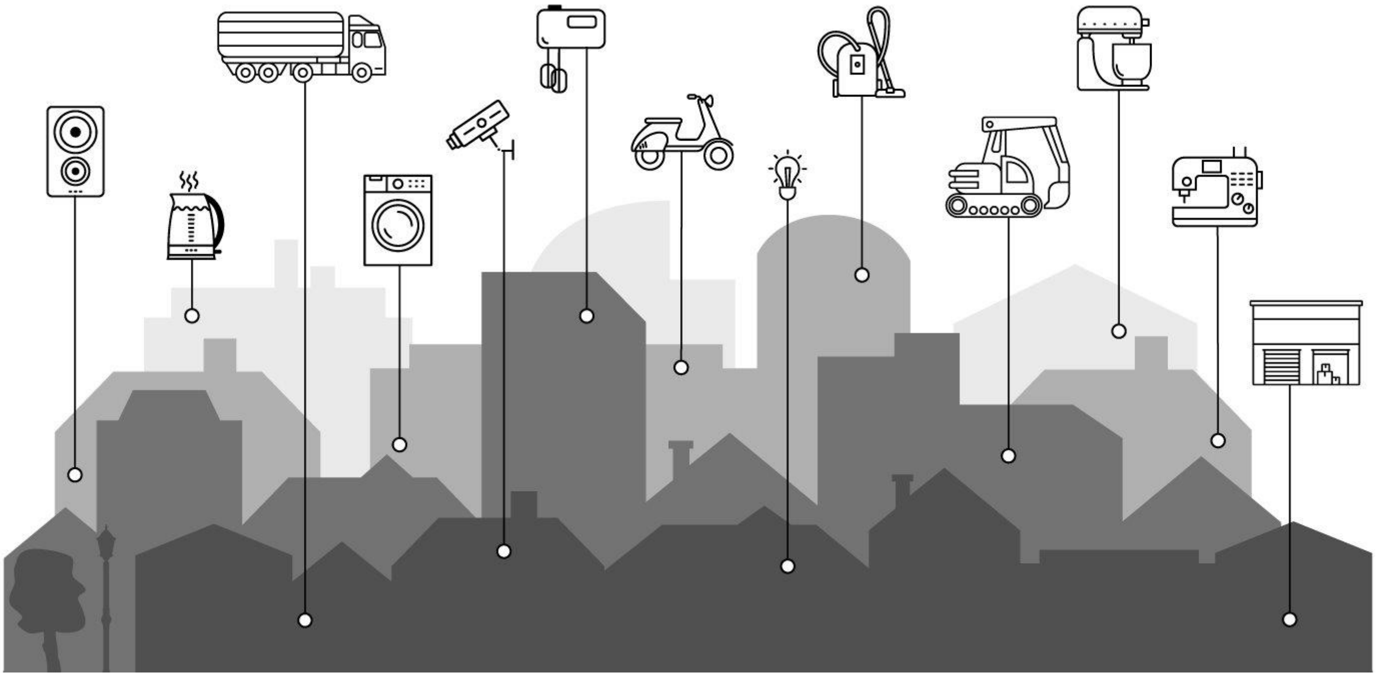

Introduction to IoT-based Systems

Lecture notes – LUT – 2023

Pedro H. J. Nardelli
Teaching assistant: Daniel Gutierrez-Rojas

LUT
Lappeenranta
University of Technology

Contents

Introduction

These lecture notes refer to the course *BL40A2010 Introduction to IoT-based Systems*, taught at LUT University also available via FITech. This course runs in periods 1 and 3. The course aims at introducing tools to analyze and design engineering systems based on the Internet of Things (IoT), where the student will learn how to:

1. Define system, information and communication,
2. Differentiate physical and symbolic realities,
3. Work with the concept of structure of awareness,
4. Characterize IoT and cyber-physical systems,
5. Model systems as constituted by physical, data and decision layers.

This course was designed to focus on the *function* of IoT (not on specific technologies) in systems. The key idea is to introduce technical, methodological and even philosophical aspects that serve as the basis of any engineering system with information-processing capabilities. The weekly contents are divided as follows.

W1: The student will be able to operate with the concept *system*, determining a particular system, its internal relations and its relation to everything else; this includes different kind of scientific rationalities that shall be taken into account while modeling, designing or assessing it.

W2: The concept of *information* will be discussed focusing on the idea of *trustworthy uncertainty resolutions*, as well as the relation between the physical and symbolic realities. This includes the analysis of misinformation and disinformation, and different levels of data processing.

W3: The different ways of organizing nodes in networks will be presented with key metrics. This characterization will be applied to networks whose goal is to disseminate information so that different *network topologies* or *structures* can be compared.

W4: IoT-based systems as constituted by physical, data and decision (interdependent while autonomous) layers will be presented as a model of *self-developing reflexive-active systems*, which has its own *structure of awareness*.

W5: Probability theory will be reviewed as a modeling tool to IoT-based systems, including predictive analysis and queues.

W6: Classical game theory and other decision-making analytic approaches will be introduced.

W7: We will revisit the core concepts presented in the course to simulate a simple IoT-based system designed for improving the stability of power grids using smart appliances in households. We will show that, if the solution is not designed in a systemic manner, there is the risk that the smartness of the appliances will lead to a stupid grid.

R These present notes cover from week 1 to 4, which needed a compilation from different sources to set the basis of the course. From week 5 onward, we will follow available texts to be included in Moodle.

0.1 Activities

- Short videos explaining the key concepts (2 h/week)
- Tutorials: Each student runs a proposed code following a supporting video (2 h/week)
- Weekly assignments (2 h/week)
- Suggested material + independent studies (30 h)
- Final work (32 h)
- Total of 104 h (about 15 h/week) = 4 ECTS

0.1.1 Video recording

Most videos were recorded in 2019; videos of 2018 are also available as a supporting material. Depending on the need, more videos will be recorded.

0.1.2 Weekly assignments and tutorial sessions

The weekly assignments are based on the tutorials and the theory presented in these notes. The tutorial material is available as codes that it can run in different cloud services whose links are indicated in the Moodle page of the course. **The deadlines are flexible, no need to ask for extensions**.

0.1.3 Independent studies

The independent studies consists in reading assignments related to the lectures. Other different sources may be suggested throughout the course (videos, blog posts, podcasts etc.). A discussion group might be opened in order to go further in the topic, including additional material, open discussions and contributions, possible implications etc. Although these activities are not graded, they are usually very important. **Feel free to contact me!**

0.1.4 Final work

The final work is an application of the core concepts and tools proposed throughout the course. It consists of assessing/designing an IoT-based system to be selected by the students or a further development of a selected scientific article. It can be done in Jupyter notebooks, but alternative solutions (media material, development of an application, etc.) are also accepted (if agreed in advance). Before the submission of the final work, there will be the submission of a proposal following a given template, when I will discuss the content. The final work may be done in groups with a clear work division; the work complexity increases with number of group members. The final work topic and group must be defined by the end of week 4. The final work accounts for 40% of the final grade. Examples of final work from 2018 are provided in Moodle. **It is expected that the student will use concepts presented in this lecture notes, and thus, code and hardware deployment require theoretical background.**

0.2 Conduct

It is expected that the students follow basic rules of conduct in relation to fabrication of results, plagiarism, falsification/misrepresentation and misappropriation. For example, no one is expected to copy anything from anybody, except when it is relevant to the argument and with proper reference. In case of doubt, refer to guidelines provided by research and education agencies[1] and contact the course instructor.

0.3 Remote students

This course is designed to be a 100% distant-learning. Therefore, all suggested material will be provided on-line. The teaching approach used is described in further details in a text available in Moodle. Approaching the end of the course, we will plan one (non-mandatory) face-to-face activity to meet students in person.

[1] http://www.tenk.fi/sites/tenk.fi/files/HTK_ohje_2012.pdf

1. System

Before starting the discussions about IoT-based systems, it is important to clarify what we mean by *systems*. During this first week, we will revisit some definitions of **system**, and specify the one to be used during this course. We will also open a discussion about three different kinds of *scientific rationalities* and how this is employed in the analysis of any kind of system given special attention to the design of engineering systems. Few examples will be provided with particular focus on IoT-based systems.

1.1 What is a system?

1.1.1 Dictionary definition

The first place to look for a definition is in the dictionary[1].

> **Definition 1.1.1 — System.** 1. A set of things working together as parts of a mechanism or an interconnecting network; a complex whole. 2. A set of principles or procedures according to which something is done; an organized scheme or method.

Although this definition indicates quite clearly our daily use of the word *system*, we still need to specify what is and what is not a system [2, pages 1-2].

R The reverse of Definition 1.1.1 does not hold: not every set of things or principles working together are systems.

Roughly speaking, a system needs to build a unity with some functional relationships and useful purposes. Only by following these considerations, one can start speaking about performance indicators such as efficiency, quality of service or throughput.

[1] https://en.oxforddictionaries.com/definition/system

1.1.2 System engineering definition

The key elements of a system are described in [2, page 2] as follows: components, attributes and relationships. From these components, system is defined.

Definition 1.1.2 — System. A system is a set of components, whose individual operating parts have specific attributes, that are combined in a certain way towards a specific common purpose.

