Determinism vs. indeterminism: the case of data packet transmission

Sebastian Fortin

CONICET – Universidad de Buenos Aires

Abstract

This paper proposes to address a little explored aspect of the determinism-indeterminism dichotomy, the pragmatic dimension linked to technology. The transmission of voice packets in digital telephony is taken as a case study. This can be implemented by means of multiplexing, which ensures that the transmitted data will reach their destination through a deterministic mechanism. Another option is the use of Internet protocols that are indeterministic and do not ensure the arrival of data. The characteristics of each technology and the reasons for the replacement of one by the other will be analyzed. In particular, the focus will be on the characteristics linked to indeterminism that provide a technological advantage.

Keywords

Determinism; Indeterminism; Digital telephony; TDMA; VoIP.

1.- Introduction

Philosophical reflection on determinism and indeterminism has a long tradition in philosophy, dating back to Aristotle and continuing to the present day. In the metaphysical realm, arguments are made both for and against a deterministic conception of reality. Within the context of modern philosophy of science, the discussion is carried into case studies from the scientific domain, specifically targeting to determine the deterministic or indeterministic nature of fundamental theories. This article seeks to explore a less explored aspect of the determinism-indeterminism dichotomy in philosophy: the pragmatic dimension, focusing on whether, in the implementation of technology, it is more helpful to adopt a deterministic or an indeterministic approach.

In a first analysis, when examining the advantages and disadvantages of both approaches, it seems reasonable to consider that a deterministic theory is more appropriate. This is because a deterministic theory allows the determination of the state of a system at all times. This feature gives rise to more tools so that, for example, an engineer can design a technological application of the theory. Of course, if a deterministic theory is not available but an indeterministic one is, the engineer can still use it to design successful applications, as demonstrated by cases in genetic engineering, nuclear engineering, statistical analysis, etc. However, if the situation allows a choice between two scenarios, namely: (i) a deterministic theory is available, and technological tools allow control over all variables; and (ii) the available theory is indeterministic, and many elements are left to chance, it seems reasonable to always prefer the deterministic scenario. Thus, from a technological perspective, determinism holds a certain preference over indeterminism. However, from a pragmatic point of view, where factors are not only theoretical and metaphysical but also influenced by economic, feasibility, sustainability, and exposure to external environments, the mentioned choice may not be the most reasonable. This article analyzes an example from communication technology where technological advancement initially enabled the implementation of a deterministic framework for data transmission. However, over time, a competing indeterministic rival emerged and gradually gained prominence, ultimately surpassing the original deterministic approach. The reasons for this replacement will be analyzed to conclude that this is not simply a case where an indeterministic technology prevails because it is "cheaper," but rather because it is genuinely better from the standpoint of efficient resource use.

The article is organized as follows. Section 2 summarizes the determinism-indeterminism debate, highlighting its origins in the metaphysical realm and its translation into the field of the philosophy of science and the philosophy of technology. This section also delineates the scenario of interest for this article. Section 3 summarizes the characteristics of the Time Division Multiple Access (TDMA) communication, which is the main model for the deterministic framework applied to modern digital telephony. Section 4 synthesizes the operating principles of the main indeterministic system in current digital telephony, IP telephony. Focus will be placed on the well-known disadvantages of this type of communication that have led to a general preference for the deterministic approach. Section 5 explores the recent success of IP telephony and analyzes the advantages of this technology rooted in its indeterministic nature. Finally, the conclusions are presented.

2.- Determinism and indeterminism

Philosophical reflection on determinism and indeterminism has a long-standing tradition in philosophy that dates back to Ancient Greece and continues to the present day. For this reason, there are different definitions and approaches to the notion of determinism. To simplify, determinism can be described as the idea that the future state of a system is determined by some kind of law or theory based on its past state. Indeed, as Carl Hoefer (2023) discusses in his article in the *Stanford Encyclopedia of Philosophy*, an initial approximation might be articulated as follows:

> "Determinism is true of the *world* if and only if, given a specified *way things are at a time t*, the way things go *thereafter* is *fixed* as a matter of *natural law*." (Hoefer 2023, emphasis in original)

From a philosophical perspective, this notion is closely connected to the idea of causality, as in a deterministic world, every event would have a cause (Earman 1986). On the other hand, when this is applied to the universe as a whole, it is also of great importance in debates about free will: if the complete state of the world is determined, then our future actions would be determined as well (Hoefer 2002, Ismael 2016). In the realm of the philosophy of science, particularly in the philosophy of physics, the orthodox view assumes that there is a set of fundamental laws governing the behavior of all entities. These laws allow us to explain how and why different events occur. In this way, the laws work as the implicit cause of all events (Maudlin 2007), and the discussion about determinism becomes a debate about whether these laws are deterministic or not. This position can be challenged or relativized from various perspectives by questioning the universal status of physical laws (see Lewis 1981, Dupré 2001.) However, this controversy will not be delved into here, as it falls outside the scope of this work.

Discussions about modern scientific theories

The discussions surrounding the determinism of scientific theories are often framed in the terms mentioned earlier. That is, they are formulated in light of whether the “world,” considered as a whole, is deterministic or not. This is why there is interest in studying this aspect of fundamental physical theories. However, setting aside metaphysical reflections on causality and free will, examining the deterministic (or not) nature of different scientific theories has an intrinsic interest. Questions about whether classical mechanics, quantum mechanics, or relativity theory are deterministic or not gain relevance from the point of view of the foundations and philosophy of physics. This relevance is due, among other reasons, to the fact that an answer to these questions can lead to conceptual clarification of the theories themselves. Also, it can provide necessary distinctions, and a refinement of the concept of determinism. For this reason, the seek for universality will be set aside in what follows. The “world” will no longer be the entity whose determinism is investigated; instead, a specific “system” of interest will be adopted as the subject of study. An example of this perspective can be highlighted within the realm of classical mechanics.

Studying a particular system, certain practical issues arise and give rise to the distinction between ontic and epistemic determinism (Atmanspacher 2002). Let us suppose that a conservative force is applied to a classical system that is in a given state and it is governed by the Newton's laws. In this case, it is possible to find a set of equations that uniquely determine its evolution. This might lead one to mistakenly believe two things: (i) from the state of the system at a given moment, it is possible to compute its state at any other moment, and (ii) it is possible to empirically predict the behavior of a real system based on the measurement of its state and the application of the laws. Although in many cases (i) and (ii) remain feasible in practice (with a reasonable margin of error), this is not always the case. For example, in systems where multiple subsystems interact, the resulting mathematical equations can become so complex that they cannot be solved. In some cases, equations lack analytical solutions, as seen in the “three-body problem.” On the other hand, it is not possible to determine the exact state of a system through measurements, only an approximation with some degree of error can be computed. This makes it impossible to predict the behavior of a chaotic system, whose equations yield very different results when using very similar initial conditions. Thus, although the theory is deterministic, it is practically impossible to account for this determinism. At this point, the distinction between ontic and epistemic determinism is introduced (Lombardi 2002, Sartenaer 2015). In the example system, given the initial conditions, its future state is determined by the laws, making the system ontologically deterministic. However, there is epistemological indeterminism because it is impossible for any observer to know that future state. The distinction between ontological and epistemological determinism is an addition that results from introducing the pragmatic dimension into the debate, thereby enriching the epistemological and metaphysical discussion. The presented case shows that real classical systems are epistemologically indeterministic but can be described by a deterministic theory. This raises the question of whether it is possible to construct another theory that describes the same phenomena but in an ontologically indeterministic manner. More generally, Hoefer (2023) frames the issue as follows:

> “if, in nature, we find a type of system that displays some or all of these latter properties, how can we decide which of the following two hypotheses is true?
>
> 1. The system is governed by genuinely stochastic, indeterministic laws (or by no laws at all), i.e., its apparent randomness is in fact real randomness.
> 2. The system is governed by underlying deterministic laws, but is chaotic.”

