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**“CATEGORIZATION FRAMEWORK FOR DATA OBJECTS IN THE
INTERNET OF THINGS”**

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JORGE EDUARDO IBARRA ESQUER

DIRECTOR: DR. FÉLIX FERNANDO GONZÁLEZ NAVARRO

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CATEGORIZATION FRAMEWORK FOR DATA OBJECTS IN THE INTERNET OF THINGS

Both the idea and technology for connecting sensors and actuators to a network to remotely monitor and control physical systems have been known for many years and developed accordingly. However, a little more than a decade ago the concept of the Internet of Things (IoT) was coined and used to integrate such approaches into a common framework. Technology has been constantly evolving and so has the concept of the Internet of Things, incorporating new terminology appropriate to technological advances and different application domains. This document presents the changes that the IoT has undertaken since its conception and research on how technological advances have shaped it and fostered the arising of derived names suitable to specific domains. A two-step literature review through major publishers and indexing databases was conducted; first by searching for proposals on the Internet of Things concept and analyzing them to find similarities, differences, and technological features that allow us to create a timeline showing its development; in the second step the most mentioned names given to the IoT for specific domains, as well as closely related concepts were identified and briefly analyzed. The study confirms the claim that a consensus on the IoT definition has not yet been reached, as enabling technology keeps evolving and new application domains are being proposed. However, recent changes have been relatively moderated, and its variations on application domains are clearly differentiated, with data and data technologies playing an important role in the IoT landscape. In addition, the study allowed us to obtain a clearer insight on this technology and what can be achieved through it. Observing the way these definitions have evolved and how different concepts, technologies and ideas have been incorporated as the IoT develops suggests that a correct description and characterization of the things at the end-points of the IoT should be one of the first goals towards a final definition.

Things are the core of the IoT and must be properly characterized according to the different functions they accomplish. Identifying their capabilities and combining them as sets provides a view on the single or joint properties of existing things and guiding in properly designing and building new things while maximizing their potential benefits within an IoT. Building on five essential but independent capabilities of things (identification, location and tracking, sensing, actuation, and processing), four categories or groups of things are defined. These groups comprise the diversity of objects found in the IoT, as trackable, data, interactive, or smart objects. A description of the aforementioned capabilities is presented, stating how each of the groups of objects includes them. Then, given that data is one of the most important assets for both organizations and individuals a further description of the data objects group is made, proposing a categorization framework that thoroughly describes and measures the level in which each of these capabilities is contained and how it contributes to the performance and data properties of any data object. The framework has the capability of allowing IoT solution designers and providers understand the scope and outcomes of both IoT products and projects. It can be used to categorize both existing objects and new objects before they are constructed, which is where designers would benefit most from it.

To Brenda, for your love and encouragement that made this work and many other things possible for almost twenty years, and counting...

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PREFACE

The Internet of Things is a field of study that has recently created a global buzz not only for researchers but as a promising technology that will change how business are done and many aspects of our lives. A few years before taking the decision to undertake a research project on the IoT it became a personal interest to learn about it and create Internet-connected gadgets and apps. I never realized at that time that I was about to enter an open field of opportunities for both development and research, but also that I had to go further into the roots of the technology to understand it properly and make valuable contributions.

Initial ideas and goals were set around the existing and diverging reference models, but as the research activities started being carried, and after proper feedback and suggestions from researchers at the Doctoral Colloquium at the 2015 Mexican International Conference on Computer Science, the focus switched to the definition of the IoT and its enabling technologies.

The present document is formed in its majority by the contents of two papers: one of them already published which is the basis for chapters II, III, and IV; and the second currently under review with the information presented in chapters V and VI. One of the goals of this work was to provide a solid reference for continuing research, as well for others' research activities, and having the first paper being cited several times gives a confirmation that this goal is being reached.

TABLE OF CONTENTS

CHAPTER I. INTRODUCTION	1
I.1 Background	5
I.2 Problem statement	8
I.3 Research questions	10
I.4 Objectives	10
I.4.1 Specific objectives.....	10
I.5 Methodology.....	10
I.6 Outline	11
CHAPTER II. METHODOLOGY FOR THE SLR	13
II.1 Research Questions	13
II.2 Source Selection.....	14
II.3 Search Strings.....	14
II.4 Execution of the SLR	15
II.5 Studies Revision	19
CHAPTER III. THE INTERNET OF THINGS CONCEPT	21
III.1 The Early Visions (Late 1990s to 2005)	21
III.2 Establishment Phase (2009 to 2011)	23
III.3 A shift Towards Data and Services (Starting in 2012)	26
III.4 Things as a Key Element.....	29
III.5 Other Names Given to the IoT	31
III.6 Discussion	34
CHAPTER IV. THINGS IN THE IOT.....	39
IV.1 Names Given to Things	39
IV.2 Properties of Things.....	40
IV.2.1 Identification.....	40
IV.2.2 Location and Tracking.....	41
IV.2.3 Sensing.....	41
IV.2.4 Actuation	42
IV.2.5 Processing.....	42
IV.3 Things Abstracted	42

CHAPTER V. CATEGORIZATION FRAMEWORK FOR DATA OBJECTS IN THE INTERNET OF THINGS.....	46
V.1 Data Objects	46
V.2 Categorization Framework	48
V.3 Impact of Capability Levels on Data Properties	52
CHAPTER VI. APPLICABILITY OF THE FRAMEWORK	57
VI.1 Use scenarios	57
VI.1.1 Using the framework for categorizing conceptual DO	57
VI.1.2 Using the framework for categorizing existing Data Objects	59
VI.2 Summary.....	61
CHAPTER VII. CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK	62
VII.1 Contributions	64
VII.2 Future work	65
REFERENCES.....	67
ANNEX A – LIST OF PUBLICATIONS	74
A.1 Tracking the Evolution of the Internet of Things Concept across Different Application Domains ..	74
A.2 Smartphones como medio de recolección de datos para aplicaciones de aprendizaje computacional	77
A.3 Categorization Framework for Data Objects in the Internet of Things	78

LIST OF FIGURES

Figure I.1 Behavior in the Hype Cycle chart of the IoT and related technologies.....	3
Figure I.2 Common elements in IoT reference models and architectures.	7
Figure II.1 Methodology for the SLR.....	16
Figure III.1 Three main visions of the IoT.	25
Figure III.5 Interaction between IoC and IoT devices.	35
Figure III.6 Orientation of the definitions and visions of the IoT.....	36
Figure III.7 Concepts and notions used by authors in presenting their visions of IoT.....	37
Figure IV.1 Capabilities of Internet connected devices as sets.	44
Figure IV.2 Subsets of the IoT.....	45
Figure V.1 Data Objects (DO) are things in the IoT with Identification or Sensing capabilities.....	46
Figure V.2 Characteristics of data provided by DO according to the level of each capability.	50
Figure V.3 Contribution of each capability to data properties in DO.	53
Figure V.4 Complexity of a DO increases as more properties are added to each capability. PC properties are the most complex among the four capabilities in this type of objects.....	55
Figure V.5 Areas covered by data objects categorized as Data intensive, Trusted, and Ready-to-use.	56
Figure VI.1 A scenario of the framework for an automotive DO.....	59
Figure VI.2 Categorization graph for the Awair air quality monitor.	60
Figure A.1 Cover for Sensors Volume 17, Issue 6, and first page of the paper.	75
Figure A.2 Cover for Komputer Sapiens Year 10, Volume 1, and first page of the paper.	78

LIST OF TABLES

Table 2.1 Results of executing ST1 and ST2 in each of the selected sources.	17
Table 2.2 First selection stage.	17
Table 2.3 Merging results from ST1 and ST2.	18
Table 2.4 Primary studies selection.	19
Table 3.1 Bill Joy’s six Webs taxonomy.....	21
Table 4.1 Things Capabilities.	44
Table 5.1 Levels of Deployment for Identification Capability (IC).	49
Table 5.2 Levels of Deployment for Location Capability (LC).	51
Table 5.3 Levels of Deployment for Sensing Capability (SC).....	51
Table 5.4 Levels of Deployment for Processing Capability (PC).....	52
Table 5.5 Capability impact on data properties.....	53
Table 6.1 Categorization for automotive DO.....	58
Table 6.2 Categorization data for the Awair air quality monitor.....	60
Table A.1 Paper citations.....	75

CHAPTER I. INTRODUCTION

The 21st century has brought a vertiginous succession of technological advances in different domains. Information and communications technologies (ICT) are not an exception, with important and consolidated developments as the smartphones, wireless networks, cloud computing, and social networks that have become a ubiquitous part of our life. On the same path, several other technologies are on a maturity stage and on the verge of a definitive adoption, as the autonomous vehicles, brain-computer interfaces, and quantum computing.

Every time a new technology is showcased, a series of expectations about its potential uses and benefits to users also emerges. On an early stage of development, it usually lacks concrete applications, which are expected to be created and made accessible to final users as soon as the technology has demonstrated its real utility and become stable. However, forecasting whether that technology is going to reach that productivity stage is not an easy task, which then poses a problem for early adopters of emerging technologies. As implied in the so-called Amara's Law, enunciated in multiple times by the former director of the Institute for the Future¹, Roy Amara, "We tend to overestimate the effect of a technology in the short run and underestimate the effect in the long run" (Searls, 2012), in reference to the problem of taking correct decisions on investing on a specific technology.

In this sense, it results important for practitioners and developers to identify and keep track of technologies labeled as disruptive from earlier stages of development. The first step is being able to identify an emerging technology and forecast/predict whether and when it will become productive. A widely used tool for aiding in this process is the Gartner's Hype Cycle chart, named after the global research and advisory firm Gartner Inc. The cycle has been published each year since 1995 and according to Gartner, provides a graphic representation of the maturity and adoption of technologies and applications, and how they are potentially relevant to solving real business problems and exploiting new opportunities (Gartner Inc., 2019), claiming it describes a common pattern with emerging technologies.

¹ The Institute for the Future is a not-for-profit organization focused on helping organizations plan for the long-term future (futures studies)
<http://www.iff.org/>

Hype cycles characterize the typical progress of emerging technologies after early proofs of concept catch the media or potential users' attention, followed by a peak of interest fed by stories about applications and benefits that might be achieved when the technology is finally available. After failures in implementations interest tends to wane until an eventual understanding of the technology's relevance and its role within a market or domain is reached (Linden & Fenn, 2003) and the technology finds a stability that allows it to become a profitable product.

Even though several inconsistencies have been pointed out with regards to this forecasting methodology (Dedehayir & Steinert, 2016), the information that provides tends to be of special use when it is applied to tracking emergent technologies that might be adopted by existing and well-established industries (Jarvenpaa & Makinen, 2008; Van Lente, Spitters, & Peine, 2013). In addition, the promises of the future that make up a hype, have a performative capacity in the present as they attract resources, coordinate activities, and spur competition (Van Lente et al., 2013). The earliness of the visibility in news media observed related to the technology's life cycle, is definitely a valuable phenomenon to further explore (Jarvenpaa & Makinen, 2008).

One of the technologies that has recently received a lot of media attention is the Internet of Things (IoT), not only because of business or economic implications but also as an academic and social motivator (Joseph, Kar, Ilavarasan, & Ganesh, 2017). The IoT was included in the hype cycle for the first time in 2011 as a technology in the triggering stage and has advanced in the graph to a point where is descending down the slope of the peak of inflated expectations in the 2018 edition of the hype cycle; from 2011 to 2015 it was included as IoT, but starting in 2015 it changed to IoT platform. Figure I.1 shows a combination of the 2008 to 2018 hype cycles for the IoT and its enabling technologies (RFID, cloud computing, mesh sensor networks, and big data). From the graph, it is observed that none of the technologies has reached past the disillusion through before it stopped being tracked in the cycle. In addition, from 2015 to the most recent edition, the only of those technologies that appears in the cycle is the IoT platform.

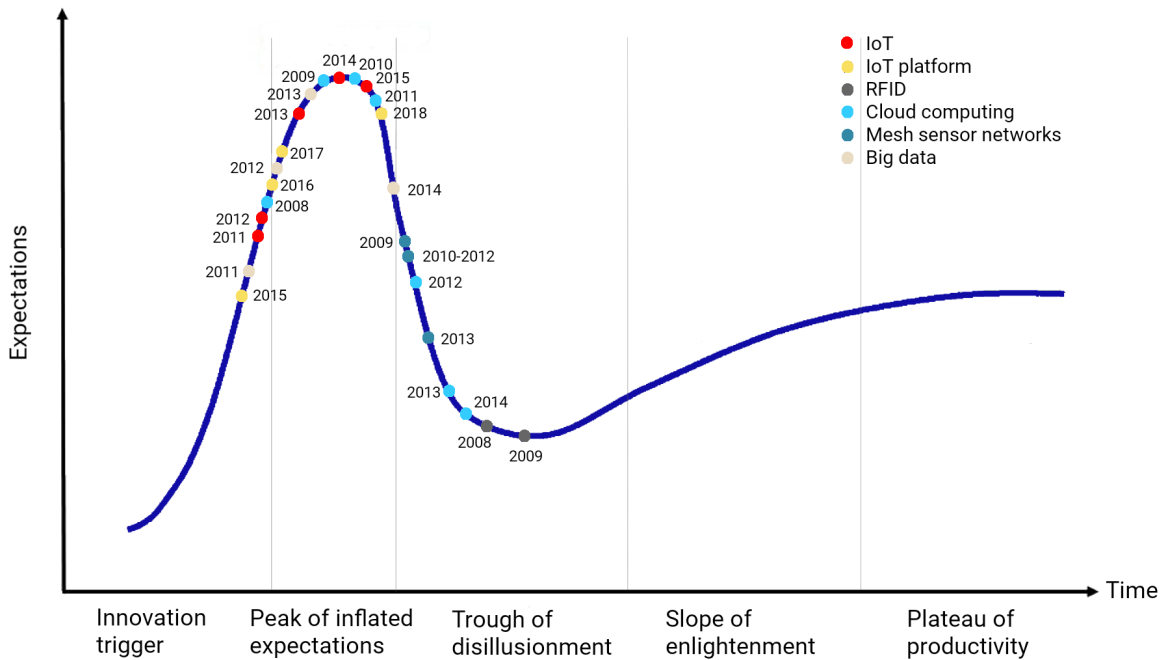


Figure I.1 Behavior in the Hype Cycle chart of the IoT and related technologies.

The fact that some emerging technologies just disappear from the cycle is one of the drawbacks that have been mentioned for the cycle. However, by analyzing the description that Gartner offers for IoT and IoT platform it can be inferred that the interest on the technologies by themselves decreased with respect to their combined use as a platform. Gartner defines IoT and IoT platform as follows:

- IoT is the network of physical objects that contain embedded technology to communicate and sense or interact with their internal states or the external environment.²
- An IoT platform is an on-premises software suite or a cloud service that monitors and may manage and control various types of endpoints, usually providing Web-scale infrastructure capabilities to support basic and advanced IoT solutions and digital business operations.³

² Gartner IT glossary - <https://www.gartner.com/it-glossary/internet-of-things/>

³ Gartner IoT platform reviews - <https://www.gartner.com/reviews/market/iot-platforms>

The initial concern on the IoT was as a connection and communication point for physical objects able to obtain data from the environment but has now changed to a more comprehensive approach where the focus is on the importance for organizations and individuals to gain access to those data and manage their connected objects for maximizing profits. Projections on billions of connected devices creating and obtaining enormous amounts of data and facilitating the automated control and monitoring of processes drive an enhanced interest on the establishment of the IoT as a productive technology for different sectors.

- Industries: Take better business decisions from the analysis of data; make more efficient use of resources and automate their productive processes; an opportunity for new business models.
- Academia: There are several open research problems and topics related to the IoT, as listed by Stankovic (2014) in a non-exhaustive manner, that should promote cooperation and communication between research communities from both academy and industry.
- Society: The promise of products and services to enhance living and everyday activities by means of the integration of smart technologies for home, schools, hospitals, buildings, and even cities.

Still a technology in development, there are multiple interpretations and definitions that have been proposed in aim to express what the IoT is about and what will be its more representative applications and benefits. Some of these proposals usually present opposing or divergent views, reflecting the particular opinion or interests of groups, organizations, or major technological companies that seek to establish their own products, methodologies, and development tools.

Taking into account the existing interest in the IoT and the level of expectations, the stage of maturity it is approaching, the multiple challenges that will allow it to become a disruptive technology and enable other technologies to fully reach their initial expectations when being used in a common platform, as well as the existing and future opportunities that will develop from the IoT and its applications, the IoT will be explored with the goal of contributing to its consolidation not only as a technology but as a complete and encompassing field. The main

purpose is to obtain and provide a solid ground on the foundations of the IoT and the way data should be understood as its most important assets.

I.1 Background

The Internet of Things (IoT) has been in the spotlight for the past decade. It is regarded as one of the disruptive technologies of this century (Alkhatib et al., 2014) and so far, has caught the attention of society, industry and academy as a way of technologically enhancing day to day activities, the creation of new business models, products and services, and as a broad source of research topics and ideas. Several alliances, institutions, enterprises and even governments have understood its importance and identified the potential benefits that can be obtained from the IoT, leading them to undertake strategic projects and initiatives aiming to develop this field and profit from it (Cisco, 2014; Dutta, Geiger, & Lanvin, 2015; European Commission, 2015; Hwang & Choe, 2013; IBM, 2015; IEEE IoT TC, 2015; ITU-T, 2012; OECD, 2014).