In this sense, the system has a purpose, i.e. a well-determined *function*, which cannot be achieved by the individual parts alone; as in the good old saying *the system is more than the sum of its parts*. Each system component may be grouped in one of the following classes [2, pages 2-3].

- **Structural components** are the static parts.
- **Operating components** are the parts that perform the processing.
- **Flow components** are the materials being processed.

Systems usually work by converting inputs into outputs as, for example, digestive system (food into energy), wind turbines (kinetic energy into electric energy) or temperature sensors (physical signal to digital data). Clearly, systems may work in hierarchy: a system composed by subsystems. An industrial plant can be analyzed as a system composed by subsystems: specific machines, persons, electricity generators, sensors etc. Each subsystem may also be composed of other subsystems. And such a regression may go on as needed.

R The determination of a specific system is relative and depends on its function, limits, boundaries and scope.

Figure 1.1 illustrates a block diagram of the so-called Hatley-Pirbhai system modeling. The following text, copied from Wikipedia[2], explains the model as follows:

> *The five components – inputs, outputs, user interface, maintenance, and processing – are added to a system model template to allow for modeling of the system which allows for proper assignment to the processing regions.This modeling technique allows for creation of a hierarchy of detail of which the top level of this hierarchy should consist of a context diagram. The context diagram serves the purpose of "establish(ing) the information boundary between the system being implemented and the environment in which the system is to operate." Further refinement of the context diagram requires analysis of the system designated by the shaded rectangle through the development of a system functional flow block diagram. The flows within the model represent material, energy, data, or information.*

This example may represent an IoT system that process input information from sensors to attend requests from the user, while generating different kind of outputs.

Figure 1.1 can be classified a *conceptual* system (i.e. symbolic) in contrast to a *physical* system (i.e. material) that it represents; it may serve as a guide before the physical system is deployed. Other classifications of systems like natural vs. man-made, or static vs. dynamic, or closed vs. open may be interesting (refer to [2, pages 4-7]).

[2]https://en.wikipedia.org/wiki/Hatley%E2%80%93Pirbhai_modeling

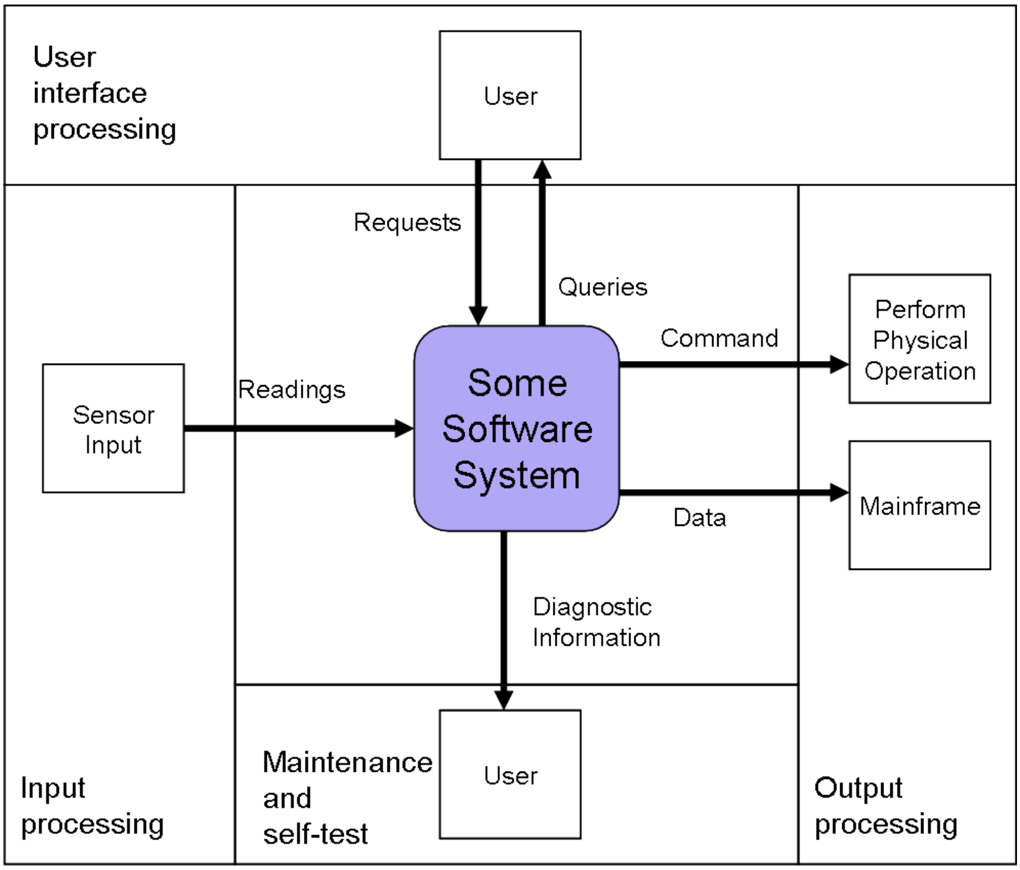

Figure 1.1: Example of a system based on the Hatley-Pirbhai modeling. Image uploaded from `https://commons.wikimedia.org/wiki/File:Hatley-Pirbhai_System_Context_Diagram.png`

1.2 System existence and its determination

Another very important aspect to analyze and design systems is the determination of its boundaries: the so-called *demarcation problem*. How it is possible to differentiate a given system from everything else, which is normally denominated by the term *environment*. The first step is to **determine a peculiar operation that characterizes that specific system as being that system and not any other**. For example, a wind turbine as a *wind turbine system* is determined by a peculiar operation of convert the kinetic energy from wind to electric power; conversely, if a system is not capable of producing and sustaining such an operation, it is not a wind turbine system. We can now state the following theorem (i.e. a general proposition not self-evident but proved by a chain of reasoning; a truth established by means of accepted truths[3]) to be used throughout this course.

Theorem 1.2.1 — System existence and demarcation. A given system differentiates itself from everything else through a peculiar operation; conversely, without this operation, there is no such a system. Such a peculiar operation determines the existence of that given system while demarcating its boundaries and relations to the environment.

[3] `https://en.oxforddictionaries.com/definition/theorem`

This theorem tells us that a system only exists if it possesses a very particular operation that makes that system being *that system*. That operation therefore must occur and be sustained within the system itself and beyond its boundaries via its dependencies on the environment. The following corollary (i.e. a proposition that follows from, and is often appended to, one already proved[4]).

> **Corollary 1.2.2 — Necessary conditions for a system existence.** There are three general groups of necessary conditions for a given system to exist as such, namely:
>
> C1 **Conditions of production** that guarantee that its peculiar operation physically/-materially can be produced;
>
> C2 **Conditions of reproduction** that guarantee the recurrence of the system operation;
>
> C3 **External conditions** are aspects outside the system boundaries that still affect, directly or indirectly, the reproduction of the system operation.

■ **Example 1.1 — Wind turbine.** Let us analyze here how one could analyze a given wind turbine as a system based on its peculiar operation and its necessary conditions of existence.

OP **Peculiar operation:** Convert kinetic power from wind to electric power.

C1 **Conditions of production:** Different electric machines that can convert kinetic energy into electric energy via electro-magnetic phenomena.

C2 **Conditions of reproduction:** Proper maintenance, connection to the grid, existence of wind,...

C3 **External conditions:** Specialized university to train personal to work, investments of the government, civil war...

■

It is clear that the lists related to the conditions of reproduction and external conditions could grow almost unlimitedly. The aspects covered by the list are not expected to be exhaustive. Rather, this systematization is to be a simplification – a way to produce a conceptual model that evinces what makes the system "alive." This approach may be very helpful in either designing new systems or analyzing the existing ones. It may be also useful to understand systems that failed. We state the following proposition in this regard.

Proposition 1.2.3 — Conceptual vs. physical systems. Conceptual systems reflect the reality they represent, but they are *always* simplifications that cannot account to *all* existing elements from their actual physical/material implementation.

The physical/material reality of a given system can then be seen as the judge of its different conceptual models. What shall and shall not be included in the conceptual models is determined by the level of abstraction and details required by the analysis/design in question. Time scales and spatial granularity are also important determinant in that issue. All in all, the conceptual system needs to be construct to answer a precise question or set of questions, which determine the level of details to be employed together with the spatial and temporal scales to be used.

[4]`https://en.oxforddictionaries.com/definition/corollary`

Back to Example 1.1, the selection to what is relevant to the system analysis/design depends on the question the analyst/designer would like to answer. A long-term investment plan in a wind turbine and a prediction of the power generate in the next hour require a different approach, with different time scales. Although these aspects are related to the wind turbine system, they are relatively autonomous and their individual analysis are usually based on some (implicit or explicit) assumptions of each other. When one is making an investment plan, the calculations most probably assume an average power to be generated hour-by-hour. Similarly, when the next hour prediction is done, it is assumed that the wind turbine is properly maintained based on the investment plan.

1.2.1 System analysis and scientific rationalities

Sciences, in contrast to other theoretical practices, involve a trustworthy mapping from specific processes into a symbolic reality. Each science has developed through its own history different norms that state the *truth* of its different statements. Different phenomena in their turn require distinct modes of rationality. For example, the scientific way to evaluate the effectiveness of vaccines is different from the way to evaluate how (mis)information about it spreads in social networks, which is also different from the ways to assess the impact of possible interventions to change the social acceptance of vaccines and its impact in public health.