In the cited article, it is mentioned that according to Patrick Suppes (1993, 1996), it is possible to use the Ornstein’s (1974) theorems to assert that some processes can be described interchangeably either as deterministic systems of classical mechanics or as indeterministic Markov processes. Indeed, Suppes concludes that

> “Deterministic metaphysicians can comfortably hold to their view knowing they cannot be empirically refuted, but so can indeterministic ones as well.” (Suppes 1993, p. 254)

A similar situation occurs with standard quantum mechanics, which is indeterministic but empirically indistinguishable from Bohmian quantum mechanics, which is deterministic (Tumulka 2021). In summary, in the study of the nature of a real physical system, it is possible to adopt a perspective with deterministic metaphysical assumptions and develop a theory that correctly describes its deterministic and indeterministic aspects at the epistemological level. Conversely, it is also possible to adopt a perspective with indeterministic metaphysical assumptions and develop a theory that accurately describes its deterministic and indeterministic aspects at the epistemological level.

Therefore, even when the claim to universality is discarded, and even when focusing on a specific type of system, a definitive argument for choosing either a deterministic or an indeterministic approach cannot be provided. Eventually, the decision may be influenced by pragmatic considerations, personal preferences, or convenience.

Determinism and indeterminism in technology

This article aims to explore the pragmatic dimension of the determinism-indeterminism dichotomy. Specifically, it will focus on the question of whether a deterministic framework is always more helpful than an indeterministic one in the implementation of a technological application. Before delving into the discussion of the specific case, it is helpful to make some clarifications that will allow us to specify which aspects of the example are pertinent and which are not.

The debates mentioned in previous subsections seek to address questions regarding the deterministic or indeterministic nature of scientific theories and the world they represent or attempt to represent. Cases such as classical mechanics versus Markov chains, and quantum mechanics versus Bohmian mechanics, have been cited. These are instances where there are two theories, one deterministic and the other indeterministic, which describe the same phenomena and make the same predictions, i.e., they are empirically equivalent. From this point onward, the focus will shift away from the case of empirically equivalent rival theories. Now the central point will be on the advisability of using a deterministic approach versus an indeterministic one in cases where the indeterministic approach accounts for fewer variables than the other. In other words, a deterministic theory that accounts for all observable aspects of the system will be compared against an indeterministic theory that accounts for some observables but not others.

A preliminary approach to the problem could suggest that a theory is better and more desirable when it offers more and better explanations and predictions. Faced with a given phenomenon, it seems reasonable to choose a deterministic theory because it can specify the value of all the observables of the system. In this way, given a particular situation, it can offer a prediction for every possible measurement of the system. In contrast, an indeterministic theory will provide predictions for some measurements but cannot predict the outcome of others. Moreover, in technological applications, the objective is to configure a set of components to produce a given effect. To implement this configuration, laws and theories are employed to provide a foundation for the functioning of the devices. This allows for the relevant variables to be kept under control, ensuring that the desired effect is achieved. For this reason, having deterministic laws and theories is advantageous, as they enable control over variables and, therefore, they are more favorable than indeterministic ones. However, this assertion, as it is formulated, may be open to objections if certain clarifications are not made. Therefore, various cases of applications based on laws or theories are presented below, highlighting the importance of relevant variables for specific implementation.

Deterministic theories that improve the results of indeterministic theories

In certain cases, to achieve a specific technological goal, employing an indeterministic theory might yield acceptable results. However, using deterministic theories can significantly enhance those results. Agricultural production technology, in particular, serves as a good example of this scenario.

For different reasons, there is a need to develop plant varieties with specific characteristics, such as drought tolerance (Monneveux et al. 2013). One approach to do this is through classical plant breeding based on Mendel’s laws. These laws are considered indeterministic because they do not allow for precise predictions of the genetic traits in a plant variety when it is obtained from two genetically distinct parents. However, Mendel’s laws provide probabilities for a plant variety to possess certain traits. This allows for a series of breeding experiments that can produce plant varieties with the desired characteristics. Traditional techniques for creating new plant varieties rely on these principles and have resulted in significant advancements. However, this process is often slow and may not succeed when the genetic probabilities do not favor the desired outcome.

A more modern technique is genetic manipulation, this method involves adding or removing genes from a plant. This approach is deterministic because it relies on the principles of modern molecular biology, which assert that a plant’s traits are largely determined by the information encoded in its genetic material, such as DNA molecules. By altering, modifying, or removing specific parts of these molecules, it is possible to introduce the desired traits through direct manipulation without relying on probabilities. While techniques based on these principles are still under development and face several challenges and setbacks, they clearly demonstrate success in achieving the intended goals. These techniques are currently being used to develop plants with new characteristics in a more precise and faster manner, especially in cases where traditional methods have failed (Nicholl 2008). An example of this is the insertion of the Hahb-4 gene, found in sunflowers and responsible for drought tolerance, into wheat and soybean varieties to produce seeds for drought-resistant wheat and soybean plants (Ribichich 2020).

Indeterministic theories better than deterministic ones

The previous example illustrates a case where the introduction of a deterministic theory allows for greater control over variables and can increase the desired technological outcomes. However, describing, predicting, and controlling more variables is not always better. This can be illustrated by using gas theory to compute environmental control systems like heaters and air conditioners.

Thermodynamics characterizes a gas as a system with three variables: pressure, volume, temperature (and the number of particles). With this system description and through a series of simple laws, it is possible to compute the gas's behavior in different situations and how it will exchange heat with other elements. By applying this theory to, for example, home heating systems, it is easy to determine which type of heater is required for a particular house. From a microscopic perspective, the gas contains particles (molecules), each with a specific position and velocity. However, thermodynamics does not allow the computation of each particle's position and velocity; in fact, these are not even included among its variables. Consequently, although thermodynamics can deterministically compute pressure, volume, and temperature, it cannot account for all the microscopic variables of the system. Thus, from a microscopic pint of view, thermodynamics is an indeterministic theory.