Though the first idea of IoT emerged no more than two decades ago, the technologies that shape and support it have been in development for many years. As its name suggests, one of the core technologies is the Internet itself, which has its origins in the ARPANET project, started in 1969 with the objectives of developing techniques and obtaining experience on interconnecting computers, improving and increasing computer research productivity through research sharing, and to permit the linking of specialized computers to the many general purpose computer centers in the U.S. Defense Department and in the private and public sectors (Bolt, Beranek, & Newman, 1981). Nowadays, the Internet is a global system of networks that interconnect computers using the standard Internet protocol suite. It has significant impact on the world as it can serve billions of users worldwide. Millions of private, public, academic, business, and government networks, of local to global scope, all contribute to the formation of the Internet (Qin et al., 2016).

Another fundamental technology for the IoT is the embedded computer system. This term was first used in 1974 and describes a computer that is physically incorporated into a larger

system whose primary function is not data processing, and integral to such a system from a design, procurement and operations viewpoint (Manley, 1974). These systems are implemented by using devices like microcontrollers and single board computers (SBC), and have recently gained popularity with affordable and easy to use prototyping platforms as Arduino, Raspberry Pi or Lego Mindstorms.

At the early 1990s, Mark Weiser proposed the concept of ubiquitous computing, later regarded as “pervasive”, where the main idea was for computers to be present and invisible in everything (Weiser, 1991). The backbone of the ubiquitous computing paradigm relies on the advances in embedded computing technologies and deploying a ubiquitous network on a scale of hundreds of computers per room. The concept might resemble that of the actual IoT, but at that time, Weiser stated that the main challenge was the design of operating systems that allow software to fully exploit the capabilities of networks, as software systems barely took any advantage of them (Weiser, 1991).

By mid-1990s, sensor nodes started developing as several technologies like wireless communications and digital electronics presented important advances. These are tiny modules capable of sensing data, which is then processed and transmitted over a network. Large numbers of sensor nodes allow for the implementation of sensor networks and have applications in several areas (Akyildiz, Su, Sankarasubramaniam, & Cayirci, 2002). Things in the IoT share some of the characteristics and purpose of sensor nodes.

Many definitions have been proposed for the IoT, but, in a general manner, it can be described as the confluence of several technologies that allow providing Internet-based services and applications supported by electronic devices attached to physical things for acquiring data and controlling processes (Ibarra-Esquer, González-Navarro, Flores-Rios, Burtseva, & Astorga-Vargas, 2017). Data obtained from such things are arguably the most important asset for organizations and individuals deploying IoT-based systems.

An architectural view of the IoT helps understanding how these technologies are arranged and organized to make such services and applications available to end-users, enabling access to data and the information derived from these data. Just as is the case with the visions and

definitions of the IoT, there are several architectures and reference models that have been proposed either from research and interest groups (Bauer et al., 2013; CASAGRAS Partnership, 2009; Rayes & Salam, 2017a) or coming from industrial developments (AWS, 2018; Cisco, 2018; Cisco, 2014; Google, 2018; Intel, 2018; Microsoft, 2018; Samsung, 2018). Even though these architectures and reference models usually reflect the interests of specific groups, companies or consortiums, some similarities might be found, and three common sections are observed: objects or things, services, and applications (Figure I.2).

Things are on the physical side of the architecture and include a variety of physical elements (Coetzee & Eksteen, 2011). Some things are digital objects that can be tracked through space and time and contain the data history related to the specific object they represent (Sterling, 2005); some of them are physical objects enhanced with small electronic devices allowing them to obtain data from the environment, process such data, temporarily store them, and send them to the Internet (Kopetz, 2011; Miorandi, Sicari, De Pellegrini, & Chlamtac, 2012; Sánchez López, Ranasinghe, Harrison, & McFarlane, 2012). In some cases, they might act on the environment via embedded actuators, and some of these objects may also provide the user with ways to interact with an application, system, and even among different things (Coetzee & Eksteen, 2011).

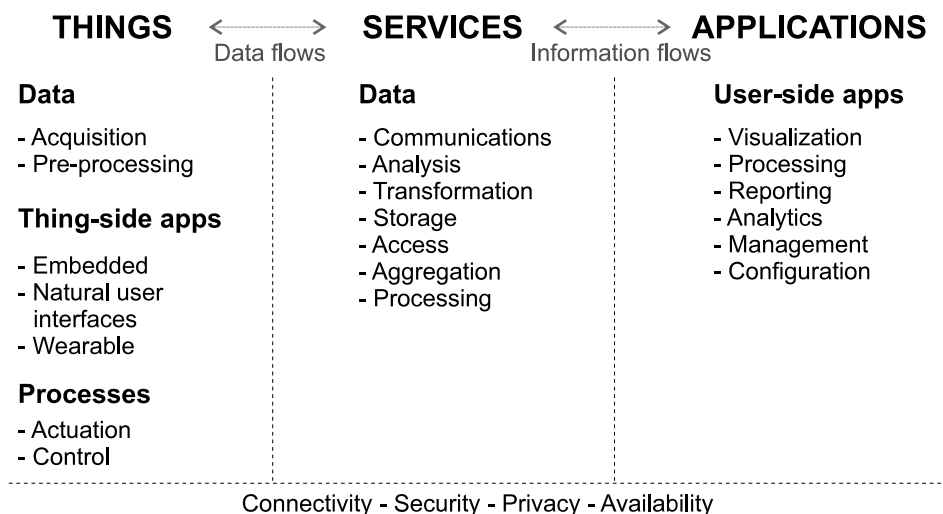


Figure I.2 Common elements in IoT reference models and architectures.

An object must have networking capabilities to be a part of the IoT. Objects may be designed with such capabilities and manufactured as Internet-ready objects; non-Internet-enabled objects can be equipped with additional networking hardware; or objects being part of an IoT system can connect to the Internet indirectly via an additional object that acts as a proxy when connecting them directly is not necessary, advisable, or possible.

Services are typically provided as cloud-based, where data are stored, processed, analyzed, aggregated, and means for accessing it are provided. While the different models and architectures consider software and hardware as important components of IoT, some of them imply a relevance of data-related services across the whole model (Cisco, 2018; Intel, 2018); or highlight the importance of the data flows between sections (Microsoft, 2018). As implied in (Sharma, Chang, Tim, Wong, & Gadia, 2018) and (Griffor, Greer, Wollman, & Burns, 2017), new services are emerging and made available due to the increasing number of IoT connected devices and as the technology itself reaches a higher maturing stage. IoT applications performing complex data-intensive computations benefit the most from these services (Sharma et al., 2018).

The end-user apps are found on the Applications section. These apps are either computer or mobile device-based and provide means for data visualization, reporting, analytics, things management and configuration, sending commands for actuation on things-side, and controlling things and systems behavior. Applications allow users to interact with connected objects via services, taking advantage of enhanced data and information useful for decision making.

Between these sections there is a continuous exchange of data and information supported by a set of technologies that provide connectivity, security, privacy, and availability to both data and services. Things obtain data and act as providers for the services section, where data are processed and turned into usable information that users on the applications side can then transform into knowledge.

I.2 Problem statement

Despite all the existing work and experience related to these and other areas such as nanotechnology, big data, identification, localization and cloud technologies, there is still no

consensus on the definition of the Internet of Things concept, as pointed out by several researchers and evidenced by the number of ideas and conceptions around the topic that can be found in research literature, magazines and websites of alliances, organizations and industry interested on development of the IoT. Since the term was used for the first time in 1999, its scope has widened and different definitions have been proposed, varying according to changes and creation of new technologies or the addition of old ones that have found a place within the IoT.

Different visions on the IoT lead to an unclear use of the concept and may mislead in the proper application of the technology when attempting to solve actual problems, and difficult the unifying and standardization efforts of alliances and organizations that seek to create a unified view and global platform that makes the IoT a reality and enables it to deliver the expected benefits. Moreover, new concepts and viewpoints have appeared as the IoT has extended into several domains or depending on the intended use of the technology.

Therefore, proper research must be conducted through the enormous scope of the IoT to ease the establishment of concepts and a common ground for design, development, and maintenance of IoT systems and the technologies that sustain such systems, as well as to support further research activities within the IoT. In addition, several research problems and topics, challenges, and opportunities have been identified (Alkhatib et al., 2014; Borgia, 2014; Stankovic, 2014) which can be taken as a reference for research and development activities across different vertical domains. One of them is the creation of knowledge from collected data, which is one of the most important topics to be researched and exploited as data is the common resource that actually connects things to applications.

As shown in Figure 1.2, data and data activities are scattered across all the sections of the reference models, created and obtained on the physical side of the IoT and then sent into the other levels for activities as storage, processing, visualization, and to be exploited by end-users. Existing models and data-centered visions on the IoT take data as an important element in the IoT, and use data flows to display how components are related and interact, but there is no representation that focuses mainly on data and how different types of data or data characteristics impact the individual components of an IoT system and the system as a whole.

I.3 Research questions

The IoT presents several challenges and areas of opportunity for development and research in different application domains. The scope of this research work is the conceptual foundations of the IoT and the means to benefit from data created and collected by things. From that premises, the following research questions are formulated:

- Q1—Can a proper and common understanding and definition of the IoT be obtained by tracking its enabling technologies and the way it has evolved in time?
- Q2—How can data and its properties be represented within an IoT context and used to describe the objects connected to the IoT?

I.4 Objectives

To develop and propose a framework to understand, characterize, categorize, and graphically describe things in the IoT by means of their data properties.

I.4.1 Specific objectives

- Construct a conceptual reference that helps with identification and disambiguation of IoT related concepts.
- Identify contexts and application domains for IoT applications and systems along with the way the IoT is referred to in each of them.
- Identify unique properties of things that permit a proper classification under well-established parameters.
- Analyze and compare existing reference models and frameworks for the IoT to identify and understand data behavior in order to define a common structure to describe and categorize things that act as data producers for the IoT.

I.5 Methodology

Taking as a starting point the diversity of views, a systematic literature review (SLR) on the evolution of the concept of the Internet of Things was conducted. It was intended to understand

the way the concept has changed and to assess the influential factors that triggered such changes. Certainly, there exist reviews, surveys and overviews that have been performed on the IoT, reflecting a considerable amount of work and analysis in order to obtain important results, but they usually try to cover a comprehensive view of the state of the art in the IoT, its enabling technologies, application areas, research opportunities and common problems. In this case, the interest was specifically on the IoT concept and the way it is understood across different application domains, to provide a detailed report that serves as a reference for future research on the area.

Besides giving an insight on the definition of the IoT, the results of the SLR were taken as a reference for creating a representation and classification of things in the IoT by means of their combined capabilities. Data-related capabilities were then structured as a graphical framework for categorizing and describing things producing data. One of the most comprehensive approaches found in the literature, on creating a framework for describing the components of the IoT was performed by the Cyber-Physical Systems Public Working Group (CPS PWG) (Griffor et al., 2017). Even though their aim is defining and shaping key characteristics of CPS, along with developing a shared understanding of CPS and its fundamental concepts and unique dimensions, the working group acknowledges an overlap between the CPS and IoT concepts, making this framework suitable also for IoT. The framework described as part of this research focuses on the data activities and properties of the things-side of the IoT.

I.6 Outline

This document comprises a total of seven chapters. The first one consists of the introduction and provides an overview of the goals, motivation, and structure.

The second chapter describes the methodology for a systematic literature review focused on the concept of the Internet of Things. Quantitative results of the review are also presented at the end of the chapter.

In chapter three, the results of the review are presented and organized in a timely manner according to the changes found on the definition and visions of the IoT. Describing the IoT by

means of things capabilities is seen as a common practice that is taken as a strategy for characterizing and categorizing objects connected to the IoT.

Chapter four deals with details on things in the IoT, describing the main properties or capabilities that are used to define them. Then, an abstraction of things from these capabilities is proposed.

In chapter five the graphical categorization framework is presented and explained. This framework derives from the level of implementations that data producing objects have for each of the data-related capabilities of things.

Chapter six presents some scenarios of use for the framework. The goal is to showcase its use and implications in both designing new IoT objects and systems, as well as categorizing existing objects from their data properties.

Finally, chapter seven presents the conclusions of this research work and outlines some of the future strategies for research.

CHAPTER II. METHODOLOGY FOR THE SLR

A systematic literature review (SLR) is a means of evaluating and interpreting all available research relevant to a specific research question, topic area, or phenomenon of interest (Kitchenham, 2004). In this case, the topic of interest is the concept of the Internet of Things, the aggregated efforts to define it, the way its definition has evolved and the technologies or factors driving such evolution.

Different definitions are found in both scientific and non-scientific publications and forums and, as solutions and applications are developed in several application domains, pertaining names tend to be used. This variety of definitions and names that are used to refer to the same concept, reflect the existing lack of agreement on a common IoT definition. Therefore, this SLR is conducted with the aim to identify, analyze, understand, and report on the efforts that have been made to define the IoT, providing a solid background for new and current research activities in this field. This section depicts the steps undertaken in this SLR, providing the reasons for each decision and summarizing the obtained results.

II.1 Research Questions

Two research questions to drive the SLR were formulated as follows:

- RQ1—How has the definition of the Internet of Things evolved?
- RQ2—What are the names given to the IoT and how is it understood across different application domains?

The first question is oriented to find different definitions for the IoT and to understand how this definition has changed and what the drivers for those changes have been. Realizing the IoT as a general designation for a technology, the goal is to identify the concepts that have been proposed in the different areas using it. So, a second question was formulated, in order to first identify such areas and then the way the IoT is referred and understood in each of them. One restriction to these questions is that the interest relies in independent points of view, either coming from academic research groups, alliances or standardization agencies, avoiding any bias

towards specific definitions, technologies and/or proprietary solutions from major industries or vendors.

II.2 Source Selection

Two main sources were selected to carry out the SLR. Both are recognized for listing and indexing publications from well renowned journals and major conferences:

- ISI Web of Science
- Scopus

Even though these sources would provide sufficient results for the SLR, four more were included as a way to provide a comprehensive and wider search. Most of their publications are indexed in the main sources, but including additional sources helped to avoid missing important papers due to non-indexed recent creation journals or indexing delays. One example of the former is IEEE Internet of Things Journal, that was first published in 2014 and not all of its papers were found while performing searches in the main sources at the time the SLR was performed. The secondary sources, sorted alphabetically, are:

- ACM Digital Library
- Elsevier’s ScienceDirect
- IEEE Xplore
- SpringerLink

II.3 Search Strings

To answer RQ1, two search strings were structured as follows:

ST1—Documents containing the phrase “The Internet of Things” in the title. These documents were considered as highly probable to contain a definition of IoT. For this query, the following terms were avoided: “call for papers”, “editor’s note”, “guest editorial”, “special issue” and “theme issue”, because of preliminary search results where these types of documents did not contribute to the review.

ST2—The second search string allowed to expand the search and obtain a comprehensive set of publications about IoT. The phrase “Internet of Things” or its acronym “IoT” in the title of the documents was used. Additionally, the search was narrowed by requiring any of the words “definition”, “concept”, “evolution”, “vision”, “story” or “approach” to be present on the title, abstract or keywords.

Each of the search strings was tailored for the source search engines, and used conforming to what each of them allowed. For instance, among the selected sources, only ACM Digital Library, Elsevier’s Science Direct, Scopus and IEEE Explore support refining search by abstract and keywords.

The approach on RQ2 was different, as there was no previous indication on the number of application domains and/or possible names given to the IoT in each of them. Documents returned from the execution of ST1 and ST2 were selected only if they clearly indicated a different name for the IoT. Additionally, the analysis of the literature provided a significant number of domains and names that are listed and briefly described in section III.5.

II.4 Execution of the SLR

The studies selection stage of the SLR was executed following the flowchart shown in Figure II.1. The quantitative results of executing both search strings are shown in Table 2.1. Main sources are listed first and sorted alphabetically. Classification was made accordingly to the most common names used for types of documents in the different sources. Totals for each source and type of document are indicated in italics in the rightmost column and bottom row respectively for each search string.