Proposition 1.2.4 — Modes of scientific rationalities. It is possible to classify three modes of scientific rationalities as follows [12].

- **Classical:** Direct observations and empirical falsification possible at each stage.
- **Non-classical:** Observations are not directly possible in physical reality, mathematical/symbolical analyses lead to non-observable steps.
- **Interventionist:** Internal awareness and interventions are part of the processes.

■ **Example 1.2 — Effectiveness of vaccines.** Anti-vaccine groups are frequently appearing in social media defending their position questioning the effectiveness of vaccines, and arguing against the vaccination of school-age children. Outbreaks of previously controlled diseases like measles are reappearing[5].

Classical: Effectiveness of vaccines is regulated by norms, historically established by the scientific community[6].

Non-classical: Mathematical models of multilayer/multiplex graphs can be employed to assess how (mis)information propagates in different social networks [9].

Interventionist: Once the mechanisms of how the (mis)information propagates and the particular epidemic characterization of a given disease, the scientists and public health professionals may become part of the phenomena they investigate by designing interventions to help stopping the outbreaks. ■

[5] https://ecdc.europa.eu/en/news-events/measles-outbreaks-still-ongoing-2018-and-fatalities-reported-four-countries

[6] http://www.euvaccine.eu/vaccines-diseases/vaccines/stages-development

1.3 Assignment

There are three main goals for this weekly assignment: (1) learning to determine a system based on its particular operation, (2) understanding different types of scientific rationalities and (3) getting familiar with Jupyter Notebooks (Python).

2. Information

During this week, we will discuss about **information**. To analyze and design systems based on information, we need first to discuss its meanings and how it is employed in different theories. The key problem is the name *information* refers to different things depending on the discipline. We will mainly follow chapters 1-5 of the book *Information: A very short introduction* [4].

2.1 What is information?

First step: going to the dictionary[1].

Definition 2.1.1 — Information. 1. Facts provided or learned about something or someone. 2. What is conveyed or represented by a particular arrangement or sequence of things. 2.1 *Computing* Data as processed, stored, or transmitted by a computer. 2.2 (in information theory) a mathematical quantity expressing the probability of occurrence of a particular sequence of symbols, impulses, etc., as against that of alternative sequences.

Those definitions tell that the word *information* may relate to some kind of new acquired knowledge or to some specific kind of *data* in technical fields. To be more specific, I would like to propose the following as the definition to be employed here.

Definition 2.1.2 — Information as a concept. The concept information indicates a (meaningful) trustworthy uncertainty resolution.

Information then brings reliable novelty. Novelty, on its turn, cannot exist in the void: there must be reference points. In this lecture, we will discuss these different possibilities by specifying some forms that concept *information* may assume within different theories.

[1] `https://en.oxforddictionaries.com/definition/information`

2.2 Data and information

Information is composed by data, but not all data is information. To constitute information, data must be both structured according to norms (syntax) and have meaning (semantics). Such meaningful structured data need moreover to carry a *true* reflection of the respective reality they represent. If this decreases the uncertainty about that reality in relation to the present state, then *data becomes information*. Therefore, information is a *relational* concept: it depends on both the source/transmitter and the sink/receiver of the data!

■ **Example 2.1** To understand this lecture, you and I should share a set of norms (English syntax) so the sounds and symbols can be mutually understandable (semantics). Data is generated by me in this way to articulate the theory about data and information, which is the reality I would like to represent. The concepts developed in this lecture must be weaved together using English to form a consistent theoretical construction (i.e. my text and speech must be a trustworthy representation of the theory). The lecture material is the means to transfer data (i.e. to communicate). After watching the lecture and reading the notes, if you learn my knowledge about the theory, then data generated by the lecture may become information. However, it only become information if, and only if, you do not have this knowledge before; otherwise, the data transmitted by me is redundancy for you. ■

2.2.1 Types of data

Data may be *analog* or *digital*. For example, my voice in the room is analog, while the same voice stored in the video you watched is digital. Analogue data may be recorded in, for example, vinyl discs. Video lectures are not recorded in this sense; they are encoded via state machines. They encode data via bits 0/1 (on/off, low/high voltage etc.). Bits can be then represented semantically (true or false answers), mathematically (including operations using Boolean algebra[2]), and physically (transistor on/off, switch open/close, etc.).

> **R** It is then possible to construct machines that can [4, p.29] *recognize bits physically, behave logically on the basis of such recognition and therefore manipulate data in ways which we find meaningful.*

There also other useful classification of data based on their type, as follows [4, p.30].

- **Primary data** are the direct data accessible as numbers in spreadsheets, traffic light, a binary string; this is the data we usually talk about.
- **Secondary data** is *the absence of data* that may be informative (for example, you cannot hear any sound from the office beside yours so the silence indicates no one is there).
- **Metadata** are data about other data as location where or time when some picture was taken.
- **Operational data** relate to the operations of the data system and its performance (e.g. blinking yellow traffic lights indicate that the system is not working properly).
- **Derivative data** are data obtained through other data as indirect sources (e.g. from the electricity consumption from your house, you know what time your baby slept in a given day).

[2] https://en.wikipedia.org/wiki/Boolean_algebra

2.2.2 Environmental information

Another important distinction concerns the existence of meaningful data independent of an intelligent producer. Floridi names this as *environmental information*. For example, the tree outside my office indicates the season of the year (green leaves, no leaf, fruits, flowers etc.). Engineering systems are also designed to be a source of environmental information as a thermometer. In general, environmental information is defined as the coupling of two (or more) processes where observable states of one or more processes carry information about the state of other process(es).

2.2.3 Semantic information

Data can be also characterized semantically as *instructional* or *factual* [4, p.34, Ch.4]. The former prescribes actions ("how to") while the later declares so that it can be judge as true or false. If the semantic factual content existing in the data is true (i.e. veridical, trustworthy to the reality they are representing), then it is information. Conversely, if it is false, the data can be classified as misinformation (unintentional) or disinformation (intentional). For example, a scientific paper with new results should be information. However, it may also be misinformation when the measurement devices were not calibrated and the authors are not aware of it so the results are unintentionally false. Making fake results to publish a paper is a case of disinformation.

2.2.4 Mathematical information

In 1948 Claude Shannon published his seminal paper *A Mathematical Theory of Communication*[3] [15], where he states: "*(T)he fundamental problem of communication is that of reproducing at one point either exactly or approximately a message selected at another point.* ***Frequently the messages have meaning; that is they refer to or are correlated according to some system with certain physical or conceptual entities. These semantic aspects of communication are irrelevant to the engineering problem.*** *The significant aspect is that the actual message is one selected from a set of possible messages. The system must be designed to operate for each possible selection, not just the one which will actually be chosen since this is unknown at the time of design.*" [my own remark]

In this sense, the well-established Shannon information theory deals with data *without* meaning, consequently it is *not* information as defined here. Floridi provides a discussion about it in [4, Ch.3]. The theory introduced by Shannon is the basis of the existing modern telecommunication networks, establishing the theoretical limits of data compression and data communication, as well as the conditions to achieve it.

Shannon information theory is then related to information at a syntactic level so it deals with [4, p.45] *messages comprising uninterpreted symbols encoded in well-formed strings of signals.* ***These are mere data that constitute, but are not yet, semantic information***. Its mathematical toolbox is widely used in many different fields as in physics to biology; Adami gives his brief introduction in [6] – which I personally have my own concerns. The core concept in Shannon is *entropy*, which evaluates the uncertainty of probabilities distributions (we will discuss more about it in week 5). Fig. 2.1 depicts the general communication scheme used to derive Shannon's famous capacity theorem (the highest data rate that can be transmitted over a noise channel with arbitrarily low error probability).

[3] `http://math.harvard.edu/~ctm/home/text/others/shannon/entropy/entropy.pdf`

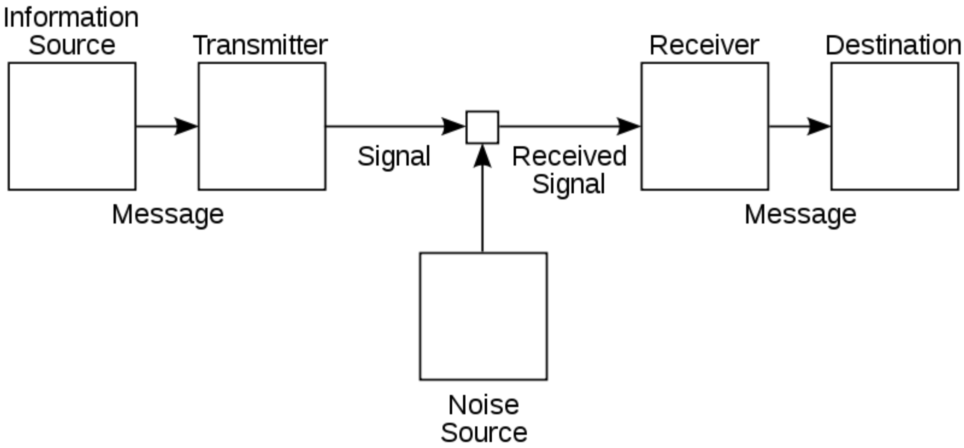

Figure 2.1: Diagram of a general communication system by Shannon. Source: `https://commons.wikimedia.org/wiki/File:Shannon_communication_system.svg`