There are other theories that provide a more detailed description of the behavior of a gas. For example, classical mechanics could describe the entire gas deterministically, accounting for the position and velocity of all particles. However, even if it were possible to use such a theory, the adoption of a formalism with more degrees of freedom adds complexity to the computations. This, require more theoretical and computational resources. In the case of the specific application being considered (heaters and air conditioners), it is not necessary to know the positions and velocities of all particles; it is sufficient to compute pressure, volume, and temperature. Therefore, the introduction of theoretical complexity and the expenditure of computational resources are not justified, as they offer no tangible benefits. Thus, in this case, the adoption of a deterministic theory is not advantageous.

The last two examples do not present any significant novelty, as they align with common sense. When a deterministic theory provides a more comprehensive description of the relevant variables for a technological application, it offers greater control over the aspects of interest within the system. Thus, it is preferable to an indeterministic theory that does not offer such control. On the other hand, when a deterministic theory offers greater control over variables that are irrelevant to the technological application, it is better to stick with the indeterministic theory. In the following sections, we will explore a different case, where, counterintuitively, a deterministic framework is replaced by an indeterministic one, despite the latter providing a poorer description of the system's variables of interest.

3.- Deterministic communication: Time-division multiple access

The following case concerns the technological implementation of digital information transfer from one point to another. Specifically, attention will focus on the transmission of digital audio packaged in frames modulated by Pulse-Code Modulation (PCM) within digital telephony. Digital telephony encompasses many variations and has reached a high level of complexity, making it difficult to summarize its operation in a few words. However, to begin explaining how digital audio is transmitted between two points (such as two different buildings or cities), a basic operational framework like the following can be considered:

1. Digitization: The sound captured by the phone's microphone is converted into an analog electrical signal, which is then encoded into a digital signal, producing a series of bits.
2. Multiplexing: The digital signal, with the recipient's user number information, is introduced into a multiplexer. The multiplexer has the function of simultaneously transmitting the signals of several different communications to the destination.
3. Transmission through the physical medium: The signal generated by the multiplexer is transmitted via a cable, fiber optic, or a similar medium to the destination point.
4. Recovery of sound: Once the multiplexed signal reaches its destination, the digital signal of interest is separated from the rest, used to reconstruct the original analog signal, and then reproduced through a speaker.

Below we will show how this type of telephony works in a little more detail.

What Is Transmitted

In telephony, the goal is to capture the sound produced by a person speaking at point A and immediately reproduce it at point B so that another person can hear it. The sound picked up by the microphone at point A generates an analog electrical signal, which can be transported to point B for reproduction through a speaker. However, for different reasons, it is more convenient to convert this signal into a digital form for transmission. Schematically, the process is: first, the sound is captured by a microphone at point A; then, the analog signal is converted into a digital signal; next this digital signal is then transmitted through the communication network to point B, where it is reconverted into an analog signal and finally reproduced through a speaker.

The standard method for digitizing an analog signal involves sampling it at regular time intervals. Based on the signal's value at each sample, a number between 0 and 255 is assigned. In this way, the signal's value at each time interval can be represented by an 8-bit binary number. According to the G.711 standard of the International Telecommunication Union (ITU-T 2000), must be taken 8000 samples per second, generating 64,000 bits per second (64 kbps) that must be transmitted from point A to point B.

How it is transported

Once the audio signal is digitized, it can be transmitted through a physical medium such as a cable, fiber optic, radio signals, etc. It is important to note that, due to the cost of setting up the necessary infrastructure for data transmission, it is generally not reasonable to implement it for a single communication. However, in cases where multiple telephone communications are established simultaneously, such as between two buildings or two cities, installing a communication system becomes practical. Thus, a technique that allows the transmission of multiple data packets over the same cable is required.

The technique that enables the transmission of multiple communications over the same medium is called multiplexing or multiple access. Schematically, multiplexing works as follows (see Figure 1): the 64 kbps data-flow generated by each source enters into the multiplexer, which then transmits a single signal to the destination point. At the destination, the signal is processed by a demultiplexer, which separates the data stream into its original channels.

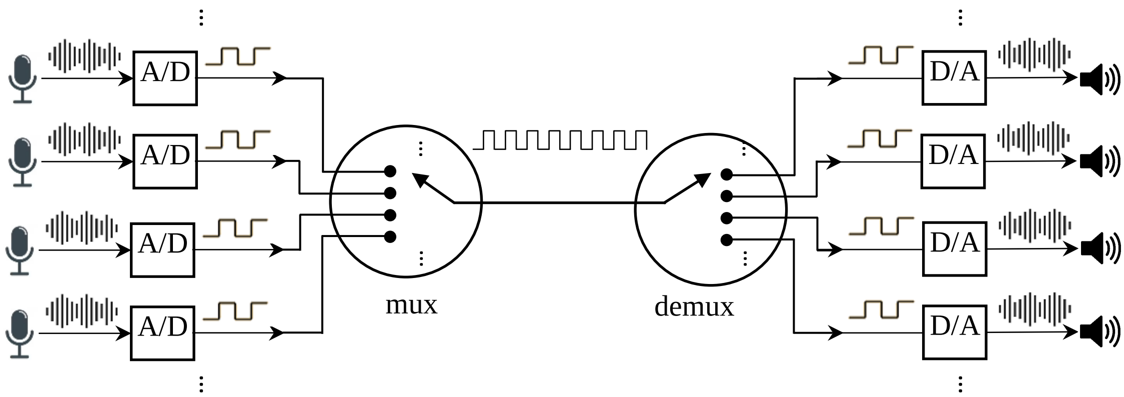

Figure 1. Diagram of voice transmission via time-division multiple access. The microphone captures the sound and converts it into an analog electrical signal, then the signal enters the analog-to-digital converter (A/D), producing a digital signal. The multiplexer then interleaves data from various sources onto a single cable. At the destination, the demultiplexer separates the signals, and the digital-to-analog converters (D/A) transform them back into analog electrical signals, which are connected to speakers.

The most used system for multiplexing digital audio signals is Time Division Multiple Access (TDMA). In this system, the idea is to assign the transmission medium to each channel for a given time period and then rotate among them. To illustrate this concept, consider the following example: we want to transmit 64 kbits from a data source (Channel 1) and 64 kbits from Channel 2, both within one second, over the same cable. First, the data flow from each channel is fed into the multiplexer, which will transmit 8 bits from Channel 1, then 8 bits from Channel 2, then 8 bits from Channel 1 again, and so on until all data is transmitted. At the destination, given that the multiplexer interleaves packets from different channels, the demultiplexer will separate the data packets from each channel. In total, 128 kbits are transmitted, 64 kbits from each channel, so to complete this task within one second, the multiplexer must operate at a speed of 128 kbps. In a real system, multiple channels are transmitted, not just two, and the data stream includes control and routing information.

