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Relational Calculus for Actionable Knowledge

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Michel Barès Ph.D. is an independent researcher in Artificial Intelligence (AI). He is a former researcher at DRET (Direction des Recherches Et Technologies) under the French Ministry of Defence. There, he conducted different innovative research projects relevant to military motivations concerning symbolic reasoning, decision support, and distributed AI. He has been a pioneer to introduce distributed AI in military command decision-making aids. In parallel to his military research work, he acted as professor for several universities and specialized French schools. Since 2017, he is a scientific advisor for Expertises Parafuse inc., a small research firm located in Québec City, Canada. He holds a Ph.D. degree from the university Paris 6, France.

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List of Abbreviations

AD	Archetypal Dynamics
AI	Artificial Intelligence
AIF	Analytics and Information Fusion
Big Data 5Vs	(Velocity, Volume, Veracity, Value, Variety)
C2	Command Control
C4ISR	Command Control, Communications, Computer, Intelligence, Surveillance and Reconnaissance
CI	Contextual Information
CoA	Course of Action
CPS	Cyber-physical Systems
CPSS	Cyber-physical and Social Systems
CSE	Cognitive System Engineering
DF	Data Fusion
DIK	Data-Information-Knowledge
DM	Decision-Making
DQ	Data Quality
DSS	Decision Support Systems
DS	Dempster–Shafer
DST	Dempster–Shafer's Theory
EBDI	Entity-Based Data Integration
ER	Entity Resolution
ES	Epistemic Structure
ETURWG	Evaluation of Technologies for Uncertainty Representation Working Group
GIT	Generalized Information Theory
GTI	General Theory of Information
HLIF	High-Level Information Fusion
H2M	Human-to-Machine
H2S	Human-to-System
IBM	International Business Machine

ICN	Information Centric Networking
ICT	Information and Communication Technology
ID	IDentification
IF	Information Fusion
IFS	Intuitionistic Fuzzy Set
IG	Interoperable Groups
Intel	Military Intelligence cycle
IoT	Internet of Things
IoE	Internet of Everything
IS	Information Systems
ISIF	International Society of Information Fusion
JDL	Joint Directors of Laboratories
JDL DIFG	Joint Directors of Laboratories' Data and Information Fusion Group
KDD	Knowledge Discovery in Databases
KID	Knowledge, Information and Data
KIME	Knowledge-Information-Matter-Energy
KS	Knowledge System
MAPE	Monitor-Analyze-Plan-Execute
MAS	Multi-agent Systems
MCDA	Multi-criteria Decision Analysis
MCDM	Multi-criteria Decision-Making
MS	Management Science
M2M	Machine-to-Machine
NATO	North Atlantic Treaty Organization
NATO SAS RG	NATO Systems Analysis and Studies Research Group
ORBAT	ORder of BATtle
OODA	Observe-Orient-Decide-Act
QoI	Quality of Information
SA	Situation Analysis
SAW	Situation Awareness
SM	Sense-Making
STO	Socio-technical Organizations
TER	Total Entity Resolution
TQM	Total Quality Management
TU	Total Uncertainty
UMM	Uncertainty Management Methods
UN	United Nations
URREF	Uncertainty Representation and Reasoning Evaluation Framework
WoT	Web of Things

List of Symbols

$\mathbb{N} = \{1, 2, 3, \ldots\}$	The set of natural numbers
$\mathbb{R}$	The set of real numbers
$\lvert A \rvert$	The cardinality of a set A
A^C	The complement of A
$\in$	Membership sign; belongs to
$\subseteq$	Subset; inclusion sign
$\subset$	Proper subset; strict inclusion
$\varnothing$	Empty set
$\cup$	Union
$\cap$	Intersection
X	Cartesian product
$<$	Less than
$\leq$	Less than or equal to
$>$	Greater than
$\geq$	Greater than or equal to
sup	Supremum
inf	Infimum
max	Maximum
min	Minimum
:: or $\stackrel{\text{def}}{=}$	Defined as; given by
$\therefore$	Therefore
~ or $\neg$	Negation
$\Longrightarrow$	Implication
$\longrightarrow$	Correspond to
$\forall$	Universal quantifier; for all
$\exists$	Existencial quantifier; there exists
$asc_{\uparrow}$	Ascendant of
$desc_{\downarrow}$	Descendent of
$\vdash$	Conclusion; turnstile symbol; assertion sign
$\Leftrightarrow$	Equivalence
Dom(R)	Domain of relation R
Rng(R) or Im(R)	Range or image of relation R
coR	The *complement* relation *coR* of R
R^{-1}	The reverse or inverse of relation R
$\neq$	Not equal
P-relation	A relation with property P
aRb	a is related to b
poset P	*a partial ordering or a partial order of P*
lub	or *sup* or $\sqcup$ *Least upper bound*
glb or *inf* or $\sqcap$	*Greatest lower bound*
$P \bigoplus Q$	The ordinal sum of two posets

$\mathbb{L} = (P, \bigsqcup, \sqcap, 0, 1)$	A lattice as a *poset* P
$R \circ S$	Composition of relations R and S
$R \triangleleft S$	Subcomposition of relations R and S
$R \triangleright S$	Supercomposition of relations R and S
$R \diamond S$	Ultracomposition of relations R and S
$x \notin A$	x is not element of A
μ	membership function
ν	non-membership function
$\mu_{A(x)}$	degree of membership of element x in A
$\upsilon_{A(x)}$	degree of non-membership of element x in A
${}^{\alpha}A$	The α-cut of A
${}^{\alpha+}A$	The strong α-cut of A
${}^{0+}A$	The *support* of A
${}^{1}A$	The *core* of A
hgt(A)	The *height* of A
plth(A)	The *plinth* of A

Chapter 1
Introduction to Actionable Knowledge

Abstract This chapter presents an introduction to actionable knowledge, its related notions, and to what general context actions are going to take effect? What is actionable knowledge? From what angle, this book is approaching it? Where and how do we position relational calculus with respect to actionable knowledge? The context of Cyber-Physical and Social Systems is briefly described. Important related notions of knowledge, dynamic decision-making, situations and situation awareness, and analytics and information fusion are being introduced. These notions are necessary to position relational calculus in the processes of creating actionable knowledge.

1.1 Actionable Knowledge

In a very recent book on knowledge and action [1], the authors start by quoting a widely accepted idea [2] that "*parts of knowledge can be defined as ability, aptitude, or 'capacity for social action' and that the production and dissemination of knowledge are always embedded in specific environments (spatial context, spatial relations, and power*[1] *structures)*."

Knowledge, learning, and information-processing determine how objectives of actions are set:

- How are situations, opportunities, and risks assessed?
- How are patterns interpreted?
- How are problems solved?

They are links between action and environment as pictured in Fig. 1.1. For instance, acting under conditions of uncertainty, people must rely on knowledge acquired from various situations and environments, and they must gather new

[1]The close relationship between knowledge and power is evident by the very fact that they have the same etymological roots. The word *power* derives from the Latin *potere* (to be able). The Latin noun *potentia* denotes an ability, capacity, or aptitude to affect outcomes, to make something possible. It can therefore be translated as both knowledge and power. (*from the same reference*)

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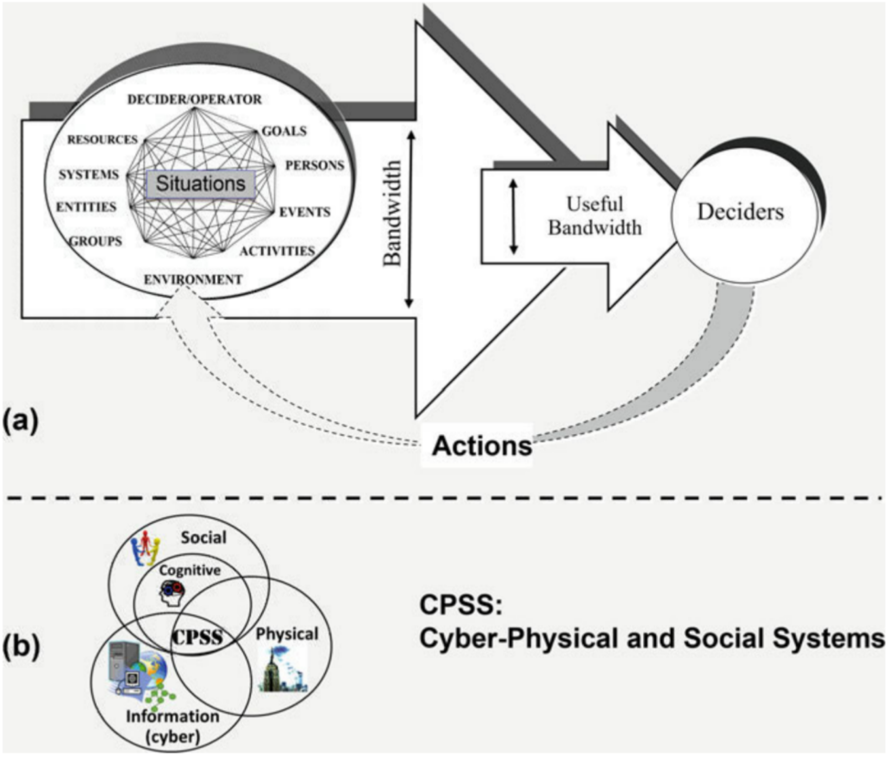

Fig. 1.1 Actionable knowledge in Cyber-Physical and Social Systems (CPSS): (**a**) a useful *information bandwidth*—a metaphor of the signal processing community and (**b**) CPSS as the intersection of various worlds

information, gain new knowledge, and develop new skills to cope with unexpected situations and unfamiliar challenges. The following points are generally accepted for people to achieve their goals:

- Goal setting is impacted by knowledge, skills, experience, and the search for new information.
- Experience rests upon former actions in specific settings.
- There are multiple relationships between knowledge and action.
- Learning processes are shaped by the social and material environment.
- The spatial dimension plays a key role in the acquisition of knowledge and implementation of actions.

