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# The Information Medium

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**Abstract** The paper offers the foundations of the theory of information media. Information media are dynamical systems with additional macro-structure of information-carrying states and information preserving transformations. The paper also defines the notion of information media network, as a system of information media connected by information transformations. It is demonstrated that many standard examples of information containing and processing systems are captured by the general notion of information medium. The paper uses the theory (and informal discussion) of information media to motivate a structural approach to the information in media. The idea is that the notion of information transformation should be regarded as more primitive than the notion of informational state. Thus in information systems, especially in the context of information technology, information is secondary, information transformation is primary.

**Keywords** Information Medium, Informational Transformations, Information Networks, Structural Approach to Information, Dynamical Systems

## 1 Introduction

One important reason the concept of information is useful, especially in the context of information and communication technologies, is because it allows more optimal high-level descriptions of the behavior of some systems. Consider computer files. At any given time, a computer file is implemented by some highly organized physical system, e.g., a collection of magnetically polarized segments on a metal disc in a hard drive. The physical aspect of the file is for most intents and purposes regarded as transient. When we say about a file that it holds information, we make both a positive and a negative claim. We say, positively, that its particular state is distinct from other possible states, and that the distinction can be made accessible to other systems; we also say, negatively, that the specific physical/causal conditions of the system implementing it are unimportant for our interaction with the file.

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By describing a file as containing information we are viewing a physical system at a particular *level of abstraction*. (Floridi and Sanders 2004a; Floridi 2008b) Some aspects of the system are irrelevant for the informational properties of the file. The physical systems implementing files and their manipulations are *abstractable* with informational notions.[1]

Such observations are not new to philosophy. They have been discussed under rubrics such as functionalism, multiple realizability, virtual machines, and supervenience. However, not much philosophical discussion exists about what allows the level of abstractions needed for informational phenomena. Technologically there is no mystery: we know how to build computer hardware that can run software. That is, we know how to build physical systems that, in the appropriate conditions, exhibit the right dynamics implementing abstractable information processes. We have made the greatest advances in the realm of *digital* information. But, the realm of information extends beyond the digital. The question of abstractability emerges in all instances of informational containment, manipulation and flow. Thus, we can ask: What are general conditions for abstractability of a system to admit an effective informational description?

A physical system that engages in informational interactions I call information *medium*.[2] The information medium is the intermediary between the "world" of dynamics and causation, and the "world" of information. The medium is the concrete stuff (this is relaxed in Sec. 4). It is the system that gets pushed and pulled by the rest of the world. It, however, is pushed, pulled and behaves in just the *right* way to support the patterns of interactions that constitute the information processes. We can, thus, reformulate the question about the general conditions of abstractability as a question about the nature of information media. This paper offers this: it offers a general theory of information media. The theory satisfies four conditions: (1) the medium must be implemented within a *base system*, (2)

[1] The notion of information, especially as discussed in recent philosophy of information literature, involves a semantic (Carnap and Bar-Hillel 1952; Dretske 1981; Floridi 2010, see the last for a more extensive bibliography) and even a pragmatic (MacKay 1969; Nauta 1970; Vakarelov 2010) component. An important distinction is made between *data* and *information,* where the concept of information is assumed to include data but also to include meaning (and truth). This paper is really about the data aspect of information. One reason I use the term information as opposed to data, beyond the fact that this is the common word in such contexts, is that I assume that information media exist within or are connected to semantic systems, and within this wider context the term information is appropriate. This being said, nothing in the theory developed below assumes semantics or pragmatics of information. Another reason is that the word *data* is often associated with the digital, more so than the word *information.* It is absolutely central for this paper that discreetness or digitality is disassociated from the notion of information medium.

[2] Let me clarify a possible equivocation of the word "medium". In general the word medium is used to indicate mediation between two things. Sometimes the word medium is used to describe an intermediary in communication. We can call this a *communication medium.* In this sense, newspapers, television and the internet are viewed as media of communication. This is why they are regarded as forms of "media". The notion of informational medium is different from communication medium. The mediating role of the information medium is not between two communicators, but between two levels of abstraction - between the implementation (physical level) and the informational level. Now, information media may play the role of communication media, however information media may be investigated at a single informational level of abstraction (disregarding the implementation), while information media cannot. As we shall see below, an information medium need not play the role of communication medium - a physical computer is an information medium. Thus the two notions are distinct but relatable.

there must be a distinction between the informational level of abstraction and the abstraction of the base system, (3) the medium must be capable of information dynamics and flow, some of which may be related to the dynamics of the base system, (4) there must be an account of how information media interact.

