that we use in this paper was elicited from a medical expert. The example is intended to illustrate several aspects of the diagnostic method. The example contains only causal links. These links are of the strength facultative, obligate, or pathognomonic. The phenomena that are possible observables (sign/symptom) are dependent on the surgery room. The equipment in a surgery room may differ, and therefore the set of possible observables may deviate from the one presented here. However, we assume that the set of observables is given. These are the boxes in fig. 1. A second note about the observables is that there is a distinction between observables that are measured incidentally (e.g. by a blood-test) or permanently (e.g. by using a sensor). Because the FAN diagnostic method does not exploit this distinction in observable types, we do neither. So the diagnostic domain knowledge consists of links of several strengths between phenomena, where some phenomena are indicated as observables. See figure 1.

4 FAN diagnosis

In the FAN project a diagnosis is defined as a set of phenomena whose presence explains observed symptoms and signs. In this section the FAN criteria to a diagnosis are described informally. In what follows the symptoms and signs to be explained will be designated as observations.

A link-chain is a list of links, either has-part or causal links. For two consecutive links of the chain, the head of the first is the same phenomenon as the tail of the second. The strength of a link-chain is equal to the minimum of the strengths of the links of the chain. In computing this minimum, we assume a total order on the link strengths: facultative < obligatory < pathognomonic.
Figure 1: Anaesthesia Knowledge elicited from a medical expert. In the figure, we use “PaO2” and “PaCO2” for partial pressure arterial blood oxygen, coal-dioxide respectively.
To qualify as a diagnosis a set of phenomena must fulfill the criteria below. We illustrate them using the example in figure 1.

1. For each observation to be explained, a link-chain exists leading from an element of the diagnosis to the observation. The fact that a link-chain exists implies that its strength is at least facultative. For instance, “Increased pulmonary venous pressure” can be explained by “Overfilling” but never by “Shunting”.

2. When a link-chain of strength obligatory or greater leads from an element of the diagnosis to an observable, that observable must be present. In other words, absence of such an observation excludes (that element of) the diagnosis. For instance, if “Underfilling” is a part of the diagnosis then “Decreased pulmonary venous pressure” must be observed. “Decreased peripheral perfusion” has not to be observed necessarily, because the causal chain between “Underfilling” and “Decreased peripheral perfusion” has a facultative strength, since it contains a facultative link, namely the link “Underfilling” to “Centralisation”.

Note that a distinction is made between observables and observations. An observable is a phenomenon whose presence can be investigated. In the figure, these are the boxes. Observations are the observed values of the observables. In diagnostic reasoning, we are looking for a diagnosis for these observations.

3. When a link-chain of strength pathognomonic leads from a phenomenon to one of the observations, the phenomenon must be part of the diagnosis. The example contains one pathognomonic link, namely between “Breathing tube disconnected” and “Disconnection”. This means that as soon as “Breathing tube disconnected” is observed, then “Disconnection” should be part of the diagnosis or there is no diagnosis at all.

4. Provided that the foregoing criteria are met, the number of phenomena constituting the diagnosis must be as small as possible.

For example in figure 1, “Underfilling” explains “Decreased PaCO2” and “Decreased pulmonary venous pressure”. An alternative explanation is “Stress” plus “Fever”, where “Stress” explains “Decreased PaCO2”, and “Fever” explains “Decreased pulmonary venous pressure”. This alternative explanation is less preferred because the explanation is greater in size.

5. Further provided that the foregoing criteria are met, a diagnosis is preferred over another when the set of phenomena explained by the former is a subset of the set of phenomena explained by the latter.

This criterion serves two purposes. First the explanation depth is kept as small as possible. It is only allowed to use a longer explanation chain, when the chain (or more precisely the head of this chain) explains more (thus other observations). Secondly the number of observables that could be explained by the diagnosis but do not need to be explained since they are not found present is kept minimal.

In our example, “Increased heart frequency” can be explained by “Decreased arterial pressure”, by “Overfilling”, by “Fever”, or by “Stress”. If we assume that all links of these explanations are facultative and that “Increased heart frequency” is the only one observation then all of them are diagnoses (otherwise we need to make the diagnostic problem more complex). “Decreased arterial pressure” will be preferred because less extra observables values are explained. This possible diagnosis explains one extra observable value (“Decreased peripheral perfusion”).