The Latin American and European system for digital voice channel transmission uses the E1 format, which consists of a 256-bit frame divided into 32 channels of 8 bits each. Two of these channels are assigned for control and signaling, leaving 30 channels available for transmitting voice data. Since the G.711 standard requires each channel to operate at 64 kbps, the total frame rate for E1 is 2048 kbps (UIT-T 2000).

Deterministic communication with TDMA

When a user at point A wishes to establish a telephone call with a user at point B, the user dials the subscriber number. The telephone exchange determines whether there is a free channel in the E1 frame. If no channel is available, the user is informed that the communication cannot be established due to congestion. However, if a channel is available, it is assigned to the requesting user. If the user at point B answers, the communication is established, and the channel remains allocated until one of the users terminates the call. For example, in the case of the E1 format, the process of establishing and monitoring the communication is regulated by the G.732 standard (UIT-T 2000). As shown in Figure 2, the data frame is divided into 32 time slots, of which 30 are used for transmitting voice data and 2 for control data.

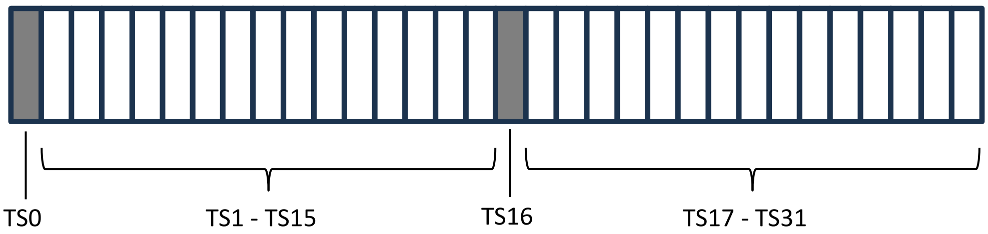

Figure 2. Time Slot (TS) Allocation in an E1 Frame. Time slots 0 and 16 are reserved for control data related to call setup and termination, synchronization, alarms, messages, etc. The remaining time slots are used for transmitting voice data.

Through the exchange of data between sender and receiver via time slots 0 and 16, communication is established and its stability is ensured. Specifically, these dedicated time slots are used to: (i) check if a channel is available for transmission, (ii) assign an exclusive channel for the communication, (iii) verify that the data has reached the destination, and if it has not, retransmit the data, (iv) apply an error control algorithm to ensure that the data sent by the sender matches the data received by the receiver; if an error is detected, the data is retransmitted. These channels are also used to monitor the signal status at both ends, send alarm signals, among other functions.

While the previous sections referred to the study of determinism or indeterminism regarding the ultimate nature of the world or physical systems, in the case of digital communication, the question of whether the components of a telephone exchange are ultimately governed by deterministic or indeterministic fundamental laws is pragmatically irrelevant. In this context, the focus shifts not to the ultimate nature of the hardware, but to the aspects that are relevant for communication. This communication system is deterministic because all aspects related to data transmission are pre-determined. Before transmitting data, a fixed channel is assigned, ensuring that once the communication is established, the channel will be dedicated to that conversation, and the data will follow that path and arrive at its destination without errors. In other words, due to the design of the system, when it operates normally, it is certain that a transmitted data packet will reach its destination, and the path it will take within the network is known in advance. Another feature that arises from this determinism is that it is not possible to establish more connections than the system allows (30 in the case of an E1 frame).

In summary, with TDMA, a dedicated and predetermined physical path is established for the call from the origin to the destination throughout the entire communication. On one hand, this ensures a constant audio quality, and on the other hand, it means that the network's capacity is used exclusively for that call. As will be discussed in the following section, this contrasts with what happens in indeterministic communication.

4.- Indeterministic communication: Voice over IP

In the previous section, the basic principles of the TDMA system were summarized, and the general guidelines for its implementation in an E1 frame were illustrated. The TDMA system maintained its dominance in private telephone systems for a long time, and organizations with locations in different areas implemented telephone communication networks based on this scheme. With the increasing use of networked computers (via an intranet or the internet, for example), the implementation of computer networks using different communication protocols became necessary. These computer networks were established in parallel to the existing telephone networks. Due to several factors, the approach to interconnecting computers followed different principles from telephony, leading to the development of distinct protocols such as IP (Internet Protocol), which is now also used in telephony.

IP Telephony Protocols

IP telephony, Voice over IP, or VoIP, refers to telephony systems that transmit their data over computer networks. The operation of IP phones is identical to that of traditional phones; that is, the number is dialed, the call is answered, and conversation proceeds. However, the internal functioning is entirely different. While the complete process of voice transmission in IP telephony can be complex and it is difficult to summarize, it can be understood schematically as including a series of basic steps:

1. Digitization: The sound captured by the phone's microphone is transduced into an analog electrical signal, which is then digitized in the same manner as in the previous section.
2. Packetization: The data is divided into packets containing the necessary routing information.

3. Transmission through the IP network: The data is transmitted over the IP network, which can be a private network (intranet) or the public network (internet).
4. Sound recovery: At the receiving end, the packets are received, the digital signal is retrieved, and the original sound is reconstructed.

The process of audio digitization is the same as that used in TDMA, so it does not require further elaboration. In what follows, the focus will be on the aspects relevant to this article, namely, its indeterministic nature. For this intention, it is useful to concentrate on the characteristics of steps 2 and 3 in this type of communication.

Packaging

Once the audio has been digitized, the data must be delivered to the receiver, where the audio signal must be reconstructed. To make this possible, it is necessary to prepare the data by adding information required for the transport. To explain this process, an analogy with postal services is commonly used: if one wishes to send a watch to another person on the other side of the planet, the package must be prepared for shipping. This preparation includes wrapping the watch, placing it in a box, adding a label with the recipient's and sender's addresses, etc. In the case of data transport in computer networks, the preparation of the digital packet involves two stages.

The first stage consists of taking the data generated during digitization, dividing it into small fragments, and assembling a sequence of bits that includes not only the digital audio data but also messages between the applications at the sender and receiver. These messages are sent by adding a small sequence of bits, or a header, with information necessary for the receiver to identify this segment of information as part of the ongoing communication. Although various protocols can be used for this purpose, the UDP protocol (User Datagram Protocol), governed by standard RFC768 (Postel 1980), is commonly employed. Unlike the protocols used in TDMA, UDP does not establish a permanent connection between sender and receiver, does not verify if the receiver is ready to receive data, does not confirm if packets were received, does not implement flow control, nor does it ensure that packets arrive in the order they were sent. In other words, it does not guarantee that the information will reach its destination correctly. However, it does offer the receiver the possibility of checking for errors in the received information. If an error is detected in a packet, it will be discarded but not retransmitted, as the sender does not retain already sent packets. UDP provides a very basic service but is fast and does not require substantial computing resources.