Conditions (1) and (2) capture the main point of the notion "information medium": that the *medium* is only an implantation on top of something else, and that it is an *information* medium because there is something about the behavior of a base system that supports another level of abstraction. Without conditions (3) and (4) there will be no point in developing the theory, because developing a theory of "information *anything*" that does not allow for information flow is futile.

The paper endorses a *structural approach* to information. The main idea is that the notion of *information state* is derived from the notion of *information transformation*. The structural approach to information is really about the information states of information media. It is not about information *per se*, at least not for the purposes of this paper.[3] Strictly speaking, the theory of information media is consistent with a conception of information where the information state is conceptually primitive and information transformations are secondary. However, it is easier to define transformations within a base system as special dynamical processes, than it is to define a new base-level ontology of information objects. Because media have their feet both in the physical/dynamical realm and the informational realm, the transformation may be defined in the physical realm without ontological burden and then, they may be used to provide the structure of the informational realm. In this way, the abstraction of information is the result of the dynamical patterns of interaction of the system.[4] Thus, if we are seeking a road towards offering a unified story about the general phenomenon of information, it pays to go through the notion of information medium first, because we save on new or queer ontological commitments. The structural approach advocated here can be interpreted as a form of structural realism (Worrall 1989; Ladyman 1998) and may be made to fit an informational structural realism position (Floridi 2008a), but it is a strictly weaker position — a position consistent with an instrumentalist conception of information.[5]

## 2 A case study

Let me motivate the discussion with a concrete example. Consider a genuine "information age" medium — the compact disc (CD). In a CD information is encoded by a spiral of pits and valleys with different reflective properties. The design specifications of an idealized CD can be limited to: encoding binary sequences readable by lasers. An actual CD, however must meet stricter requirements. It must be read reliably in the noisy environment of a CD player, and it must be able to cope with

[3] So why not call it a "structural approach to information states"? One reason is to maintain terminological consistency with other work. Ultimately, but not in this paper, I use the notion of information medium to offer a more general account of information that includes semantics and pragmatics. The structural approach endorsed here translates to a more general structural approach to information.

[4] I have argued for this even for semantic information in (Vakarelov, 2010)

[5] I will return to this connection in Section 3.

both random errors and sequential error bursts from scratches. The stricter requirements change fundamentally how data are encoded and decoded. What may be an obvious encoding for an ideal CD, becomes completely inappropriate for a reliable physical CD. Existing specifications for CD encoding require a sequence of consecutive encoding mechanisms: (1) at the lowest level, a binary sequence is encoded using a non-returned-to-zero inverted (NRZI) encoding, where 1 is encoded as a transition between pits and valleys and 0 as a lack of transition; (2) to assure that the lengths of pits and valleys are not too short or too long, each byte word (8 bits) of the original sequence is converted by an Eight-to-Fourteen Modulation encoding (a convention table) to a 14 bit word with more regular properties — all pits and valleys come in one of nine sizes; (3) to guard against random and sequential errors, special redundancy is included that can recover the data by a Cross-interleaved Reed-Solomon algorithm. To convert a binary data string in a format to be recorded to a disc, it first must pass through Cross-interleaved Reed-Solomon encoding, then it must pass through Eight-to-Fourteen Modulation encoding, then it must be encoded in a sequence of pits with variable lengths and distances in a way that corresponds to NRZI encoding. For the data to be read back, the decoding must be performed in reversed order.[6](Immink 1999)

Several questions must be examined: (1) In what sense can we say that the medium *contains* the information? (2) What determines the appropriate level of abstraction needed to describe the CD as an information medium? (3) Is the CD a prototypical example of an information medium?