Figure 1.1a illustrates the flow of information required to assess situations that are occurring in real world. Using an analogy borrowed from the signal processing community, one can imagine a useful "information" bandwidth where the overall goal would be to provide useful information to deciders, i.e., actionable knowledge. That conceptual multidimensional "useful bandwidth" could be defined by

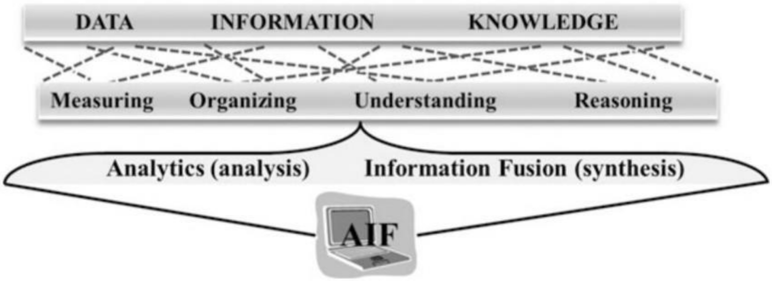

Fig. 1.2 Analytics and information fusion (AIF) as a computer-support system

assembling appropriate smart filtering and metadata-based technologies to perform analysis and synthesis of information that we refer as analytics and information fusion (AIF), pictured in Fig. 1.2.

Relationships between knowledge, action, and environment are quite complex, some of them are still not fully understood. To understand the interrelations of knowledge and action, it yields to pose the following questions:

- To what extent is knowledge a precondition for action? How much knowledge is necessary for action?
- To what extent do various types of knowledge influence aspirations, attention, evaluation of situations, search for alternatives, implementation of intentions, decision-making, and problem-solving?
- How do different representations of knowledge shape action?
- How does the digital revolution change the formation of knowledge?
- How can one measure an environment's impact on action and knowledge production?
- . . .?

These and other questions indicate that relations between knowledge, action, and environment are not simple and affect the modeling of decision and risk. The questions above suggest a need to explore the interdependencies of knowledge, action, and environment from a multidisciplinary perspective. With the evolution of societies, the so-called "*environment*" has become quite complex. Information overload and complexity are core problems that both military and civilian organizations are facing today. With the increase in networking, these large military and civilian organizations are referred to as Cyber-Physical and Social Systems (CPSS) (see Fig. 1.1b and next section).

Executives or commanders want better ways to communicate complex insights so they can quickly absorb the meaningful information (actionable knowledge) to decide and act. *Big data* [3] is contextual to CPSS complex dynamic environments. *Big data*, being at the same time a problem or an opportunity, has emerged with its 5Vs (*volume, veracity, variety, velocity, and value*) dimensions and it is the main object of a newly created scientific domain named "*data science*."[2] It requires that new technology be developed to provide the analysis (e.g., analytics) and synthesis (e.g., information fusion) support for the decision-makers to make sense out of data-information to create actionable knowledge for efficient actions.

A nice factual description of what CPSS is dealing with is given in [3] as follows:

> Every day, around 20 quintillion (10^{18}) bytes of data are produced. This data includes textual content (unstructured, semi-structured, and structured) to multimedia content (images, video, and audio) on a variety of platforms (enterprise, social media, and sensors). The growth of physical world data collection and communication is supported by low-cost sensor devices, such as wireless sensor nodes that can be deployed in different environments, smartphones, and other network-enabled appliances. This trend will only accelerate, as it's estimated that more than 50 billion devices are currently connected to the Internet Extending the current Internet and providing connections and communication between physical objects and devices, or 'things,' is described under the general term of Internet of Things (IoT). Another often used term is Internet of Everything (IoE), which recognizes the key role of people or citizen sensing, such as through social media, to complement physical sensing implied by IoT. Integrating the real-world data into the Web and providing Web-based interactions with the IoT resources is also often discussed under the umbrella term of Web of Things (WoT)

Data science [4] is facing the following major challenges:

1. Developing scalable cross-disciplinary capabilities.
2. Dealing with the increasing data volumes and their inherent complexity.
3. Building tools that help to build trust.
4. Creating mechanisms to efficiently operate in the domain of scientific assertions.
5. Turning data into actionable knowledge units.
6. Promoting data interoperability.

Actionable knowledge is not a new term. It has been qualitatively and intensively studied in management and social sciences. It illustrates the relationship between theory and practice. Actionable knowledge is linked with its user: the practitioner. It has been positioned as a response to the relevance of management research to management practice. Is the generated knowledge actionable by the users whom it is intended to engage (business practitioners, policymakers, researchers)? Actionable knowledge should advance our understanding of the nature of action as a phenomenon and the relationship between action and knowledge (modes of knowing) in organizations.

Actionable knowledge is explicit symbolic knowledge that allows the decision-maker to perform an action, such as select customers for a direct marketing campaign or select individuals for population screening concerning high disease risk. Its main connection is with data mining, an emerging discipline that has been booming for the

[2] **Data science** is an interdisciplinary field that uses scientific methods, processes, algorithms, and systems to extract knowledge and insights from structured and unstructured data and apply knowledge and actionable insights from data across a broad range of application domains. Data science is related to data mining, machine learning, and big data. (https://en.wikipedia.org/wiki/Data_science)

last two decades. Data mining seeks to extract interesting patterns from data. However, it is a reality that the so-called interesting patterns discovered from data have not always supported meaningful decision-making actions. This shows the significant gap between data mining research and practice, and between knowledge, power, and action. This has motivated the evolution of data mining next-generation research and development from data mining to actionable knowledge discovery and delivery [4–6].

Although big data is highly linked to business and social sciences and the genesis of actionable knowledge is from there, a CPSS environment present cases where the actions are much more complex than the implementation of conventional one-time decisions. A CPSS environment presents situations where interdependent decisions take place in a dynamic environment due to previous actions or decisions and events that are outside of the control of the decision-maker [7]. In addition to conventional one-time decisions, CPSS present dynamic decisions. The latter field is typically more complex than one-time decisions and much more relevant to the environments of Big Data and IoT. In addition, dynamic decisions occur in real time. In complex CPSS, if we wish to provide actionable knowledge, one must understand and explain the decision-making and action processes in such complex environments. The extraction of actionable knowledge will be consequently more demanding.

Two main influential streams [8, 9] are generally recognized to understand decision-making. The first stream refers to a rational approach that is based on formal analytic processes predicted by normative theories of probability and logic. The second stream, called naturalistic or intuitive theories, is based on informal procedures or heuristics to make decisions within the restrictions of available time, limited information, and limited cognitive processing. Bryant et al. [8] insist upon a continuum in decision strategy to adopt the approach that is best tailored to the situation and may use elements of the two approaches at the same time (Fig. 1.3).

More and more, IoT and Big data are perceived as two sides of the same coin where Big Data would be a subset of IoT [10–12]. As mentioned above, Big Data is evidently contextual to Cyber-Physical and Social Systems (CPSS) [13–17]. CPSS emerge from the interrelation of social, cognitive, information/cyber and physical worlds as pictured in Fig. 1.1b. Social and cognitive dimensions interface with the physical world through the cyber world.