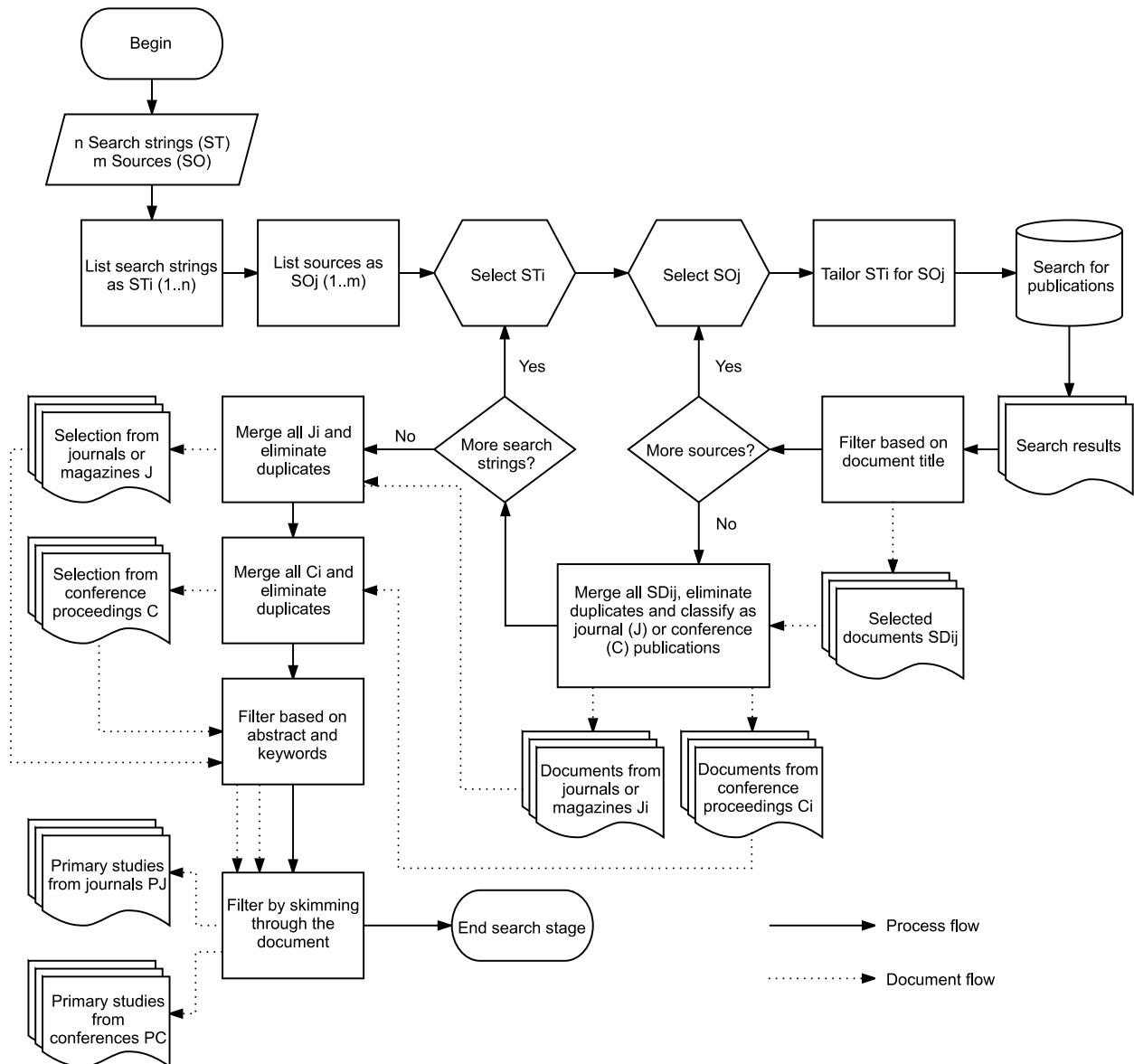


Figure II.1 Methodology for the SLR.

A first selection of studies was based on the publication title, and classified in two disjoint sets: published in journals, magazines and reviews; and published in conference proceedings and book chapters. This classification was carried out because it is expected that the former studies have passed through a more exhaustive reviewing process and results would be more suitable to the SLR's goals. This first step was made iterating through all the sources for every search string, merging results from the different search engines and eliminating duplicates (Table 2.2). Results from different search strings were then merged, keeping them classified and new duplicates found were eliminated (Table 2.3).

Table 2.1 Results of executing ST1 and ST2 in each of the selected sources.

Search String 1					
Base String	“The Internet of Things”				
NOT	“call for papers”	“editor’s note”	“guest editorial”	“special issue”	“theme issue”
Results	Journal/Magazine	Conferences/Book chapters		Reviews	Total
ISI	236	0		16	252
Scopus	470	909		38	1417
ACM	18	98		0	116
Elsevier	85	0		0	85
IEEE	111	571		0	682
Springer	46	192		0	238
	966	1770		54	2790

Search String 2					
Base String	“Internet of Things” OR “IoT”				
AND (Title+Abstract+keywords)	“definition” “story”	“concept” “approach”	“evolution”	“vision”	
Results	Journal/Magazine	Conferences/Book chapters		Reviews	Total
ISI	42	0		2	44
Scopus	464	973		25	1462
ACM*	24	138		0	162
Elsevier	16	0		0	16
IEEE*	115	949		0	1064
Springer	92	310		0	402
	753	2370		27	3150

Table 2.2 First selection stage.

Selection by Document Title (ST1)				
	Journal/Magazine	Conferences/Book Chapters	Reviews	Total
ISI	40	0	6	46
Scopus	97	96	21	214
ACM	8	11	0	19
Elsevier	13	0	0	13
IEEE	23	64	0	87
Springer	17	33	0	50
	198	204	27	429

Selection by Document Title (ST2)				
	Journal/Magazine	Conferences/Book Chapters	Reviews	Total
ISI	8	0	0	8
Scopus	60	104	10	174
ACM	12	21	0	33
Elsevier	16	0	0	16
IEEE	19	126	0	145
Springer	15	50	0	65
	130	301	10	441

Duplicate Detection and Removal				
ST1	Total by Type	Duplicated	Final Set	
Journal/Magazine	198	19	179	J1: Non-duplicated results from journals, magazines and reviews. C1: Non-duplicated results from conferences or book chapters.
Conferences/Book chapters	204	0	204	
Reviews	27	3	24	
	429	22	407	
ST2	Total by Type	Duplicated	Final Set	
Journal/Magazine	130	5	125	J2: Non-duplicated results from journals, magazines and reviews. C2: Non-duplicated results from conferences or book chapters.
Conferences/Book chapters	301	20	281	
Reviews	10	0	10	
	441	25	416	

Table 2.3 Merging results from ST1 and ST2.

Merged Results from all Search Strings				
	ST1	ST2	Total	
Journal/Magazine/Reviews	203	135	338	
Conferences/Book chapters	204	281	485	
	407	416	823	
Duplicate Detection and Removal				
	Total by Type	Duplicated	Final Set	
Journal/Magazine/Reviews	338	92	246	J = J ₁ ∪ J ₂ C = C ₁ ∪ C ₂
Conferences/Book chapters	485	157	328	
	823	249	574	

The final selection of primary studies was performed in two steps. The first step involved reading the abstract and keywords, selecting those papers with a clear indication on providing a definition for the IoT or discuss its definition, and excluding those related to its architecture, reference models, related technologies, or applications in specific areas, like automotive, health or fashion. These documents were excluded from the SLR, but kept as separate sets as future research deals with such topics, and they could also provide an answer to RQ2.

Even though some terms in the search strings had the purpose of excluding some types of publications, several editorials, technology news, market reports, essays, and project descriptions were still found at this step. These documents were discarded, along with a few others that could not be obtained in full text.

Several documents did not provide enough information in the abstract or keywords to decide on either including or excluding them as primary studies. For these cases, a second step was performed, skimming through each document to get a clearer insight on its purpose. At the end, a set of two disjoint lists of documents {PJ, PC} was selected and its elements were used as primary studies for the SLR (Table 2.4), where PJ are the primary studies found in journals, magazines and reviews, and PC the ones found in conference proceedings and book chapters.

Table 2.4 Primary studies selection.

Set	Total	F1	F2	
J	246	68	36	F1: Filter by abstract and keywords.
C	328	57	39	F2: Skimming. Remaining documents are final sets PJ and PC.

II.5 Studies Revision

A total of 75 studies were selected for revision, 36 in the PJ set and 39 in PC. Studies in PJ were published from 2002 to 2016, while those in PC were published from 2010 to 2016. Each study was revised to extract the following data:

- Definition of IoT, either by the authors or adherence to previously published definitions.
- Technologies that support the definition given or used.
- Application domains of the IoT, as well as the names used in each domain to refer to the IoT, if any.
- Additional literature to be included in the review.

After fully reviewing the studies, it was found that 29 of the studies in PJ and 22 in PC deal with the concept of the IoT at some extent. Several studies coincide on the lack of a common or unified definition, as the technology itself is still on a maturing stage or it is interpreted in accordance to specific needs, interests, or technical bias of a given group (Atzori, Iera, & Morabito, 2010a; Borgia, 2014; Chen, Xu, Liu, Hu, & Wang, 2014; Dorsemayne, Gaulier, Wary, Kheir, & Urien, 2015; Gathegi, 2013; Hurlburt, 2015; Shin, 2014; Tsai, Lai, & Vasilakos, 2014; Whitmore, Agarwal, & Li, 2015; Wortmann & Flüchter, 2015; Yan, Lee, & Lee, 2015). In addition,

as expressed by Borgia, the meaning of the term continuously evolves because technology and the ideas behind it change themselves over time (Borgia, 2014).

Some of the characteristics of the studies and journals are: The number of citations in the set of selected studies had a mean of 43.081 with a median of 3. Trimming studies with 0 citations makes a mean of 62.5 with a median of 6. In the set of discarded studies, means for each of the previous cases are 6.49 and 9.42, while medians are 1 and 2. Selected studies with at least 1 citation had a mean of 10.92 citations per year, while the discarded studies were cited 1.87 times per year. The average number of years since publication is 4.20 for all the selected studies, and 4.08 for the discarded ones. The average Journal Citations Report (JCR) impact factor (IF) for journals where selected studies were published was 2.055, most of them being in the second quartile of the JCR. The Scimago Journal Ranking (SJR) that Scopus uses to rank journals, had a mean of 0.81 for journals in the set of selected studies, with most of them being in the first quartile of this ranking. IF and SJR means for journals in the set of discarded studies resulted almost identical to means in the set of accepted studies.

The following chapter shows the different ideas, concepts, visions and definitions of the IoT found while analyzing the results of the primary studies from the SLR, as well as gray literature identified during the analysis. They are listed in chronological order, grouping some of the results that share some perspectives, and pointing the most relevant facts. A discussion is included afterwards.

CHAPTER III. THE INTERNET OF THINGS CONCEPT

One of the premises for using and making profit from a technology is to understand it. In the case of the IoT, it is not only about a single technology but a growing group of technologies that have been evolving and maturing enough to be used together in an efficient way. This chapter sums the findings of the SLR described in Chapter II, offering a chronological view of the development and definition of the IoT.

III.1 The Early Visions (Late 1990s to 2005)

The notion of IoT has evolved since it was conceived in the late 1990s. Bill Joy initially proposed it as part of his six Webs taxonomy (Table 3.1) in a speech at the World Economic Forum in Davos (Switzerland), which was later replicated as a lecture in several technological and academic forums (Pontin, 2005). The sixth of such Webs is referred as device to device (D2D) and defined as an internet of sensors distributed across a mesh network, setting up urban systems for maximum efficiency (Joy, 2015).

Table 3.1 Bill Joy's six Webs taxonomy.

Category	Description
Near Web	It refers to the version of the Web that is closer to us, which is accessed using a computer by means of interfaces like keyboards and mice. It is defined by information and provides a notion of mobility through wireless networks.
Here Web	The version of the Web that can be accessed anytime and from any place using a device that is always with a person, becoming part of his or her identity.
Far Web	This Web refers to accessing contents through broadband networks. Such contents usually infer an innovation in entertainment.
Weird Web	The Web that is accessed with natural user interfaces. Its style of use defines it as the most pervasive of the first four Webs.
B2B	In this version of the Web, business computers talk to each other about business processes. It was initially identified as "e-commerce Web".
D2D	The device-to-device Web refers to devices communicating to share information to manage, control and monitor processes. It was initially identified as "pervasive Web".

Kevin Ashton first coined the phrase Internet of Things in 1999 as the title of a presentation where he linked the use of RFID in Procter & Gamble's supply chain to the Internet. He described a vision where computers would be capable of gathering data without human help and render it into useful information, which would be possible with technologies like sensors and Radio

Frequency Identification (RFID) that enable computers to observe, identify and understand the world (Ashton, 2009).

In a report for the Auto-ID Center⁴, Sarma, Brock, & Ashton (2001) describe a world where every electronic device is interconnected and every object, electronic or not, is electronically tagged with information related to it. Such tags would allow obtaining the information in a remote and contactless fashion, setting the objects as nodes in an internetworked physical world, analogous to the Internet and regarded as a new “Internet of Things.” A key element for this architecture was the Electronic Product Code (EPC) as a means to identify all physical objects and link them to the network (Brock, 2001). Here, the network was understood as a seamless, ubiquitous and inexpensive system that would automatically link physical objects to the global Internet, adopting standards in cooperation with governing bodies, commercial consortiums and industry groups.

The earliest document returned by the searches where the phrase “Internet of Things” appeared as part of the title was written by C. R. Schoenberger and published in Forbes Magazine in 2002. Quoting Ashton, the IoT was deemed as a standardized way for computers to understand the real world, portraying RFID-based applications for inventory management and customer experience improvement (Schoenberger, 2002).

A more comprehensive proposal was the so-called Internet-0 (I0) (Gershenfeld, Krikorian, & Cohen, 2004). The potential uses and benefits of connecting everyday objects to a data network were exemplified in a series of exhibits enhanced with embedded computers and sensors. The intention with I0 was not to replace the existing Internet, but provide a compatible layer below it where connected devices depend on existing routers, gateways and name servers. Here, the original Internet idea of linking computer networks into a seamless whole was considered feasible to be extended to networks of all types of devices, a concept known as interdevice internetworking (Gershenfeld et al., 2004).

⁴ A non-profit collaboration between private companies and academia that pioneered the development of an Internet-like infrastructure for tracking goods globally through the use of RFID tags carrying Electronic Product Codes. The center closed its doors in September 2003. (Ref: RFID Journal Glossary <https://www.rfidjournal.com/glossary/term?11>)

One of the earliest contributions to defining and understanding the IoT was the International telecommunication Union (ITU) Internet of Things report, published in 2005. They prospect devices and all kinds of things becoming active users of the Internet on behalf of humans, with most of the traffic flowing between them, and a number of active connections that could be measured in terms of tens or hundreds of billions. Connecting inanimate objects and things to communication networks, in addition to the deployment of higher-speed mobile networks that provide an always-on connectivity, would fulfill the vision of a truly ubiquitous network, “anytime, anywhere, by anyone and anything” (ITU, 2005).

The ITU portrays the IoT as a virtual world mapping the real world, where everything in our physical environment has its own identity in virtual cyberspace, thus enabling communication and interaction between people and things, and between things. This vision is based on the application of key technological enablers that would account for an expanded Internet, able to detect and monitor changes in the physical status of connected things in real-time (ITU, 2005).

III.2 Establishment Phase (2009 to 2011)

Building on the previous ideas, the concept starts changing from what can get connected to the network, to what can be done with the things that are connected to the network. Haller, Karnouskos, & Schroth (2009) state that the role of the Internet of Things is to bridge the gap between the physical world and its representation in information systems. In accordance, they define the IoT as “A world where physical objects are seamlessly integrated into the information network, and where the physical objects can become active participants in business processes. Services are available to interact with these smart objects over the Internet, query their state and any information associated with them, taking into account security and privacy issues”.

Based on the belief of continuous and steady advances in microelectronics, communications and information technology, Mattern and Flöerkemeier (2010) see the Internet extending into the real world embracing everyday objects. Physical items connect to the virtual world where they are controlled remotely and can act as physical access points to Internet services.

The gap between the virtual and physical world is bridged by several technical developments taken together. Such developments provide the objects with capabilities like communication, cooperation, addressability, identification, sensing, actuation, embedded information processing, localization, and novel user interfaces, which contribute to an evolution of the IoT paradigm that started with the remote identification of objects to a system where smart objects actually communicate with users, Internet services and even among each other. More than defining the IoT, they describe the features of the objects that get connected in the IoT, a characteristic commonly found in the reviewed papers, which is discussed in Chapter IV. Two definitions that are commonly adopted by researchers or used as a starting point for their own definitions are the results of European Commission promoted initiatives. The first of these concepts was determined within the Coordination and Support Action for Global RFID-related Activities and Standardization (CASAGRAS) project as (CASAGRAS Partnership, 2009):

“A global network infrastructure, linking physical and virtual objects through the exploitation of data capture and communication capabilities. This infrastructure includes existing and evolving Internet and network developments. It will offer specific object-identification, sensor and connection capability as the basis for the development of independent cooperative services and applications. These will be characterized by a high degree of autonomous data capture, event transfer, network connectivity and interoperability”.

Then, the European Commission, through the Cluster of European Research Projects on the Internet of Things (CERP-IoT), defines the IoT as “a dynamic global network infrastructure with self-configuring capabilities based on standard and interoperable communication protocols where physical and virtual things have identities, physical attributes, and virtual personalities and use intelligent interfaces, and are seamlessly integrated into the information network” (CERP-IoT, 2010).

Several interpretations and definitions of the IoT are discussed in (Atzori, Giusto, Iera, & Morabito, 2010b). They state the basic idea of this concept is the pervasive presence around us of a variety of things or objects—such as RFID tags, sensors, actuators, mobile phones, etc., which, through unique addressing schemes, are able to interact with each other and cooperate with their neighbors to reach common goals (Atzori et al., 2010b). In their analysis, the IoT

paradigm is depicted as the result of the convergence of three main visions: Things-oriented, Internet-oriented, and Semantic-oriented—see Figure III.1.

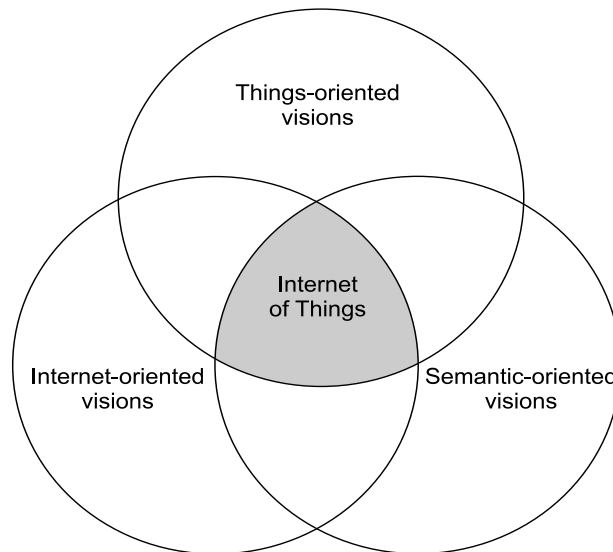


Figure III.1 Three main visions of the IoT.