The CD is a container medium — its purpose is to store information in virtue of its *stable* internal structure. Thus, one hypothesis can be that the stable structure of the CD alone determines its information. That is, the information is intrinsic to the CD. Now, can there be a notion of *intrinsic information* (or data)? First note that a notion of intrinsic information need not contradict a requirement that data (and thus information) are relational. (Floridi 2005) The disc and its internal structure exist in a space of alternative possibilities. It is clear that however data are stored, it is because alternative states are possible. Thus, if there is a problem with viewing the CD as containing the information intrinsically, it is not because relationality is violated. Going back to the question: there is a well-defined notion of (physical) intrinsic information formulated in (Collier 1990). Collier, following (Brillouin 1962), connects the physical information in a system to its order, i.e. to its deviation from equilibrium. He defines intrinsic information as the sum of two quantities: the deviation of the system from a state of maximal uniformity (maximal entropy) and a measure of order due to rigid constraints (defined using algorithmic information theory, Li and Vitanyi 1997). According to this definition, a CD has fixed (and much) intrinsic information in virtue of its highly organized structure. The question is: is the intrinsic information of the CD the information it contains *vis* the described information medium? Is the intrinsic information equivalent to the binary string it is supposed to contain? Or, at least, can the binary string be derived from the intrinsic information?

[6] The actual mechanisms for data encoding on an optical disk are more complicated. For example, in recordable media the spiral is given a slight sinusoidal variation, whose frequency is described as the wobble frequency. The wobble frequency is used for time synchronization, and modulations in the frequency are used for encoding second-order information about the disc, such as its type, maximum recording speed, etc.

Let us resort to a standard philosophical thought experiment — an advanced civilization of Martians. What would happen if Martians discover a CD? Would the Martians be able to recover the original strings of bits? Let us assume that the Martians can determine exactly the intrinsic information of the CD. Let us say, the Martians examine the disc with an electron microscope and notice the non-random structure of pits. Should it be read as an inward or outward spiral? Due to the Eight-to-Fourteen Modulation encoding, the lengths of the pits come in one of nine sizes. Do these represent an encoding in a nine-ary number system? How about the distances between the pits — the lengths of lands — they also come in one of nine sizes? Do they encode an independent string, two encodings merged together, or should the pits and lands be regarded as a single encoding system? How should the Martians guess that NRZI encoding was used (even if such an encoding is known)? Then, how should Eight-to-Fourteen Modulation be discovered? Statistical analysis may help, but what if the Martians know of more optimal encodings that have the same statistical properties? Should they guess that Eight-to-Fourteen Modulation was *not* used? How about the Cross-interleaved Reed-Solomon coding algorithm? The problem is that even if the Martians decide that the disc encodes a binary string, there are so many ways of converting the string into another string that it would be impossible to know which is *the* string of the disc.

Maybe the encoded string contains some highly unlikely internal order. Say, it encodes a picture of a flower. Could it be that, by trying all possible (or a large set of reasonable) decoding procedures, the Martians discover one sequence that stands out? It may be a sequence with internal order that is not a side effect of the algorithm, but a genuine order in the source — an order, like the picture of the flower, that is too unlikely to exist unless something intentionally put it there. Maybe then the Martians would have a test for correctness and would use it to reverse engineer a process for decoding the data. Possible, but what if the disc contains a pre-computed pseudo-random sequence? There will be no chance of reverse engineering the right decoding procedure from this. Put differently, short of guessing the algorithms by chance (without knowing that they have done so), the only way the Martians can reverse engineer the encoding is if they place the disc in a larger context of its use, by making assumptions about intentions of what may be encoded. But then, the intrinsic information of the disc is not the only consideration.

What can we conclude from this imaginative exploration? The disc by itself does not contain unique data without the fixed processes for converting to and from the disc to something else. If a CD is taken as a prototypical information medium, it can be concluded that a system is an information medium to the extent that there are transformations from and to the medium to and from some other media — write and read operations — that can be regarded as information preserving transformations.[7] Of course, the structure of the CD matters tremendously, but it is not sufficient to determine the information in it. Rather, the structure assures that appropriate transformations are possible. The CD is an information medium only viewed in the context of possible systematic interactions with the various

[7] We need not assume that the operations are directly invertible, in the sense that there may not be a transformation back from the reading medium, the medium to which the reading transformation maps. However, there should be a cycle of transformations going to some other media that goes back to the original medium.

technologies enabling the write and read operations. The disc is not an information medium without disc drives, encoding conventions and algorithms capable of correctly generating binary sequences based on the physical devices interacting with the physical disc. Of course, such devices, conventions and algorithms would be impossible to function without the CD having unique structural properties. Thus, the physical structure of the CD is an enabling condition for the devices to implement the systematic informational transformations to and from the disc, but it is the transformations that determine the informational character of the CD.