1.2 Our World: Cyber-Physical and Social Systems (CPSS)

Our world is an interlocking collective of Socio-Technical Organizations (STO) recently referred to as Cyber-Physical Social Systems (CPSS) [13, 18, 19] in the literature. CPSS consist of inhomogeneous, interacting adaptive agents capable of learning: large number of groups of people hyperlinked by information channels and interacting with computer systems, and which themselves interact with a variety of physical systems in conditions of good functioning. Primary examples of CPSS include Command and Control Organizations such as 911/Emergency Response

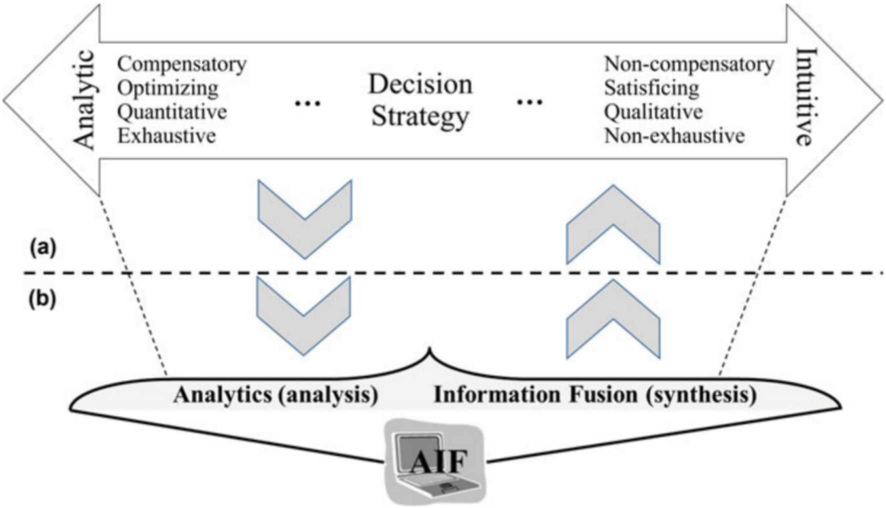

Fig. 1.3 Decision strategy: (**a**) the spectrum of decisions and (**b**) computer-based decision support. AIF, analysis and synthesis of information for decision-making

Systems and military organizations, as well as organizations that manage "critical infrastructures": transport, health, energy, defense, and security. Part (b) of Fig. 1.1 illustrates that CPSS emerge from the interrelation of social, cognitive, information/cyber and physical worlds. The interrelation (cyber) is achieved by the means of what we call *information*.

Information overload and complexity are core problems to both military and civilian CPSS of today. Executives or commanders want better ways to communicate complex insights so they can quickly absorb the meaning of the data and act on it. That problem has also been referred to as Big Data in recent literature [20]. The advances in Information and Communications Technologies (ICT), in particular smart ICT, although providing a lot of benefits to improve dependability, efficiency and trustworthiness in systems, have also increased tremendously the networking capabilities so creating the conditions of complexity by enabling richer, real-time interactions between and among individuals, objects, systems and organizations. As a result, events that may once have had isolated consequences can now generate cascades of consequences, consequences that can quickly spin out of control (e.g., blackouts, catastrophes) and affect badly the system dependability or trustworthiness.

Dependability of a system (simple, complicated, or complex) reflects the user's degree of trust in that system. It reflects the extent of the user's confidence that it will operate as users expect and that it will not fail in normal use. The crucial dimensions of dependability are maintainability, availability, reliability, safety, and security. The high-level requirements for current and future CPSS are expected to be dependable, secure, safe, and efficient and operate in real time in addition to be scalable, cost-effective, and adaptive. Dependability can be achieved by effective high-quality *information*.

Cyber-Physical Systems (CPS) [21, 22] and the Internet of Things (IoT) [10, 11, 23] are big contributors to Big Data problems or opportunities. There is still a bit of confusion about the definition of Big Data whether it is best described by today's greater volume of data, the new types of data and analysis, social media analytics, next-generation data management capabilities, or the emerging requirements for more real-time information analysis. Whatever the label, organizations are starting to understand and explore how to process and analyze a vast array of information in new ways.

Cyber-Physical Systems (CPS) [24] are the integration of computation with physical processes. In CPS, embedded computers, and networks, monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa. That integration of physical processes and computing is not new as evidenced by predecessors to CPS called "embedded systems." However, embedded systems are rather "stand-alone" devices and they are usually not networked to the outside. What Internet and its evolutions are bringing is the networking of these devices. This is what we call Cyber-Physical Systems (CPS) [22] or Internet of Things (IoT) [25]. The following two definitions allow to see the distinction or the similarity between both CPS and IoT:

Helen Gill, NSF, USA [22]: "*Cyber-physical systems are physical, biological, and engineered systems whose operations are integrated, monitored, and/or controlled by a computational core. Components are networked at every scale. Computing is deeply embedded into every physical component, possibly even into materials. The computational core is an embedded system, usually demands real-time response, and is most often distributed*."

Benghosi et al. [25]: "*... define the Internet of Things as a network of networks which enables the identification of digital entities and physical objects – whether inanimate (including plants) or animate (animals and human beings) – directly and without ambiguity,* via *standardized electronic identification systems and wireless mobile devices, and thus make it possible to retrieve, store, transfer and process data relating to them, with no discontinuity between the physical and virtual worlds*."

The generation of actionable knowledge to support decision-making in CPSS is challenged by the concurrent nature and laws governing the social, cognitive, cyber, and physical worlds. Figure 1.4 pictures crucial elements of that CPSS world and presents, at the same time, the global context of this book. The cybernetics functions of coordination, integration, monitoring, and control for dependable CPSS cannot be achieved efficiently without a profound understanding of the data-information-knowledge (DIK) processing chain that is practically realized through Analytics and Information Fusion (AIF) processes. The cybernetics functions summarize in some sort, the world of actions. System dependability in CPSS is an overall sine qua non-objective. Knowledge is always about the structure of a phenomenon rather than the essence of it. Relation is an ontological element of that structure. The contribution of this book is to discuss how relation and its calculus can be exploited

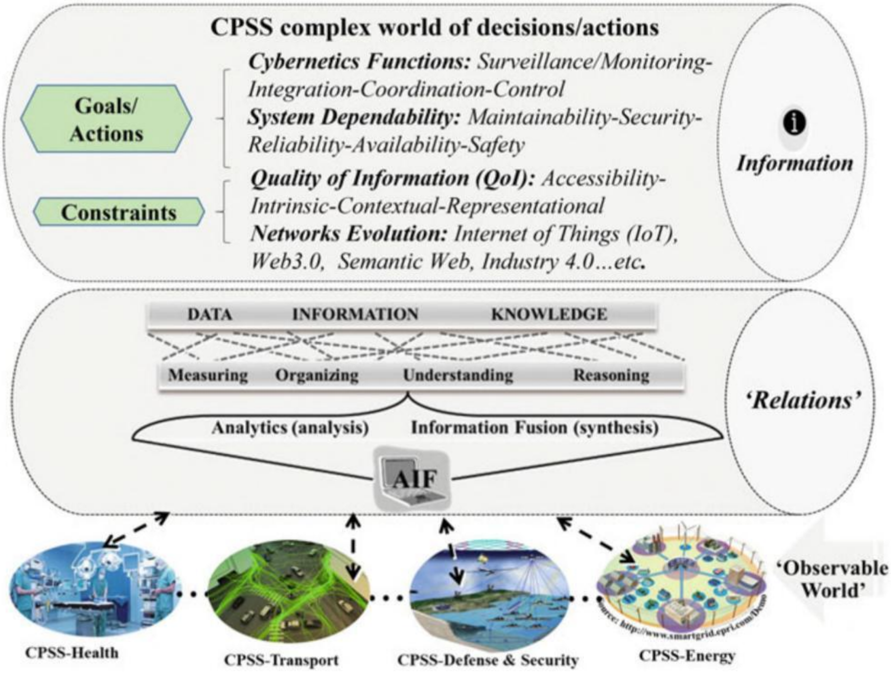

Fig. 1.4 Crucial elements of a CPSS complex world of decisions/actions

in the multifaceted process of creating actionable knowledge (Fig. 1.4) which is, by the way, the main goal of any AIF computer-based decision support systems.

1.3 Societal Behavior Face to Knowledge and Information

The massive pervasion of novel Information and Communication Technologies (ICTs) into contemporary society undoubtedly causes large-scale societal transformations and the awareness of major issues on the part of decision-makers. The new behaviors and strategies allowed by this pervasion allow us to open new fields of action whose outlines are already perceptible through [26, 27]:

- The tightening of the meshes of telematics networks.
- An optimized search for the organization and retention of knowledge in general.
- The lines of force of a new economy with the emergence of new types of commercial services (e.e-commerce), general exchange mechanisms, various services.
- The emergence of new relations between citizens and their administration (e.g., e-government).

- New relationships to knowledge, access, usage, and maintenance, and the establishment of new mechanisms of innovation.

The effects of this intrusion are concretely apparent from now on:

- By networking skills in various sectors of socioeconomic activity.
- By effectively capitalizing on different knowledge.
- By setting up and development of partnerships to better polarize the energies of production and innovation.

These transformations imply that the means of the nation, ever more numerous, are solicited to compete to a certain evolution of a society oriented by, if not fully dedicated to, knowledge. It aims to be more in line with the aspirations and needs of the citizen for knowledge. On the other hand, knowledge freely accessible to all, constitutes an incontestable democratization factor since eliminating all social discrimination.

The corollary of the information evolution of our society is the increase of its fragility: the systematized availability of knowledge, responding to a legitimate desire to make them accessible to all, increases the vulnerabilities. It is a safe bet that these will be unfortunately exploited by some pursuing criminal purposes. What happens every day on the networks is there to remind us. It is also to be feared that, in the event of a crisis, this vulnerability of the information society will become the subject of new forms of conflict. This can take the form of a war of meaning: the manipulation of deviant information about an adversary whom one seeks to destabilize psychologically.