I will quote the explanation of Fig. 2.1 given by Shannon himself [15]:

> By a communication system we will mean a system of the type indicated schematically in Fig. [2.1]. It consists of essentially five parts:
>
> 1. An information source which produces a message or sequence of messages to be communicated to the receiving terminal. The message may be of various types: (a) A sequence of letters as in a telegraph of teletype system; (b) A single function of time $f(t)$ as in radio or telephony; (c) A function of time and other variables as in black and white television — here the message may be thought of as a function $f(x;y;t)$ of two space coordinates and time, the light intensity at point $(x;y)$ and time t on a pickup tube plate; (d) Two or more functions of time, say $f(t)$, $g(t)$, $h(t)$ – this is the case in "three dimensional" sound transmission or if the system is intended to service several individual channels in multiplex; (e) Several functions of several variables — in color television the message consists of three functions $f(x;y;t)$, $g(x;y;t)$, $h(x;y;t)$ defined in a three-dimensional continuum – we may also think of these three functions as components of a vector field defined in the region – similarly, several black and white television sources would produce "messages" consisting of a number of functions of three variables; (f) Various combinations also occur, for example in television with an associated audio channel.
>
> 2. A transmitter which operates on the message in some way to produce a signal suitable for transmission over the channel. In telephony this operation consists merely of changing sound pressure into a proportional electrical current. In telegraphy we have an encoding operation which produces a sequence of dots, dashes and spaces on the channel corresponding to the message. In a multiplex PCM system the different speech functions must be sampled, compressed, quantized and encoded, and finally interleaved properly to construct the signal. Vocoder systems, television and frequency modulation are other examples of complex operations applied to the message to obtain the signal.

3. The channel is merely the medium used to transmit the signal from transmitter to receiver. It may be a pair of wires, a coaxial cable, a band of radio frequencies, a beam of light, etc.

4. The receiver ordinarily performs the inverse operation of that done by the transmitter, reconstructing the message from the signal.

5. The destination is the person (or thing) for whom the message is intended.

This is a quite general description, and still the basis of communications engineering projects and research. The courses *Wireless Communications Systems* and *Wireless Communications Networks*, as well as their respective laboratory course (taught at LUT/FITech) will go through many developments in the field of communications and some basis of Shannon information theory.

2.2.5 Physical information

Up to know we have discussed about data and information as semantic and mathematical domains. Although both are related in their own ways to physical processes by stating the relation between reality and semantic content, or how much data can be reliably transmitted over a noisy channel, we have not yet investigated information as a physical process. Storing and processing data and information consume energy. The laws of thermodynamics therefore become important analytic tools.

The first law tells that energy is conserved in closed-systems so energy cannot be created, only transformed. The second law tells that physical entropy ("level of disorder") tends to increase. There is an interesting link here. Information may help thermodynamical processes to be more efficient; for example, how technical sciences (as an information process) have been employed to design machines that have a better efficiency in converting energy (thermodynamical process). On the other hand, information processes consume energy as illustrated by the growing research and development to improve the energy efficiency of data centers [7]. Thermodynamics and Shannon information theory state the *physical limits* of how efficient can be all possible thermodynamical and/or information systems; in other words, absolutely nothing (now and in the future) can do better then what those theories state as the fundamental limits. Not even quantum computing or other kind of technology as blockchain, artificial intelligence, deep learning etc. can transpose those boundaries.

2.3 Physical and symbolic realities

There is another line of discussion about the nature (i.e. metaphysics) of information, introduced in [4, p.69-72]. I have my own position about the topic and, although interesting, I do not share the ideas presented there.

Proposition 2.3.1 — Physical and symbolic realities. Physical (material) processes exist and constitute the physical reality. Symbolic (data) processes can only exist supported, directly or indirectly, by the physical reality.

In plain language, I am telling that physical processes are always present but symbolic processes not – their existence depends on the physical reality. However, symbolic processes may exist in different levels in relation to the physical reality, as follows.

Definition 2.3.1 — Level of processes. Reality can be classified into levels. Level-0 refers to processes within the physical reality. Level-1 refers to the symbolic processes directly concerning the physical reality. Level-2 refers to symbolic processes concerning at least one level-1 process. Level-N refers to symbolic processes concerning at least one level-$(N-1)$ process.

Corollary 2.3.2 Data used in a level-N process must be acquired from at most level-$(N-1)$ processes.

■ **Example 2.2** A car moving in a highway is a physical (level-0) process. The car speedometer can be seen as part of a level-1 process as a measurement of the speed that the car in the highway; speed is the data acquired from a level-0 process and employed in a level-1 process . The speedometer has also a transmitter device that sends via a wireless channel a message to the traffic authority whenever the car goes beyond the speed limit of the highway. The traffic authority charges a fine (level-2 process) if it receives three messages (data acquired from the level-1 process) from the same car in a 12-month period. The government may use the number of fines to draw their budget, or to create new laws. ■

From this very simple example, it is possible to see that the space of analysis could grow (exponentially) bigger and bigger since symbolic processes are in some sense unbounded due to its existence in different levels. Note that higher levels indicate that more data processing. In this sense, some high level processing may provide new kind of data, which has the potential to become information in our strict sense (Definition 2.1.2). Once the domain on the physical reality is mapped into the data, the number of ways that this acquired data can be combined grows to infinity. However, as we have discussed, there are limits that cannot be passed.

Corollary 2.3.3 — Energy limit of symbolic reality. Symbolic reality always involve processes (e.g. data acquisition, storage and manipulation) that need energy, which is limited.

Corollary 2.3.4 — Information limit of symbolic reality. Information presupposes trustworthy structured data of a given reality, regardless of the level. Therefore, the number of informative combinations of data is limited.

In this case, processing data is limited by energy and, more restrictively, the structure required by the acquired data to become information limits even more the boundaries that a trustworthy symbolic reality can be constructed.

2.4 Assignment

There are three main goals for this weekly assignment: (1) defining and classifying information in different ways, (2) analyzing the relation between physical reality and symbolic realities, as well as their limits, and (3) example of acquiring information from data using Jupyter.

3. Network

During this week we will introduce basic concepts of *Network Science/ Graph Theory* to analyze the characteristics of different topologies and their effects in data/information exchanges. The introduction to the topic is based on [1, Ch.2][1], while the analysis of communication within the network will be based on other chapters from the same book.

3.1 Graphs

Graph theory is a field in mathematics that deals with structures using pairwise relations. A well-known example is the so-called *Seven Bridges of Königsberg* [1, Sec. 2.1]. Wikipeadia describes the problem as follows[2].

> The Seven Bridges of Königsberg is a historically notable problem in mathematics. Its negative resolution by Leonhard Euler in 1736 laid the foundations of graph theory and prefigured the idea of topology. The city of Königsberg in Prussia (now Kaliningrad, Russia) was set on both sides of the Pregel River, and included two large islands - Kneiphof and Lomse - which were connected to each other, or to the two mainland portions of the city, by seven bridges. The problem was to devise a walk through the city that would cross each of those bridges once and only once. By way of specifying the logical task unambiguously, solutions involving either reaching an island or mainland bank other than via one of the bridges, or accessing any bridge without crossing to its other end are explicitly unacceptable. Euler proved that the problem has no solution. The difficulty he faced was the development of a suitable technique of analysis, and of subsequent tests that established this assertion with mathematical rigor.

[1] `http://networksciencebook.com/`

[2] `https://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg`

Figure 3.1: Euler's approach to prove that the problem has no solution. Source: `https://en.wikipedia.org/wiki/Seven_Bridges_of_K%C3%B6nigsberg`.

Euler solved the problem by modeling the bridges and islands as *edges* and *vertices*, as presented in Fig. 3.1. His solution[3] is seen as the basis of the modern graph theory and then network science.

3.1.1 Key concepts

As indicated before, edges and vertices are the basis of graph theory. Let's take the third sub-figure from Fig. 3.1. That is a graphical representation of a graph with 4 vertices (blue circles) and 7 edges (black lines) with a specific structure, i.e. *topology*. As an abstraction, the same graph may represent different *networks*.

> **R** Networks are often related to actual systems whose elements (*nodes*) interact. The elements interacting with each other are connected via *links*. Depending on the case, the links may be *undirected* ("go in both ways" – bidirectional) or *directed* ("go only from one node to the other, while the reverse path is not valid" – unidirectional).

There is a plethora of networks: transit (places connected by streets and highways), airline (airports connected by airplanes), computer, sexual, friendship, etc. Fig. 3.2 shows a graph representation of an undirected network with $N = 6$ nodes and $L = 7$ links. This network can easily be used to show the connections of separated buildings (similar to LUT architecture) as: building 6 is connected to 4, which is connected to 3 and 5 in addition to 6 and so on. Likewise, it may represent researchers' collaboration: researcher 6 has a paper in collaboration with 4, who has also collaborated with 3 and 5 etc.

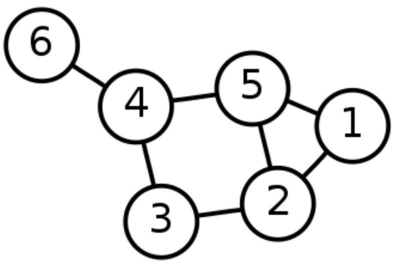

Figure 3.2: Example of an undirected network with $N = 6$ nodes and $L = 7$ links. Source: `https://commons.wikimedia.org/wiki/File:6n-graf.svg`.