After UDP adds its header, in the second stage the data segment is appended with the necessary information for the transport within the network, primarily the source and destination addresses. Usually, there is no direct connection between sender and receiver, then, the network must be used to route the packet through various nodes until it reaches its destination. To achieve this, considering the characteristics and status of the available network, routers must determine the best path to take. In the case of packet data transport in IP telephony, this logistical function is managed by the IP protocol specified in RFC 791 (Postel 1980) or RFC 2460 (Deering and Hinden 1998). This protocol is responsible for routing packets within the network to their destination. Therefore, when packets are delivered to the network, they include the fragmented digital audio data, a UDP header, and an IP header, as illustrated in Figure 3.

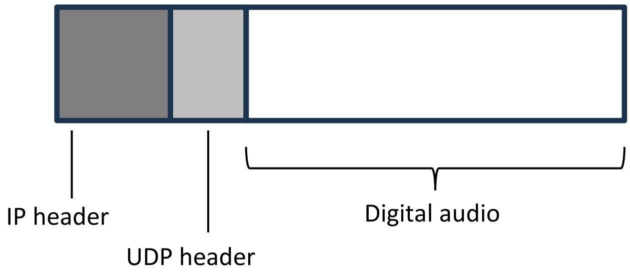

Figure 3. Diagram of the format of packets transported over the network in IP telephony.

Comparing Figure 2 with Figure 3, it is possible to observe a fundamental difference between TDMA and VoIP. In TDMA, it is necessary to use two headers (TS0 and TS16) for the transportation of data from 30 communications, whereas in the VoIP, individual packets are sent, each with its own header. This distinction will have consequences that will be detailed below.

Transport

Contrasting with the protocol discussed in the previous section, UDP/IP communication does not establish a connection between the sender and receiver, making it a connectionless system. It is responsible for transmitting data packets from the sender to the receiver without verifying that the receiver is available and ready to receive the data. Once the data packet is assembled, it is sent to the router, which reads the destination address and, based on the available information about the network's state, forwards it to another router that brings the packet closer to its destination. As described in the previous section, TDMA establishes a physical connection between the sender and receiver during a time window that repeats periodically through a multiplexer. In IP networks, routers manage packet transmission differently. Instead of assigning a fixed time slot to each communication, packets are transmitted as they arrive, one after the other without a predefined order (Figure 4 illustrates this process for communication between two routers).

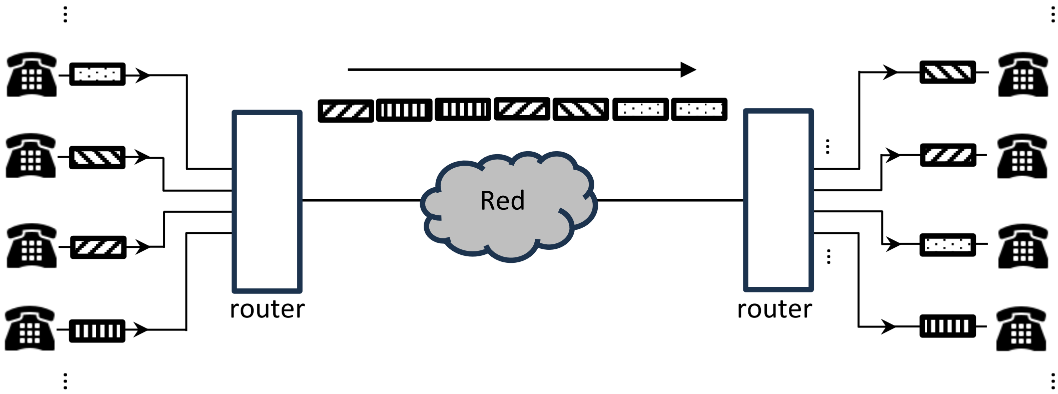

Figure 4. Diagram of packet transmission in an IP network. There is no connection assigned to each communication, but packets are sent as they arrive.

This way of transmitting packets gives rise to several differences with TDMA that configure its indeterministic character, among which the following stand out:

i. In TDMA, a time slot is assigned to each communication, so each sender transmits its digital voice signal at the designated time intervals. In IP telephony, none of this is predetermined; IP phones send packets to the router in an uncoordinated and random manner as they are generated. For example, when there is silence in the conversation, the phone does not send packets, whereas it does send packets when someone speaks, making packet transmission completely random.

ii. Since TDMA coordinates the timing of each sender's access to the channel, it is predetermined when, and for how long, each sender can transmit over the physical medium. In other words, when the sender transmits data, the transmitters are prepared to transmit. In VoIP, this is not always the case. When a phone sends a packet to the router, the router may be either free or occupied with another transmission. If it is free, the packet is transmitted; if it is occupied, the packet is stored in a buffer until the router becomes available and can transmit it. The timing of when packets from a given conversation will be transmitted is not predetermined.

iii. In TDMA, data arrives at regular intervals, whereas with VoIP, packets arrive at irregular and unpredictable intervals. This is because packets are sent as router availability permits, which depends on random factors such as the amount of traffic the router is handling at that moment.

iv. In TDMA, data delivery to the destination is guaranteed due to the allocation of an exclusive channel, while in IP telephony, if there are many simultaneous packet transmission requests, the buffer may fill up and packets may be lost.

v. In TDMA, there is a fixed number of available channels, with each communication assigned an exclusive channel. For instance, in E1, there is capacity for 30 simultaneous communications, and a 31st communication cannot be established. This is because the line bandwidth is 2048 kbps, and with each channel allocated 64 kbps, there is capacity for only 32 channels (30 for audio and 2 for control). In VoIP, the concept of a channel is less rigid because packets are accommodated in the physical medium as they arrive, so new communication requests can be accepted as long as the buffer does not become saturated. Thus, more than 30 communications can be accommodated within a 2048 kbps bandwidth, at the cost of not guaranteeing 64 kbps for each communication, which affects service quality. If the buffer is not full, there will be communication delays, and if it becomes full, packets will be lost.

The UDP and IP protocols are designed to operate in networks where packet delivery is unreliable. For this reason, various techniques are implemented with the aim of attempting to deliver the data to its destination, but without providing guarantees of success.

Indeterministic quality of service

As you can see from the way UDP and IP work, telephone service quality can be poor under certain circumstances. Contrasting TDMA, where a physical channel is dedicated to each communication, this type of communication suffers from typical computer network issues related to the balance between high traffic and available bandwidth. Specifically, internet protocols introduce a series of well-known difficulties.

When a data packet enters into the network, its successful delivery to the destination cannot be promised; some packets may be lost along the way. This can be due to a link with a high error rate, buffer overflow in routers, etc. When the network is used for other types of issues, such as transferring a file from one computer to another, mechanisms can be introduced to check the received file and, if there is a lost packet, it is possible to request the sender to retransmit a copy. In this way, lost packets are recovered at the expense of delaying the transmission. However, telephony involves real-time data transmission, making it impossible to implement such mechanisms, resulting in vocal distortion from *lost packets*.