It can also take the form of a war of potentials whose offensive nature is marked by the propagation of false information to weaken the adversary by targeting the sensitive elements (which may be of a diverse nature) constituting the essence of its potential. These are threats to information societies, which, despite their apparent harmlessness, must give rise to the same level of vigilance as is required by the usual forms of conflict. They are one of the many facets of the information war.

All nations have realized the importance of conserving on public networks all cognitive elements directly or indirectly involved in the socio-political and economic life. Huge or gigantic collective memories are worldwide created that require to be organized and managed for the benefit of all human communities. The access increasingly trivialized to servers, greatly democratized by the Internet, offers to all without social or cultural discrimination an access to contemporary knowledge. This is an important sociological fact that one must take the full measure because it will have a significant impact on social organizations, changing patterns of thought and action among its members, and, to some extent, on the modes of action of policy makers. Collective behavior will conform to new habits to learn to decide and act. This will also have an impact on citizens who now can directly perform administrative procedures using specialized servers.

Our relationship to knowledge is changing, becoming more direct and immediate, and furthermore showing changes in our learning techniques and in our modes of appropriation of knowledge. This will certainly impact the definition and implementation of future vocational training. The computer, networks, servers, and specialized software used together now possess all the attributes to become omniscient tutors and be most effective because they are available at any time. All ingredients and special-purpose nurturers are thus gathered to create a tremendous evolution of societies immerged in the world of information and communication. Already, a telematics infrastructure as the Internet, resting on finely capillaries-like networks, is both the foundation and nervous system of new informational situations.

The informational evolution concerns not only the major institutions of societies but also its basic cells: homes, where the computer becomes part of the family furniture. Connected to the Internet, the computer becomes a privileged instrument of dialogue for the entire family. The family becomes, ipso facto, by analogy with the concept of economic agent, an "*informational agent*" by consuming services and information products available on the World Wide Web. We must also expect to see some situations that generate their own "informational pollution" because no longer obedient to rational expressed needs. The outlook of a sustainable development will undoubtedly lead to eliminate superfluous inherent overabundant consumption and production in favor of the only treatments corresponding to a user 'strict needs to know'.

In information society, new possibilities for action are offered to actors that expand their intervention context and gear their knowledge. It follows a modern philosophy of action, which is observed in many places:

- Techniques, whatever their origin, must no longer be stationed in areas of elitist employment.
- Everything must be done to remove the technical point of contact between a server and a user: it should be kept away from technical arcana and generate maximum easements for implementation and operation.
- The repositories of information must be organized rigorously and practically. The emergence of new knowledge enables a rational exploitation and access facilitated by telematics.
- The information, from its initial creation, must be structured to be integrated into the memories of server computers.
- The coupling between a server supporting a domain of knowledge and a telematics infrastructure has a multiplier effect on a decision-maker. The decision-maker is a priori a non-specialist of the knowledge they seek to the extent that:
- The collective memory stores knowledge as diverse as specialized and from worldwide origin. The latter portends that we have access to knowledge derived from recent discoveries in the world since servers are timelessly updated.
- Access to information for all is almost instantaneous, whatever the extent of their geographical position is.

Boundaries become transparent to exchanged messages ipso facto making the transboundary information exchange mechanisms. This informational evolution announces changes for the usual way of thinking and acting hitherto maintained in a society often founding its modes of action on cultural bases. Novel forms of action appear that are more directed by rational domestication of a sort of "*informational energy*." For the new "*energy actors*" of the information age, involved in the major functions of management and finance, there is food for thought before designing and proceeding with entrepreneurship in organizations and various institutions.

The information also presents great interest to become a lever for saving energy, in the sense that its proper use in different operating environments allows both: reduce servo and improve regulations for instance in inventory management and control optimization of industrial processes. Along with these changes, there is no doubt that attitudes will change and help shape the contours of a new civilization, where the action will be led by a better mastery of knowledge and a more rational assimilation of knowledge.

1.4 Informational Situations

Wishing to know, having to know, or simply trying to stay aware represents a true informational challenge [26]. Are we witnessing an information revolution through a huge convergence of a multitude of techniques coming from various origins? It is more reasonable to substitute evolution to the term "revolution" since it is the combined effects of adaptation and maturation of several techniques. The integration of these techniques into advanced architectures of information systems materializes as an important factor of societal evolution, sparking changes in behavior and opening new fields of application. Evolution also generates a constant search for circumstantial adaptation of terms of employment or simultaneous implementation of those techniques as, for instance, the joint use of several modes of interaction: gesture designation with voice control, for instance.

Informational situations exemplify new contours drawn because of a systematic digitization of multimedia and of communication and data transmission networks as well as a large-scale miniaturization of information storage systems. This results in numerous consequences. Information contents are indeed the clear tendency to emancipate themselves from their traditional media, including paper, thereby focusing more on the "object of knowledge"or information content carried by the media or the message without much having to worry about the physical characteristics of the container or vehicle. The techniques related to the semantics of information have undoubtedly found a new tone and new concepts such as Information-Centric Networking (ICN)[3] [28] to network contents rather than devices that hold the contents. Internet usage has drastically shifted from host-centric end-to-end

[3] "*The ICN concept has born in the era that more and more users are shifting their interests to the content itself rather than the location or server where contents are stored. This content-centric behavior of user applications has rendered the point-to-point communication paradigm of IP networks inefficient.*"

communication to receiver-driven content retrieval. One important feature of ICN architectures is to improve the transmission efficiency of content dissemination. ICN has emerged as a promising candidate for the architecture of the Future Internet.

The informational development within the society has generated an ever increasing need to transport data and has imposed a big load on telematics networks, usually via existing telecommunications infrastructure and its evolutions. Careful observation of bandwidths in telecommunications infrastructure shows high availability to transport more than only voice signals. More means that a channel, in addition to the voice signal, would carry the various typical vectors of information: text, graphics, photos, videos. This objective is at the origin of multi-service networks: to propagate on dedicated tracks, the pictorial information (previously digitized) with or without animation, with the same apparent ease than with usual computer data (e.g., 5G). The research community is currently exploring advanced approaches to transform the Internet, as we know it today, into a system more capable of effective content distribution and sharing, according to today's (and tomorrow's) needs.

It is tempting to draw an analogy between information and raw material. From the perspective of raw material, information must undergo some processing steps before becoming a commodity because, despite an intangible nature, it must be transformed each time it must respond to new needs or get developed products to meet specific requirements. That differs little from the processing steps of the industrial revolution actions with respect to a mineral. Therefore, it can easily be likened to a commercial product undergoing the usual phases of transformation, (re) packaging, and distribution before the arrival at the market. Here the analogy stops because the information has a surprising substantive nature: when a transformation process is applied, then that does not cause a change to its intrinsic nature as in the case of a mineral.

Information can be consumed and replicated indefinitely under energy-free processing steps. Moreover, and this is not the slightest interest, it may, whatever the nature of the exchange mechanism used, be shared endlessly without the emitting source being altered. The information becomes a commodity in its mercantile sense, insofar as access to knowledge, deposited in a server, resulting in commercial transactions. The birth of this new market is not immune to the usual trading imperatives: production costs, profitability, competition. Note that the transmission of knowledge, through its various media, has never been completely free, its price is often dependent on its support implementation parameters. A book full of information can be sold at the same price as a book informatively devoid of interest, insofar as it represents the same production cost.

The current trend of information is continuously to be emancipated from its traditional media or vehicle. Data retrieved from a server and available immediately through telematics infrastructure account for a significantly higher quality of service compared with paper-based information geographically dispersed or difficult to access, especially by ordinary means of transmission (e.g., fax).

The Internet and its associated applications are, in this respect, a major factor of integration. The concept of information dissemination has not been more detrimental, as in the past. In this case, we buy only the information we need precisely without concern or the nature of the vector or its locality. The knowledge delivered by the server cannot be separated from its electromagnetic support. This, however, is not a handicap as in the case of print media, since the information generated by the server is no longer a frozen product. It can be enriched on demand using specialized software, depending upon the service requested. That will help to expand the informative field or restrict it by better focusing if necessary.

Raw information extracted from data servers can also give rise to successive transformations through the punctual use of specialized software. In doing so, the information is treated as a work in progress in a production cycle of a commercial product. The merchandise qualifier is fully justified within the context of raw material industry with the epiphenomenon of informational fields appearing more or less "open sky" with variable information concentration. Note that the information industry fits well into the context of sustainable development, since by its nature, it allows to go to manufactured products and consume less energy, while incorporating more "intelligence." This quality of smart product can, however, be achieved if we knew how to handle large amounts of information (e.g., IoT, Big Data) and assimilate as much knowledge to manufacture such products.

Millions of people now use online social network applications such as Twitter, Facebook, and Google+. This kind of application offers the freedom for end users to easily share contents on the Internet. For instance, there is a large consensus that the Internet of Things (IoT) will play a primary role in providing global access to services and information offered by billions of heterogeneous devices (or *things*), ranging from resource-constrained to powerful devices (and/or virtualized everyday life objects) in an interoperable way.