Is the CD a prototypical example of an information medium? A disc is special in some ways. (a) It is an artifact — its transformations, while non-arbitrary, are conventional. (b) The transformations needed to read and write the data are fairly complex. (c) It can hold arbitrary information — an arbitrary binary string (of limited size). A different, more "natural" medium may not have such complex, conventional or arbitrary information-carrying capacity. Its natural organization may favor some "reading" and "writing" operations, but it cannot determine the data state uniquely. Even if there is a unique *best* way of using a system as an information medium, the actual use of the system may be different. The information/data in an information medium is never intrinsic.[8] It always depends on the informational transformations to and from the medium. To this extent, the CD is a prototypical example of an information medium.

## 3 Structural Principle for Information

The CD example motivates an approach to informational states — the *structural principle for information* (SPI).[9]

SPI: The *informational states* of a medium are determined by the informational transformations in which the medium enters.

Some consequences of this principle are: (1) The same system can act as different information media (including simultaneously) depending on what informational transformations are applied. For example, a CD can be read by a laser on one side and by a human on the other side where the label is displayed. The two media modes are completely independent and simultaneous.

(2) Being an information medium is a dispositional property. Every system can potentially be an information medium.

(3) The principle needs only a weak ontology of information/data in the sense that, all that is required for a realm to "have" information is for there to be a system that supports appropriate (potential) transformations. In a sense, ontologically, information transformations and information flow are more basic than information. As I insist in the next section, the states and transformations of a medium are derived from the characteristics of the underlying dynamical systems. SPI is only a principle about information in information media. It regards information as an emergent/macro phenomenon. As such, it is much weaker than the

[8] Collier's notion of intrinsic information can at best be an enabling condition for information in a medium.

[9] I use the term "structural" in the way it is used in mathematics, whereby an abstract mathematical object is defined structurally if it is defined up to isomorphism by what happens when transformations or operations are applied to it.

informational structural realism (ISR) (Floridi 2008a), which views information as a deeper ontological category. ISR can be viewed as a natural strengthening of SPI. Still, even if at a basic ontological level, the world has some fundamental *differentiae de re*, they need not be the *differentiae* of the medium in question.

(4) Information is not *stuff*. When information feels concrete — a something whose existence and character is independent of the rest of the world, a *distinct existence*, to use a Humean phrase — it is because one assumes a generic set of transformations that are not made salient. The notion of information, as distinct from the transformations, is useful because it allows us to track invariance under the transformations. When we say that the CD contains information, this is because the CD can be read and written reliably by a system sensitive to its pits and lands, and capable of performing the encoding/decoding transformations. The transformations are in the background, problem of the engineers. A user can pretend that the information is in the CD, and the CD alone, similar to the way she can pretend that the apples are in the basket.

If one accepts SPI, does it mean that unless transformations are specified, a physical system cannot be regarded as an information medium? In some cases we may be confident that a medium contains particular information, even if we don't know how to translate it in a different form — a stone with ancient inscriptions that we cannot decode. Does it mean that the stone should not be regarded as a medium until the code is cracked? Of course not! However, one is justified in regarding the system as a medium only when one has meta-information about it — that it is an inscription produced with a fixed set of transformations. One can conclude that the stone is a medium because it can be placed in an appropriate cultural context where unique, even if undiscoverable, translation rules exist. Imagine, alternatively, that an advanced alien civilization has managed to achieve technological sophistication where they can use the quantum states of the whole universe to perform computations, in a way that does not affect macroscopic decoherence in our part of the universe. It could be that the stone in one's hand contains information for this computer. There is no interesting sense in which one can claim that the stone is an information medium if the practices of this civilization are not known.