Another characteristic of IP networks is that the time interval between receiving one packet and the next is not constant. This is because the time it takes for a packet to arrive, depends on the traffic, the path it took, and temporary synchronization losses, etc. As each packet takes a different amount of time to arrive, some packets may not arrive in the order they were transmitted. This problem, known as *jitter*, also affects audio quality, introducing issues such as echoes, distortions, or late-arriving packets.

Latency, or delay, is the time it takes for a signal to travel from source to destination. If this delay is perceptible, it may cause that in a bidirectional phone conversation one party start speaking because nothing is heard from the other side. As the audio takes a long time to arrive, the other participant also starts talking, believing that the other person is silent, so that both end up talking at the same time or both remain silent, making communication difficult. This phenomenon is not exclusive to IP communication, as it also occurs in satellite links or long-distance communications requiring multiple retransmissions. However, IP networks tend to increase latency because the process of a router receiving a packet, checking its destination, deciding the best route, and forwarding it takes time; moreover, a packet may pass through several routers on its way from source to destination.

Packet duplication occurs when two copies of the same packet arrive at the destination at different times. This can happen due to errors in a highly congested and unstable network router. Since UDP does not include duplicate packet detection, it can introduce noise into the telephone communication. This issue, like packet loss, could be addressed by using a more advanced protocol such as TCP (Transmission Control Protocol), which employs various control mechanisms to make packet transmission more reliable (Kurose and Ross 2017). However, introducing such protocols or additional control mechanisms would increase latency and jitter to levels that would significantly reduce audio quality. In the realm of telephony, it is preferable to lose some packets and have a fluid conversation with noise than to have reliable but slow communication filled with overlaps and silences.

Due to these challenges in IP telephony, it is necessary to implement various strategies to increase communication quality. One obvious option is to increase the network's bandwidth to support more traffic, thereby reducing congestion and delays. However, this strategy has limits, as it involves costs for routers and cabling, and such expansions may also increase latency. For this reason, protocols at the application layer are typically used to compensate for the unreliability of UDP and IP. In other words, since transport (UDP) and network (IP) protocols do not guarantee communication quality, an intermediate step is added between digitization and packaging to address UDP and IP deficiencies as much as possible. These strategies are implemented in what is commonly known as the application layer and can be challenging, as adding steps to the communication process may introduce new problems or exacerbate existing ones. Typically, such improvements are implemented in the Real-time Transport Protocol (RTP) and the Session Initiation Protocol (SIP), regulated by RFC1889 (Audio-Video Transport Working Group et al. 1996) or RFC3550 (Schulzrinne et al. 2003) for RTP and RFC3261 (Rosenberg et al. 2002) for SIP. It is important to note that these protocols do not modify the way packets are constructed and transmitted but rather facilitate processes that occur before UDP packets are assembled at the sender and after they are received at the receiver.

Attempts to improve quality

Given that high network traffic can cause congestion that degrades communication quality, one strategy is to reduce traffic. This can be done by compressing data packets through some form of encoding. By encoding, the same information occupies fewer bits, thus it reduce the total network traffic. However, this cannot be done with 8-bit samples; for data compression to be efficient, several samples must be grouped together and compressed at once. For example, the G.711 standard used in TDMA does not compress the data, and each sample is transmitted as it is generated, as explained in Section 3; thus, an 8-bit frame is produced every 0.125 ms, requiring a transmission rate of 64,000 bits per second. On the other hand, the G.729 compression standard (ITU-T 2012) used in IP telephony collects 80 samples of 8 bits in 10 ms, i.e., it gathers 640 bits and then compresses them to occupy 80 bits. In this way, only 8,000 bits per second need to be transmitted, reducing network traffic by an order of magnitude compared to G.711. This reduction in network traffic decreases the probability of congestion, which causes packet loss, but it has a consequence. On the one hand, audio compression degrades audio quality, theoretically in a way that is not very perceptible to the human ear when dealing with human voice. However, it produces an effect that users describe as a loss of “clarity” in the voice (Hardy 2003). More importantly, this loss of quality makes it impossible to transmit music or FAX signals. Furthermore, to implement G.729, both the sender and receiver must have a circuit or software capable of storing the 80 samples and performing the compression and decompression operations, requiring more advanced and expensive equipment. Additionally, since the samples are stored for 10 ms before being transmitted, undesirable effects such as latency, round-trip delay, and echo are increased.

As mentioned, when transmitting data via UDP, IP, and RTP, some bits must be added to indicate the source address, the recipient, and some control data: in total, 320 bits are added to the header. This is a significant amount of data when compared to the 80 bits of the frames that G.729 produces every 10 ms, i.e., 8,000 bps. If the frames are transmitted one by one, then the total of useful data plus headers requires a transmission speed of 40,000 bits per second, meaning that most of the bandwidth is used for addressing and control information rather than transporting the cargo. One way to mitigate this problem is to assemble larger packets so that fewer packets are transported, but this will increase latency, delay, and echo. Another approach is to introduce header compression, which requires increased computing power and also increases latency, delay, and echo, though to a lesser level.

In summary, packet transport across the network is always carried out using UDP and IP protocols, which inherently involve issues of latency, packet loss, jitter, and echo. The incorporation of compression, RTP, and SIP helps to mitigate these problems to some extent but does not eliminate them and introduces its own challenges. With careful and thoughtful network design, satisfactory telephone communications can be achieved under normal network conditions. Nonetheless, transport remains indeterministic because packets are transmitted across the network using UDP and IP. The key difference between TDMA-based communication and IP-based communication is that, in the fist, a dedicated path is established exclusively for the call from the source to the destination for the entire duration of the communication, ensuring that the data will arrive at the destination without errors, interruptions, or delays, thus providing consistent audio quality. In contrast, in IP telephony, no dedicated path is established exclusively for the call; instead, data packets are transmitted over a network that carries all kinds of data and are exposed to loss or delay. As a result, service quality cannot be guaranteed; at best, the goal is to provide the best possible service under given circumstances, but without any certainty. The challenges of IP telephony might suggest that it is inferior to traditional TDMA; however, there are several reasons why organizations today are increasingly opting for IP over TDMA.

4.- The advantages of an indeterministic approach

In the previous section, the basic principles of IP telephony were summarized in a simplified way, and some of its main challenges were outlined. The origin of these challenges lies in the fact that there is no dedicated channel for each communication; rather, packets are sent into the network for routers to somehow decide which path will be used to attempt to deliver them to their destination. That is, the origin of these problems is its indeterministic nature. The fact that the indeterministic nature of this approach is closely related to reliability problems is the main reason why the deterministic scheme dominated the telecommunications world for decades. However, in recent years, IP telephony has spread widely and now accounts for between 30% and 50% of the telephone market, competing with TDMA (Research and Markets 2021). This translates to financial reports predicting that the volume of the telephony market will grow from $85.2 billion in 2021 to $102.5 billion in 2026 (Persistence Market Research 2023). This reflects the replacement of a reliable technology with one that has traditionally been considered inferior. The following section will analyze the reasons for this shift in the implementation of communication systems.