[3] `http://eulerarchive.maa.org//docs/originals/E053.pdf`

Mathematically, we can use the following notation[4]. Let $G=(V,E)$ be a graph composed by the set V of vertices v_i's that are linked by the set E of edges $e_k=(v_i,v_j)$. Let me take Fig. 3.2 as an example so that the set of vertices $V=\{v_1,v_2,v_3,v_4,v_5,v_6\}$. The undirected edges are: $E=\{(v_1,v_2),(v_1,v_5),(v_2,v_3)(v_2,v_5),(v_3,v_4),(v_4,v_5),(v_4,v_6)\}$.

Let N be the cardinality (the number of elements) of the set V. N is then used to define the *size of the network* represented by graph G. Likewise, the cardinality of E gives the number L existing in the network. Note that networks with undirected links have in fact $2L$ directed links; in specific cases, this must be taken into account. Sometimes, it is also possible to have edges to itself, i.e. $e_k=(v_i,v_i)$.

Another way to describe the edges is based on the *adjacent matrix* A with elements $a_{i,j}$, with $i,j=1,...,N$, so that $a_{i,j}=1$ or $a_{i,j}=0$ indicating the presence or absence of a (directed) edge from vertex v_i to vertex v_j. In our example:

$$A=\begin{pmatrix}0&1&0&0&1&0\\1&0&1&0&1&0\\0&1&0&1&0&0\\0&0&1&0&1&1\\1&1&0&1&0&0\\0&0&0&1&0&0\end{pmatrix},$$

where the size of the system in $N=6$. The number of edges can be computed directly from A as:

$$L=\frac{1}{2}\sum_{i=1}^{N}\sum_{j=1}^{N}a_{i,j},$$

where the $1/2$ assumes that the graph is directed. In our example, we have $L=7$.

Another important concept is the *degree of a node*, which indicates how many links to another node it has. Mathematically, the degree of node i is

$$k_i=\sum_{j=1}^{N}a_{i,j}-a_{i,i}.$$

Computing it for our case, the nodes have the following degrees: $k_1=2$, $k_2=3$, $k_3=2$, $k_4=3$, $k_5=3$, and $k_6=1$. As the size of the graph grows, the statistical analysis of the network becomes desirable. We will discuss it later in the lecture related probability.

The edges may also have some specific characteristics such as space limitation (e.g. capacity of the highway) or strength of the relation (e.g. how many papers two researchers wrote together). This indicates that the network should be modeled with *weighted links*. The elements of the matrix A becomes not only 0 and 1, but also values that reflect the weight the respective link. Let us consider the following matrix represent our example but with weights now.

$$A'=\begin{pmatrix}0&2&0&0&1&0\\2&0&1&0&1&0\\0&1&0&1&0&0\\0&0&1&0&1&4\\1&1&0&1&0&0\\0&0&0&4&0&0\end{pmatrix}.$$

[4] The lecture notes from Prof. Ruohonen is an example of the mathematical formalism involved in graph theory `http://math.tut.fi/~ruohonen/GT_English.pdf`.

In the case of researchers' network, this represents that researchers 4 and 6 have four papers together and researchers 1 and 2 have two; this indicates a stronger link between them. This may also indicates how many people can move from one building to another through that connection.

Other important concept is the so-called *path length*, which indicates how many edges are between two vertices. It is usual to have different paths linking two vertices so their lengths also vary. The shortest path length is defined as the *distance* between two vertices. Once again, in our example from Fig. 3.2 to move from vertex 5 to 6, one might have: $5 \to 4 \to 6$, or $5 \to 2 \to 3 \to 4 \to 6$. The first has length 2 while the second 4. In this case, the distance $d_{5,6} = 2$. It is also possible to identify the number of shortest paths between two edges. From 2 to 6, there are two shortest paths whose distance is $d_{2,6} = 3$ (check it). It is possible to compute these directly from the adjacent matrix; refer to [1, Box 2.4][5]. The *diameter* of the graph is obtained as the maximum distance between two vertices.

There are also other interesting metrics that help the assessment of networks, namely connectedness, clique, components, and clustering coefficient. It is said that a network is *connected* if there is at least one path from any two nodes, otherwise the network is *disconnected*. If all vertices are connected to each other, we have a *complete graph* or a *clique* . A *component* or *cluster* is a subset of the network where exists at least one path from any two nodes. A link between two components is called *bridge*. The link 4 and 6. in Fig. 3.2 is a bridge linking two components: one is the node 6, and the other is nodes 1 to 5. If the bridge is broken, then the graph will become disconnected. It is also possible to compute the *cluster coefficient* from any node in the network as follows:

$$C_i = \frac{2L_i}{x_i(x_i - 1)},$$

where L_i is the number of links between the x_i neighbors of node i. Note that the cluster coefficient is a number between 0 and 1 so that $C_i = 0$ means the neighbors of node i are not linked to each other; $C_i = 1$ indicates that i and its neighbors form a complete graph. Node 1 has $x_1 = 2$ (two neighbors: 2 and 5) and $L_1 = 1$ (one link between them), then $C_1 = 1$ indicating that the subgraph formed by 1,2 and 5 is complete. Node 3 has: $x_3 = 2$ (two neighbor: 2 and 4) and $L_3 = 0$ (no link between them), then $C_3 = 0$ indicating that 2 and 4 are not linked. Now node 5 has: $x_5 = 3$ (two neighbor: 1, 2 and 4) and $L_1 = 1$ (one link between 1 and 2), then $C_5 = 1/3$ indicating the existence of some connections between neighbors (clustering).

3.2 Communication networks

Now that we have the basic understanding of the concepts employed in graph theory and network science, we can look at different topologies of communication networks. We will present here a qualitative analysis of them; the simple quantitative assessment will be required as assignment.

3.2.1 Single-link

Only two nodes are present and are connected to each other. This scenario is know as *peer-to-peer* or *single-link network*.

[5] `http://networksciencebook.com/chapter/2#paths`

Figure 3.3: Example of a single link (peer-to-peer) topology. Source: `https://commons.wikimedia.org/wiki/File:David_Cameron_and_Barack_Obama_at_G8_summit,_2013.jpg`.

Fig. 3.3 exemplifies this topology, where Obama and Cameron are talking to each other in an empty field: there should be no one else there to spy or to interferer in their conversation. This scenario is then noise-limited. It is important here that the network might be composed by undirected links (both talk) or directed links (only one talks). Shannon seminal paper [15], already discussed in the previous week, gives the fundamental limits of how much data can be reliably transmitted from a node to another via a communication channel (i.e. the channel capacity) .

3.2.2 Broadcast

The *broadcast topology* is when only one node transmit data while all others receive; this case is also known as *one-to-many topology*. This case is a directed link between a central node and many others in one-hop (i.e. the distance between the central node and any other is 1). Fig. 3.4 presents a potential example of this: it is an illustration of the well-known Fidal Castro long speeches where he speaks and all others listen. Other examples like TV or radio stations as they broadcast shows. Traffic lights might also be considered a form of broadcast.

Clearly, the “talking” node is special and holds power to inform, misinform and disinform. As they are connected to all nodes, it strongly impacts in what data is received by all the “listeners” (which in this topology cannot speak to each other). The degree of the talking node is the size of the network minus one (itself), while the others have degree 1. The differences can be evaluated mathematically using the concepts introduced before.

Figure 3.4: Example of a broadcast (one-to-many) topology. Source: `https://commons.wikimedia.org/wiki/File:Fidel_Castro_speech.jpg`.

Shannon information theory also deals with this problem, known as *Broadcast Channel*, which as not yet solved in its general form. Refer, for example, to [8][6] as key reference of theoretical research in the field is carried out. As in the case of the broadcast channel, the link is just an illustration of the mathematical formalism involved in Shannon information theory research, which is an active (very prestigious) research field.

3.2.3 Many-to-one

The *many-to-one* topology is the "inverse" of the previous one: there is one "hearing node" at the center while all the others are talking to it. Once again, we have directed links, but here from the "edge" to the center. Fig. 3.5 illustrates this, where four megaphones are trying to communicate different messages to a single person. The central node has consequently difficult to decode the four messages. The different messages interfere to one another. Examples of this are also diverse: meetings when many people are specifically talking to one person, many laptops sending data to a single base-station (uplink), or a mass protest against a single person. In Shannon information theory, this topology is known as *Multi-access Channel* (MAC), whose capacity was also not solved in the general case[7].

3.2.4 Star

The *star topology* is the syntheses of one-to-many and many-to-one, it is a network with undirected links so that one central node is connected to all other nodes. Once again, this node is a special one that connects the network: all messages pass through him.

[6] `http://www-isl.stanford.edu/~cover/papers/transIT/0002cove.pdf`
[7] `https://www3.nd.edu/~jnl/ee698g/materials/summaries/wenyi-v1.pdf`

Figure 3.5: Example of many-to-one topology. Source: https://artemis.marketing/wp-content/uploads/2018/03/Many-megaphones-shouting-at-a-businessman.jpg.