Under this paradigm, three fundamental building blocks of the IoT concept can be inferred: the way objects or things get connected to the network, the capabilities of interaction and communications provided by the latter, and the use and interpretation of the information provided by things. As the authors in (Atzori et al., 2010b) suggest, the IoT has the potential to add a new dimension to the process of interaction between people and machines, by enabling communications with and among smart objects, thus leading to the vision of “anytime, anywhere, any media, anything” communications.

Huang and Li (2010) analyzed the semantic meaning of the phrase Internet of Things to understand the properties of IoT. They see it as a network for globally sharing information about things, which they refer to as products. After reflecting on both the literal and intrinsic meaning, they propose a semantic meaning for IoT as a global system for sharing product information among interconnected products.

A similar approach is offered in (Zhang, Han, & Feng, 2010) where the IoT is defined as a network that uses sensing and localization devices attached to things, or articles, connected to the Internet for information exchange and communication, to achieve intelligent recognition,

location, tracking, monitoring and management functions. They understand it as an extension and expansion of the existing Internet, which remains as the core and foundation of IoT, with articles that make use of clients for Internet services.

According to Ma (2011), the IoT can enable the interconnection and integration of the physical world and the cyberspace; representing the trend of future networking, while leading the third wave of the IT industry revolution. Comparing IoT with Wireless Sensor Networks (WSNs), Internet, ubiquitous networks and further analysis, the author defines IoT as a network that interconnects ordinary physical objects with identifiable addresses, providing intelligent services. The IoT is based on traditional information carriers like the Internet or telecommunication networks. Furthermore, the instrumentation of ordinary objects, their interconnection through autonomic terminals, and providing intelligent pervasive services are listed as important characteristics of the IoT.

There are visions where the IoT is perceived as an extension to the existing Internet. This is supported by the fact that, in the IoT, not only subjects but also objects will be connected and enabled to exchange and share information. In addition, the development of the IoT is considered as one of the manifestations of the concept of ubiquitous computing (Van Lier, 2011).

Coetzee and Eksteen see the IoT as part of the Future Internet (Coetzee & Eksteen, 2011). They describe a vision where objects become part of the Internet: where every object is uniquely identified, and accessible to the network, its position and status known, where services and intelligence are added to this expanded Internet, fusing the digital and physical world, ultimately impacting on our professional, personal and social environments. The driver for the IoT is an expansion of the Internet through the inclusion of physical objects combined with an ability to provide smarter services to the environment as more data becomes available.

III.3 A shift Towards Data and Services (Starting in 2012)

In most recent definitions and visions, the role of things as data producers and the network as enabler of new services are highlighted. In (Miorandi et al., 2012) the IoT is seen as an extension of the existing Internet and the Web into the physical realm. As they state, the IoT uses

the Internet as a global platform for letting machines and smart objects communicate, dialogue, compute, and coordinate. These objects act as providers and/or consumers of data related to the physical world, giving the IoT a focus on data and information rather than on point-to-point communications. They define the IoT from a system-level perspective, as a highly dynamic and radically distributed networked system, composed of a very large number of smart objects producing and consuming information.

With a different perspective, Mayordomo et al. (2011) envisage the IoT as a sort of evolution of the Internet to reach the physical everyday objects. They define it as a new dynamic network of networks, where every daily object can communicate to each other.

The Internet is seen evolving from a network of interconnected computers to a network of interconnected objects, bolstered by the combination of several technologies including embedded microcontrollers, sensors, actuators, network interfaces, and the greater Internet (Lee, Crespi, Choi, & Boussard, 2013). They recognize three principal viewpoints from where different interpretations of the IoT emerge: Internet or network oriented; Objects or things oriented; and complex distributed systems. In the opinion of Lee et al. (2013), these diverging views have brought many attempts to define IoT that it results advisable to move forward with a common understanding in a global perspective.

According to (Gubbi, Buyya, Marusic, & Palaniswami, 2013), even though the definition of “Things” has changed as technology evolved, making it more inclusive in order to cover a wide range of applications, the main goal of making a computer sense information without the aid of human intervention has remained the same. This represents an evolution of the current Internet into a network of interconnected objects, able to harvest information from the environment, interact with the physical world and use existing Internet services for information transfer, analytics, applications and communications.

Building on previous works in the field of ubiquitous computing, they provide a user-centric definition for the IoT in the context of smart environments, as the “interconnection of sensing and actuating devices providing the ability to share information across platforms through a unified framework, developing a common operating picture for enabling innovative applications”

(Gubbi et al., 2013). Though the definition might seem too general, the authors claim its purpose is to allow development and deployment of long-lasting applications using the available state of the art protocols at any given point in time, enabled by seamless ubiquitous sensing, data analytics and information representation with cloud computing at the center of a conceptual IoT framework.

In June 2012, the ITU approved recommendation ITU-T Y.2060, which provides an overview of the IoT and has the objective of highlighting it for future standardization. As part of the recommendation, they define the IoT as “a global infrastructure for the Information Society, enabling advanced services by interconnecting (physical and virtual) things based on, existing and evolving, interoperable information and communication technologies”, understanding it as a far-reaching vision with technological and societal implications (ITU-T, 2012). This definition has since been adopted by several researchers, as it is supported by a comprehensive reference model updated from their 2005 report (ITU, 2005).

Another aspect that gets considered in IoT conceptualizations is that of intelligence. Mzahm, Ahmad, & Tang (2013) introduce it through the concept of Agents of Things, understanding the IoT as the enabler for objects or things to connect and communicate with other objects in the world via the Internet. However, they find some deficiencies as things lack the ability to reason on their environments and make intelligent decisions and actions to achieve their objectives. Accordingly, they infer the system as a whole may be represented as being intelligent but not individual things. This interpretation is shared by Chen et al. (2014), who describe the IoT as an intelligent network which connects all things to the Internet for exchanging information and communicating through the information sensing devices in accordance with agreed protocols. Such protocols need not to be reinvented. As suggested in (Aggarwal, Ashish, & Sheth, 2013), if the objects are uniquely addressable and connected to the Internet, then the information about them can flow through the same protocol that connects our computers to the Internet.

Some visions of the IoT highlight the business impact of the IoT as a provider of new services. In (Alam, Nielsen, & Prasad, 2013) the IoT is observed evolving from the field of Machine to Machine (M2M) communication, adding value to services and applications for businesses relying on the M2M value chain, taking advantage of the network infrastructure and computing

capabilities to improve operational and business processes and enhance customer experience. As the authors describe it, “the IoT to be seen tomorrow is a concept that moves beyond the basic connectivity and technological innovations and merges the gap to the envisioned use cases in order to bring the needed functionality and business values. This includes a focus on platforms and how solutions are delivered with horizontal platforms that are able to support a multitude of vertical solutions”.

(Chaouchi, Bourgeau, & Kirci, 2013) describe the IoT as a provider of new services to networked and connected objects, which in turn will provide services to persons. They imply the Internet model must be adapted to support the connectivity and traffic transport of the new services based upon the connected objects.

For Skaržauskienė and Kalinauskas (2015), the main idea of the IoT is circling around a connected network or networks in which things and other sensor-based objects communicate with each other. They state that the ability to integrate small, energetically efficient and cheap sensor-based objects into clouds of networks would cause the new business and service models and expand beyond the human-machine interaction approach which is most frequently used in Internet-based environments.

III.4 Things as a Key Element

Even though it has been over a decade of evolution for the IoT, in recent publications the IoT is still considered to be in its early stages. As Borgia points out, IoT refers to an emerging paradigm consisting of a continuum of uniquely addressable things communicating one another to form a worldwide dynamic network (Borgia, 2014). Chen states that in the future, digital sensing, communication, and processing capabilities will be ubiquitously embedded into everyday objects, turning them into the IoT. In this new paradigm, smart devices will collect data, relay the information or context to each another, and process the information collaboratively using cloud computing and similar technologies. Finally, either humans will be prompted to take action, or the machines themselves will act automatically (Chen Y.-K. , 2012). As a long-term vision, the trend of IoT is the fusion of sensing and Internet, where all the networked things are flexible, smart, and autonomous enough to provide required services (Li, Xu, & Zhao, 2015).

In 2015, the results of a study aimed to define the IoT were published at the IEEE IoT Initiative Web portal. Authors proposed two definitions depending on size and complexity of systems. For low complexity systems, they define the IoT as a network that connects uniquely identifiable things to the Internet, where the things have sensing/actuation and potential programmability capabilities and, through the exploitation of unique identification and sensing, information about the thing can be collected and its state can be changed from anywhere, anytime, by anything. For global distributed systems, where a large number of things can be interconnected to deliver a complex service and support an execution of a complex process, they propose the following definition of IoT (Minerva, Biru, & Rotondi, 2015):

“Internet of Things envisions a self-configuring, adaptive, complex network that interconnects ‘things’ to the Internet using standard communication protocols. The interconnected things have physical or virtual representation in the digital world, sensing/actuation capability, a programmability feature and are uniquely identifiable. The representation contains information including the thing’s identity, status, location or any other business, social or privately relevant information. The things offer services, with or without human intervention, through the exploitation of unique identification, data capture and communication, and actuation capability. The service is exploited through the use of intelligent interfaces and is made available anywhere, anytime, and for anything taking security into consideration.”

This definition encompasses many of the previously found definitions, but it resembles more a comprehensive description of the IoT than a definition. However, viewing the IoT according to the complexity and size of the systems could actually lead to a better understanding and ease implementation of solutions at different scales.

Some recent definitions revolve around four basic actions: identifying, sensing, networking and processing. The use of technology required for those actions is evolving in terms of the number and kinds of devices as well as the interconnection of these devices across the Internet. The IoT proposes to attach this technology to everyday devices and making them online, even if they were not initially designed with this capability in mind (Whitmore et al., 2015). Hurlburt describes a model for the IoT involving sensing, thinking, and acting, which usually occur iteratively in that order. He compares sensing to the human five primary senses, thinking to the

way the human brain processes information, and acting to interaction, which represents a difference to the concept of autonomy proposed by others (Hurlburt, 2015). Despite proposing a definition mostly around the interconnection of objects, Pintus, Carboni, Serra, & Manchinu (2015) support the need for interaction between people and things, which they present as a humanized view of the IoT.

Finally, a pair of definitions were found that, as others before, take a data approach, but stress on what is done with data and how it is transformed into knowledge via data mining techniques. (Dorsemaine et al., 2015) define the IoT as a group of infrastructures interconnecting connected objects and allowing their management, data mining and the access to the data they generate. They identify a connected object as a device equipped with sensors and/or actuators carrying out a specific function and being able to communicate with other equipment. Authors back their definition with a four-layer architecture.

On their part, (Qin et al., 2016) focus their study of the Internet of Things from a data perspective, considering that data is processed differently in the Internet of Things and traditional Internet. In the Internet of Computers (IoC), both main data producers and consumers are human beings. However, in the Internet of Things, the main actors become things, which means things are the majority of data producers and consumers. Therefore, computers will be able to learn and gain information and knowledge to solve real world problems directly with the data fed from things. As a goal, computers enabled by the Internet of Things technologies will be able to sense and react to the real world for humans.

III.5 Other Names Given to the IoT

As the IoT extends into several application contexts, so does the way it is named and understood. This section presents the names given to the IoT in such contexts, as found in the reviewed literature, accompanied by a brief description. Some of these names represent complete new concepts on their own, while others are mere specializations of the IoT.

The Web of Things (WoT) is a concept described in (Kindberg et al., 2002) as making things web-present by embedding web-servers in them or by hosting their web-presence within a web

server. The name was first used as part of Sun Microsystem's project JXTA (Traversat et al., 2003), defining a set of protocols for building applications and deploying them on a virtual network. More recently, (Guinard & Trifa, 2009) proposed an architecture for making devices an integral part of the Web by using HTTP as an application layer. In this context, the term Web of Objects is also used (Chaouchi et al., 2013) as well as Physical Web (Want, Schilit, & Jenson, 2015). It is important to note that all of the Web-based visions consider naming services of things as an important feature.

Extending from the IoT and the WoT, the notion of Wisdom Web of Things (W2T) represents a holistic intelligence methodology for realizing the harmonious symbiosis of humans, computers, and things in the hyper world. This concept relies on different abstractions of intelligence and the creation of knowledge from data. The word "wisdom" implies that each thing in the WoT can be aware of both itself and others to provide the right service for the right object at a right time and context (Zhong et al., 2013).

A frequently used name is the Future Internet of Things (FIoT), based on the gradual development and incorporation of several innovative techniques into the IoT. Among these techniques, how to extract data from sensing and transfer it into knowledge is usually found (Tsai et al. , 2014). The term Future Internet is often used to make reference to the future conditions and applications that will be available through the Internet.

In (Mzahm et al., 2013), the Agents of Things (AoT) concept is proposed to mitigate the effect of the IoT deficiencies and limitations in terms of intelligence. The core idea of AoT is that everything in this concept should have an internal reasoning and intelligence capability, enabling the things to interact directly with other things in the same or different system types.

Building on the idea of adding intelligence to the IoT, the concept of Cognitive Internet of Things (CIoT) is proposed. A CIoT is an IoT with cognitive capability which is integrated to promote performance and achieve intelligence. Given that there is a business process flow corresponding to a given application, CIoT comprehends current business types and network conditions, analyzes the perceived information based on the prior knowledge, makes intelligent decisions,

and performs adaptive and control actions, aiming to maximize network performance and meet the application requirements (Zhang et al., 2015).

A different approach is that of the Social Internet of Things (SIoT), which is based on a sort of social relationship among objects, analogous to what happens for human beings. The SIoT represents an innovative paradigm of interaction among objects, where the basic idea is the definition of a “social network of intelligent objects” (Atzori, Iera, & Morabito, 2011).

The human perspective of the social aspect of the IoT is represented in the Internet of People (IoP), envisaged as people becoming part of ubiquitous intelligent networks having the potential to seamlessly connect, interact and exchange information about themselves and their social context and environment (Hernández-Muñoz et al., 2011). Integrating the notions of the IoT, IoP and SIoT allows to present the idea of a Humanized Internet of Things (HIoT), which enables interactions between communicating entities: smart things and people, the physical world and the digital one (Pintus et al., 2015).

The interaction with the environment is also important for any type of system, and that is represented in the Green IoT. It is defined as the energy efficient procedures, either in hardware or software, adopted by IoT to facilitate reducing the greenhouse effect of existing applications and services or to reduce the impact of greenhouse effect of IoT itself (Shaikh, Zeadally, & Exposito, 2017).

A concept that is used along the IoT is Cyber-Physical Systems (CPS). CPS can be considered a confluence of embedded systems, real-time systems, distributed sensor systems and controls (Rajkumar, Lee, Sha, & Stankovic, 2008). They are integrations of computation with physical processes by means of embedded computers and networks that monitor and control the physical processes, usually with feedback loops where physical processes affect computations and vice versa (Lee et al., 2013).

CPS are physical systems designed with the electronic devices for communications, sensing, and controlling as a part of them and hence invisible to the user, providing a sense of immediacy; in the IoT, these devices may be embedded into existing physical systems to get them connected.

Hence, some authors identify the IoT as a subset of CPS (Borgia, 2014; Camarinha-Matos, Goes, Gomes, & Martins, 2013).

One of the most popular designations is the Industrial Internet of Things (IIoT) or just Industrial Internet. This is a form of IoT where the devices, or things, are objects in manufacturing plants, dispatch centers, process control industries, etc. (Stankovic, 2014). This name, proposed by General Electric, is mostly used in North America, while European initiatives usually rely on the German designation of Industry 4.0, referring to the fourth industrial revolution and often understood as the application of the generic concept of CPS to industrial production systems (cyberphysical production systems) (Drath & Horch, 2014).

Several other fields are adopting the IoT and specific interpretations are being proposed. The idea in each case is to take advantage of the sensing, actuating, communications, data processing, identification, and interaction capabilities of objects pertaining to each application domain. Some of the most commonly found in the literature are the Internet of Vehicles (Gerla, Lee, Pau, & Lee, 2014), Health Internet of Things (Kan, Chen, Leonelli, & Yang, 2015; Ma, Wang, Yang, Miao, & Li, 2016), Internet of Personal Health (IoPH) (Williams, Holloway, & Miodownik, 2016), Internet of m-health Things (m-IoT) (Istepanian, Sungoor, Faisal, & Philip, 2011), Internet of Agriculture (Ahrary, Inada, & Yamashita, 2016), and Agriculture Internet of Things (Hu, Wang, She, & Wang, 2011; Kshetri, 2017).

III.6 Discussion

Two clear trends were identified in the literature: some authors describe the IoT as an extension to the existing Internet, while others present it as an evolution of the Internet. It is important to make a distinction, as the first idea represents that new technology, devices, applications and services are being added and made available through the Internet, while the second implies a progressive change that would end in a replacement of the existing technology. These diverging views clearly represent some of the reasons why the SLR was conducted, and exemplify the lack of consensus on defining the IoT expressed by several authors (Atzori et al., 2010a; Borgia, 2014; Chen et al., 2014; Dorsemayne et al., 2015; Gathegi, 2013; Hurlburt, 2015; Shin, 2014; Tsai et al., 2014; Whitmore et al., 2015; Wortmann & Flüchter, 2015; Yan et al., 2015).