A consequence of this criterion is that phenomena with a longer explanation chain are only allowed when they are needed for explaining some observations. For instance, “Increased pulmonary venous pressure” is never a preferred diagnosis (or part of the diagnosis) because it explains no extra observation in comparison to “Increased left half heart filling”.

5
diagnostic-method(BM, OBS, CXT, SOL) if \( f \)

1. Obs-mapping(OBS) = \( \langle \text{Obs}_{\text{cov}}, \text{Obs}_{\text{con}} \rangle \)
2. \( ES = \{ E \mid BM_T \cup E \cup CXT \vdash_{\text{con}} OBS_{\text{cov}} \} \) and \( BM_T \cup E \cup CXT \vdash_{\text{con}} OBS_{\text{con}} \) and \( E \subseteq \text{Vocabulary}(BM) \) and \( \text{Selected} \)
3. \( ES_{\text{min}} = \{ E' | \text{Selected}(\text{Selection-criterion}, ES, E') \} \) and \( \text{Solution-form}(ES_{\text{min}}, SOL) \)

Figure 2: General diagnostic method defined in terms of the parameters

5 Diagnostic framework

A general definition of a diagnostic problem is a discrepancy between observed and expected behaviour of a system. The diagnostic task is to find an explanation of this discrepancy. The diagnosis is based on a model of the systems behaviour.

In [1] a general framework for diagnostic reasoning is proposed. The framework is a generalization of the 'spectrum' described by Console and Torasso [10]. The framework describes diagnostic reasoning in terms of six parameters. A specific diagnostic reasoning method is given by instantiating each of the six parameters. The parameters of the framework are described below.

1. Obs-mapping: Based on the observations, two groups of observables are discerned. The first group consists of the observables to be covered by the explanation. The second group consists of the observables that must be consistent with the explanation. The Obs-mapping parameter determines how observables are divided into the two groups.

2. \( \vdash_{\text{con}} \): This parameter determines what it means for observables to be covered by the explanation.

3. \( \vdash_{\text{con}} \): This parameter specifies what it means for observables to be consistent with an explanation.

4. Vocabulary: This parameter gives the entities that can serve as explanations. For example, it can consist of faulty components or diseases.

5. Selection-criterion: This parameter determines which are the most interesting among possible explanations. These explanations are called minimal.

6. Solution-form: This parameter determines the form in which the diagnosis is represented. The choice of the solution-form depends on the purpose of the diagnosis. For example for prescribing a therapy or drugs in the medical domain a diagnosis represented as a disease is useful, but a diagnosis represented as a set of all the current states of the patient’s body parts is not.

In figure 2 the general diagnostic method is described in terms of the parameters. The parameters, described above, are underlined.

The seven formula’s express essential elements of diagnosis. However the parameter they use need not be exclusively defined in terms of the objects to which they apply. For example, the
**OBS-mapping** maps the set of observations **OBS** into a pair of sets \((\text{OBS}_{\text{cov}}, \text{OBS}_{\text{cov}})\). \text{OBS}_{\text{cov}} is a set containing observables that have to be covered. \text{OBS}_{\text{cov}} is a set containing observables that must be consistent with explanations.

For a particular diagnostic method, it is not necessary that the **OBS-mapping** is defined strictly in terms of **OBS**. A situation where the **OBS-mapping** is defined strictly in terms of **OBS** occurs when the positively observed observables go into \(\text{OBS}_{\text{cov}}\) and the negatively observed into \(\text{OBS}_{\text{cov}}\). Other diagnostic methods use knowledge from the behaviour model \(BM\) (see below). For example, it is possible that \(BM\) distinguishes between specific and unspecific observables. A diagnostic method using this model can put specific observables in \(\text{OBS}_{\text{cov}}\) and unspecific observables in \(\text{OBS}_{\text{cov}}\). In principle, the definition of each of the parameters can use each of the argument sets: \(BM, \text{OBS}\) and \(CXT\).