Economic aspects

The simplest way to explain this technological replacement is by focusing on the economic aspect, as an organization that chooses the indeterministic approach can save money. This is because the traditional way of setting up infrastructure for, say, a company involves implementing one network for computers and another for telephony. For the computer network, internal cabling with corresponding connection panels at each workstation is needed, along with the purchase and installation of routers, etc. Implementing the telephone network also requires cabling, but of a different type; different types of cables, connection panels, etc., are used. Therefore, the expenses for cables, equipment, installation technicians, and maintenance workers to ensure the proper functioning of both networks are doubled. In contrast, IP telephony operates over the computer network infrastructure, leading to savings in installation, maintenance, and operation. Furthermore, due to its massive adoption, the hardware for IP networks is less expensive than that used for traditional telephony. The same applies to technical staff: because of the large number of specialists in IP networks, it is more economical to operate and maintain this type of network. Additionally, the ability to use the internet for transmission reduces the cost of long-distance and international calls.

Without a doubt, the economic factor is important, but this advantage is not intrinsically coupled to the indeterministic nature of IP telephony. Instead, it stems from other factors, such as the availability of a large number of professionals in this field. For this reason, the economic aspect is not a legitimate advantage attributable to the indeterministic nature of the approach. What follows will attempt to argue that the choice is not simply based on the fact that “it is cheaper,” but rather that there are certain aspects of this approach that represent a real advantage beyond the cost of implementation, operation, and maintenance. There are several advantages of IP telephony that are a direct consequence of its indeterministic nature. Some of these advantages arise in situations where the data traffic within the network undergoes abrupt changes.

Functional aspects

The fact that there is no predefined route for communication between two points allows for a more efficient use of the available network resources. Data packets can follow different paths to their destination; essentially, each packet is sent via the optimal route available at the time of transmission. In this way, traffic is distributed uniformly, avoiding congestion and bottlenecks. It is important to note that real communication systems generally attempt to implement some hybrid elements. For example, in telephone exchanges using TDMA, it is possible to program an alternative route in case a link becomes congested. Likewise, in VoIP, routers can be configured to prioritize voice communications. However, such strategies have limits and may complicate the analysis that is relevant to this work. For this reason, a simplified idealized model of a small network is analyzed below, where a pure deterministic scheme and a pure indeterministic scheme are applied alternately, allowing for comparison.

A toy model to illustrate some of these advantages could be a small network of three nodes: A, B, and C. Where all points are interconnected through links that support n simultaneous calls. Suppose that on a normal day, during the morning, call traffic between A and C is very intense, while traffic between A and B, and between B and C is light. However, during the afternoon, call traffic between A and B becomes very demanding, while traffic between A and C, and between B and C is light. In a rigid deterministic scheme, calls between A and B are routed directly through the A-B link, and calls between A and C are routed directly through the A-C link, as shown in Figure 5.

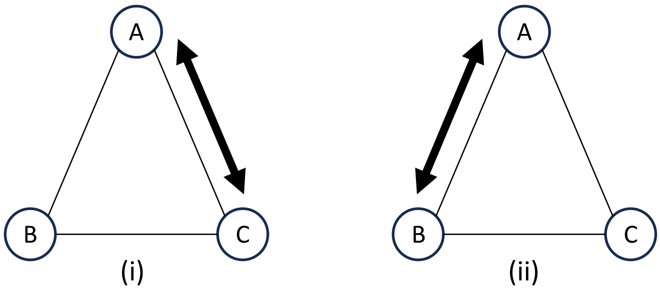

Figure 5. Traffic in a simple 3-point interconnected deterministic network. (i) in the morning link A-C is overloaded while the rest remain idle, (ii) in the afternoon link A-B is overloaded while the rest remain idle.

If, in a network of this type, for example, at a certain time in the morning there are *n* simultaneous calls on the A-C link, and a user attempts to make one more call, the system will deny service due to congestion. If this occurs frequently, it will be necessary to install higher-capacity links that can handle larger volumes of calls without becoming congested. However, when considering the application of an indeterministic scheme using the same links, it becomes possible to avoid congestion and accommodate more traffic. Calls between A and B can be routed directly through the A-B link, but they can also be routed indirectly via A-C-B. Similarly, calls between A and C can be routed through the A-C link or via A-B-C, as shown in Figure 6. In this way, there is no need to install high-capacity links because the traffic can be evenly distributed across the entire network. As illustrated in Figure 6i, by distributing the flow of calls, more calls can be handled than the set limit for each link, i.e., more than *n* calls. This avoids overloading individual links and allows the network to handle more traffic than a deterministic scheme using the same links would allow.

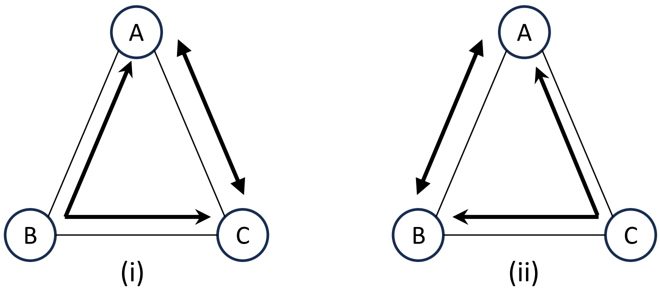

Figure 6. Traffic in a simple 3-point interconnected indeterministic network where no link remains idle or becomes overloaded. (i) in the morning, traffic between A and C is split between links A-C and A-B-C, (ii) in the afternoon, traffic between A and B is distributed on links A-B and A-C-B.

The example presented demonstrates how the indeterministic framework allows for adapting the data flow to a given usage pattern. Another advantage of this scheme is its flexibility to changes in patterns. Following the previous model of the network with nodes A, B, and C, if it is necessary to implement the deterministic option, it would be necessary to strengthen the A-B and A-C links by increasing the number of cables or bandwidth. In this way, a costly but reliable network is achieved. However, what happens if, for some reason, the usage pattern suddenly changes? For example, if one morning the call flow between A and C decreases while the flow between B and C increases. This change in pattern could be temporary or permanent. If it is temporary, since the network is not prepared for heavy traffic on the B-C link, there will be congestion, and many calls will not be completed. If the change is permanent, congestion will persist until the B-C link can be reinforced, leading to both costs and the loss of many calls during the time it takes to modify the network. However, with an indeterministic network, these issues do not arise. If the usage pattern shifts as described, the routers will handle the distribution of traffic from B to C through the various alternative routes, avoiding congestion. Contrary to what might be expected, the indeterministic scheme proves to be more reliable when the usage pattern is variable.