What can be inferred from the literature is that the Internet of Computers (IoC) and the Internet of Things (IoT) are complementary entities in an ecosystem of Internet-connected devices, providing data and services for each other. Therefore, even though in terms of devices the IoC and IoT can be seen as two disjoint sets in a universe of Internet reachable devices, in terms of data and software, devices in the IoC function as means for accessing those in the IoT for configuration, modification, and data storage, processing and visualization. Figure III.5 displays examples of devices and applications that can be found in each of these sets, sharing different types of data, like binary strings containing commands or raw data, documents in application-specific formats, or images. By means of their networking capabilities, elements in both sets can communicate to each other and take advantage of their specific characteristics and features, and the services they provide.

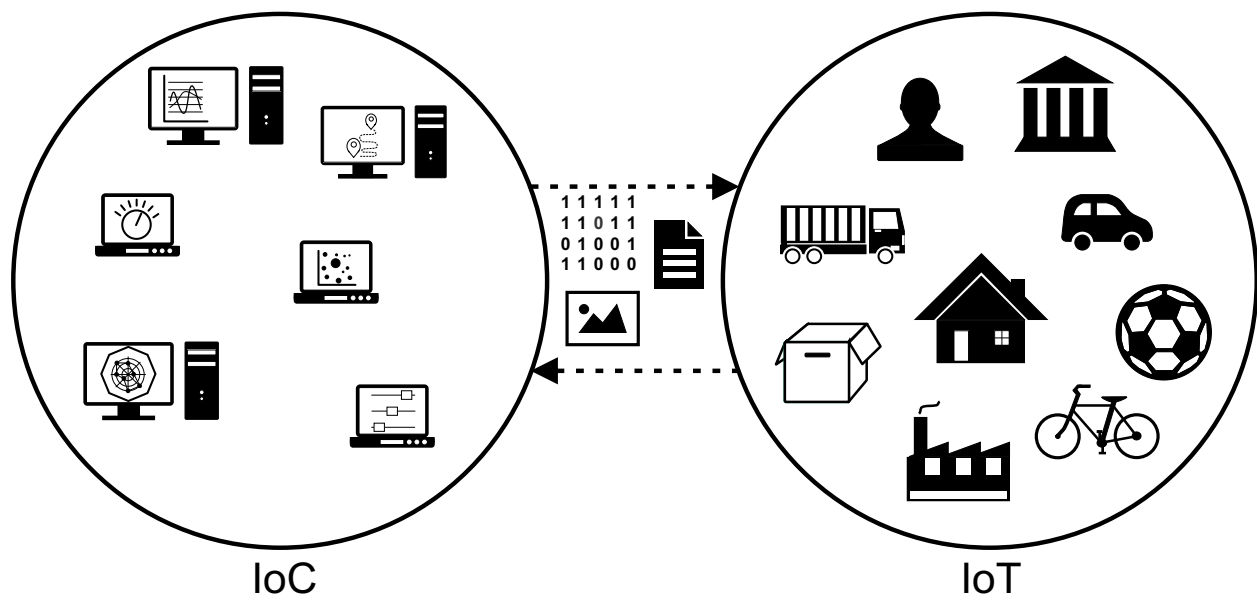


Figure III.5 Interaction between IoC and IoT devices.

Definitions of the IoT tend to be centered on distinct aspects. The initial notions of Ashton and Joy made clear references to the capabilities of things to sense data from the environment. However, for most of the first decade the focus of the definitions was on networking issues and RFID-based services. Later, desired characteristics of communications were integrated into the concept, and the view on services shifted towards business processes, new business models and customer experience, describing services as independent, cooperative, intelligent or advanced. The work of (Atzori et al., 2010a) is the first to explicitly define the IoT in terms of the networks

requirements for connecting things, their capabilities for communications and interaction, and the use and interpretation of data.

More recent definitions, while still mentioning network and communications characteristics, are more oriented to describe the capabilities and properties of things and the importance of harvesting and processing data that can be turned into knowledge for the improvement of business processes. Figure III.6 shows where definitions and visions of the IoT were centered in the selected studies (Only the last name of the first author is shown).

	Late 90s	2000-2005	2009	2010	2011	2012	2013	2014	2015	2016
	Joy Ashton	Sarma Brock Schoenberger Gershenfeld ITU	Haller CASAGRAS	Sundmaeker Mattern Alzori Zhang Huang	Ma van Lier Coetzee Mayordomo	Micrandi Aggarwal ITU Chen	Lee Gubby Mzahm Alam Chaouchi	Chen Borgia Li Whitmore	Skaržauskiene Minerva Hurlbut Pintus Dorsemaine	Qin
Networking										
Services										
Communications										
Data										
Things										

Figure III.6 Orientation of the definitions and visions of the IoT.

In Figure III.7, the most relevant concepts and notions that were used by authors in explaining their visions of IoT are listed. Terms like identification, location, tracking, and specific technologies like RFID were taken off the list as they don't provide additional information to what has been said before. Also, most of the authors make use of specific applications or whole application fields as to exemplify and describe the potential impact of the IoT. The last three columns, shadowed in light gray, correspond to publications where the authors describe the characteristics and properties of things instead of a definition or vision of the IoT. Some of the publications shown in Figure III.6 do not appear in Figure III.7, as the selected concepts are not used by their authors.

	Late 90s	2000-2005	2009	2010	2011	2012	2013	2014	2015	2016	2005	2011	2012
	Joy Ashton	Brock Schoenberger Gershensfeld ITU	Haller CASAGRAS	Sundmaeker Mattern Alzori Zhang	Ma Coetzee	Miorandi Aggarwal ITU Chen	Lee Gubby Mzahim Alam Chacouchi	Chen Borgia Li Whitmore	Skarżauskiene Minerva Hurlburt Pirtius Dorsemaine	Qin	Sterling	Kopetz Speed	Sanchez Xue
Sensors													
Intelligence													
Actuators													
Security/Privacy													
Data mining													
Interoperability													
Std. comm protocols													
Business processes													
Cloud													
Object naming													
Information processes													
Social processes													
Big data													
Data analytics													
Industry													
User interfaces													
Visualization													

Figure III.7 Concepts and notions used by authors in presenting their visions of IoT.

The three most recurring concepts are sensors, intelligence, and actuators. While sensing capabilities have been considered since the first interpretations of the IoT, it is not the case with intelligence and actuators. Intelligence in the IoT is used in several contexts, but its common understanding is the ability to process data, which in its most common use refers to data processing. Concepts like security, privacy, interoperability, and the need for standard communication protocols are often used in presenting the visions, but they are seldom included in the final definitions.

The execution of data mining processes is seen as essential for the IoT in recent definitions, as well as the use of cloud technologies for providing services and storing data. This can accelerate knowledge acquisition via information processes and, with the aid of data analytics and visualization techniques improve the outcomes of both business and social processes mediated by things in the IoT, which also will have important benefits for industry, an actor portrayed as one of the main participants in the future development of IoT.

As explained in most of the descriptions of the IoT, including those specific to different application domains, a huge number of things will be or have already been deployed, generating data that should be treated with technologies and algorithms for big data, which is also mentioned by some authors. For all connected things, two important factors are enabling end users to easily find and use them. As we are used to find a website by its name, finding a thing by

its name may appear as an obvious choice, and so it is proposed by several authors. On the other side, not many of them seem to pay special attention to the final user means of interaction with things, but those who are concerned with describing things and their properties emphasize the importance of designing proper user interfaces.

CHAPTER IV. THINGS IN THE IOT

An imperative component of the IoT are the objects that get connected to it, or simply things. Characterizing them helps understanding the capabilities and possibilities of the IoT and that's why many researchers have made an effort in describing and defining things as a means to express their conception of the IoT. As pointed by (Coetzee & Eksteen, 2011), the definition of things in the IoT vision is very wide and includes a variety of physical elements, like personal objects we carry around such as smart phones, tablets and digital cameras. It also includes elements in our environments as well as things fitted with tags which become connected via a gateway device. In this section, several definitions, descriptions and properties of things, as found in the analysis phase of the SLR, are presented.

IV.1 Names Given to Things

Within the context of the Internet of Things, a thing is defined as a real/physical or digital/virtual entity that exists and moves in time and space and that can be identified (Van Lier, 2011). This definition reminds of that of the spime, presented by Bruce Sterling in his book "Shaping Things". He refers to spimes as manufactured objects whose informational support is so overwhelmingly extensive and rich that they are regarded as material instantiations of an immaterial system. These are digital objects that can be tracked through space and time and contain the data history related to the specific object they represent. Therefore, a key element to the spime is identity, i.e. a spime must be a thing with a name (Sterling, 2005).

A more commonly used name is the smart object. Kopetz (2011) considers smart objects the building block of the IoT and describes them as everyday physical things that are enhanced by a small electronic device to provide local intelligence and connectivity to the cyberspace established by the Internet. Aggarwal et al. (2013) see smart objects as examples of the spime, describing them as tiny computers which have sensors or actuators, and a communication device. Smart objects are also defined by their characteristics, as objects that (Miorandi et al., 2012; Sánchez López et al., 2012):

- Have a physical embodiment and a set of associated physical features.

- Possess a unique identifier.
- Are associated to at least one name and one address.
- Can sense and store measurements made by sensor transducers associated with them.
- Have a minimal set of communication functionalities that allow them to make their identification, sensor measurements, and other attributes available to external entities such as other smart objects or systems.
- May possess means to trigger actions having an effect on the physical reality.
- Possess some basic computing capabilities which can be used to make decisions about themselves and their interactions with external entities.

Usually, things are referred to just as objects. An object in the IoT is regarded to as any machine, device, application, computer, virtual or physical object involved in a communication that could connect to the Internet, and could have the ability to create, request, consume, forward or have access to digital information (Elkhodr, Shahrestani, & Cheung, 2013). There are similar concepts often mentioned in literature like smart parts, smart items or intelligent products.

IV.2 Properties of Things

Several properties of things are found in the literature, often with different names but implying the same meaning. In this section, the properties that better describe things in the IoT are listed.

IV.2.1 Identification

This property dates to the initial visions of the IoT where each object was meant to include an RFID tag allowing it to be uniquely identified. In the ITU's 2005 report, they mention RFID provides the means for location-specific item identification that is fundamental to thing-to-thing communication, implying that tagging virtually every object on earth with an RFID tag would become feasible, and deeming RFID as a key enabler of the IoT (ITU, 2005). With a more general perspective, Sánchez López et al. (2012) consider automatic identification technologies as

fundamental to the realization of the IoT because they enable things to be linked with their virtual identity on the Internet. Miorandi et al. (2012) mention three pillars on which the IoT is built, the first of them being the ability of smart objects to be identifiable.

Additionally, Borgia (2014) suggests this identification should be based on assigned numbers, names, or addresses. Miorandi et al. (2012) say things are associated to at least one name and one address, where the name is a human-readable description of the object and can be used for reasoning purposes, while the address is a machine-readable string that can be used to communicate to the object. Moreover, the vision of the IoT, where billions of smart objects can communicate via the Internet, requires a well-thought-out naming architecture to be able to identify a smart object and to establish an access path to the object (Kopetz, 2011).

IV.2.2 Location and Tracking

As huge amounts of objects get connected to the IoT, and provided they can be uniquely identified, individual objects will be tracked, its condition and location communicated in real time to a higher-level service (Coetzee & Eksteen, 2011). Chaouchi et al. (2013) present a classification of objects, adapted from the CASAGRAS project, where they consider aspects of movability, with objects that are inherently mobile and need to be tracked, while others maintain a fixed position and this property is not needed. The way things get connected to the IoT, either wired or wireless, provides a lead to where they might stand in this classification and their need to be tracked. However, as implied by (Speed, 2011), tracking a thing not only refers to being aware of its physical location, but also to its individual history, since manufacturing to the end of its lifetime. This way, a single thing can provide useful information that wouldn't be available otherwise.

IV.2.3 Sensing

This property refers to the ability of things to collect data from the environment. The ITU names things equipped with sensors as “feeling things” and consider sensors complement human senses (ITU, 2005). The use of sensors as a key element of the IoT was introduced in the first visions proposed in the late 1990s (Ashton, 2009; Joy, 2015), though the earliest implementations of the IoT focused mainly on identifying, locating and tracking objects. With sensors, things can

become aware of their characteristics, context and situation (Lee et al., 2013). This is, a thing not only provides information about its environment, but also about its status.

IV.2.4 Actuation

By means of actuators, things can influence their environment (Coetzee & Eksteen, 2011). This actuation can be based on sensed data and controlled remotely via the Internet (Borgia, 2014; Xue, Li, Liu, & Liu, 2012) and is fundamental for automation of processes.

IV.2.5 Processing

The property of processing data and executing commands is frequently mentioned as intelligence. The ITU describes “thinking things” in reference to materials and things that get labeled as smart (ITU, 2005). Sánchez López et al. describe it as embedded processing for local intelligence and autonomy (Sánchez López et al., 2012). In (Xue et al., 2012), authors give the denomination of robots to things that perform intelligent computing and execute agents. On their part, Razzaque, Milojevic-Jevric, Palade, & Clarke (2016) imply that as the processing capabilities of things improve, they can become not only providers of data but also of services.

Additional properties are mentioned in literature but are not considered to be critical to objects in the IoT. However, an interesting feature is proposed by (Jazayeri, Liang, & Huang, 2015), for IoT devices to easily plug and play, each IoT device needs to be self-describable and self-contained in order to communicate with other objects or services, so they can describe and advertise themselves and their capabilities. They also imply a need for interoperability, as communication protocols and data encoding for current IoT devices are usually proprietary and different from each other.

IV.3 Things Abstracted

By taking the aforementioned properties as capabilities of things, they can be abstracted as devices in overlapping sets that possess one or more of such capabilities. In the context of the IoT, a thing is considered a physical object with attached, embedded or built-in electronic devices with Internet connecting capabilities. Considering as a requirement being connected to the

Internet, things can be categorized as follows, where at least one of the first four capabilities is required to be part of the IoT:

- Identification capability (IC): Things that can be uniquely and unmistakably identified, either by an electronic tag, hard-coded serial number or printed label that is read by another object.
- Localization capability (LC): Things that know their precise physical location in the world by their own means, e.g. using embedded geolocation devices, and can communicate it to other things and services.
- Sensing capability (SC): Things equipped with sensors to obtain data from their actual state or the environment. They may or not include temporary storage capabilities or make use of cloud-based storage services.
- Actuation capability (AC): Things equipped with actuating devices that can be remotely controlled to modify the environment.
- Processing capability (PC): Things that can process information obtained by themselves or received via the Internet. Connected devices with processing capabilities but none of the previous, are considered as part of the Internet of Computers (IoC), but not the IoT.

These capabilities allow categorizing objects in the IoT according to what they can perform. Table 4.1 shows a description of the capabilities, including some examples for each case. The first three capabilities {IC, LC, SC} refer to objects creating and providing data; {AC} is for objects that can act on the environment in response to collected data or instructions received from the Internet; the last one {PC} corresponds to a capability of transforming data that was obtained by the object using its sensors, or received from the Internet.

They can be combined in several ways according to the requirements of the IoT application they are designed for, not being imperative to possess the five capabilities. The connectivity requirement may be a part of the object or provided by an additional object, which is the case for the original things that the IoT was devised to integrate, i.e. electronic tags attached to objects, that would be read by another object allowing to identify them at any time and

communicate data through the Internet (Sarma et al., 2001), also referred as Tagged Things and deemed as the first generation of IoT solutions (Atzori, Iera, & Morabito, 2017).

Table 4.1 Things Capabilities.

Capability	Description	Examples
IC	Being uniquely and unmistakably identified.	Electronic tags, hard-coded serial numbers, or printed labels that are read by other objects.
LC	Being able to know their precise physical location in the world by their own means.	Embedded geolocation devices.
SC	Obtaining data from the environment or their actual state.	Sensors for different physical parameters or variables (e.g. temperature, pressure, acceleration).
AC	Acting on the environment, modifying its parameters.	Actuators for controlling systems (e.g. motors, valves, solenoids).
PC	Processing data obtained by them or received via the Internet.	Embedded processors or programmable devices.

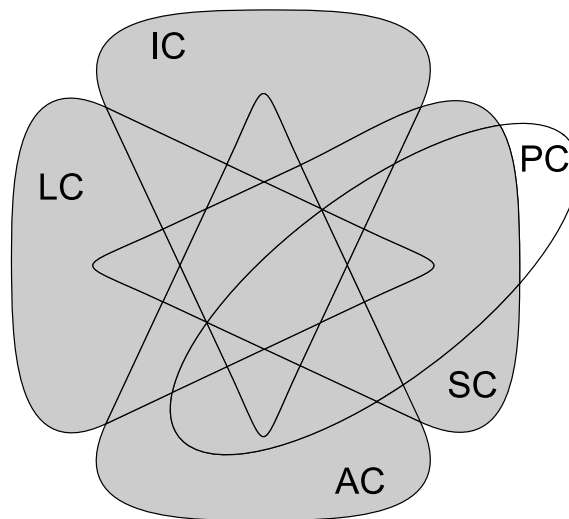


Figure IV.1 Capabilities of Internet connected devices as sets.

Figure IV.1 presents a Euler diagram with the relationships between the capabilities of Internet connected devices. Devices with any of the capabilities in the shaded area of the diagram are considered part of the IoT. The diagram shows that any combination of the first four capabilities is possible. However, having processing capabilities in things that can only be identified or located is not seen as an added value, as these types of things only share information about their characteristics or physical location, without creating or transforming data from their

environment or received from the Internet. From this, four subsets that result of interest in the IoT are identified and shown in Figure IV.2.