In the framework formula’s the following objects are used:

- **BM** denotes the knowledge of the system under diagnosis. **BM** contains the behaviour theories (\(BM_T\)), and additional knowledge for specific definitions of a diagnostic method. For example, a set of possible observables or a set of components of the system.
- **BM_T** denotes a behaviour model. This is a case-independent input to the diagnostic method. **BM_T** can contain several kinds of causal relations: necessary, conditional, and possible causal relations. Other kinds of knowledge which can be contained in the **BM** are abstraction and structure relations, etc.
- **OBS** denotes the set of observations to be explained. This is a case-specific input to the diagnostic method. \(\text{OBS}\) observations are expressed in the language of **BM_T**.
- **CXT** denotes contextual observations. These do not have to be explained by the diagnosis but help in finding explanations. An example of an element of **CXT** is “the gender is male”. **CXT**, like **OBS**, is case specific and expressed in the language of **BM_T**.
- **SOL** denotes the inferred diagnosis. It is output by the diagnostic method given **BM**, **OBS** and **CXT**.
- **E** denotes a possible explanation. It consists of a set of phenomena. Possibility of an explanation is determined by 'hard' requirements given by lines 2 - 5 of the diagnostic method using parameters **OBS-mapping**, \(\text{obs}_{\text{cov}}, \text{obs}_{\text{cov}}\) and **Vocabulary**.
- **ES** denotes the set of possible explanations.
- **E'** denotes a preferred explanation. Whether an explanations among a group of possible explanations is preferred is determined by the **Selection-criterion** parameter.
- **ESmin** denotes the set of preferred explanations.

### 6 Applying framework to FAN

In this section the work on FAN and the work on the diagnostic framework come together. Firstly our viewpoint is from FAN: it is analyzed how the FAN diagnosis criteria can be expressed in framework parameters. Subsequently our viewpoint is from the framework: the instantiation of each parameter is given.

#### 6.1 From FAN to framework

The FAN criteria can be expressed in terms of the framework as follows.

- The first FAN criterion requires that for each observation to be explained, a link-chain exists between an element of the explanation and the observation. This can be expressed by
choosing \textit{OBS-mapping} and the cover relation \( \vdash_{\text{cov}} \) as follows. \textit{OBS-mapping} puts the observables that have been positively observed (as observations) in \( OBS_{\text{cov}} \). For the existence of a \( \vdash_{\text{cov}} \) relation between an explanation and \( OBS_{\text{cov}} \) it is \textit{necessary} that for each of the elements of \( OBS_{\text{cov}} \) an element of the explanation exists that is linked to it.

- The second FAN criterion requires that a diagnosis must be such that the observables whose presence it implies with strength obligatory or greater are not absent. In other words, assertion of absence of these observables is not consistent the explanation. This can be expressed by choosing \textit{OBS-mapping} and the consistency relation \( \vdash_{\text{cons}} \) as follows. \textit{OBS-mapping} puts negations of observables to which lead links of strength obligatory or greater into \( OBS_{\text{cons}} \). A \( \vdash_{\text{cons}} \) relation exists between an explanation and \( OBS_{\text{cons}} \), when no pair of phenomena \((ph1, \neg ph2)\) exists, with \( ph1 \) element of the explanation and \( ph2 \) element of \( OBS_{\text{cons}} \), such that a link-chain of at least strength obligatory connects phenomena \( ph1 \) and \( \neg ph2 \).

- The third FAN criterion requires that when a link-chain of strength pathognomonic leads from a phenomenon to one of the observations, the phenomenon is part of the diagnosis. This can also be expressed by the covering relation \( \vdash_{\text{cov}} \).

For the existence of a \( \vdash_{\text{cov}} \) relation between an explanation and \( OBS_{\text{cov}} \) it is \textit{necessary} that each phenomenon \( ph \) connected to an element of \( OBS_{\text{cov}} \) by a pathognomonic link-chain is part of the explanation. Note that, since this is a hard requirement, it can not be represented as a selection criterion. In combination this necessary condition and the necessary condition given in the first item define the \( \vdash_{\text{cov}} \) relation.