IoT aims to connect each device with the Internet, so that these devices can be accessed at any time, at any place, and from any network. Smart objects like smart washing machines, smart refrigerators, smart microwave ovens, smart-phones, smart meters, and smart vehicles connected via Internet enable applications like smart home, smart building, smart transport, digital health, smart power grid, and smart cities. When billions of these devices are connected to the Internet (IoT), combined with the data produced by multiple sources like Facebook, YouTube, etc., we end up in a situation that we call BigData. In fact, most of the IoT applications are *information-centric* in nature, since they target data regardless of the identity of the object that stores or originates them. For example, road traffic monitoring applications are ignorant to the specific car/sensor that provides the information.

Let us conclude this section by this citation from Burgin [29] that is still quite actual:

> Creation of information technology of our time is, may be, the most important revolution in human evolution. Now information processing plays more and more important role in life of people and functioning of society. One of the most threatening features of the contemporary society is the common lack of ability to discriminate between useful, sound, and trustworthy information and a worthless, often harmful, and misleading stuff that has always been around but now with the advent of the Internet, e-mail systems and other communication

> tools, it multiplies with unimaginable rate. . . ., a lot of information carrying media are full of information that is of low quality and quite often imprecise and even false. The usage of such information to achieve a chosen objective may bring and often brings unwelcome results.

1.5 Mastering and Improving Knowledge

The context of better knowledge promotes a better perception, representation, and interpretation of reality. This should facilitate decision-making better suited to circumstances and actions that are wisely carried out on the world. In so doing, the world in which we are acting evolves. It follows that the state of it will change, by retroactive effect, resulting in a change of its cognitive state. Indeed, every time that ideas change as well as behaviors about the universe of action, this implies that a renewed vision inevitably has a direct impact on future actions. For all these reasons, it is necessary to have a global and permanent vision on the activities and processes generating information, as well as on the different information worlds, hence the idea to have an informational framework encompassing all. From there, the idea of an informational meta-space emerges, dedicated to better monitoring the informational flows and facilitating the coherence between knowledge and action and properly arranging knowledge to be actionable.

This singular or informational space, which some people call, is an *infosphere* [30–32]. This term has not yet been given a well-defined academic definition, giving rise to different connotations. The sphere invokes the concept of unifying volume, an informational integration between the physical, virtual, and cognitive worlds since everything that refers to it enters into the same plan of an informational integration. The notion of a well-accepted infosphere must also effectively facilitate the capitalization of knowledge by erasing any boundary between diverse fields of knowledge and proceeding, as it were, to a common denominator.

The boundaries, both those which exist naturally and those which have been created artificially (often justified by the emergence of difficulties in the perception of the universe), materializing subdivisions may prove to be later penalizing for an action. The infosphere has an undeniable interest in amalgamating all the knowledge, which favors the ability to "derive" knowledge useful to the conduct of an action, in particular by means of inference techniques. It also represents the ideal place to orient the acquisition of knowledge enabling its enrichment.

Finally, the infosphere constitutes a support adapted to the development of a knowledge strategy by better orienting the methods of collecting, organizing, and disseminating knowledge by improving the innervation of technical and technological fabrics by including them properly in objectives for policies or strategies and for the development of knowledge centers. At the level of political decision-makers, the infosphere can facilitate the functioning of crisis units, giving them early warning and decision-making skills, obtained by a mastery of the timely knowledge, constantly refreshed by a rational organization, the recognition of factual information about the crisis, its collection and treatment.

1.5.1 Toward a Better Mastery of Knowledge

Mastering knowledge depends first on a dilemma evoked by the question [26]:

- What is it necessary to know exactly or to what extent is it permissible to ignore when one intends to conduct an efficient action?

In fact, well beyond the relevant knowledge, which we need to have in order to respond to the concern for efficiency, there arises the question of the strict level of sufficiency of knowledge. It is necessary to stay conscious that to master the totality of knowledge remains illusory. An illusion that remains for many, in a simplistic vision, that the universal in its totality is completely accessible because of:

- An irresistible and continuous push from the web.
- A permanent tightening of the meshing of telematics infrastructures.
- A growing and apparent permeability between knowledge and all the worlds of action.
- The capitalization of knowledge, greatly facilitated by the fineness of networking.
- The federation of energies linked to innovation.
- The development of partnerships set up in a concerted information policy.

If you use a metaphor of a river that rushes out of its bed, the consequences of the flooding are hardly parable if the flood continues. This is the same situation with information overflow, or deluge of information, or Big Data, to which we quickly confront the incessant development of the web. The result is a certain disorder, which is difficult to control, since there is nothing to suggest a decrease in flows, on the contrary. This disorder, which is assimilated to a growing difficulty in the accessibility of knowledge, as soon as we consider it from the point of view of the universal, will modify our relationship to knowledge unexpectedly and probably in depth.

For the scholars of the eighteenth century, it was permissible and conceivable to enroll in a single framework all the knowledge of their time, an undertaking which, moreover, found its justification with Diderot in the realization of the Encyclopedia. Due to a weak evolution of sociological contexts and a very moderate progression of techniques, the availability of knowledge useful for any activity did not present difficulties, all seeming to proceed, it might be said, with a certain informational stability. It then became reasonable to assume that knowledge in general could comply with the requirements of a totalization, thus making it possible to establish quasi-exhaustive references.

With the concepts of infosphere and cyberspace or informational meta-space that concretize all environmental contexts and activities subordinate to the web, attitudes of the eighteenth century are no longer reproducible. These concepts, in fact, constitute a new way to "universal knowledge" by introducing, as it were:

- A *virtual access* so qualified insofar as it gives the impression of being able to access all knowledge, produced here and there, if all domains of the "*known*" are covered at a given moment.

- *Real access* because it cannot go beyond the framework of a subset of knowledge, in spite of the efforts deployed and the quality of the techniques implemented.
- *Effective and relevant access* which, in the case of real access, only achieves the desired useful knowledge.

Due to the capitalization of knowledge, the profusion of reticular means, and the sophistication of the search engines, it is now possible to gain access to all knowledge, whatever be its origin and nature. It should be noted that the "universal knowledge"referred to above may in fact be decomposed into different fields more truly accessible. Moreover, it would be futile to think that knowledge which is easily generalizable is nevertheless truly accessible. They are often the reflection of requirements corresponding to needs, responding to community interests which, as a result, are subject to rapid changes. The absence of proven durability removes the privilege of generality since they are of interest to their promoter at a given moment or a given period of time. It is therefore necessary to restrict the field which is really accessible to a useful subdomain which can make sense with regard to the actions envisaged.

1.5.2 Universality and Mastering Knowledge

To complete our discussion of the accessibility of "universal knowledge," it is useful to examine how the relations between knowledge and universality are established over time, according to the modes of communication, without forgetting their implications on semantics. This examination can be carried out in three stages [26]:

- In societies having only the mode of oral communication, exchanges took place in the same context, since the one who emitted a message could only do so in the presence of its recipient. The two communicating actors being "immersed" in the same situation, ipso facto (with a few rare exceptions) gave the same meaning to the objects of communication, thus achieving a certain semantic closure.
- The arrival of the printing press and the development of written materials (case1), initiated a new communication space in the sense that exchanges of information could be carried out without requiring a physical presence. The notion of common situation, the sharing of knowledge, and immediacy were blurred in favor of a circulation of messages distorting cultural differentiations and temporal shifts: a message that could be exploited much later than its production. The arrival of the textual supports (case2), did not take place without consequence. Linguistic conventions become more imperative than in case1 to allow exchanges, hence the rationale for: syntaxes, the birth of grammars, pragmatics, etc. All these efforts, when properly coordinated, contribute to a large extent to establishing the notion of universality. In case2 the relation to the sense changes with respect to case1 because every text carry within it, a signified, which must remain in spite of the diversity of users, contexts, temporal places and conditions of use: message

written yesterday must make sense as much in the present and future time and, of course, whatever the place of its writing.
- The new informational and communication space created by the generalization of electronic media brings to light a new form of universal which must be assimilated more to a global approach and to a planetary vision of the availability of the means, with the avowed objective, that all can communicate with all.

Surprisingly, this universal is non-totalizing insofar as a large number of the inhabitants of the planet remain excluded from the new agoras which materialize the infosphere and nothing further indicates whether updates remain to be done. The notion of totality singularizing the written supports is emptied of its meaning because the fields of knowledge are in perpetual evolution, just as the networks of hypertexts are constantly changing.

It should be noted, in opposition to what has been said in case2 that cyberspace becomes conducive to a certain return of contextualization with a difference in scale compared to case1 especially with the development of forums on the Internet. It is within these forums that represent the interests of certain communities that organizations are formed whose essence is to make sense in their rapprochement, when it is not simply a question of sharing it, because of the centers of common interest.

Without access to only limited and partial knowledge areas, ad hoc means are needed to gain access to the only areas of relevance, in other words, those that make sense in decisions and actions which it is desired to implement and ensure. This led us to suggest an approach that can help to achieve this objective by developing around the chain of knowledge a set of modalities that range from the way we grasp the universe of actions to its formalized representation.