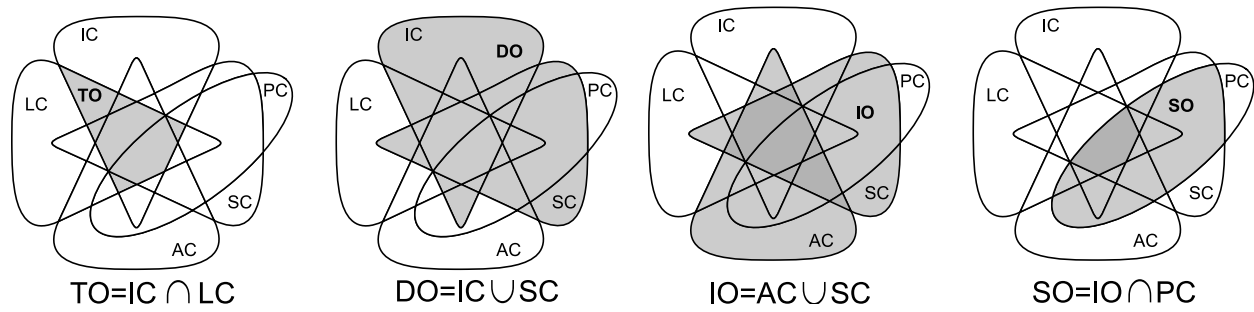


Figure IV.2 Subsets of the IoT.

The subsets are described as follows:

- **Trackable Objects (TO):** Mobile things that can be uniquely identified and are aware of their physical location.
- **Data Objects (DO):** Things producing data either from sensors or their current properties or state.
- **Interactive Objects (IO):** Things that allow an interaction with the environment where they are immersed, either by measuring environmental variables, modifying the environment or both. In the figure, the darker area represents the latter type of things.
- **Smart Objects (SO):** Interactive things that can apply some degree of processing to data obtained or received and act accordingly. Objects in the darker area have the five capabilities and are the most comprehensive devices in the IoT.

Several other subsets could be observed, with actual objects fitting more than one of them. However, it is not the interest of this work to widen the definition and description of things in the IoT, but to center and focus on data. The type of objects that fit the interest is DO, which are treated in detail in the next chapter.

CHAPTER V. CATEGORIZATION FRAMEWORK FOR DATA OBJECTS IN THE INTERNET OF THINGS

Different combinations of capabilities result in several subsets for things in the IoT, as described in the previous chapter. This chapter deals with the characteristics and properties of the Data Objects (DO) subset, shown in the shaded area in Figure V.1, which consists of any object having the Identification or Sensing capabilities. These objects can get data from the environment by means of sensors, or internal data from their current state, properties, or identity. A thorough description of DO is presented next.

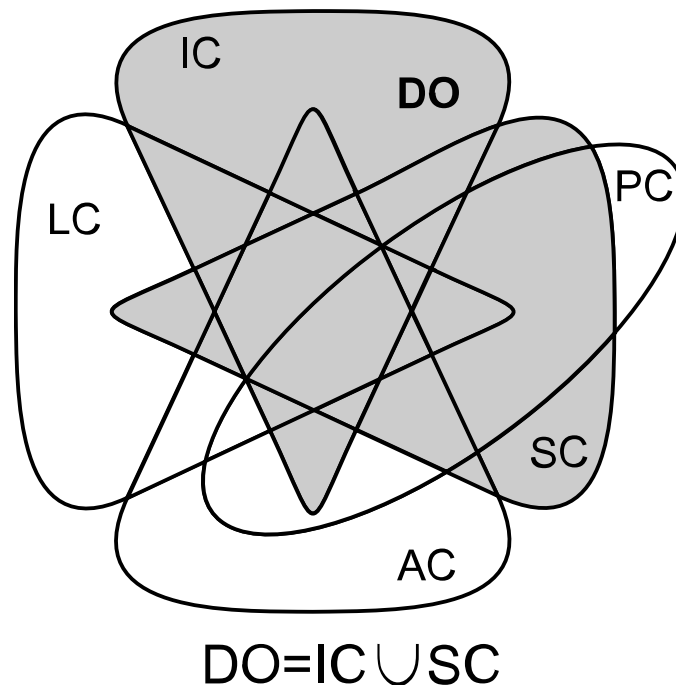


Figure V.1 Data Objects (DO) are things in the IoT with Identification or Sensing capabilities.

V.1 Data Objects

In section IV.3 Data Objects (DO) are defined as things producing data either from sensors, their current properties or state, or providing some type of data that allows identifying the object. The first two cases indicate obtaining variable data, while the latter is about constant values that may be specific to the object, useful for identifying it from related registries stored in cloud repositories and accessible to applications.

Variable data are obtained through sensors. These are devices needed to measure signals and parameters of an engineering system and its environment (Da Silva, 2015), forming the front end of the IoT devices (Rayes & Salam, 2017b). Equipping a physical object with sensors allows the object to interact with the environment as a human does by mean of the five senses. Thus, an object with sensing capabilities (SC) can obtain one or several types of physical data and transmit it through an Internet connection, either raw or pre-processed if the object also has processing capabilities (PC).

On the other side, the object properties or state refer to internal parameters of the object. Examples of such are battery level, internal temperature, current task progress, or whether a certain object is turned on or off. Therefore, SC refers to an object ability to sense data from their environment, measure internal properties, or both.

The other capability of DO is the Identification Capability (IC). It refers to the identity of the thing, which is the most basic type of data that can be obtained. This is a set of constant values leading to different levels of identification of an object (e.g. type or class of object, brand, model, serial number). Initial IoT visions were based on the concept of being able to electronically tag and identify any object, anywhere at any time without the need of human intervention, linking them to the global Internet (Ashton, 2009; Brock, 2001). As stated before, there are different levels of identification, which might be associated to the specific needs of an IoT system or application or restricted by the available technologies for its implementation. In addition, IC can range from the complete object or system seen as a thing in the IoT (e.g. a car, a tree, or even a person) to the particular device enabling the object to become a part of the IoT (e.g. a microcontroller, a smart sensor, or an electronic tag).

As things become more complex, so does the type of data that can be obtained from them. This is accomplished by adding capabilities to a DO. For instance, if the location capability (LC) is added to an already identifiable object (i.e., the intersection of IC and LC) we obtain Trackable Objects (TO). TO are mobile things that can be uniquely identified and are aware of their physical location. In other words, TO are DO that can go from one place to another and be identified and physically located by a requesting IoT service or application. Even though location of a thing is actually data being measured by a location sensor, objects that only produce this type of data

were not included as part of the DO set, as it would indicate the existence of an object at a specified physical location, but no extra information could be inferred and used, or actions be taken on the object. The capability is presented separate from SC, as the type of data measured is very specific to the location of an object, while in SC the number of sensors and type of physical parameters that can be read are numerous and can grow as new types of sensors are created.

By inspecting the diagram in Figure V.1, there are 22 possible combinations of capabilities within the DO set. TO subset is just one of them, but they can range from the simple identifiable objects to fully interactive and data processing smart objects. However, two objects possessing a given capability not necessarily are capable of sensing, processing and providing the same type of data, as technical restrictions, or even the needs of the system or application where each object is embedded require different levels of deployment for each capability. Thus, categorizing and describing a DO is not just a matter of the capabilities of the object, but also determined by how they are used by the object.

The diagram in Figure V.1 also shows the actuation capability (AC) as part of some data objects. However, AC does not provide, create, or act on data collected by the object and so is not mentioned in any further description or discussion about DO.

Taking this into account, a categorizing framework for data objects based on the level of deployment of data object capabilities is proposed and described in the next section.

V.2 Categorization Framework

Identifying the subset of capabilities of any single DO provides a high-level description of the object and a basic view of what can be achieved by making it part of an IoT system. For instance, stating that a DO has SC indicates it is able to measure data, but does not provide any details on the specific type of data the object can sense and provide, and the same situation applies for any of the data producing capabilities {IC, LC, SC, PC}. A different representation is needed to obtain a richer description and understanding of the DO, as each capability might be achieved at a different level, thus having a proportional effect on the object's behavior and its contributions to the system in terms of data. This representation is obtained by taking the four capabilities that

are used to identify and describe a DO, measuring them individually according to the specific activities or properties they provide to the object and then arranged in a graphical manner to create a unified view of a DO and a more precise specification of the data that can be obtained from it.

The proposal consists on a graphical categorization framework for DO by means of a qualitative 4-axis radar chart, with three discrete levels for each of the axes. One axis is used for each of the data producing capabilities in a DO with three data-related features for measuring these capabilities. Figure V.2 presents a general view of the features and sets a first level of identification of data and data activities in DO.

On the IC axis, three levels of identification are proposed for an object as category, type or class, and unique ID, being the latest the most precise and including the previous levels. A brief description and examples of identification are presented in Table 5.1. Either IC or SC are required capabilities for DO, with the simplest DO having only a basic level of identification indicative of an object’s presence in the Internet, like a beacon; non-identifiable DO are also a possibility for IoT systems that gather sensor data but do not need to identify the source, or the identity is implicit in the system.

Table 5.1 Levels of Deployment for Identification Capability (IC).

Level	Description	Examples
Basic	A general category of the object.	A motor vehicle.
Intermediate	The specific class or type of object.	Sedan, SUV, Crossover.
Advanced	A unique identifier leading to the precise identification of the object.	Vehicle serial number or license plate.

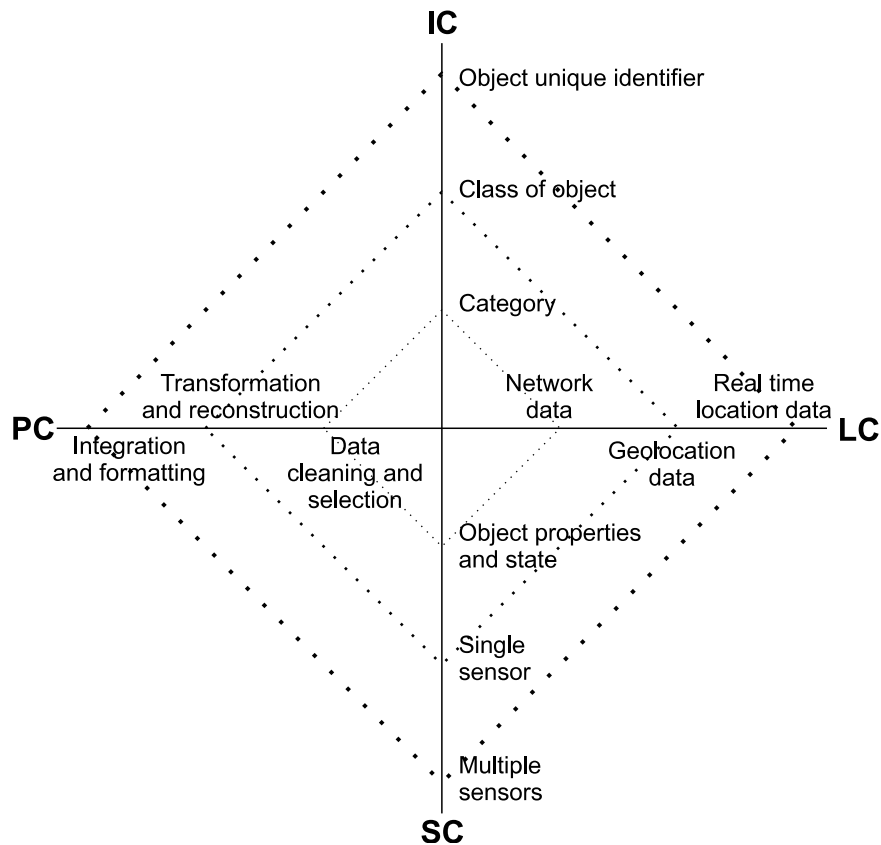


Figure V.2 Characteristics of data provided by DO according to the level of each capability.

Likewise, three levels are defined for the LC axis according to the type of data the object can provide in order to know its precise location. Different from identification data, location data are dependent on different conditions from the environment, location technology, characteristics of the object, and needs of the IoT system that impact on its accuracy and volume. A description of the levels is presented in Table 5.2, along with examples of typical implementations. Most accurate technologies for location are based on global navigation satellite system (GNSS), being the global positioning system (GPS) the most common implementation of them. An extensive description and analysis of location technologies is presented in (Chen et al., 2017).

The SC axis helps in characterizing the type and amount of data provided by the object (Table 5.3). A DO with SC constitutes the basic element for an IoT system that monitors conditions on the physical side of the system: a DO can provide internal data as its current properties or state, external data obtained with a single sensor, or contain multiple sensors that collect several types of data.

Table 5.2 Levels of Deployment for Location Capability (LC).

Level	Description	Typical implementation
Basic	Approximate location of the object. Useful for IoT systems where the objects tend to remain in the same location and precise location is either not needed or can be inferred from additional data related to or measured by the specific object.	Passive location obtained from network parameters.
Intermediate	Geolocation data provided by the object when network connections are available for analyzing and processing the data. Suitable when real time location is not mandatory in the IoT system.	Assisted-GNSS and Cloud-GNSS positioning technologies.
Advanced	Real time location data obtained and provided by the object. Needed when keeping track of the object location and position related parameters is important for the IoT system.	GNSS receivers incorporated into the devices.

Table 5.3 Levels of Deployment for Sensing Capability (SC).

Level	Description	Examples
Basic	Data created or measured inside the object.	Internal sensors providing data to monitor the state of the object and parameters as battery level, energy consumption, or temperature of the object.
Intermediate	A single external parameter measured by a sensor.	Data from any physical phenomena of the environment where the DO is located.
Advanced	Multiple external parameters measured by sensors.	Multivariate data from physical phenomena of the environment where the DO is located.

The PC axis states what a DO is capable of doing with the data before sending it to the Internet, ranging from data cleaning to integration and formatting (Table 5.4). If a DO does not have PC it will send raw data to the IoT system. Most advanced data activities might combine data obtained from multiple sensors or even from multiple DO to create ready-to-use datasets that will be provided to the services layer for processing. The goal of having PC in a DO is to increase the ratio of usable data that are sent to the IoT system. Data compression algorithms can also aid in reducing the volume of data transmitted, at expenses of more processing power and latency in transmission of data.

Table 5.4 Levels of Deployment for Processing Capability (PC).

Level	Description	Common data activities
Basic	Objects execute data cleaning and selection algorithms.	Noise, duplicates, or outlier detection and removal.
Intermediate	Objects can transform and reconstruct data obtained by sensors.	Create new data from measured values or reconstruct missing data.
Advanced	Objects perform data integration and formatting.	Combine values from multiple sensors and create the datasets needed by the IoT system.

Identifying or defining the level of deployment for each capability in a DO helps visualizing the type and characteristics the data created or obtained by things will possess when provided to the IoT system, as well as technology requirements for constructing new things. Furthermore, this level has an impact on data properties that should be taken into account as it also influences the performance of an IoT system. The following section complements the description of the framework by elaborating on this impact on data properties.

V.3 Impact of Capability Levels on Data Properties

A more descriptive view of the level of contribution of each capability is presented in Figure V.3. A legend is added to every axis expressing a data-related property of the object that is improved as the level of contribution of that capability increases, along with the effects of increasing in level as depicted in Figure V.2. In addition, and as a result of those contributions, each capability impacts on a different level the quality, volume and confidence of generated data (Table 5.5).

A higher level in the IC axis implies an increased trustability on the data and the object itself. In other words, as more certain an IoT system is on a data provider's identity, there is a higher confidence in both the data and the system performance. Trusting the provider and the data results of special importance when an IoT system contains several DO and data-derived decisions are important not only at system-level but also as individual or node-level. An example of the first type is the air pollution monitoring and forecasting system presented in (Xiaojun, Xianpeng, & Peng, 2015), where data from all the sensors in the system are used to feed a neural network. In (Zheng, Zhao, Yang, Xiong, & Xang, 2016) a similar system is described, but data are processed,

and results displayed to users for each of the monitoring nodes, making it necessary for the system to uniquely identify each node.

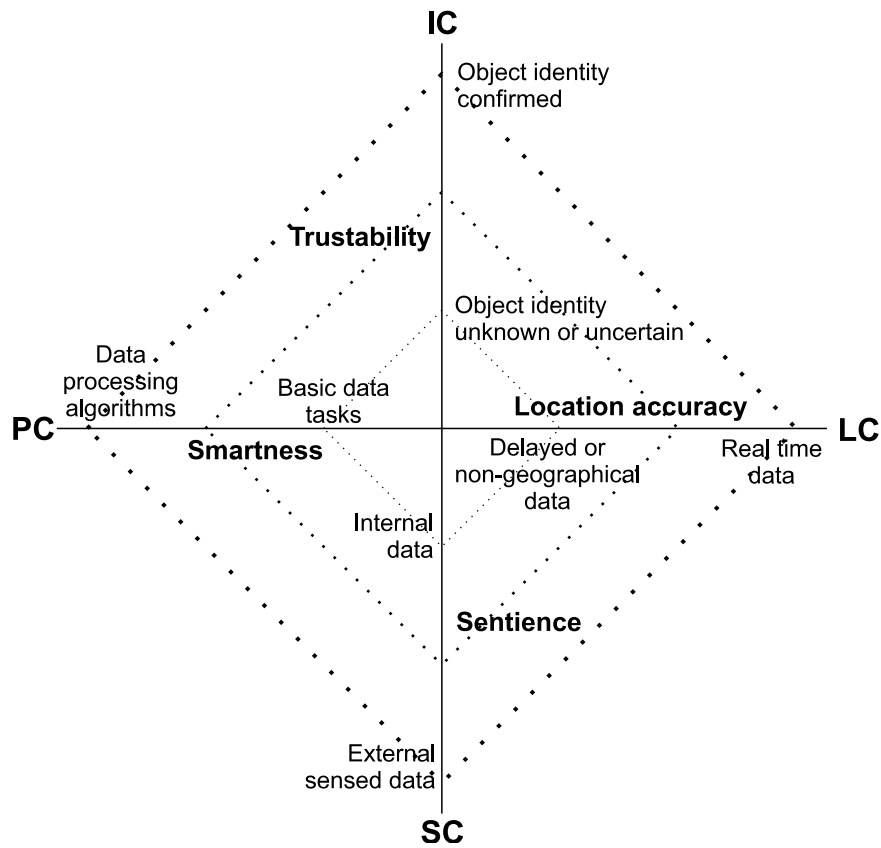


Figure V.3 Contribution of each capability to data properties in DO.