- The last two FAN criteria concern the minimality of solutions. Explanations are selected based on the number of phenomena in an explanation and inclusion relations between the sets of phenomena implied by a explanation.

6.2 From framework to FAN

In this subsection the input of the framework (\( BM \)) and the definitions of the framework parameters instantiating the FAN reasoner are given. Like explained in section 2, \textit{causal} and \textit{has-part} links are equivalent in FAN’s diagnostic reasoning method. Therefore the term \textit{link} is used when expressing the FAN reasoning method in terms of the framework. A link can either denote a \textit{causal} link or a \textit{has-part} link.

Terms of the form \( \text{link}(ph1, ph2, \text{strength}) \) can appear in the behaviour theory \( BM_T \). Such a term denotes that a link of strength \text{strength} exists between phenomena \( ph1 \) and \( ph2 \). The possible values of \text{strength} are \textit{facultative}, \textit{obligatory} and \textit{pathognomonic}.

In the definitions it is assumed that it is known which phenomena are observable. In section 2, it was explained that the FAN knowledge structure does not distinguish between observable phenomena (symptoms and signs) and non observable phenomena (the others of the mentioned categories). For expressing the FAN reasoner in terms of the framework we will however assume the existence of a set \( BM_{OBS} \) containing the observables among the phenomena. \( BM_{OBS} \) is contained in \( BM \). The set \( BM_{OBS} \) is given by the boxes in the figure 1.

Furthermore, it will be assumed that \( CXT = \emptyset \), since no distinction is made between \( CXT \) and \( OBS \) in FAN.

In the definitions it is assumed that the operator \( < \) is defined in accordance with the ordering assumed on strengths: \textit{facultative} \( < \) \textit{obligatory} \( < \) \textit{pathognomonic}. Likewise it is assumed that the function \( \text{min} \) returns the minimum of two strengths given the ordering.

In a number of definitions the \textit{link-chain} relation will be used. This is defined as follows.
\( \text{link-chain}(ph1, ph2, \text{strength}) \leftrightarrow \\text{link}(ph1, ph2, \text{strength}) \in \text{BM} \lor \exists ph3: (\text{link}(ph1, ph3, \text{strength1}) \in \text{BM} \land \text{link-chain}(ph3, ph2, \text{strength2}) \land \text{strength} = \min(\text{strength1}, \text{strength2})) \)

In our example, we have for instance:

\( \text{link-chain} \text{(Underfilling, Decreased periferal perfusion, facultative)} \)
\( \text{link-chain} \text{(Underfilling, Decreased left heart half filling, obligatory)} \)

We now give definitions for the framework parameters. We will use the following diagnostic problem for illustrating the parameter values of the FAN diagnostic method:

\( OBS = \{\text{Breathing tube disconnected, Increased PaCO2, Decreased PaO2}\} \)

**OBS-mapping**  
**OBS-mapping** maps \( OBS \) to a pair \( \langle OBS_{cov}, OBS_{con} \rangle \). \( OBS_{cov} \) is the set of observables to be covered and \( OBS_{con} \) is the set of observables that must be consistent with an explanation.

According to the FAN diagnostic method for each observation to be explained, a link-chain must exist between an element of the explanation and the observation. A diagnosis must be such that the observables whose presence it implies with strength obligatory or greater, are not absent. The latter FAN requirement can be encoded by choosing as observations that should not be contradicted the absences of non observed phenomena in the **OBS-mapping**. In combination with the choice of the **Consistency** parameter this ascertains the required behaviour.

The \( BM_{cov} \) are the observed observables and the \( BM_{con} \) are not observed observables.

