# Chapter 1

# Definitions

## 1.1. Introduction

Fusion has become an important aspect of information processing in several very different fields, in which the information that needs to be fused, the objectives, the methods, and hence the terminology, can vary greatly, even if there are also many analogies. The objective of this chapter is to specify the context of fusion in the field of signal and image processing, to specify the concepts and to draw definitions. This chapter should be seen as a guide for the entire book. It should help those with another vision of the problem to find their way.

## 1.2. Choosing a definition

In this book, the word "information" is used in a broad sense. In particular, it covers both data (for example, measurements, images, signals, etc.) and knowledge (regarding the data, the subject, the constraints, etc.) that can be either generic or specific.

The definition of information fusion that we will be using throughout this book is given below.

DEFINITION 1.1 (Fusion of information). *Fusion of information consists of combining information originating from several sources in order to improve decision making.*

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Chapter written by Isabelle BLOCH and Henri MAÎTRE.

This definition, which is largely the result of discussions led within the GDR-PRC ISIS[1] workgroup on information fusion, is general enough to encompass the diversity of fusion problems encountered in signal and image processing. Its appeal lies in the fact that it focuses on the combination and decision phases, i.e. two operations that can take different forms depending on the problems and applications.

For each type of problem and application, this definition can be made more specific by answering a certain number of questions: what is the objective of the fusion? what is the information we wish to fuse? where does it come from? what are its characteristics (uncertainty, relation between the different pieces of information, generic or factual, static or dynamic, etc.)? what methodology should we choose? how can we assess and validate the method and the results? what are the major difficulties, the limits?, etc.

Let us compare this definition with those suggested by other workgroups that have contributed to forming the structure of the field of information fusion.

Definition 1.1 is a little more specific than that suggested by the European workgroup FUSION [BLO 01], which worked on fusion in several fields from 1996 to 1999[2]. The general definition retained in this project is the following: gathering information originating from different sources and using the gathered information to answer questions, make decisions, etc. In this definition, which also focuses on the combination and on the goals, the goals usually stop before the decision process, and are not restricted to improving the overall information. They include, for example, obtaining a general perspective, typically in problems related to fusing the opinions or preferences of people, which is one of the themes discussed in this project, but this goes beyond the scope of this book. Here, improving knowledge refers to the world as it is and not to the world as we would like it to be, as is the case with preference fusion.

Some of the first notable efforts in clarifying the field were made by the data fusion work group at the US Department of Defense's Joint Directors of Laboratories (JDL). This group was created in 1986 and focused on specifying and codifying the terminology of data fusion in some sort of dictionary (Data Fusion Lexicon) [JDL 91]. The method suggested was exclusively meant for defense applications (such as automatically tracking, recognizing and identifying targets, battlefield surveillance) and focused on functionalities, by identifying processes, functions and techniques [HAL 97]. It emphasized the description of a hierarchy of steps in processing a system. The definition we use here contrasts with the JDL's definition and chooses another perspective, focusing more on describing combination and decision

1. www-isis.enst.fr.

2. This chapter greatly benefited from the discussions within this workgroup and we wish to thank all of the participants.

methods rather than systems. It is better suited to the diversity of situations encountered in signal and image processing. In this sense, it is a broader definition.

Another European workgroup of the EARSeL (European Association of Remote Sensing Laboratories) extended the JDL's definition to the broader field of satellite imagery [WAL 99]: the fusion of data constitutes a formal framework in which the data originating from different sources can be expressed; its goal is to obtain information of higher quality; the exact definition of "higher quality" will depend on the application. This definition encompasses most of the definitions suggested by several authors in satellite imagery, which are gathered in [WAL 99]. Definition 1.1 goes further and includes decisions.

The meaning of the word fusion can be understood on different levels. Other concepts, such as estimation, revision, association of data and data mining, can sometimes be considered as fusion problems in a broad sense of the word. Let us specify these concepts.