Table 5.5 Capability impact on data properties

Capability	Quality	Volume	Confidence
IC	Very low	Very low	Very high
LC	Very low	High	Low
SC	Low	Very high	None
PC	Very high	Low	Low

Moving ahead in the LC axis accounts for better location accuracy of an object. At the lowest level, an object could be located using its last location reported, for objects that are not permanently connected to the Internet, or within the coverage area of a network. An object able to provide geographical data can be located within the availability and accuracy of GPS. A higher rate of positioning data leads toward real time location of the DO, which is important when

objects change location continuously, with the drawback that the amount of data generated grows as the update frequency increases.

The SC axis describes the sentience of the DO with respect to its surrounding environment. A non-sentient object will only provide internally generated data that help monitoring the object's state and performance-related parameters. As sensors are added to an object it becomes sentient of the environment, being able to measure its properties and gather data. With more sensors, multiple properties can be measured, making the object more sentient of different types of data and increasing the volume of collected data.

The PC axis defines the smartness of a DO as it provides the object with means to act on received or collected data. Smartness increases as the object advances from executing basic data tasks to complex data processing algorithms, though this implies more resources needed for processing. As the devices embedded on physical things are usually resource constrained and typically running on batteries, it is advisable to limit the data processing to basic tasks and relying on edge, fog, or cloud processing for more complex activities. However, with smaller, energy-efficient and more powerful devices being developed and made available for the IoT, DO will be able to execute that type of activities and create better data.

Based on this framework, it is possible to categorize any existing DO in the IoT and establish a general notion of the complexity of these and new objects from early design stages of an IoT system. This complexity can be observed graphically by moving clockwise in the chart, starting from the IC axis, i.e. IC properties are less complex to include on a DO than PC properties (Figure V.4), as an electronic tag is enough to identify the object, but in order to clean or filter data the object needs an embedded processor and memory resources. Following this same path but also moving up gradually on each of the axis would describe a spiral of complexity for DO, with more complete, capable, and complex objects away from the origin of the chart.

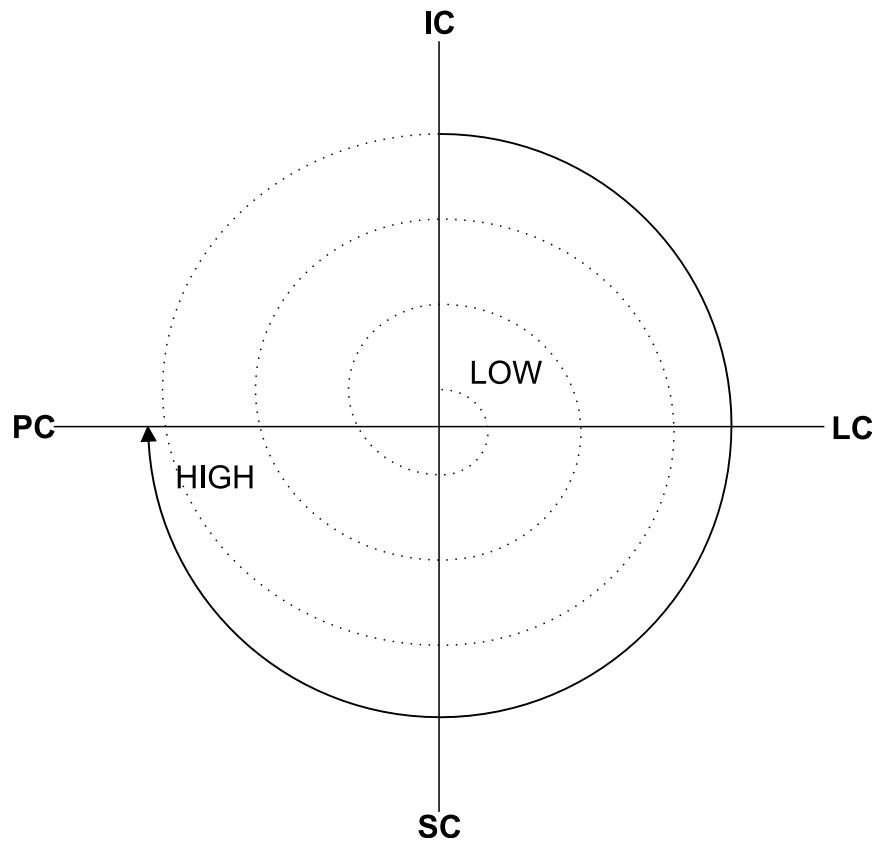


Figure V.4 Complexity of a DO increases as more properties are added to each capability. PC properties are the most complex among the four capabilities in this type of objects.

Summing up the previously discussed considerations, several categories for DO are realizable as the combination of deployment of capability levels and their combined contribution to data quality, volume, and confidence allows. General categories could be set as Data intensive objects, Trusted objects, and Ready-to-use data objects, by taking the description of capabilities impact on data. These categories can be joint when a DO incorporates high-levels of deployment of its capabilities that would cover more than one category, and sub-categories could also be defined based on lower levels of deployment.

Rather than providing a comprehensive listing of categories the recommendation is to use the framework in a graphical manner, categorizing the DO according to the shaded area in the radar chart. Objects belonging to any of the proposed categories would cover the shaded areas shown in the charts of Figure V.5. High levels of SC and LC are present in Data intensive objects; IC is high while LC and PC can range from medium to low levels in Trusted objects; Ready-to-use DO have strong PC with mid to high levels of SC and LC.

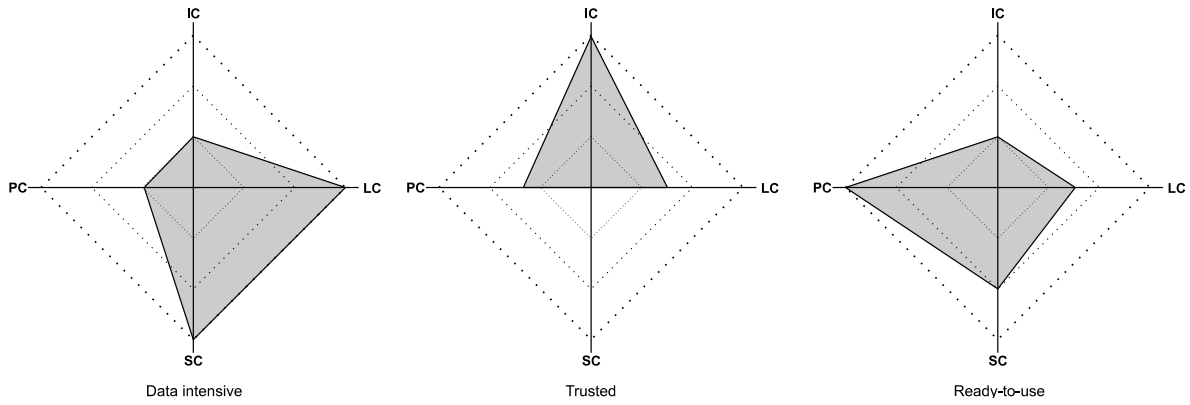


Figure V.5 Areas covered by data objects categorized as Data intensive, Trusted, and Ready-to-use.

The framework described above allows to assign a category in terms of properties of data produced by an object connected to the IoT. In the next chapter, a pair of use scenarios are presented that show how the framework can be applied.

CHAPTER VI. APPLICABILITY OF THE FRAMEWORK

Categorizing objects by means of the framework allows to establish a common reference to visualize or estimate the characteristics of data provided by the object, but also the requirements for an object to perform properly, either by itself or as part of an IoT system. In this regard, the structure of the framework allows for categorizing both existing objects and new objects that might be on early design stages, either at object or system-level. This chapter presents examples of how to use the framework, covering different cases and types of objects.

VI.1 Use scenarios

The applicability of the framework is exemplified with two scenarios. The first one is a fictitious vehicle-related scenario, categorizing a conceptual thing for an automotive IoT system; the second scenario takes an existing commercial IoT air quality monitor (Awair, 2018) and characterizes it. In both cases the radar charts are used to specify the level of implementation of each capability and an assessment on the DO categories is inferred from the resulting shape.

VI.1.1 Using the framework for categorizing conceptual DO

Creating new things for the IoT is a process that should take into consideration the data that is going to be collected and the activities that will be performed on such data. Using the framework as part of the design process would provide a tool to visualize and offer additional insight in selecting the platform, tools, and data processing algorithms that best fit the proposal of individual things and IoT systems, along with a projection of the complexity for implementing it.

A description of a mid-complexity DO with high data volume generation and class-level identification is presented by means of a scenario where several vehicles provide temperature readings and report their locations in real time as part of an IoT system. In the system, vehicles would act as the things providing data, or data objects, equipped with sensors for location and temperature, and an embedded processor for basic data tasks.

The specific example shows the vehicle identified by its type, providing real time positioning data and temperature recorded by the sensor. The embedded processor performs outlier detection and removal on the sensor data, improving the quality of the data and limiting the transmission of unusable data.

In this case, the framework is used to categorize things at object-level, i.e. vehicles as DO independent of the contribution that multiple objects have as a system. From the description or requirements of the system, the chart shown in Fig V.2 is completed by making an estimate of the projected implementation of each capability in the DO, placing a mark on the axis according to the level, and then joining the marks to create the shape. A summary of the categorization criteria is presented in Table 6.1. The shaded area in the chart of Figure VI.1 covers a large portion of the suggested area for a data intensive object and also has elements to provide a high degree of confidence to the data in the ways a Trusted object is proposed (Fig V.5).

Table 6.1 Categorization for automotive DO.

Capability	Estimated level of deployment	Object features	Data characteristics
Identification	Intermediate	Vehicle identified by type	Class of object
Location Sensing	Advanced Intermediate	Reported in real-time Temperature sensor Outlier detection and removal on data measured by the sensor	Real time location data Single sensor
Processing	Basic		Data cleaning and selection

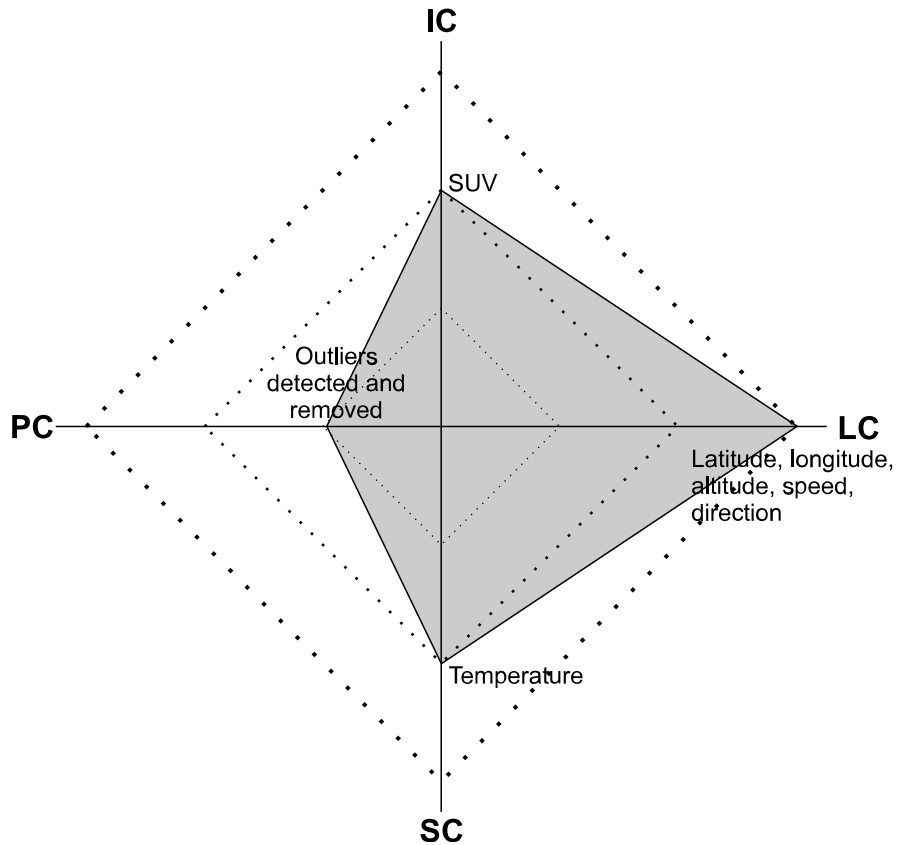


Figure VI.1 A scenario of the framework for an automotive DO.

VI.1.2 Using the framework for categorizing existing Data Objects

The framework can also be used to categorize existing IoT objects. To illustrate this feature, an IoT device for the smart homes market was selected and, by means of the properties and capabilities listed by the manufacturer (Awair, 2018) summarized in Table 6.2. These characteristics belong to a Bitfinder Awair air quality monitor, which is a device that senses temperature, humidity, CO₂, chemicals, and small dust particles (PM₂) present in the air, providing the user with a real time view of air quality in the space where the device is located. The monitor has direct Internet connection via WiFi and is locked to a user account and identified by a name assigned by the user; the Awair cloud services collect network data to provide location-specific insights on the environment, while specific indoors location data is provided by the user at setup-time. A proprietary app is used to setup the device, user preferences, and to connect to the cloud services in order to see historical data and suggest the user with air quality improvement actions based on collected data.

Table 6.2 Categorization data for the Awair air quality monitor.

Capability	Estimated level of deployment	Object features	Data characteristics
Identification	Advanced	The monitor is identified by an ID and a user-assigned name	Object unique identifier
Location	Basic	Services collect network data to infer location	Network data
Sensing	Advanced	Temperature, humidity, CO ₂ , chemicals, and small dust particles (PM2) sensors	Multiple sensors
Processing	Intermediate	Data is encrypted to protect privacy	Data transformation

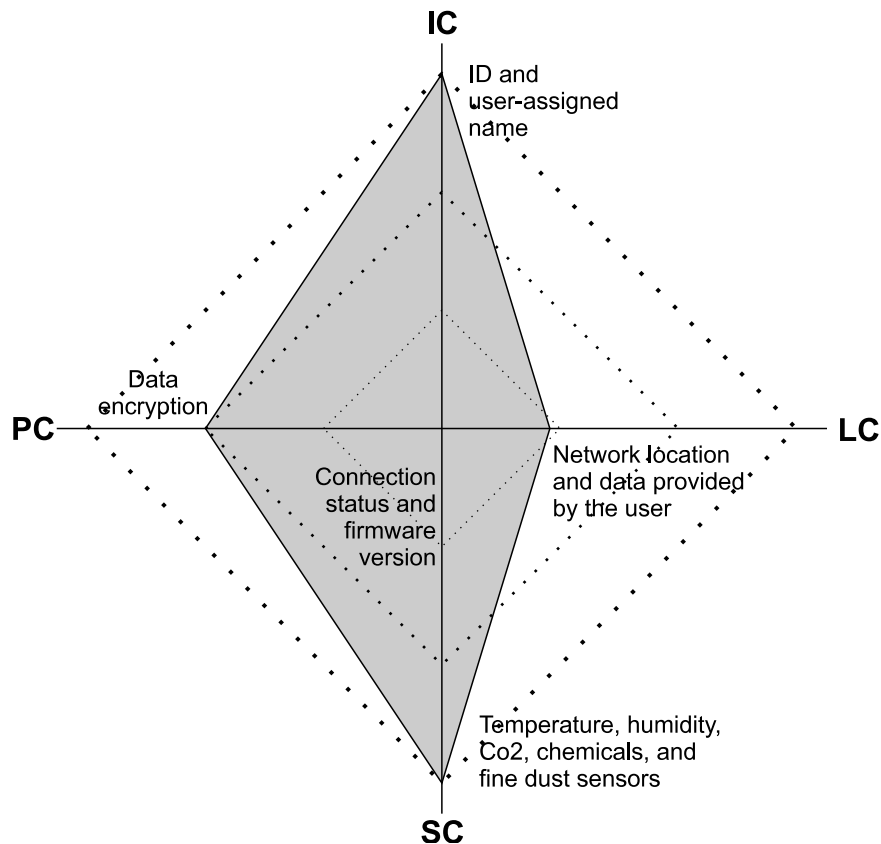


Figure VI.2 Categorization graph for the Awair air quality monitor.

The shape for the air quality monitor (Figure VI.2) was drawn using the properties listed in Table 6.2. The resulting chart covers the areas proposed for trusted and data intensive objects. The device can be identified as a mid to high complexity DO as it obtains several types of data

and performs transformation tasks on the data to increase privacy and security. In addition, the monitor has actuation capabilities to generate a visual feedback to the user and push notifications that are received and shown by the app.