\( OBS-mapping^{FAN}(OBS) = \langle OBS, \{\neg ph : ph \in (BM_{OBS} \setminus OBS)\} \rangle \)

An example of using the anaesthesia domain knowledge is:

\( OBS-mapping^{FAN}(\{\text{Breathing tube disconnected, Increased PaCO2, Decreased PaO2}\}) = \langle OBS_{cov}, OBS_{con} \rangle, \) where

\( OBS_{cov} = \{\text{Breathing tube disconnected, Increased PaCO2, Decreased PaO2}\} \)
\( OBS_{con} = \{\neg \text{Decreased temperature,} \neg \text{Increased systemic arterial pressure,} \neg \text{Increased pulmonary venous pressure,} \neg \text{Increased PaO2,} \neg \text{Decreased PaCO2,} \neg \text{Increased heart frequency,} \neg \text{Decreased periferal perfusion,} \neg \text{Decreased pulmonary venous pressure,} \neg \text{Increased temperature}\} \)

**Vocabulary**  
This framework parameter contains the phenomena that can serve as explanations. More precisely an possible explanation must be a subset of the vocabulary.
In FAN no explicit vocabulary is distinguished. Every link tail can be part of the explanation. The FAN links are contained in $BM_T$, which is an argument of the $Vocabulary$ function.

$$Vocabulary^{FAN}(BM_T) = \{ e \mid link(e, ph, strength) \in BM_T \}$$

In our example are all phenomena part of the vocabulary except the bottom nodes of the network, such as “Increased PaO\(_2\)”, “Increased heart frequency”, etc.

**Cover** Above it was concluded that the covering relation in FAN is determined by two conditions. Firstly each observation must be explained by an element of the explanation via a link-chain. Secondly, pathognomonous explanations for observations must be part of the explanation. The first requirement is expressed by means of the $link-chain$ predicate and the second by the $patho-explanations$ function in the definition below.

$$BM_T \cup E \vdash^{FAN}_{cov} OBS_{cov} \iff \neg(OBS_{cov} \models \bot) \land \forall o \in OBS_{cov} : (\exists e \in E, strength : link-chain(e, o, strength)) \land patho-explanations(OBS_{cov}) \subseteq E$$

where

$$patho-explanations(OBS) = \{ e \mid link-chain(e, o, pathognomononic) \land o \in OBS \}$$

“Disconnected”, “Disconnected and Shunting” or “Disconnected and Underfilling” are examples of cover explanations for our diagnostic problem example and the computed $OBS_{cov}$ set.

Further the cover relation must be defined such that $cover$ $inconsistency$ can be detected. Formula (3) of the framework (section 5) requires that an explanation is cover consistent: an explanation is cover inconsistent when $\bot$ is covered. Thus the cover relation must be defined such that $\bot$ is covered when an explanation is inconsistent.

$$BM_T \cup E \vdash^{FAN}_{cov} \bot \iff \exists e \in E, o, s1, s2 : \quad link-chain(e, o, s1) \land link-chain(e, \neg o, s2) \land s_1 \models obligatory \land s_2 \models obligatory$$

**Consistency** The $\vdash_{con}$ parameter of the framework is used to express the second FAN criterion to diagnoses. An explanation is consistent when $OBS_{con}$ does not contain an element the negation of which is implied obligatorily by the explanation. This is defined as follows.

$$BM_T \cup E \vdash^{FAN}_{con} OBS_{con} \iff \neg\exists o \in OBS_{con} : link-chain(E, \neg o, strength) \land strength \models obligatory$$

In our example “Disconnected and Underfilling” is not an explanation because “Increased heart frequency” is not observed. Notice that this is caused by the obligatory links. If one of the links in the chain “Underfilling” to “Increased heart frequency” were facultative, then the “$\neg$Increased heart frequency” element of $OBS_{con}$ does not exclude “Underfilling” as explanation. However “Underfilling” is still excluded by “$\neg$Decreased pulmonary venous pressure”.
**Selection-criterion** The last two points in the informal description of the FAN reasoner are selection criteria. They select which among possible explanations are preferred.

The first selection criterion establishes that explanations with a minimal number of phenomena are preferred. This is designated as *cardinality* minimality in the literature [7]. Cardinality minimality is represented by the *card-min* predicate.

\[
\text{card-min}(ES, E) \iff E \in ES \land \neg \exists E' : (E' \in ES \land E \neq E' \land ||E'|| < ||E||)
\]

The second selection criterion is applied after the first. It establishes that an explanation is preferred over another when a subset relation exists between the sets of phenomena explained by the former and the latter. This criterion is represented by the *expl-inclusion* predicate.

\[
\text{expl-inclusion}(ES, E) \iff E \in ES \land \neg \exists E' : (E' \in ES \land E \neq E' \land \text{explained}(E') \subset \text{explained}(E))
\]

where *explained*(E) denotes the set of phenomena explained by explanation E.

\[
\text{explained}(E) = \{ph \mid \exists e \in E, \text{strength : link-chain}(e, ph, \text{strength})\}
\]

For instance *explained*(Disconnection) = \{increased PaCO2, decreased arterial PaO2\}.