The problems are related not only how to coordinate the reception of messages, but also how to coordinate the listening and talking together. If it is possible to do at the same time, we call this as full-duplex mode, while half-duplex indicates that only transmit or receive is possible at a given time. If the person in Fig. 3.5 starts replying to the megaphones, this scenario becomes the star topology. A computer server, a base station (uplink + downlink), or someone being interviewed by many reporters may exemplify it.

3.2.5 Other topologies

Beyond these case, there are other possible topologies. Fig. 3.6 shows different topologies: ring (every node has 2 neighbors and forms a ring), mesh (nodes with different number of connections), star, fully connected, line, tree (mother node and sons) and bus (there is a shared path connecting the nodes).

R In real scenarios, we usually have a hybrid of these topologies. As analysts and designers of systems, we need to choose the most suitable model to the specific problem/phenomenon at hand.

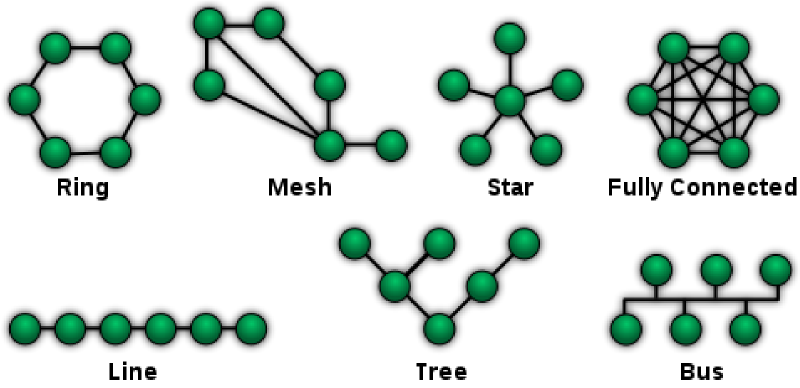

Figure 3.6: Different topologies. Source: `https://commons.wikimedia.org/wiki/File:NetworkTopologies.svg`.

Example 3.1 — Vaccination. A TV show broadcast misinformation about vaccination has a different structure than the same misinformation being propagated neighbor-by-neighbor or in social media. In the first case, we would have a broadcast difficult to argue against, while the second a discussion about it is possible and the misinformation might be countered. The case of social media (very relevant nowadays) is meshed where two clusters may be formed (agreeing or disagreeing) and become self-reinforcing their positions (regardless of the reliability of the data); bridges between these cluster usually exist but are "weak." The issue is that these three phenomena co-exist so that effective interventions against disinformation and misinformation are unclear. ■

3.3 Assignment

There are three main goals for this weekly assignment: (1) characterizing networks, (2) building them using the library NetworkX[8] from Python, and (3) analyzing communication networks based on network science concepts.

[8] `https://networkx.github.io/`

4. Reflexive-active systems

In this week, we will build upon the the previous three weeks by introducing the concept of *reflexive-active system*, where a system has data processing capabilities that are structured via a communication network. This will be denominated as the system's *structure of awareness* from where the *agents* (i.e. the elements that can act) collected data/information to support their decision-making. Through this approach, the system is analyzed by having three constitutive layers, namely *physical, data and decision layers*. This chapter is also the first one to introduces the *Internet of Things*, or simply *IoT* (finally we reach it!). The function of the IoT is to build the structure of awareness of systems, creating then an *IoT-based systems*. We will here follow few main references here: the book *Conflicting Structures*[1] [5] and the papers *Dynamics of complex systems built as coupled physical, communication and decision layers*[2] [11] and *Why smart appliances may result in a stupid energy grid?*[3] [13]. A previous version of this lecture was presented as a tutorial[4].

4.1 Structure of Awareness

4.1.1 The poker problem

Let us start by describing a well-known card game: poker. Although I do not play myself, this example can illustrate very well the ideas to be presented during this week. Wikipedia gives following description[5]: *Poker is a family of card games that combine gambling, strategy, and skill. All poker variants involve betting as an intrinsic part of play, and determine the winner of each hand according to the combinations of players' cards, at least some of which remain hidden until the end of the hand.*

---

[1] `https://goo.gl/Xyhxpe`
[2] `http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0145135`
[3] `https://arxiv.org/abs/1703.01195`
[4] `https://arxiv.org/abs/1708.06506`
[5] `https://en.wikipedia.org/wiki/Poker`

Individual (good) players are strategic: they are always processing data from the game table to guide their actions to become the final winner (i.e. the last one in the table). As any card game, there are prescribed rules and an intrinsic aleatory component ("which card will appear now?"). Looking as an observer, the matches' dynamics come from the interactions between individual players inside the game. The game assumes that the players are *independent agents* only having the table information (i.e. reliable data). But, in reality, one could imagine other situations including: preliminary agreements, study of adversaries and bluffing. Then, we could ask the following questions.

- What would happen if two players are able to communicate during the game?
- What happens when players know the betting strategies of others?
- Why some players bluff every now and then?

To help us to answer this question, we need to go back to a study done in the 60's [5], wrote by a psychologist-mathematician, where he proposed an algebra to mathematically characterize a given reality including not only the specific phenomenon under consideration but also how the involved persons perceive the whole scenario. This book appeared translated to English in 1977 with the name *The Structure of Awareness*; the book also appears in a different edition with the name *Conflicting structures* (which is the name given in its Russian version). In the following, we will present a short review of so-called *algebra of reflexive processes*.

4.1.2 An algebra of reflexive processes

The book's first chapter starts by defining what reflexive processes are (my highlight) [5]:

> *Imagine a room full of crocked mirrors like those in amusement parks. The mirrors are placed at different angles. Let a pencil be dropped. Its fall will be fantastically reflected. Thus, the trajectory, already distorted in the various mirrors, will be further distorted in the avalanche of multiply reflected images.* ***A reflexive system can be thought of as a system of mirrors and the multitude of reflexions in them.*** *Each mirror represents a "persona" characterized by a particular position. The vastly complex flow of reflexions represents the reflexive process.*

A straight differentiation can be done here: a specific physical process (pencil falling) and the several reflections of it (reflections, reflections of reflections etc.); the reality of the reflexive system is constituted by all these processes. Therefore, its algebraic representation shall incorporate and differentiate them.

Definition 4.1.1 Let T be the physical process under consideration. This physical process is observed by three data processing elements X, Y and Z. The images of T done by X, Y and Z are denoted Tx, Ty and Tz, respectively. In other words, Tx, Ty and Tz are the reflections of T by X, Y and Z. The reflexive system Ω is $\Omega = T + Tx + Ty + Tz = T(1 + x + y + z)$, where the term $(1 + x + y + z) = \omega$ defines its *the structure of awareness*. Let say that element Z cannot observe T directly, but only through the observation done by Y. Then, the system changes to a new reality $\Omega' = T + Tx + Ty + Tyz = T(1 + x + y + yz) = T\omega'$.

R It is important noting that the structure of awareness does not tell whether the reflection is reliable, but only their existence as part of the system.

Although both Ω and Ω' represent exactly the same physical process T, the system has a different structure of awareness (ω and ω', respectively), which modifies its internal development. The proposed notation can capture such – subtle or even invisible – structural modification. The system Ω may also dynamically change following the physical process T or the data processing procedures Tx, Ty and Tz, or the system's structure of awareness ω.

Excluding both external interference and the rules of the supporting process (e.g. physical laws or poker rules), the system can be only modified by the actions of the elements X, Y and Z. Note that not all elements need to take actions; the agents are a subset of data processing elements[6]. Such actions – which are always related to a decision/regulatory rule (random decision is also a rule) – may modify any part of the system: the support process itself, the data processes, the structure of awareness, and even the decision rules. If we consider a discrete time $n \in \mathbb{N}$, then we have Ω_n as a *self-developing reflexive-active system* [12][7].

A special case of system evolution is related to *the operator of awareness*, denoted by the symbol $*$. Consider the evolution of the system Ω_n:

$$\begin{aligned}
\Omega_0 &= \quad T \\
\Omega_1 &= \quad \Omega_0 * (1+x) = T * (1+x) = T + Tx \\
\Omega_2 &= \quad \Omega_1 * (1+y) = (T+Tx) * (1+y) = T + Tx + (T+Tx)y.
\end{aligned}$$

Putting the sequence in plain words: ($n = 0$) there only exists the physical process T; ($n = 1$) element X becomes aware of T; ($n = 2$) element Y becomes aware of both T and the information processing Tx that X is doing, i.e. Y constructs its own image of X image of T, resulting Txy. Note that the awareness operations represent a dynamical behavior in n, but they also lead to a static structure of awareness for the time n. The formalism used to manipulate the algebra of reflexive systems is presented next just as a general reference.

Definition 4.1.2 — Algebra of reflexive systems.

- Given set of symbols: capital and lowercase letters, and "1".
- Symbols written in sequence without comma are called words.
- Words differing in the number of occurrences of "1" are equivalent; it can always be canceled except when the word consists of a single "1".
- Polynomials are of the form $\omega = \sum_{i=1}^{k} \alpha_i\, a_i$, where α_i's are Boolean functions and a_i are words. If $a_i = a_j = a$, then $\alpha_i a_i + \alpha_j a_j = (\alpha_i + \alpha_j)a$.
- Addition of polynomials are cumulative: $\omega_1 + \omega_2 = \omega_2 + \omega_1$.
- The product of two polynomials $\omega_1 = \sum_{i=1}^{k} \alpha_i\, a_i$ and $\omega_2 = \sum_{j=1}^{l} \beta_j\, b_j$ is defined as: $\omega_1 * \omega_2 = \sum_{i=1}^{k} \sum_{j=1}^{l} \alpha_i \beta_j\, a_i b_j$.
- Postulate: $w^0 = 1$.
- Product is associative, but not generally commutative: $(\omega_1 + \omega_2) * \omega_3 = \omega_1 * \omega_3 + \omega_2 * \omega_3$ and $\omega_3 * (\omega_1 + \omega_2) = \omega_3 * \omega_1 + \omega_3 * \omega_1$.