## 4 Information Media

### 4.1 The medium

It is time to make the notion of information medium precise. First, we must relax the intuition that a medium is implemented in a physical system. While we can assume that technological systems are physical systems, some media may be "virtual". In a virtual medium the states are themselves informational states in another, lower level medium. The lower level medium may be implemented physically or in a long chain of "virtual" media. It is important that there exist a functional level of abstraction between the implementation of the base and the virtual medium. Consequently, the definition of information medium must already assume a level of abstraction for describing its implementation level.[10]

[10] If media are to be described with the method of levels of abstractions (Floridi and Sanders 2004b; Floridi 2008b), they will be special two-level gradients of abstraction. Investigating the

A powerful base for discussion of information media is the theory of dynamical systems. A dynamical system contains a space of states and a function describing the system dynamics; that is, a function describing the trajectories of a system from various initial conditions according to some temporal order. (Hinrichsen and Pritchard 2005)

Definition An *information medium* is a triple $\mathcal{M} = \langle \mathcal{D}, \mathcal{IC}, \mathcal{F} \rangle$ where $\mathcal{D}$ is a dynamical system, $\mathcal{IC}$ is a collection of disjoint non-empty sets of states of $\mathcal{D}$ called the *information-carrying states*, and $\mathcal{F}$ is a collection of functions from $\mathcal{D}$ to $\mathcal{D}$ that respect the information-carrying states—i.e. $\forall f \in \mathcal{F}$, if $I, J \in \mathcal{IC}$ and $x, y \in I$ and $f(x) \in J$, then $f(y) \in J$.

An information medium, thus, is a structured dynamical system where the states of the system (the possible ways the system can be) are categorized according to states that carry information, and there are operations that can transform the system (move it from one state to another) that have no effect on the information. More specifically in the definition the different parts can be interpreted as follows: $\mathcal{D}$ is the base system of the medium. Note that in the definition only the states of $\mathcal{D}$ are used. However, it is useful to distinguish between media whose dynamics are different because in many cases the dynamics may play an informational role in defining a transformation (see 4.2.1), or be relevant for the semantic character of the information. (Vakarelov, 2010) We think of the disjoint sets of the dynamical states, $\mathcal{IC}$, as the *information-carrying states* of the system. Note that $\mathcal{IC}$ is not a partition of $\mathcal{D}$; there may be dynamical states that play no informational role. The information-carrying states are the states relevant for informational purposes. As far as the informational properties of the system are concerned, the particular dynamical state does not matter, as long as it is in a fixed information-carrying state. We can interpret $\mathcal{IC}$ as defining the "syntax" of the medium. It determines the minimum distinctions the medium can make. The "syntax" however can make redundant distinctions. Two information-carrying states may contain the same information. The functions in $\mathcal{F}$ are interpreted as *information-preserving transformations.* In other words, if $f \in \mathcal{F}$ and $f$ maps $I$ to $J$ then we think of $I$ and $J$ as containing the same information. Even though $f$ operates on the dynamical states, the requirement that it respects the information-carrying states allows us to treat it as if it is a function on the information-carrying states. For this reason, when convenient, we can regard functions that respect information-carrying states as functions on $\mathcal{IC}$. The distinction between information-carrying states and the information-preserving transformations allows us to distinguish between how information can be "expressed" within a medium, which may often be a property of the medium, and what information it contains, which may depend on how the medium is connected to other systems. In many cases, the functions in $\mathcal{F}$ may be defined externally, consistent with SPI.

Sometimes, it may be more convenient to define information medium not in terms of information preserving transformations, but with equivalence classes of $\mathcal{IC}$ sets. The information preserving transformations define an equivalence relation on $\mathcal{IC}$, where two information-carrying states are equivalent if there is a sequence of information preserving transformations taking one to the other. We can call the set of equivalence classes, $\mathcal{I}$, the set of *information states* of the medium. While the

connection of the theory developed below and the method of levels of abstraction is beyond the scope of this paper.

two definitions are not equivalent — the same information states can be defined with different sets of information preserving functions — I will use both below, allowing the context to justify the choice.

## 4.2 Informational transformations

As was suggested in Section 2, information media are never interesting by themselves. They are interesting when information can be transferred to and from other media, and when they can be manipulated in a way relevant for the transfer operations. It is important, therefore, to define classes of dynamical transformations on the media that play informational roles. We need to consider two classes of transformations: one that transforms a single medium, and one where information from one medium is connected to information in another.