*Fusion and estimation.* The objective of estimation is to combine several values of a parameter or a distribution, in order to obtain a plausible value of this parameter. Thus, we have the same combination and decision steps, which are the two major ingredients of Definition 1.1. On the other hand, numerical fusion methods often require a preliminary step to estimate the distributions that are to be combined (see section 1.5) and the estimation is then interpreted as one of the steps of the fusion process.

*Fusion and revision or updating.* Revising or updating consists of completing or modifying an element of information based on new information. It can be considered as one of the fields of fusion. Sometimes, fusion is considered in a stricter sense, where combination is symmetric. As for revision, it is not symmetric and it draws a distinction between information known beforehand and new information. Here, we will be considering dynamic processes among others (particularly robotics), and it seems important for us to include revision and updating as part of fusion (for example, for applications such as helping a robot comprehend its environment). Revision involves the addition of new information that makes it possible to modify, or specify, the information previously available about the observed phenomenon, whereas updating involves a modification of the phenomenon that leads to modifying the information about it (typically in a time-based process).

*Fusion and association.* Data association is the operation that makes it possible to find among different signals originating from two sources or more those that are transmitted by the same object (source or target). According to Bar-Shalom and Fortman [BAR 88], data association is the most difficult step in multiple target tracking. It consists of detecting and associating noisy measurements, the origins of which are

unknown because of several factors, such as random false alarms in detections, clutter, interfering targets, traps and other countermeasures. The main models used in this field are either deterministic (based on classic hypothesis tests), or probabilistic models (essential Bayesian) [BAR 88, LEU 96, ROM 96]. The most common method [BAR 88] relies on the Kalman filter with a Gaussian hypothesis. More recently, other estimation methods have been suggested, such as the Interactive Multiple Model estimator (IMM), which can adapt to different types of motion and reduce noise, while preserving a good accuracy in estimating states [YED 97]. This shows how the problems we come across can be quite different from those covered by Definition 1.1.

*Fusion and data mining.* Data mining consists of extracting relevant parts of information and data, which can be, for example, special data (in the sense that it has specific properties), or rare data. It can be distinguished from fusion that tries to explain where the objective is to find general trends, or from fusion that tries to generalize and lead to more generic knowledge based on data. We will not be considering data mining as a fusion problem.

## 1.3. General characteristics of the data

In this section, we will briefly describe the general characteristics of the information we wish to fuse, characteristics that have to be taken into account in a fusion process. More detailed and specific examples will be given for each field in the following chapters.

A first characteristic involves the type of information we wish to fuse. It can consist of direct observations, results obtained after processing these observations, more generic knowledge, expressed in the form of rules for example, or opinions of experts. This information can be expressed either in numerical or symbolic form (see section 1.4). Particular attention is needed in choosing the scale used for representing the information. This scale should not necessarily have any absolute significance, but it at least has to be possible to compare information using the scale. In other words, scales induce an order within populations. This leads to properties of commensurability, or even of normalization.

The different levels of the elements of information we wish to fuse are also a very important aspect. Usually, the lower level (typically the original measurements) is distinguished from a higher level requiring preliminary steps, such as processing, extracting primitives or structuring the information. Depending on the level, the constraints can vary, as well as the difficulties. This will be illustrated, for example, in the case of image fusion in Chapter 3.

Other distinctions in the types of data should also be underlined, because they give rise to different models and types of processing. The distinction between common and

rare data is one of them. Information can also be either factual or generic. Generic knowledge can be, for example, a model of the observed phenomenon, general rules, integrity constraints. Factual information is more directly related to the observations. Often, these two types of information have different specificities. Generic information is usually less specific (and serves as a "default") than factual information, which is directly relevant to the particular phenomenon being observed. The default is considered if the specific information is not available or reliable, otherwise, and if the elements of information are contradictory, more specific information is preferred. Finally, information can be static or dynamic, and again, this leads to different ways of modeling and describing it.

The information handled in a fusion process is comprised, on the one hand, of the elements of information we wish to fuse together and, on the other hand, of additional information used to guide or assist the combination. It can consist of information regarding the information we wish to combine, such as information on the sources, on their dependences, their reliability, preferences, etc. It can also be contextual information regarding the field. This additional information is not necessarily expressed using the same formalism as the information we wish to combine (it usually is not), but it can be involved in choosing the model used for describing the elements of information we wish to fuse.