On the other hand, the indeterministic scheme also provides resilience in the event of a link failure. If a link directly connecting two points in the network is present, it will become the preferred route for communication between them. However, if for any reason this route fails, the points will not be cut off from communication because the routers will automatically redirect the traffic through alternative paths. In the example, if the A-B link is disconnected, the calls between A and B will be routed through node C. This will allow, on the one hand, for new calls to be routed via a longer path, but still reach their destination. On the other hand, since the decision regarding which path to take is made on a packet-by-packet basis, ongoing calls at the time of the failure will not be affected and can continue. This type of automatic traffic rerouting is implemented when a link is accidentally broken, but it also represents an advantage when maintenance tasks or network expansions are needed. It is possible to disconnect a cable or a router to carry out the work, relying on the system to handle the traffic redirection through the available routes. This prevents the need to halt all communications within the organization to perform such jobs.

6.- Conclusions and perspectives

This work addresses the determinism-indeterminism debate from a pragmatic perspective inherent to technological applications. Specifically, two rival technologies for data transmission in digital telephony were considered: Time Division Multiple Access (TDMA), which is deterministic, and IP telephony, which is indeterministic. The fundamental principles of deterministic digital telephony and its key characteristics were outlined: (i) before communication is established, it is confirmed that the receiver is available to accept the call, (ii) a physical channel is reserved for transmitting information, and (iii) the audio is transmitted without modifications. These features ensure reliable, distortion-free communication. In contrast, IP telephony is indeterministic because it does not verify whether the receiver is available to receive packets, nor does it define a specific path for data to reach its destination. Instead, each packet is sent into the network, relying on routers to determine the most suitable path for each. Additionally, the audio is compressed, leading to less reliable communication with potential distortions, echoes, delays, and other issues. For these reasons, deterministic telephony was considered superior for decades. However, due to its indeterministic nature, IP telephony has the advantage of flexibility, which allows it to adapt more effectively and rapidly to changing traffic conditions, whether these changes are abrupt or gradual, accidental or planned. This ability to adapt to change has become more desirable than reliability in an era where shifts and realignments are frequent.

In broader terms, this example highlights a conclusion that could be applied to other technological systems. Given its intrinsic characteristics, determinism in its strictest form contrasts with flexibility. Despite the disadvantages that an indeterministic approach may present, when flexibility is a sought-after feature, it can often be the preferable option.

References

Atmanspacher, H., 2002. "Determinism is ontic, determinability is epistemic," in Atmanspacher, H. and Bishop, R., *Between Chance and Choice: interdisciplinary perspectives on determinism*, Thorverton: Imprint Academic.

Audio-Video Transport Working Group, Schulzrinne, H., Casner, S., Frederick, R. y Jacobson, V., 1996. "RTP: A Transport Protocol for Real-Time Applications", RFC 1889, DOI: 10.17487/RFC1889

Deering, S. y Hinden, R., 1998. "Internet Protocol, Version 6 (IPv6) Specification", RFC2460, DOI: 10.17487/RFC2460

Dupré, J., 2001. *Human Nature and the Limits of Science*, Oxford: Oxford University Press.

Earman, J., 1986. *A Primer on Determinism, Dordrecht: Reidel*, Dordrecht: Reidel.

Kurose, J. y Ross, K 2017. *Computer Networking: a top-down approach*, London: Pearson Education.

Hardy, W. 2003. *VoIP Service Quality*, New York: McGraw-Hill.

Hoefer, C. 2002. "Freedom From the Inside Out" in C. Callender (ed.), *Time, Reality and Experience*, Cambridge: Cambridge University Press.

Hoefer, Carl, 2023. "Causal Determinism", *The Stanford Encyclopedia of Philosophy* (*Winter 2023 Edition*), Edward N. Zalta & Uri Nodelman (eds). URL=https://plato.stanford.edu/archives/win2023/entries/determinism-causal/

Ismael, J., 2016. *How Physics Makes Us Free*, Oxford: Oxford University Press.

Lewis, D., 1981. "Are We Free to Break the Laws?", *Theoria* 47: 113-121.

Lombardi, O., 2002. "Determinism, internalism and objectivity", in Atmanspacher H. and Bishop, R. (eds.), *Between Chance and Choice: Interdisciplinry Perspectives on Determinism*, Exeter: Imprint Academic.

Maudlin, T., 2007. *The Metaphysics Within Physics*, Oxford: Oxford University Press.

Monneveux, P., Ramírez, D., Pino, M. (2013). "Drought tolerance in potato (S. tuberosum L.): Can we learn from drought tolerance research in cereals?, Plant Science, 205–206: 76-86.

Nicholl, D., 2008. *An Introduction to Genetic Engineering*, Cambridge: University Press.

Tumulka, Roderich, 2021. "Bohmian Mechanics", in Eleanor Knox and Alastair Wilson (eds), *The Routledge Companion to the Philosophy of Physics*, New York: Routledge.

Ornstein, D. S., 1974. *Ergodic Theory, Randomness, and Dynamical Systems*, New Haven: Yale University Press.

Persistence Market Research 2023, "VoIP Services Market", Persistence Market Research reports. URL= www.persistencemarketresearch.com/market-research/voip-services-market.asp

Postel, J. 1980. "User Datagram Protocol", RFC 768, University of Southern California/Information Sciences Institute. DOI: 10.17487/RFC0768

Postel, J. 1981. "Internet Protocol", RFC 791, University of Southern California/Information Sciences Institute. DOI: 10.17487/RFC0791

Research and Markets 2021, "Global VoIP Services Market 2021-2026", Research and Markets reports.
URL=www.researchandmarkets.com/reports/5457497/global-voip-services-market-2021-2026

Ribichich, K., Chiozza, M., Avalos-britez, S., Cabello, J., Arce, A.; Watson, G., Arias, C., Portapila, M., Trucco, F., Otegui, M. y Chan, R., 2020. "Successful field performance in warm and dry environments of soybean expressing the sunflower transcription factor HaHB4", *Journal of Experimental Botany* 71: 3142-3156.

Rosenberg, J., Schulzrinne, H., Camarillo, G., Johnston, A., Peterson, J., Sparks, R., Handley, M. y Schooler, E., 2002. "SIP: Session Initiation Protocol", RFC3261, DOI:10.17487/RFC3261

Sartenaer, O., 2015. "Emergent evolutionism, determinism and unpredictability", *Studies in History and Philosophy of Science Part A* 51: 62-68.

Schulzrinne, H., Casner, S., Frederick, R. y Jacobson, V., 2003. "RTP: A Transport Protocol for Real-Time Applications", RFC 3550, DOI: 10.17487/RFC3550

Suppes, P., 1993. "The Transcendental Character of Determinism", *Midwest Studies in Philosophy* 18: 242-257.

Suppes, P. and M. Zanotti, 1996. *Foundations of Probability with Applications*, New York: Cambridge University Press.

UIT-T, 2000. *Políticas de telecomunicaciones para las Américas El Libro Azul*, 2.a edición, ISBN 92-61-08383-8, Ginegra: Unión Internacional de Telecomunicaciones (UIT).

UIT-T, 2012. "Coding of speech at 8 kbit/s using conjugate-structure algebraic-code-excited linear prediction (CS-ACELP)", International Telecomunication Union, G.729 Recommendation.