[6] If this is the case, you can differentiate them by a symbol. For example, if X cannot act in the system, you can refer to it as X^*.

[7] This name is a slightly modification from V. Lepskiy description of the *post-non-classical cybernetics of self-developing reflexive-active environment*.

4.1.3 Back to the poker problem

Let us return to the poker game from the previous section to verify whether poker is a self-developing reflexive-active system. Even though poker is defined by its specific rules, it does not exist without players (even if they are all robots). The matches' dynamics, as indicated before, are determined by a combination of strategic behavior by players and some randomness. Such a behavior means actions based on processed data from the game reality aiming at specific individual goals. Therefore, sequential poker matches can be indeed represented as a self-developing reflexive-active system.

The support ("physical") process T in this case is determined by the rules (i.e. how the cards are mixed, the betting periods, the order of players etc.). Considering four players X, Y, Z and W who have never played together so they do not have any idea about the specific behavior of their opponents (the only known thing is that every player wants to win the game, as in any competition). Before the first match, only the rules exist: $\Omega_0 = T$. In the first match the system comes to life as $\Omega_1 = T(1+x+y+z+w)$, i.e. the match is running and the players are aware of the rules of the game, their individual cards and the public information (open cards and bets). After few matches, only player X inferred how Y behaves based on his perception of Y's aggressive betting behavior. After this operation of awareness done by X, the system becomes: $\Omega_2 = T(1+x+y+z+w+yx)$.

As $\Omega_2 \neq \Omega_1$, the system changed so its dynamics and outcomes, regardless of the correctness of the image Txy. The awareness operations realized by the players change the structure of awareness of the system. This is a fully symbolic operation that can be controlled (or guided). From this perspective, the questions posed before can be answered.

In the first case, two players communicating to each other creates a reciprocal structure; if X and Y communicates, then the system have the following elements: Txy and Tyx. To answer the question about knowing strategies, let us consider that X is a very well-known player so all other players have an image of him so the system shall include: $X(y+z+w)$. In the last case, bluffing should work as follows: a strategic action by one player to create an illusion of the "physical reality of the hidden cards", also creating a future image of – and a certain uncertainty about – that player (i.e. the others would never be sure about that player attitudes). Back to our example, let say that player Y purposefully wants to pass the image of aggressive player so other players may create a guided image of him. We see that Y was indeed able to create such an image of the way of playing poker in X. This image Tyx modifies how X play in a guided way that might be exploited by Y. And, if Y becomes aware of X image, a new image needs to be included in the game reality: $Tyxy$. Then: $\Omega_3 = T(1+x+y+z+w+yx+yxy)$. And, this kind of "psychological" (reflexive) game could go forever.

4.2 The Internet of Things

The name Internet of Things (IoT) indicates that "things" – in contrast to humans – also connect to each other, forming a specific network to exchange data. This is indeed not new: sensor networks are around for many decades. Temperature monitoring in different places provides a simple example. So, what demarcates the difference between IoT and sensor networks? The answer is somehow fuzzy, but we identify two interrelated aspects where the differentiation shall take place: scale and structure. What is this difference then? How the "old" sensor networks and "new" IoT are related?

The IoT concept indicates a massive number of (relatively autonomous) sensors building a communication network, whose role is to acquire data about specific processes ("supporting" processes) *to inform* agents (human or not) to decide about their interventions. This large number of sensors build a structure of information exchange different from traditional small-scale, dedicated sensor networks. Such bigger and structured network is what we call IoT. In the following box, we reproduce the Wikipedia definition of IoT[8].

Definition 4.2.1 — The Internet of Things (IoT). The Internet of Things (IoT) is the inter-networking of physical devices, vehicles (also referred to as "connected devices" and "smart devices"), buildings, and other items embedded with electronics, software, sensors, actuators, and network connectivity which enable these objects to collect and exchange data. The IoT allows objects to be sensed or controlled remotely across existing network infrastructure, creating opportunities for more direct integration of the physical world into computer-based systems, and resulting in improved efficiency, accuracy and economic benefit in addition to reduced human intervention. When IoT is augmented with sensors and actuators, the technology becomes an instance of the more general class of cyber-physical systems, which also encompasses technologies such as smart grids, virtual power plants, smart homes, intelligent transportation and smart cities. Each thing is uniquely identifiable through its embedded computing system but is able to interoperate within the existing Internet infrastructure. Experts estimate that the IoT will consist of about 30 billion objects by 2020.

Wikipedia provides a broad definition of IoT. This definition covers the previously mentioned sensor networks. It also includes a new common-sense understanding[9] that considers IoT as a sensing technology linked to mobile applications to track individual behaviors related to, for instance, physical activities; the list of possible applications is almost infinite. While acknowledging all these, we rather use IoT as a very specific concept, opening up a path for scientific theory that shall guide practical deployment. However, before we provide such a definition, we shall go through a brief discussion about large-scale infrastructures.

From Oxford dictionary, infrastructure is[10] *the basic physical and organizational structures and facilities (e.g. buildings, roads, power supplies) needed for the operation of a society or enterprise*. A more detailed definition is given by the USA National Research Council in its 1987 "Infrastructure for the 21st Century" framework for research agenda [3], which includes examples and the social function of large-scale infrastructures.

> Public works infrastructure includes both specific functional modes – highways, streets, roads, and bridges; mass transit; airports and airways; water supply and water resources; wastewater management; solid-waste treatment and disposal; electric power generation and transmission; telecommunications; and hazardous waste management — and the combined system these modal elements comprise. A comprehension of infrastructure spans not only these public works facilities, but also the operating procedures, management practices, and development policies that interact together with societal demand and

[8] https://en.wikipedia.org/wiki/Internet_of_things

[9] For example: https://www.theatlantic.com/technology/archive/2015/06/the-internet-of-things-you-dont-really-need/396485/

[10] https://en.oxforddictionaries.com/definition/infrastructure

> the physical world to facilitate the transport of people and goods, provision of water for drinking and a variety of other uses, safe disposal of society's waste products, provision of energy where it is needed, and transmission of information within and between communities.

Infrastructures are then the substrate of a specific kind of social relations; as they are not given, but human-built through technology targeting a specific use, they are also technological systems. Therefore, large-scale infrastructures – when functioning (i.e. when things are flowing) – are techno-social systems, IoT clearly fits in this definition as a system whose particular operation is flow of data. We are here, however, more interested in the function of *IoT as a layer of data acquisition, processing and dissemination* (although we could, and should, analyze its actual physical infrastructure). IoT builds symbolic reflection of the physical infrastructure to guide agents and their actions to achieve a prescribed goal (e.g. improve the flow of cars in the peak hour). IoT builds then the structure of awareness of techno-social cyber-physical systems, which are defined in the box below.

Techno-social cyber-physical systems

Modern techno-social systems [17] *consist of large-scale physical infrastructures (such as transportation systems and power distribution grids) embedded in a dense web of communication and computing infrastructures whose dynamics and evolution are defined and driven by human behavior.*

A cyber-physical system (CPS)[a] *is a mechanism controlled or monitored by computer-based algorithms, tightly integrated with the internet and its users. In cyber-physical systems, physical and software components are deeply intertwined, each operating on different spatial and temporal scales, exhibiting multiple and distinct behavioral modalities, and interacting with each other in a myriad of ways that change with context.*

[a] `https://en.wikipedia.org/wiki/Cyber-physical_system`

Definition 4.2.2 — IoT as a concept. IoT functions as the structure of awareness of specific techno-social cyber-physical systems, which are special cases of (self-developing) reflexive-active systems.

4.3 Three-layer modeling of systems

We are now ready to present the idea of the three-layer modeling of systems introduced by Kühnlenz and me in [11], but now with some nomenclature changes. The idea is to model systems (as defined in Chapter 1) in order to capture the constitutive relations existing in (a) a given supporting ***physical layer*** that has (physical) limits and constraints, (b) a ***data layer*** that processes and distributes (via a communication network) data acquired from the supporting layer, and (c) a ***decision layer*** whose elements use the processed data – possibly information – to decide about actions to be taken in order to modify all the three layers. In this case, we say that the three layers are *constitutive* since the system dynamics cannot be understood without knowing the relation within and across the three layers.

R Knowing the dynamics within each layer is a necessary condition to model the system but not sufficient to characterize the self-development of the reflexive-active system as a whole.

■ **Example 4.1** Imagine you are an engineer who was asked to design an algorithm to control the movements of a new class of autonomous cars. The first thing to do is to identify the system where the autonomous car will be part of; this system is the traffic system where many other cars, vehicles, human and even animals co-exist sharing the same physical space to move to one point to another. As many others in the system, the autonomous car must be capable of getting data from the surround environment, processing it to obtain information that will be the basis of its (re)action. Figure 4.1 illustrates a possible scenario with autonomous vehicles.