One of the important characteristics of information in fusion is its imperfection, which is always present (fusion would otherwise not be necessary). It can take different forms, which are briefly described below. Let us note that there is not always a consensus on the definition of these concepts in other works. The definitions we give here are rather intuitive and well suited to the problem of fusion, but are certainly not universal. The different possible nuances are omitted on purpose here because they will be discussed further and illustrated in the following chapters for each field of fusion described in this book.

*Uncertainty.* Uncertainty is related to the truth of an element of information and characterizes the degree to which it conforms with reality [DUB 88]. It refers to the nature of the object or fact involved, its quality, its essence, or its occurrence.

*Imprecision.* Imprecision involves the content of the information and therefore is a measurement of a quantitative lack of knowledge on a measurement [DUB 88]. It involves the lack of accuracy in quantity, size, time, the lack of definition on a proposal which is open to different interpretations or with vague and ill-defined contours. This concept is often confused with uncertainty because both these imperfections can be present at the same time and one can cause the other. It is important to be able to tell the difference between these two terms because they are often antagonistic, even if they can be included in a broader meaning for uncertainty. On the contrary, other classifications with a larger number of categories have been suggested [KLI 88].

*Incompleteness.* Incompleteness characterizes the absence of information given by the source on certain aspects of the problem. Incompleteness of the information originating from each source is the main reason for fusion. The information provided by each source is usually partial, i.e. it only provides one vision of the world or the phenomenon we are observing, by only pointing out certain characteristics.

*Ambiguity.* Ambiguity expresses the possibility for an element of information to lead to two interpretations. It can be caused by previous imperfections, for example, an imprecise measure that does not make it possible to distinguish two situations, or the incompleteness that causes possible confusion between objects and situations that cannot be separated based on the characteristics exposed by the source. One of the objectives of fusion is to erase the ambiguities of a source using the information provided by the other sources or additional knowledge.

*Conflict.* Conflict characterizes two or more elements of information leading to contradictory and therefore incompatible interpretations. Conflict situations are common in fusion problems and are often difficult to solve. First of all, detecting conflicts is not always simple. They can easily be confused with other types of imperfections, or even with the complementarity of sources. Furthermore, identifying and classifying them are questions that often arise, but in different ways depending on the field. Finally, solutions come in different forms. They can rely on the elimination of unreliable sources, on taking into account additional information, etc. In some cases, it can be preferable to delay the combination and wait for other elements of information that might solve the conflicts, or even not go through with the fusion at all.

There are other, more positive characteristics of information that can be used to limit the imperfections.

*Redundancy.* Redundancy is the quality of a source that provides the same information several times. Redundancy among sources is often observed, since the sources provide information about the same phenomenon. Ideally, redundancy is used to reduce uncertainties and imprecisions.

*Complementarity.* Complementarity is the property of sources that provide information on different variables. It comes from the fact that they usually do not provide information about the same characteristics of the observed phenomenon. It is directly used in the fusion process in order to obtain more complete overall information and to remove ambiguities.

The tools that can be used to model the different kinds of information and to measure the imperfections of the information, as well as redundancy and complementarity, will be described in Chapter 6.

## 1.4. Numerical/symbolic

There has been a great deal of discussion in the fusion community regarding the duality between numerical and symbolic fusion. The objective in this section is not to go over the details of these discussions, but rather to present the different levels on which this question can be expressed. By cleverly describing these levels, it is often possible to silence these debates. The three levels we will distinguish here involve the type of data, the type of process applied to the data and the role of representations. They are discussed in detail in the following sections.

### 1.4.1. *Data and information*

By numerical information, we mean information that is directly given in the form of numbers. These numbers can represent physical measurements, gray levels in an image, the intensity of a signal, the distance given by a range-finder, or the response to a numerical processing operator. They can be either directly read inside the data we wish to fuse or attached to the field or the contextual knowledge.