1.6 Data, Information, and Knowledge

Burgin's books [29, 33] give a broad overview of the main mathematical directions to support general theories of information and knowledge. The general theory of information provides a unified context for existing directions in information studies, making it possible to elaborate on a comprehensive definition of information; explain relations between information, data, and knowledge; and demonstrate how different mathematical models of information and information processes are related. The material in this section is mainly from Burgin's books [29, 33].

1.6.1 What Is Data?

Data has experienced a variety of definitions, largely depending on the context of its use. Here are some expressions reflecting the usage of the term *data* that assign some meaning to this term:

- In information science, data is defined as unprocessed information.
- In other domains, data are treated as a representation of objective facts.
- In computer science, expressions such as a data stream and packets of data are commonly used.
- Having sources of data or working with raw data are other commonly encountered ways of talking about data.
- We can place data in storage, e.g., in files or in databases, or fill a repository with data.
- Data are viewed as discrete entities: they can pile-up, be recorded or stored and manipulated, or captured and retrieved.
- Data can be mined for useful information, or we can extract knowledge from data.
- Databases contain data.
- It is possible to separate different classes of data, such as operational data, product data, account data, planning data, input data, output data, and so on.
- Data are solid, physical, things with an objective existence that allow manipulation and transformation, such as rearrangement of data, conversion to a different form or sending data from one system to another.
- Data are symbols that represent properties of objects, events, and their environments.
- Data are products of observation by people or automatic instrument systems.
- Data is a set of values recorded in an information system, which are collected from the real world.

There are different kinds and types of data. As a substance, data can be measured. The most popular way to measure data is in bits where *bit* is derived from the term binary digit, 0 or 1. Namely, the vast majority of information processing and storage systems, such as computers, calculators, embedded devices, CD, DVD, flash memory storage devices, magneto-optical drives, and other electronic storage devices represent data in the form of sequences of binary digits.

1.6.2 What Is Information?

The question "What is information" is singled out as one of the most profound and pervasive problems for computer science. It reflects the kind of far-reaching issues that drive day-to-day research and researchers toward understanding and expanding the frontiers of computing. Few books concerning information systems clearly define the concept of information. One of the most common ways to define information[4] is to describe it as one or more statements or facts that are received by people and that have some form of worth to the recipient (Losee [34]).

[4]Etymologically the term information is a noun formed from the verb "*to inform,*" which was borrowed in the fifteenth century from the Latin word "*informare,*" which means "*to give form to,*" "*to shape,*" or "*to form.*"

Shannon himself never defined information and wrote only about the quantity of information and called it a theory of communication but not of information. Shannon [35] also was very cautious writing: "*It is hardly to be expected that a single concept of information would satisfactorily account for the numerous possible applications of this general field.*" Burgin [29] reports several citations from researchers on the difficulty to define that term "*information*." Some of them are listed below:

- Belkin [36] argues (1978), "*The term information is used in so many different contexts that a single precise definition encompassing all of its aspects can in principle not be formulated.*"
- Scarrott [37] writes (1989), *"During the last few years many of the more perceptive workers in the information systems field have become uneasily aware that, despite the triumphant progress of information technology, there is still no generally agreed answers to the simple questions—What is information? Has information natural properties? What are they?—so that their subject lacks trustworthy foundations."*
- Wilson [38] writes (1993), "*Information is such a widely used word, such a commonsensical word, that it may seem surprising that it has given 'information scientists' so much trouble over the years.*"
- Flückiger [39] (1995) came to the conclusion: "*those working in areas directly related to information had apparently accepted that the problem with the definition would remain unsolved and considered Shannon's concept of information as the most appropriate.*"
- Barwise and Seligman [40] write (1997), "*There are no completely safe ways of talking about information. The metaphor of information flowing is often misleading when applied to specific items of information, even as the general picture is usefully evocative of movement in space and time. The metaphor of information content is even worse, suggesting as it does that the information is somehow intrinsically contained in one source and so is equally informative to everyone and in every context.*"
- Capuro and Hjorland [41] also stress (2003), "*for a science like information science (IS) it is of course important how fundamental terms are defined." In addition, they assume that even "discussions about the concept of information in other disciplines are very important for IS because many theories and approaches in IS have their origins elsewhere.*"
- Burgin [29] remarks (2010), "*One more problem is that trying to tell what information is a necessary clear distinction is not made between a definition and an attribute or feature of this concept. Normally, describing or naming one or two attributes is not considered a definition. However, there are authors who stress even a single feature of information to the point that it appears to be a definition.*"
- Opinions of other researchers [29] argue that: "*... multifarious usage of the term information precludes the possibility of developing a rigorous and coherent definition.*"

The situation with the difficulty of defining the term *information* is being illustrated by the famous ancient story of the blind men and an elephant[5] related in Burgin [29], p.39, and replicated as example 1.1.

Example 1.1 Ten Blind Men and An Elephant Once upon a time there was a certain raja, who called his servant and said, "*Go and gather together near my palace ten men who were born blind... and show them an elephant.*" The servant did as the raja commanded him. When the blind men came, the raja said to them, "*Here is an elephant. Examine it and tell me what sort of thing the elephant is.*"

- **The first blind man** who was tall found the head and said, "*An elephant is like a big pot*."
- **The second blind man** who was small observed (by touching) the foot and declared, "*An elephant is like a pillar.*"
- **The third blind man** who was always methodical heard and felt the air as it was pushed by the elephant's flapping ear. Then he grasped the ear itself and felt its thin roughness. He laughed with delight, saying "*This elephant is like a fan*."
- **The fourth blind man** who was very humble observed (by touching) the tail and said, "*An elephant is like a frayed bit of rope.*"
- **The fifth blind man** who was daring walked into the elephant's tusk. He felt the hard, smooth ivory surface of the tusk and its pointed tip. "*The elephant is hard and sharp like a spear,*" he concluded.
- **The sixth blind man** who was small observed (by touching) the tuft of the tail and said, "*An elephant is like a brush.*"
- **The seventh blind man** who felt the trunk insisted the elephant was *like a tree branch*.
- **The eighth blind man** who was always in a hurry bumped into the back and reckoned the elephant was *like a mortar*.
- **The ninth blind man** was very tall. In his haste, he ran straight into the side of the elephant. He spread out his arms and felt the animal's broad, smooth side and said, "*This animal is like a wall.*"

Then these nine blind men began to quarrel, shouting, "*Yes it is*!," "*No, it is not*!," "*An elephant is not that*!," "'*Yes, it's like that*!," and so on.

- **The tenth blind man** was very smart. He waited until all others made observations and told what they had found. He listened for a while how they quarreled. Then he walked all around the elephant, touching every part of it, smelling it, listening to all its sounds. Finally, he said, "*I do not know what an elephant is like. That is why I am going to write an Elephant Veda, proving that it is impossible to tell what sort of thing the elephant is.*"

[5] -- originating from India, having different versions, and being attributed to the Hindus, Buddhists, or Jainists.

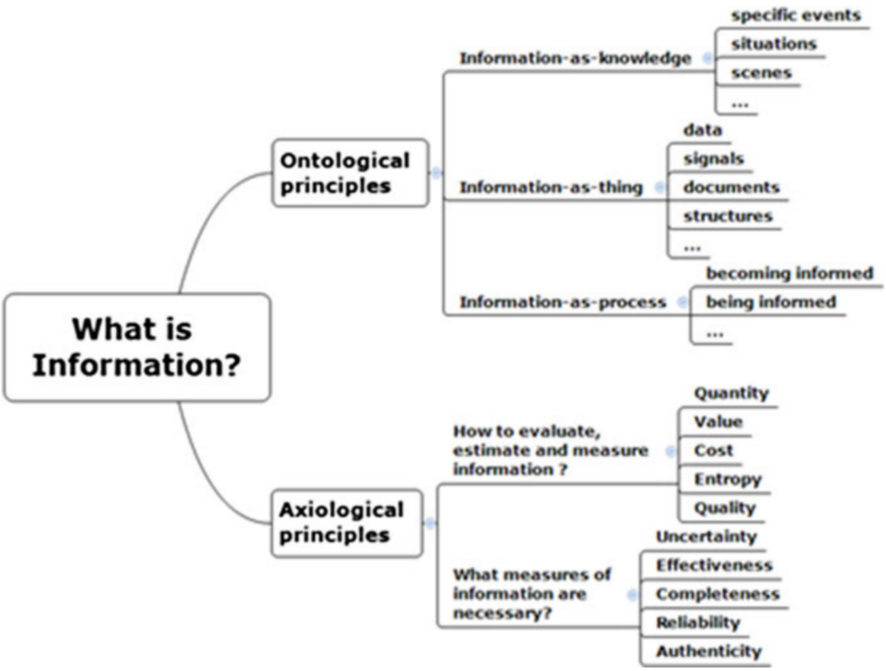

Fig. 1.5 Principles of information from Burgin's general theory of information [29]

Face to a huge diversity of meanings of the word *information*, elicited above, Burgin [29] develops the General Theory of Information (GTI). GTI makes it possible to unify these understandings and to explicate the essence of such a critical phenomenon. The parametric definition of information in GTI utilizes a system parameter called an *infological* system that plays the role of a parameter that discerns different kinds of information, e.g., social, personal, chemical, biological, genetic, or cognitive, and combines all existing kinds and types of information in one general concept of "*information.*" The GTI parametric type of comprehensive definition of information explains and determines what information is. Knowledge obtained in known directions of information theory such as statistical (Shannon 1948 [42], Fisher 1925 [43]), semantic (Bar-Hillel and Carnap 1953 [44]), algorithmic (Kolmogorov 1965 [45], Chaitin 1977 [46]), economic (Marshak 1971 [47]) may be treated inside GTI as its particular cases. Burgin's GTI is a system of principles as illustrated in Fig. 1.5. There are two groups of such principles: ontological and axiological.