VI.2 Summary

The framework was applied to a pair of IoT devices, one of them in a fictitious system and the other a commercial IoT air quality monitor. By means of these examples the procedure for using the framework is presented, and an interpretation of the resulting shapes in terms of complexity is also provided.

One of the main benefits of this framework is that its graphical nature allows to easily read the level of deployment of each capability within a DO, categorize it from the combination of such levels, and infer the complexity of the object. Creating the graphs is also a streamline process, given that the information of the objects is available or can be obtained. For new objects this information should be part of requirement specification and design documents, but for existing objects has to be extracted and inferred from technical documents, user manuals, support forums, or websites.

The scope of application and expected use is different for both cases. Categorizing and characterizing a DO in terms of data since early design stages may guide in the selection of hardware and software tools and platforms that best fit the object and the system containing it. For existing objects, it delivers an outline of the data and types of data created by the object that, besides categorization, can be used for evaluating its performance, or to compare and aid in choosing between devices for a specific application from a data perspective. However, additional categorization tests are required for both existing and new objects in order to provide further validation of the framework.

CHAPTER VII. CONCLUSIONS, CONTRIBUTIONS, AND FUTURE WORK

The Internet of Things is the confluence of several technologies that allow providing Internet-based services and applications supported by electronic devices attached to physical things for acquiring data and controlling processes. As a general understanding, this phrase might well describe the IoT, but the variety of definitions and visions found in literature prove defining a complex technology or range of technologies is also a complex process.

However, though these definitions might appear as diverging, they are usually presented around five elements, occasionally including more than one of them: networking, services, communications, data and things. Earlier definitions were more commonly centered on networking aspects, while the most recent tend to be more comprehensive, as expected when a technology is in a maturing stage and its scope begins widening and more capabilities and possibilities are discovered.

Conducting a SLR on the concept of the IoT allowed to obtain a clearer insight on this technology and what can be achieved through it. Observing the way these definitions have evolved and how different concepts, technologies and ideas have been incorporated as the IoT develops suggests that a correct description and characterization of the things at the end-points of the IoT should be one of the first goals towards a final definition. Latest efforts are paying more attention to things and what things can do as part of new services, applications and business models inspired by the IoT.

Several visions and definitions of the Internet of Things were found and analyzed. They can be categorized in different ways, as to how the technology is understood, which part of the IoT spectrum is the definition biased to, or the technologies that are mentioned as fundamental part of specific visions. These definitions are extended and complemented with specific terms of the different application domains of the IoT, often with designations that researchers adapt to each domain.

Just as important is how data gets immersed in the whole concept. Enormous amounts of different data will be gathered from a myriad of sources, and a lot more can be inferred from

what is directly obtained by sensors. One of the main goals of the IoT should be the creation of new data and obtaining data that couldn't be obtained otherwise. So, advanced and novel data mining, big data, and data analytics techniques and algorithms will be required to treat this data and shouldn't be excluded from a definition of the IoT.

The things-side is the part of the IoT that draws the main attention, as there is where objects are identified and tracked, data is collected, processes controlled, and the main expected benefits observed. Regardless of the size of the projected system or application, understanding the Things component of an IoT architecture provides clear insights on the type of devices, communication protocols, data-related tools and techniques, as well as how both user and thing-side applications would allow interaction with the whole IoT system.

Using sets of capabilities to describe different types of things or objects results in visual representations that offer a quick glimpse of the actions an object can perform and the types of data it can provide. One of the sets of bigger relevance is Data Objects (DO), given that it assembles capabilities that enable objects to gather data either from the environment or the object itself and send it to cloud-based services for processing, storage, and made available to end-user apps.

These capabilities can be deployed at different levels, describing data objects with common characteristics that we categorize by means of a graphical framework, setting a four-axis radar chart where each axis is assigned to one of the data-related capabilities. A capability-contribution diagram helped with observing how each capability contributes to enhance a DO trustability, location accuracy, sentience, and smartness. This diagram also allows to observe and infer the technological needs and requirements of the DO. Capabilities also impact data properties like quality, volume, and confidence, that are important parameters for the IoT system containing the DO.

When seen as a whole, capabilities have a combined effect on the DO and its data in both a qualitative and quantitative way. The framework aids in visualizing and describing this effect, along with the general properties of data provided by a DO, and the complexity for realizing the object.

Several categories can be proposed for DO, but the recommendation is to adhere to the graphical nature of the framework and using the shaded areas in radar charts to visualize and infer object properties from a few general categories. An example based on a proposed scenario shows how an actual DO would be described using the framework. A commercial IoT air quality monitor was also categorized using the framework, showing its applicability with already existing objects.

The framework has the capability of allowing IoT solution designers and providers understand the scope and outcomes of both IoT products and projects. It can be used to categorize both existing objects and new objects before they are constructed, which is where designers would benefit most from it.

The framework is independent on the specific technologies and application domains. A slight exception is the LC axis, which is described around network and GPS location technologies that are the most widespread among GNSS technologies. However, technologies where recent and future advances have been achieved, especially in indoor location, may be effortlessly swapped into the framework. In addition, the number of levels in each axis can be modified, providing flexibility to the framework in order to adapt to specific needs of an IoT system, creating more detailed views of the DO structure, features and properties.

VII.1 Contributions

The main contributions of this work are listed next:

- A general understanding of the IoT is proposed from existing definitions and visions. These were traced in the manner of a timeline through three major stages that clearly differentiate how the IoT was referenced and described since its conception to near present time. If not a definition on its own, it shows a concise and thorough idea of the IoT and its core elements that can be used for further reference.
- Conducting an SLR on the exclusive topic of the IoT presents a different approach to similar exercises previously reported on literature, where the objective tends to be the technology as a whole or the application domains, or IoT verticals. A clear and detailed

methodology is presented for how the SLR was performed, with a level of abstraction that allows applying it to review studies in any field.

- A description of the IoT from its physical components is presented, with a novel strategy based on what things are capable of doing when equipped with electronic devices that provide them with capabilities for being identified, located, sense data, actuate on their environment, or process collected and received data, in addition to connect to the Internet. The concept of capabilities had been mentioned in IoT context in existing literature but no representation of them and how different types of things could behave under different combinations of these capabilities was previously presented or discussed.
- The graphical categorization framework develops from the importance of data in the IoT and the capabilities of data-producing objects, taking the description and representation of data to the place where it is either created or obtained. Using radar graphs for describing the level of deployment of each capability creates a shape that allows to infer a category and complexity of an object in accordance to its data-related capabilities, guide in the physical-side development of things and systems under any IoT reference model or architecture, and describe data with a higher level of detail than the usually found in reference models.

VII.2 Future work

Having explored the concept of the IoT through its enabling technologies, and understood how individual advances were put together to give shape to the IoT brings a solid ground to base future research. The initial scope that was set for this work considered a broader coverage of reference models and overall frameworks, but given the lack of agreement on basic concepts the orientation was switched to those topics. At this point, reviewing the current models is the next step to go, together with the most used and complete IoT platforms.

Further validation of the proposed framework with different types of DO is needed to find whether it actually fits all types of DO or some adjustments are needed. Applying it to IoT systems was also left off the scope of this work. In addition, using the framework for categorizing objects

and systems for the design stage in a non-fictitious scenario would aid in demonstrating and confirming its applicability for new objects and IoT systems.

Along with exploring the IoT platforms comes the analysis and use of IoT development tools, protocols, and technologies, both for hardware and software. A correct and thorough study on these topics is needed for the design and creation of well-sustained IoT systems.

Last, one missing part on the considerations of DO in the IoT was the creation of knowledge from the collected data. A slight hint on this topic was made with the comparison of models and frameworks, but further study on the data and information flows through IoT systems, and how this data is turned into knowledge is one of the most important benefits that end-users can obtain from the IoT.

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ANNEX A – LIST OF PUBLICATIONS

A.1 Tracking the Evolution of the Internet of Things Concept across Different Application Domains

This publication describes the methodology and results of the SLR performed on the definition of the IoT, and the proposed description of things based on their capabilities. Details of the publication are listed next, and the cover of the journal and the first page of the paper are shown in Figure A.1:

- Journal: Sensors
- Publisher: MDPI
- ISSN: 1424-8220
- DOI: 10.3390/s17061379
- Date: 16/June/2017
- Volume: 17
- Issue: 6
- JCR Impact Factor: 2.475 (2017), 3.014 (5 year)
- JCR category rank: 16/60 (Q2) in “Instruments & Instrumentation”

The paper has been cited a total of 19 times, which are listed in Table A.1 sorted by year and type of publication. From the citations, 2 are on book chapters, 1 on a capstone project, 3 in conferences, 10 on journals (5 of these listed on JCR and one in the Emerging Sources Citation Index), and 3 in master theses. It was possible to gain access to 15 of the documents; from them, 12 are citing the section of the paper that deals with the definition, or lack thereof, of the IoT; 2 reference the section about the capabilities of things; the last one cites both parts of the paper.

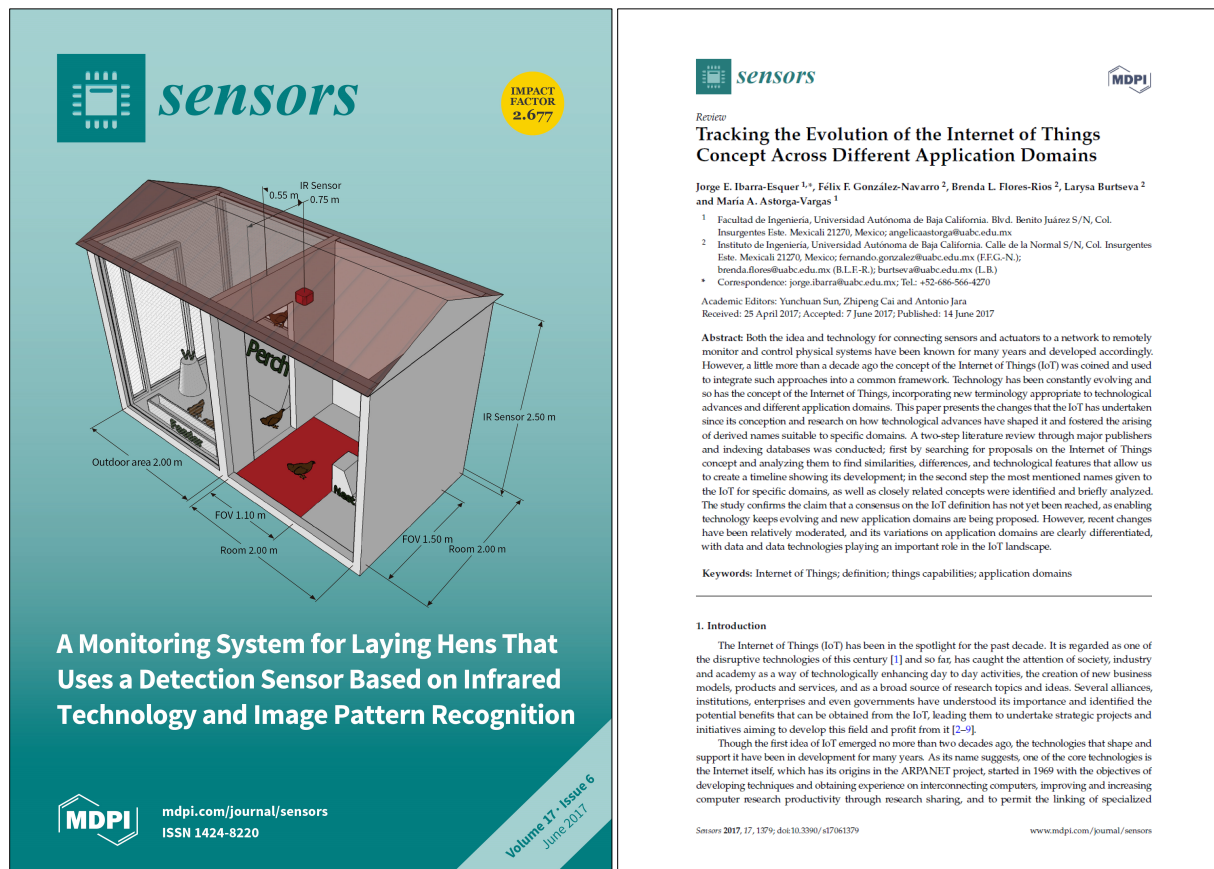


Figure A.1 Cover for Sensors Volume 17, Issue 6, and first page of the paper.

Table A.1 Paper citations.

Authors	Title	Source	Year	Type
Portillo, C.D., Lituchy, T.R.	An examination of online repurchasing behavior in an IoT environment	The Internet of People, Things and Services: Workplace Transformations	2018	Book chapter
Sharma, N., Shamkuwar, M., & Singh, I.	The History, Present and Future with IoT. In Internet of Things and Big Data Analytics for Smart Generation	Internet of Things and Big Data Analytics for Smart Generation	2019	Book chapter
Nawrot, O.	Accepting Blockchain Tech to Increase Bitcoin Acceptance	La Salle University	2019	Capstone project
Grandon, E. E., Ibarra, A. A., Guzman, S. A., Ramirez-Correa, P., & Alfaro-Perez, J.	Internet of Things: Factors that influence its adoption among Chilean SMEs	2018 13th Iberian Conference on Information Systems and Technologies (CISTI)	2018	Conference
Karunaratne, G. R., Kulawansa, K. T., & Firdhous, M. M.	Wireless Communication Technologies in Internet of Things: A Critical Evaluation	2018 International Conference on Intelligent and Innovative Computing Applications (ICONIC)	2018	Conference

Authors	Title	Source	Year	Type
Rieger, C., & Majchrzak, T. A.	A Taxonomy for App-Enabled Devices: Mastering the Mobile Device Jungle	International Conference on Web Information Systems and Technologies	2017	Conference – Extended version
Adnan, H.B., Rahimah, K., Hasnah, M., Zakaria, I.H.	Information Real-Time Delivery (IRTD) system through the Internet of Things (IoT): An improvement in truck management environment	International Journal of Engineering and Technology (UAE)	2018	Journal
Coşkun, M. & Toğay, A.	Internet of Things on the Axis of Design and Technology Interaction: IOT Products as a New Product Paradigm	Online Journal of Art and Design	2018	Journal
Durão, L. F. C., Carvalho, M. M., Takey, S., Cauchick-Miguel, P. A., & Zancul, E	Internet of Things process selection: AHP selection method	The International Journal of Advanced Manufacturing Technology	2018	Journal
Mozaquatro, B., Agostinho, C., Goncalves, D., Martins, J., & Jardim-Goncalves, R.	An Ontology-Based Cybersecurity Framework for the Internet of Things	Sensors	2018	Journal
Sjöman, H., Autiosalo, J., Juhanko, J., Kuosmanen, P., & Steinert, M.	Using Low-Cost Sensors to Develop a High Precision Lifting Controller Device for an Overhead Crane—Insights and Hypotheses from Prototyping a Heavy Industrial Internet Project	Sensors	2018	Journal
Sjöman, H., Kalasniemi, J., Vartiainen, M., & Steinert, M.	The Development of 1Balance: A Connected Medical Device for Measuring Human Balance	Technologies	2018	Journal
Romanowski, R., & Lewicki, M.	Internet of Things in the Smart City Concept	Roczniki Kolegium Analiz Ekonomicznych / Szkoła Główna Handlowa	2018	Journal
Lanza, J., Sánchez, L., Gómez, D., Santana, J. R., & Sotres, P.	A Semantic-Enabled Platform for Realizing an Interoperable Web of Things	Sensors	2019	Journal
Patel, N. D., & Patil, H. D.	Defining Internet of Things: A Survey	International Journal of Management, Technology and Engineering	2019	Journal
S. Jagtap, S. Rahimifard	The digitisation of food manufacturing to reduce waste – Case study of a ready meal factory	Waste Management	2019	Journal

Authors	Title	Source	Year	Type
Borhade, P. D.	Smart Surge Irrigation Using Microcontroller Based Embedded Systems and Internet of Things.	University of Arkansas	2018	Master thesis
Maiwald, C.	With Spime to Circular Service Design: Introducing Service Design to an IoT Platform Provider's Delivery Process	Laurea University of Applied Sciences	2018	Master thesis
Zaidi, R. N. B. R	Water Quality Monitoring System with IoT	Universiti Teknologi Malaysia	2018	Master thesis

A.2 Smartphones como medio de recolección de datos para aplicaciones de aprendizaje computacional

While not directly related to the main topic of this research, this publication was in response of an invitation to publish for participants at the 2015 Mexican International Conference on Computer Science, where the first ideas and objectives were presented at the Doctoral Colloquium. The paper deals with the enormous data volumes that can be obtained from personal devices as smartphones and used for machine learning applications. These devices can as well play that same role as data producers in the IoT, and categorized as Data Objects with advanced identification, location, sensing, and processing capabilities. Details of the publication are listed next, and the cover of the journal and the first page of the paper are shown in Figure A.2:

- Journal: Komputer Sapiens
- Publisher: Sociedad Mexicana de Inteligencia Artificial, A.C.
- ISSN: 2007-0691
- DOI: 10.3390/s17061379
- Date: 16/June/2017
- Year: 10
- Volume: 1
- Indexed: CONACYT IRMDCT and Latindex



Figure A.2 Cover for Komputer Sapiens Year 10, Volume 1, and first page of the paper.

A.3 Categorization Framework for Data Objects in the Internet of Things

This paper was submitted to the IEEE Internet of Things Journal and is currently on review. It covers most of the information presented in chapters V and VI of this document. The general idea for this section and the outline of the paper were planned while performing research activities at Universitat Jaume I in Castellon de la Plana, Spain in summer 2017.