By symbolic information, we mean any information given in the form of symbols, propositions, rules, etc. Such information can either be attached to the elements of information we wish to fuse or to knowledge of the field (for example, proposals on the properties of the field involved, structural information, general rules regarding the observed phenomenon, etc.).

The classification of information and data as numerical or symbolic cannot always be achieved in a binary way, since information can also be hybrid, and numbers can represent the coding of information of non-numerical nature. This is typically the case when evaluating data or a process, or when quantifying imprecision or uncertainty. In such cases, the absolute values of the numbers are often of little importance and what mostly counts is where they lie on a scale, or the order they are in if several quantities are evaluated. The term "hybrid" then refers to numbers used as symbols to represent an element of information, but with a quantization, which makes it possible to handle them numerically. These numbers can be used for symbolic as well as numerical information.

### 1.4.2. *Processes*

In the context of information processing, a numerical process refers to any calculation conducted with numbers. In information fusion, this covers all of the methods that combine numbers using formal calculations. It is important to note that this type of process does not necessarily formulate any hypotheses regarding the type of information represented by numbers. At the beginning, information can be either numerical or symbolic in nature.

Symbolic processes include formal calculation on propositions (for example, logic-type methods or grammars, more details of which can be found in [BLO 01]), possibly taking into account numerical knowledge. Structural methods, such as graph-based methods, which are widely used in structural shape recognition (particularly for fusion), can be included in the same category.

We use the phrase hybrid process for methods where prior knowledge is used in a symbolic way to control the numerical processes, for example, by declaring propositional rules that suggest, enable or on the contrary prohibit certain numerical operations. Typically, a proposition that defines in which cases two sources are independent can be used to choose how probabilities are combined.

### 1.4.3. *Representations*

As shown in the two previous sections, representations and their types can play very different roles. Numerical representations can be used for intrinsically numerical data but also for evaluating and quantizing symbolic data. Numerical representations in information fusion are often used for quantifying the imprecision, uncertainty or unreliability of the information (this information can be either numerical or symbolic in nature) and therefore to represent information on the data we wish to combine rather than the data itself. These representations are discussed in greater detail in the chapters on numerical fusion methods. Numerical representations are also often used for degrees of belief related to numerical or symbolic knowledge and for degrees of consistency or inconsistency (or conflict) between the elements of information (the most common case is probably the fusion of databases or regulations). Let us note that the same numerical formalism can be used to represent different types of data or knowledge [BLO 96]: the most obvious example is the use of probabilities to represent data as different as frequencies or subjective degrees of belief [COX 46].

Symbolic representations can be used in logical systems, or rule-based systems, but also as *a priori* knowledge or contextual or generic knowledge used to guide a numerical process, as a structural medium, for example, in image fusion, and of course as semantics attached to the objects handled.

In many examples, a strong duality can be observed between the roles of numerical and symbolic representations, which can be used when fusing heterogenous sources. Examples will be given in different fields in the following chapters.

## 1.5. Fusion systems

Fusion generally is not an easy task. If we simplify, it can be divided into several tasks. We will briefly describe them here because they will serve as a guide to describing theoretical tools in the following chapters. Let us consider a general fusion problem with $m$ sources $S_1, S_2, \ldots, S_m$, and where the objective is to make a decision

among $n$ possible decisions $d_1, d_2, \ldots, d_n$. The main steps we have to achieve in order to build the fusion process are as follows:

1) modeling: this step includes choosing a formalism and expressions for the elements of information we wish to fuse within this formalism. This modeling can be guided by additional information (regarding the information and the context or the field). Let us assume, to give the reader a better idea, that each source $S_j$ provides an element of information represented by $M_i^j$ regarding the decision $d_i$. The form of $M_i^j$ depends of course on which formalism was chosen. It can, for example, be a distribution in a numerical formalism, or a formula in a logical formalism;

2) estimation: most models require an estimation phase (for example, all of the methods that use distributions). Again, the additional information can come into play;

3) combination: this step involves the choice of an operator, compatible with the modeling formalism that was chosen, and guided by the additional information;

4) decision: this is the final step of fusion, which allows us to go from information provided by the sources to the choice of a decision $d_i$.