Ontological principles reflect major features of information essence and behavior. The principles give an answer to the question "*What is information?*" In particular, information is defined as "*a phenomenon that exists in nature, society, mentality of people, virtual reality, and in the artificial world of machines and mechanisms created by people*." The term information is used in different ways, including "*information-as-knowledge,*" "*information-as-thing,*" and "*information-as-process.*"

Axiological principles explain how to evaluate, estimate, and measure information and what measures of information are necessary. Axiological principles provide a reference frame for a diversity of information measures, such as "*. . ., information quality, information quantity, information value, information cost, information entropy, information uncertainty, average information score, information effectiveness, information completeness, information relevance, information reliability, and information authenticity.*"

Information is a basic multifaceted phenomenon. As a result, it has many diverse types and classes. Information is better processed if we know to what class or type this piece of information belongs, for instance, distinctions between "*genuine information, false information, misinformation, disinformation, and pseudo-information.*"

Werner Loewenstein [48] reveals that information is the foundation of life. He provides his own definition of information, being unable to apply the conventional definition that comes from the Hartley-Shannon's information theory. According to Loewenstein, "*information, in its connotation in physics, is a measure of order—a universal measure applicable to any structure, any system. It quantifies the instructions that are needed to produce a certain organization.*" This is one of the reasons why the principle of information entropy is so important.

Finally, Burgin [29] provides the following general remark on the definition of information[6] as follows: "*Information is not merely a necessary adjunct to personal, social and organizational functioning, a body of facts and knowledge to be applied to solutions of problems or to support actions. Rather it is a central and defining characteristic of all life forms, manifested in genetic transfer, in stimulus response mechanisms, in the communication of signals and messages and, in the case of humans, in the intelligent acquisition of understanding and wisdom.*"

To explicit his ontological principles, Burgin [29] introduces the notion of an "infological" system IF(R) of a system R. As an example of an IF(R) of an intelligent system R, is the system of knowledge of R. It is called in *cybernetics* the thesaurus[7] Th(R) of the system R. Identifying an infological system IF(R) of a system R allows to define different kinds and types of information relative to this system.

---

[6]Excerpts from Burgin's book as well: "*. . . the term information has been used interchangeably with many other words, such as content, data, meaning, interpretation, significance, intentionality, semantics, knowledge,* etc. *In the field of knowledge acquisition and management, information is contrasted to knowledge. Some researchers assume that if Plato took knowledge to be "justified true belief", then information is what is left of knowledge when one takes away belief, justification, and truth.*"

[7]A thesaurus can form part of an ontology. It is used in natural language processing for word-sense disambiguation and text simplification.

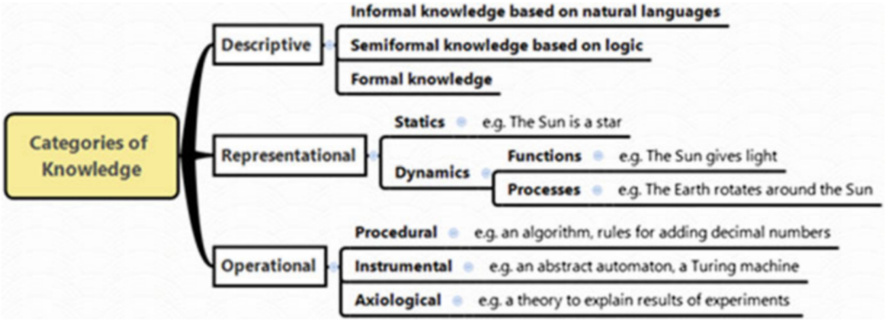

Fig. 1.7 Burgin's categories of knowledge

- **Structural analysis** of knowledge that strives to understand how knowledge is built; this is the main tool for the system theory of knowledge, knowledge bases, and artificial intelligence.
- **Axiological analysis** of knowledge that aims at explanation of those features that are primary for knowledge; this is the core instrument for philosophy of knowledge, psychology, and social sciences.
- **Functional analysis** of knowledge that tries to find how knowledge functions, is produced, and acquired; this is the key device for epistemology, knowledge engineering, and "cognitology."

In the structuration of knowledge, one can distinguish three categories of knowledge as shown in Fig. 1.7 with associated self-explained examples. Burgin [33] (Chap. 6) provides a rather detailed discussion about the structures and processes associated with Fig. 1.7.

The mathematical theory of knowledge developed by Burgin [33] puts the emphasis on structural and axiological analysis. As explained in his book, despite a millennium of effort by philosophers, there is no consensus on what knowledge is and, consequently, there are many definitions of knowledge. As explained in Example 1.2, knowledge is distinct from its representation. The representations are not knowledge itself as the same knowledge can have different representations. However, representations are a very important kind of structures in order to process knowledge.

Informal definitions of knowledge are not practical for computer processing of knowledge since computers can process only formalized information. Formal definitions of knowledge are often linked with some specific knowledge representation. There exist a great variety of formalized knowledge representation schemes and techniques: semantic and functional networks, frames, productions, formal scenarios, relational and logical structures, etc.

Example 1.3 Knowledge Versus Knowledge Representation Consider an event that is described in several articles written in different languages, for example, in English, French, Spanish, and Chinese, but by the same author. These articles convey the same semantic information and contain the same knowledge about the event, but the representation of this knowledge is different.

We always have knowledge about something, some object. However, to distinguish an object, we have to name it. A name may be a label, number, idea, text, and even another object of a relevant nature. Knowledge is acquired by an epistemic system *E* (see next chapter) under **the actions of information**, i.e., knowledge is the result of the information impact. Three basic stages of knowledge acquisition by a cognitive (intelligent) system are (1) information search and selection; (2) information extraction, acquisition, and accumulation; and (3) transformation of information into knowledge. That is why we treat knowledge in the context of epistemic structures. Examples of epistemic structures used by cognitive processes are concepts, notions, statements, ideas, images, opinions, texts, beliefs, knowledge, values, measures, problems, schemas, procedures, tasks, goals, etc. Note that an epistemic space is a set of epistemic structures or their representations with relations and operations. Examples are vector bundle, lattices, groups, or partially ordered sets.

1.7 Important Notions Related to Actionable Knowledge

Knowledge, experience, and information-processing are the primary foundations determining how goals of actions are established; how situations, opportunities, and risks are assessed; and how groups, cues, and patterns are interpreted. Knowledge, learning, and information-processing can be regarded as links between action and environment. Environment plays a key role in the acquisition of knowledge and the implementation of actions. The relations between knowledge, action, and environment are not simple and current models of decision-making may require refinements. The interdependencies of knowledge, action, and environment from different disciplinary perspectives, scales of analysis, time dimensions, and ontologies have not been sufficiently explored. Each scale of analysis bears specific insights that other scales cannot deliver. Time lags between knowledge acquisition (e.g., research) and successful action (e.g., innovations) can amount to many years or even decades.

The book of Meusburger et al. [1] "*Knowledge and Action*" addresses the issues discussed in the previous paragraph from business and social sciences perspectives. The book we are proposing takes the angle of data science and focuses on information and knowledge processing in dynamic environments. This section presents currently used high-level models of important notions related to actionable knowledge in dynamic environments: dynamic decision-making, situations, situation awareness (SAW), and analytics and information fusion (AIF).