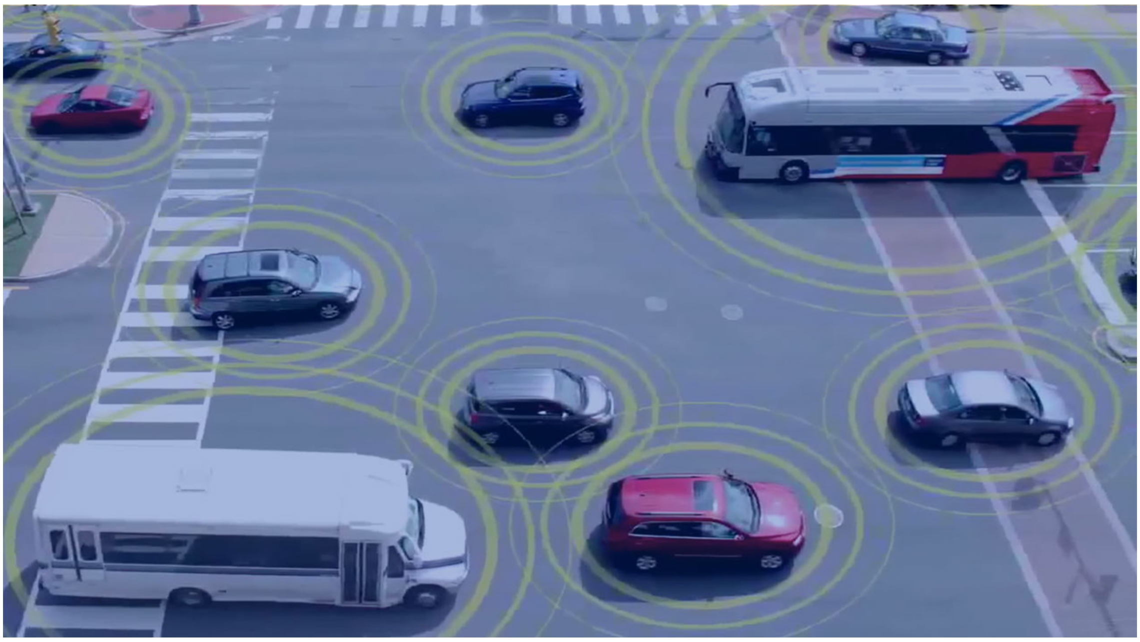

Figure 4.1: Schematic of a traffic system with autonomous vehicles. Source: `https://www.cnu.org/publicsquare/2016/09/06/autonomous-vehicles-hype-and-potential`.

Taking this figure as our basis, we can model the system following the three layer model as follows. The supporting layer is "physical": the road, cars and buses so that cars and buses cannot be at the same location in the road (if this "happens", we have a collision). The road is represented by T while the cars by C_i with i being the number of cars and buses by B_j with j being the number of buses; both cars and buses are agents in the system denoted by Ω. There are "images" in the system: Tc_i and Tb_j (agents know the road conditions, traffic light etc.), and also C_ib_j and B_jc_i (agents know the presence of other agents around it). Yet, there need to be a second level reflection of the kind Tc_ic_k with $k \neq i$ indicating that car C_k has an image of how C_i will react to T. The question that the engineer needs to solve is how to design an algorithm that captures all these level of reflections, which are directly related to the level of process to be evaluated (remember Chapter 2), so that the autonomous car can properly fit within the existing system dynamics, including its structure of awareness. ■

4.4 Assignment

There are three main goals for this weekly assignment: (1) review the previous lectures and apply the concepts in the three-layer modeling, (2) get introduced to agent-based model and multi-agent simulation, and (3) analyze how the structure of awareness affects the dynamic of systems.

5. Probability theory

This chapter follows Chapter 1 from Alberto Leon-Garcia, *Probability, statistics, and random processes for electrical engineering*.

5.1 Assignment

There are two main goals for this weekly assignment: (1) generate random variables in Pyhton and (2) plot empirical probability distributions (histogram).

6. Game theory and decision-making

This chapter follows the *A Brief Introduction to the Basics of Game Theory*[1] [10, Sec. 1] by Matthew O. Jackson. Additionally, the text *Why game theory never will be anything but a footnote in the history of social science*[2] [16] by Lars Pålsson Syll discusses the limitations of game theory, and the Wikipedia page *Decision making*[3] lists different ways of approaching decision-making processes.

6.1 Assignment

There are two main goals for this weekly assignment: (1) analyze scenarios in which game theory models are sound and (2) learn how to assess games in Python.

[1] `https://papers.ssrn.com/sol3/papers.cfm?abstract_id=1968579`
[2] `http://www.paecon.net/PAEReview/issue83/Syll83.pdf`
[3] `https://en.wikipedia.org/wiki/Decision-making`

7. IoT-based systems

This chapter follows the paper Why Smart Appliances May Result in a Stupid Energy Grid?Why Smart Appliances May Result in a Stupid Grid: Examining the Layers of the Sociotechnical Systems[1] [13, Sec. III onwards]. We will go through the analysis step-by-step demonstrating how to use the methodology developed in this course to design “smart appliances” that do not create a “stupid electricity power grid”. The tutorial session will be focused on replicating [13, Fig. 5] with data from Finland[2]. A more detailed analysis of the frequency variations can be found in a recent paper published in Nature Energy[3] [14]. There is no assignment for this week so that the students can focus on the final work.

7.1 Final words

This is the last lecture and I hope the students have learned different tools to analyze and (re)design systems that are based on IoT. In this sense, I hope words like system, data, (mis/dis)information, network, communication, coordination among others are now practical operative concepts. All in all, I would like to reinforce the importance of using the three-layer approach to model (reflexive-active) systems in which IoT functional role is to build their structure of awareness.

[1] `https://lutpub.lut.fi/handle/10024/158697`
[2] `https://data.fingrid.fi/en/dataset/frequency-historical-data`
[3] `https://arxiv.org/pdf/1807.08496.pdf`

8. Bibliography

Books

[1] Albert-László Barabási et al. *Network science*. Cambridge university press, 2016 (cited on pages 21, 24).

[2] Benjamin S. Blanchard and Wolter J. Fabrycky. *Systems engineering and analysis*. Prentice Hall Englewood Cliffs, NJ, 1998 (cited on pages 9, 10).

[3] National Research Council. *Infrastructure for the 21st Century: Framework for a Research Agenda*. Washington, DC: The National Academies Press, 1987. ISBN: 978-0-309-07814-6. DOI: 10.17226/798. URL: https://www.nap.edu/catalog/798/infrastructure-for-the-21st-century-framework-for-a-research-agenda (cited on page 33).

[4] Luciano Floridi. *Information: A very short introduction*. OUP Oxford, 2010 (cited on pages 15–17, 19).

[5] Vladimir A. Lefebvre. *Conflicting structures*. Leaf & Oaks Publisher, 2015 (cited on pages 29, 30).

Articles

[6] Christoph Adami. “What is information?” In: *Phil. Trans. R. Soc. A* 374.2063 (2016), page 20150230 (cited on page 17).

[7] Maria Avgerinou, Paolo Bertoldi, and Luca Castellazzi. “Trends in data centre energy consumption under the European code of conduct for data centre energy efficiency”. In: *Energies* 10.10 (2017), page 1470 (cited on page 19).

[8] Thomas Cover. “Broadcast channels”. In: *IEEE Transactions on Information Theory* 18.1 (1972), pages 2–14 (cited on page 26).

[9] Manlio De Domenico et al. “The physics of spreading processes in multilayer networks”. In: *Nature Physics* 12.10 (2016), page 901 (cited on page 13).

[10] Matthew O. Jackson. “A brief introduction to the basics of game theory”. In: (2011) (cited on page 39).

[11] Florian Kühnlenz and Pedro H. J. Nardelli. “Dynamics of complex systems built as coupled physical, communication and decision layers”. In: *PloS one* 11.1 (2016), e0145135 (cited on pages 29, 34).

[12] Vladimir Lepskiy. “Evolution of cybernetics: philosophical and methodological analysis”. In: *Kybernetes* 47.2 (2018), pages 249–261 (cited on pages 13, 31).

[13] Pedro H. J. Nardelli and Florian Kühnlenz. “Why Smart Appliances May Result in a Stupid Grid: Examining the Layers of the Sociotechnical Systems”. In: *IEEE Systems, Man, and Cybernetics Magazine* (2018) (cited on pages 29, 41).

[14] Benjamin Schäfer et al. “Non-Gaussian power grid frequency fluctuations characterized by Lévy-stable laws and superstatistics”. In: *Nature Energy* 3.2 (2018), page 119 (cited on page 41).

[15] Claude E. Shannon. “A mathematical theory of communication”. In: *Bell Syst. Tech. J.* 27 (1948), pages 623–656 (cited on pages 17, 18, 25).

[16] Lars Pålsson Syll. “Why game theory never will be anything but a footnote in the history of social science”. In: *real-world economics review* (2018), page 45 (cited on page 39).

[17] Alessandro Vespignani. “Predicting the behavior of techno-social systems”. In: *Science* 325.5939 (2009), pages 425–428 (cited on page 34).