### *4.2.1 Information Processing Transformations*

Definition An *information processing transformation* of an information medium $\mathcal{M} = \langle \mathcal{D}, \mathcal{IC}, \mathcal{F} \rangle$ is a partial function $f : \mathcal{D} \to \mathcal{D}$ that respects the information-carrying states.[11]

We encountered examples of information processing transformations already: the information preserving transformations. Information processing transformations form a large class, and for particular purposes most are uninteresting.

Although the definition of information medium includes a dynamical system, the dynamics function of the system never enters the definition (except for identity of media). Indeed, dynamical systems are interesting because one can describe principles that specify how the system changes depending on the state. In general, this function need not respect the information-carrying states. But in the cases it does, we will say that it is a *canonical information processing* transformation.

Because information media are open dynamical systems that are subsystems of larger systems, their dynamics usually depends on "external" factors. We can think of these factors as the context of the system, in which case the canonical transformations will depend on the context. In cases where the context can be controlled, it can be used to modulate the canonical transformation, effectively controlling the information processing transformations on the medium.

In many cases the most important information processing transformation of a medium is its canonical transformation. For example, a physical computer without external concurrent inputs is constructed so that its natural physical dynamics transforms the state of its memory (its tape, for a Turing machine) in a fixed manner, determined by the portion of the memory holding the "program" and the portion containing the input data (which may contain parts of the program). The difficult engineering task of building a computer is exactly making sure that the dynamics of the system is insensitive to the minor perturbations of the system, and it respects the information-carrying states of the memory. A physical computer is an information processing medium with a canonical information processing transformation. All information operations within it are special sub-cases

[11] It is always assumed that the function is defined on the $\mathcal{IC}$ sets.

of the canonical transformations. This is because each operation is represented by a part of the data state of the system, the program code. Thus, every information processing transformation can be achieved by moving the system to a point in the dynamical state space (loading the program) and running the canonical information processing transformation. This is the sense in which the computer is a universal machine.

Some media have canonical transformations that are not significant for information processing. For example, a piece of paper with ink scribbles can be viewed as an information medium. The natural dynamics of the paper and ink is such that the information is preserved with time (at least for a short period). In this case, the canonical transformation of this medium is an information preserving transformation. This is why a paper or a CD or a stone tablet can be used as a medium, while a gas cloud cannot in the same way.

The paper with scribbles is interesting in a different way. In the effort to offer a formal theory of computation, Turing imagined human computers working out algebraic problems on paper. A computer writes sequentially (and possibly scratches away) statements of a particular grammatical system (this determines the information-carrying states). She transforms the states of the paper/ink scribble system according to rules of algebra and logic. She performs information processing transformations on the medium, provided she has mathematical competency to apply the rules correctly. In this example the information processing transformations on the medium are performed by an external system. The medium itself cannot perform the operations. Instead, the medium provides constraints on the operation. In the case of the paper/ink system the constraints are minimal — this is why it is such a flexible system. In the case of other physical instruments that can be regarded as information media, such as maps, compasses or slide rules, the constraints are more rigid.

#### *4.2.2 Information management transformations*

We can think of "information management", informally, as an activity of manipulating the *form* of the information — selecting the appropriate medium for its containment, distribution, and manipulation. Following this informal usage as a motivating example, I define a theoretical notion of information management transformation as follows:

Definition Let $\mathcal{M}_1 = \{\mathcal{D}_1,\mathcal{IC}_1,\mathcal{F}_1\}$ and $\mathcal{M}_2 = \{\mathcal{D}_2,\mathcal{IC}_2,\mathcal{F}_2\}$ be two media. An *information management transformation* (IMT) is a function $m{:}\mathcal{D}_1 \rightarrow \mathcal{D}_2$ that respects the information-carrying states of the systems.

Information processing transformations are a special case of information management transformations when the two media coincide; however, I will use the name "information management transformation" only in cases when the two media are different.