1.7.1 Dynamic Decision-Making Models

Decision-making is involved in all aspects of our lives, and it is of particular importance for the critical CPSS (Fig. 1.8): health, transport, energy, and defense and security. With the advancement of Information and Communications

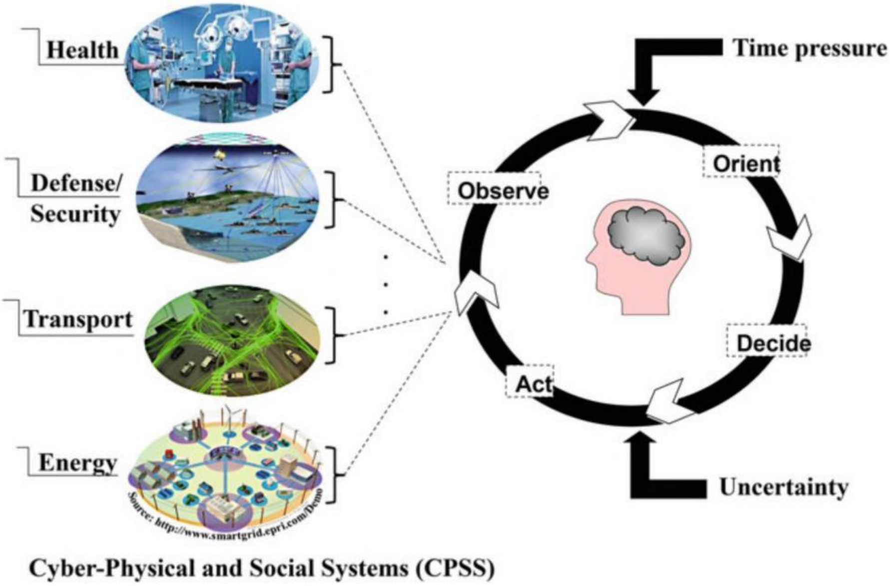

Fig. 1.8 Illustrations of Boyd's OODA loop and four critical CPSS. (Source [50])

Technologies (ICT), these four environments become more and more complex and challenge decision-making. The oversimplified Boyd's Observe-Orient-Decide-Act (OODA) loop [49], illustrated in Fig. 1.8, is used to describe the decision process. Although the OODA loop might give the impression that activities are executed in a sequential way. In reality, the activities are concurrent and hierarchically structured. The processes of the loop are typically performed in a very dynamic and complex environment and are heavily influenced by factors such as uncertainty and temporal stress.

The four CPSS environments in Fig. 1.8 present cases where interdependent decision-making takes place in an environment that changes over time either due to the previous actions of the decision-maker or due to events that are outside of the control of the decision-maker [7]. In this sense, CPSS present, in addition to conventional one-time decisions, dynamic decisions. Dynamic decisions are typically more complex than one-time decisions. They occur in real time and involve observing the extent to which people can use their experience to control a particular complex system, including the types of experience that lead to better decisions over time.

In a problem-solving approach for complex environments such as CPSS, understanding and framing the problem are the most important steps. Over the years, multiple efforts have thus been deployed to better understand and explain decision-making. Fields like decision sciences, management sciences, administrative sciences, social choice, psychology, or naturalistic decision-making are examples of the growing effort in modeling and understanding the individual as well as organizational decision-making.

needs, and what part of the task can be automated or supported. This understanding is crucial and only achieved via a number of specialized human factor investigations known as cognitive engineering analyses [77–79].

1.7.3 Situations and Situation Analysis

The definitions of "*situation*" and "*situation analysis*" are based on the numerous works of J. Roy mainly from [65, 80]. He defined situation analysis (SA) as "*a process, the examination of a situation, its elements, and their relations, to provide and maintain a product,* i.e.*, a state of situation awareness, for the decision maker*"; and situation as "*A specific combination of circumstances,* i.e.*, conditions, facts, or states of affairs, at a certain moment.*"

The SA process is concerned with understanding the world. There is a real situation in the environment, and the SA process will create and maintain a mental representation in the mind of the decision-maker(s). The idea of "*awareness*" has to do with having knowledge of something. In addition to the cognition facet, awareness is also linked with the notions of perception and understanding/comprehension. The two basic elements involved in situation awareness are the situation and the person. The situation can be defined in terms of events, entities, systems, other persons, etc., and their mutual interactions. The person can be defined according to the cognitive processes involved in situation awareness (SAW), or simply by a mental or internal state representing the situation.

Roy [80] states that the main two basic situation elements are "*entity*" and "*event*." He pursues the description of elements of a situation, illustrated in Fig. 1.11, the following way: "*…an entity is an existing thing (as contrasted with its attributes),* i.e.*, something that has independent, separate, self-contained, and/or distinct existence and objective or conceptual reality. An event is something that happens (especially a noteworthy happening). Hence, entities exist, while events occur. A scenario is defined as a sequence of events. A group represents a number of individuals (entities and/or events) assembled together or having some unifying relationship,* i.e.*, an assemblage of objects/events regarded as a unit. The term activity refers to the notions of action, movement, and motion. It is appropriate when something has the quality or state of being active,* i.e.*, when something is characterized by action or expressing action as distinct from mere existence or state. Finally, one may think of a global situation as being composed of a set of local situations. The term scene,* i.e.*, a single situation in this set, could be used to refer to a local situation.*"

Roy [80] finishes the description of basic elements of a situation (Fig. 1.11): "*A fact is defined as something that has actual existence, or an actual occurrence. It is a piece of information presented as having objective reality. Clearly, a fact has to do with the notions of truth, verity, and reality. Data is indeed factual information used as a basis for reasoning, discussion or calculation. Cues,* i.e.*, features indicating the nature of something perceived, are generated and received from the various data/*

Table 3.6 Savage's (acts-states-consequences) framework

Acts	States			
	s_1	s_2	...	s_m
a_1	c_{11}	c_{12}	...	c_{1m}
a_2	c_{21}	c_{22}	...	c_{1m}
⋮	⋮	⋮	⋮	⋮
a_n	c_{n1}	c_{n2}	...	c_{nm}

- In *Knightian's risk*, individuals can act on the basis of a probability that is objective (in the sense that any reasonable person would agree on it) and known. This probability may be of one of the following two kinds: a priori or statistical probability. A priori probabilities can be attributed objectively by logical reasoning, without the need to perform any experiments or trials. Statistical probabilities are relative frequencies.
- In *Savage's uncertainty* [81, 82], the notion of subjective probabilities, originally developed by Ramsey and de Finetti [83], is used. Subjective theory of probability treats probability as a degree of belief and makes possible to assign precise numerical probabilities to virtually any proposition or event. Betting rates are the mechanism through which subjective probabilities can be inferred.

Dequech [60] states that Knightian's risk can be seen as a special case of Savage's uncertainty since the latter can handle subjective probabilities, with or without objective probabilities.

Decision-making under weak uncertainty, as viewed by Savage, chooses among acts as in Table 3.6. Each act, a_i, has a consequence, c_{ij}, depending on which state, s_j, occurs. A state of the world is "a description of the world, leaving no relevant aspect undescribed." The set of states is exhaustive and defined independently of the set of acts. States are mutually exclusive, and each state has a probability, p_j. The expected utility of each act, a_i, is the weighted average of the utilities of the several consequences, where the weights are the probabilities of the respective states:

$$u(a_i) = \sum p_j u(c_{ij})$$

In the case of "strong" uncertainty associated with the notion of **procedural uncertainty**, the decision problem is complex and populated by individual or collective agents with limited mental and computational capabilities. In [60], based on literature [84] back in 1997, two problems have been identified on procedural uncertainty: (1) large amounts of information, referred to as *extensiveness*; (2) the other called *intricacy* refers "to the density of structural linkages and interactions between the parts of an interdependent system." Using flavor of the day language, one can easily relate *extensiveness* and *intricacy* to "data deluge" and complex networking, i.e., to the Vs dimensions of Big Data: volume, velocity, variety, veracity, and value.

In a situation involving **ambiguity**, the decision-maker cannot unambiguously assign a definite probability to each and every event because some relevant information that could be known is missing. Dubois [85] explains that Savage's rational decision-making chooses according to expected utility with respect to a subjective probability but that in the presence of incomplete information: (1) decision-makers do not always choose according to a single subjective probability; (2) there are limitations with Bayesian probability for the representation of belief; and (3) a single subjective probability distribution cannot distinguish between uncertainty due to variability and uncertainty due to lack of knowledge. Dubois [85] pursues with eliciting motivations for going beyond pure probability and set representations. He suggests to find uncertainty representations that combine probability and sets such as imprecise probability theory [86, 87] (sets of probabilities); Dempster-Shafer theory [88–90] (random sets); and numerical possibility theory [91, 92] (fuzzy sets). Finally, under the above theories, an event can be represented with a degree of belief (certainty) and a degree of plausibility, instead of a single degree of probability.

Fundamental uncertainty in Table 3.5 is the lack of knowledge that results from the characterization of social reality as subject to non-predetermined structural change [60]: "Future knowledge is not knowable in advance, in the sense that we do not know exactly what we are going to learn over the next years and when we are going to learn it." Innovations, which cause non-predetermined structural change in economic relationships, are very illustrative of fundamental uncertainty brought by human creativity and change in knowledge in the economic reality. To illustrate further, two types of economic reality are being mentioned in [93]: "immutable" and "transmutable." An "immutable" reality is one in which "the future path of the economy and the future conditional consequences of all possible choices are predetermined" also referred to as *ontological uncertainty*. A "transmutable reality" is described as: "the future can be permanently changed in nature and substance by the actions of individuals, groups … and/or governments, often in ways not completely foreseeable by the creators of change." There is *epistemological uncertainty* when "some limitation on human ability … prevents agents from using (collecting and analyzing) historical time-series data to obtain short-run reliable knowledge regarding all economic variables."

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