We will not go into further detail about these steps here because it would require discussing formalisms and technical aspects. This will be the subject of the following chapters.

The way these steps are organized defines the fusion system and its architecture. In the ideal case, the decision is made based on all of the $M_i^j$, for all of the sources and all of the decisions. This is referred to as global fusion. In the global model, no information is overlooked. The complexity of this model and of its implementation leads to the development of simplified systems, but with more limited performances [BLO 94].

A second model thus consists of first making local decisions for each source separately. In this case, a decision $d(j)$ is made based on all of the information originating from the source $S_j$ only. This is known as a decentralized decision. Then, in a second step, these local decisions are fused into a global decision. This model is the obvious choice when the sources are not available simultaneously. It provides answers rapidly because procedures are specific to each source, and can easily be adapted to the addition of new sources. This type of model benefits from the use of techniques from adaptive control and often uses distributed architectures. It is also referred to as decision fusion [DAS 96, THO 90]. Its main drawback comes from the fact that it poorly describes relations between sensors, as well as the possible correlations or dependences between sources. Furthermore, this model very easily leads to contradictory local decisions ($d(j) \neq d(k)$ for $j \neq k$) and solving these conflicts implies arbitration on a higher level, which is difficult to optimize, since the original information is no longer available. Models of this type are often implemented for real-time applications, for example in the military.

A third model, "orthogonal" to the previous one, consists of combining all of the $M_i^j$ related to the same decision $d_i$ using an operation $F$, in order to obtain a fused form $M_i = F(M_i^1, M_i^2, \ldots, M_i^m)$. A decision is then made based on the result of this combination. In this case, no intermediate decision is made and the information is handled within the chosen formalism up until the last step, thus reducing contradictions and conflicts. This model, just like the global model, is a centralized model that requires all of the sources to be available simultaneously. Simpler than the global model, it is not as flexible as the distributed model, making the possible addition of sources of information more difficult.

Finally, an intermediate, hybrid model consists of choosing adaptively which information is necessary for a given problem based on the specificities of the sources. This type of model often copies the human expert and involves symbolic knowledge of the sources and objects. It is therefore often used in rule-based systems. Multi-agent architectures are well suited for this model.

The system aspect of fusion will be discussed further in an example in Chapter 10.

## 1.6. Fusion in signal and image processing and fusion in other fields

Fusion in signal and image processing has specific features that need to be taken into account at every step when constructing a fusion process. These specificities also require modifying and complexifying certain theoretical tools, often taken from other fields. This is typically the case of spatial information in image fusion or in robotics. These specificities will be discussed in detail in the case of fusion in signal, image and robotics in the following chapters.

The quality of the data to be processed and its heterogenity are often more significant than in other fields (problems in combining expert opinions, for example). This causes an additional level of complexity, which has to be taken into account in the modeling, but also in the algorithms.

The data is mostly objective (provided by sensors), which separates them from subjective data such as what can be provided by individuals. However, they maintain a certain part of subjectivity (for example, in the choice of the sensors or the sources of information, or also of the acquisition parameters). There is also some subjectivity in how the objectives are expressed. Objective data is usually degraded, either because of imperfection in the acquisition systems, or because of the processes to which it is subjected.

In fact, one of the main difficulties comes from the fact that the types of knowledge that are dealt with are very heterogenous. They are comprised not just of measurements and observations (which can be heterogenous themselves), but also of general cases, typical examples, generic models, etc.

The major differences with other application fields of information fusion first stem from the fact that the essential question (and therefore the objective of fusion) is not the same. In signal and image processing, it consists essentially, according to Definition 1.1, of improving our knowledge of the world (as it is). This implies the existence of a truth, even if we only have access to a partial or deformed version of it, or if it is difficult to obtain, as opposed to the fusion of preferences (the way we want the world to be), the fusion of regulations (the way the world should be), or voting problems, where typically there is no truth, etc. [BLO 01].

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