The second selection criterion is applied to the subset of possible explanations preferred according to the first. This is represented by the meta-operator *SEQ* for combining selection criteria.

\[
\text{selected}(\text{min}^{\text{FAN}}, ES, E) \iff \text{selected}((\text{card-min } \text{SEQ} \text{ expl-inclusion}), ES, E)
\]

In section 4, we gave already some examples that illustrated these minimality criteria.

**Solution-form** FAN does not require a particular representation of solutions. Therefore the solution-form parameter of the framework is instantiated to the identity relation: SOL is equal to ES\text{min}.

### 7 Discussion & Conclusion

The formalisation of FAN has produced the following results:

- A better understanding of the diagnostic reasoning process envisioned for FAN has been achieved. Expressing a diagnostic reasoning method in terms of the framework enforces its precise definition.

The use of facultative and obligatory links is comparable to the possible and necessary causal relations found in the literature [2]. In FAN pathognomonic links are added, which requires a more complicated Cover component. However, following the explanation chains is in the spirit of abductive approaches. The intention of the *mapping*\textsuperscript{\text{FAN}} Obs-mapping can also be found in the standard abductive method. The Vocabulary and Solution-form also found in the literature. The Selection is built from a standard selection criterion (*card-min*), often found in the literature,
and a more or less new one (expi-inclusion). In the literature subset minimality is often used for selection of the explanations which are subset minimal in their causes. However, expi-inclusion is subset minimal in the objects explained. In literature the observables and the explanations are usually disjoint sets. In the FAN method however they are coincident; for instance, “Decreased pulmonary venous pressure” is both an observable and part of the vocabulary.

- The framework proved to be general enough to describe an independently developed diagnostic reasoning method. The framework was developed as a generalisation of a number of diagnostic reasoning methods described in the literature. The FAN diagnostic reasoner was not developed as an instantiation of one of the literature methods but “bottom up”. Nevertheless the framework proved to be general enough to describe the FAN reasoner. However, the FAN domain knowledge distinguishes has-part relations and causal-relations, but the method does not exploit this difference in knowledge types. How to exploit these knowledge types in diagnosis should be investigated. In other words the FAN diagnostic method might be improved.

- Its formalisation offers the possibility to compare the FAN reasoner to other diagnostic reasoners described in the literature and expressed in the framework (e.g. [2, 7], [3, 8, 4]).

To enable further comparisons alternative representations of the FAN notions can be analysed. A link between phenomena A and B can be expressed propositionally as “A \rightarrow B” when it is pathognomonic, as “A \rightarrow B” when it is obligatory and as “A \land \alpha \rightarrow B” when it is facultative.

The obligatory and the facultative links also correspond respectively to the necessary and possible causal relations in [2]. The formalisation described in this section more closely reflects the notions used in the FAN project.

- Instantiating the framework for an independently developed diagnostic method enlarged our insight in the nature of the framework parameters. The guidelines for instantiating the parameters have been improved.

A next step for future work is to connect the data of the FAN project to the implementation of the framework. We can prototype the FAN reasoner using the FAN domain knowledge, the framework implementation, and the parameter definitions presented here.

This will be very useful for validating the FAN method. It allows us to run a representative set of examples and compare the diagnoses obtained with those from anesthesiologists. The example that we have used in this paper shows that the requirement of being consistent with those observables which have at least an obligatory strength is possibly too strong. This requirement determines the diagnosis often completely, because many possible explanations have very specific observables which are obligatory. Furthermore validation of the FAN method leads properly to improvement of the use of has-parts and causal knowledge in the diagnostic method. We expect that the two types of knowledge would be used differently in the FAN method. However, until now this is not the case. Formalizing the method enables us to validate and improve the FAN method.

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**References**