An important kind of information management transformation is "information preserving" management transformation. A necessary condition for a management transformation to be information preserving is for it to respect the information preserving transformations on each medium. That is, if $a$ and $b$ are two information-carrying states, $m$ is an IMT , $f : a \longmapsto b$ is an IPT, and if $m : a \longmapsto a'$ and $m : b \longmapsto b'$ then there exist an IPT in the co-domain medium $f' : a' \mapsto b'$; moreover, if there doesn't exist $f : a \longmapsto b$, there must not be a $f' : a' \longmapsto b'$. If in addition, there exists an inverse management transformation such that the composition is identity up to IPTs, then we have a sufficient condition. In many cases however, we may not have such an inverse.[12] Still, a management transformation may be regarded as information preserving for the larger system. In fact, it may be regarded as such by stipulation, effectively defining the information preserving transformations on one medium by that of the other.[13]

Similar to the case of information processing transformations, we can define the notion of *canonical information management transformation*. We assume that $\mathcal{D}_1$ and $\mathcal{D}_2$ are subsystems of a larger dynamical system, and that their states are correlated. Then the correlation may define a function between the states. If the function respects the $\mathcal{IC}$ states, then we call it the *canonical information management transformation* between the media. Consider a case where a supercomputer simulates the behavior of a remote blackhole based on a set of physical parameters. Both the blackhole (together with the macro-states determined by the parametrization) and the simulated blackhole can be regarded as information media. The idea of simulation is that the dynamics of the virtual blackhole and the dynamics of the real blackhole (with respect to the parametrization) are correlated. Thus, the simulation can convey information about the real blackhole, i.e. it defines a canonical information management transformation. This may be the only possible information management transformation from a blackhole.

As before, a canonical information management transformation may depend on a context $C$, and manipulation of $C$ may be used to manipulate which information management transformations are performed.

### 4.3 Information media networks

In technological contexts one is interested in how information media interact to produce a larger informational system. Consider the structure of the Internet. It is a collection of information processing systems (kinds of information media) communicating *via* a densely connected network of information management transformations, mediated by a complex system of hubs and routers (also kinds of information media). The interesting and most transformative aspect of the Internet is that the network itself, not merely the individual media, takes a life of its own. The most exciting innovations of the Internet are network innovations, not computer innovations. In recent years, with the advent of cloud and distributed computing, the very conception of computation has evolved, to accommodate the idea that the network itself is the computer. Clearly then, no theory of information media can do without a theory of information media networks.

Definition An information media network, IMN, is a triple $< \mathfrak{N}, \mathfrak{P}, \mathfrak{M} >$ where for an index set $I$, $\mathfrak{N} = \{\mathcal{M}_i | i \in I\}$ is a set of information media, $\mathfrak{P} = \{P_i | i \in I\}$ is a set of collections of information processing transformations for every medium,

[12] Of course, such a transformation may be defined formally, but in some cases the set of transformations may be restricted in an informal way, say, by available operations that can be performed by a user.

[13] In fact, we can do more! Because information management transformations are functions on the dynamical states, we can define information-carrying states *via* another medium and a function stipulated to be an information preserving management transformation.

and $\mathfrak{M} = \left\{Mt_j^i | i, j \in I, i \neq j\right\}$ is a set of collections of information management transformations from $\mathcal{M}_i$ to $\mathcal{M}_j$ for every ordered pair of different media.

Essentially, an IMN is a collection of media, each endowed with a (possibly empty) set of information processing transformations (information preserving processing transformations are already included in the definition of each medium), and a bunch of information management transformations among the media. No requirement is placed on there being information preserving management transformations, nor for closure of the network under composition of transformations.

A focus on information media networks is important for three reasons: (1) it allows the powerful machinery of network science to be integrated in a theory of information processing. For an information network it becomes possible to investigate the relative contributions of (a) individual information media and (b) the network organization and topology, to the behavior of the total system. The spectrum of information networks ranges from highly distributed networks with simple media (like simple models of the brain), where information processing is primarily the result of the network architecture, to simple networks with sophisticated media where most of the informational work is performed by the individual media, (like the first years of the Internet). Both highly distributed and highly localized networks have received significant theoretical investigation. This is not the case for networks in the middle that contain both complex network structure and complex media. Most information networks that emerge in real life are of this intermediate group. This includes networks such as: the modern internet, especially the constrained virtual networks on top of the Internet, like peer-to-peer networks; the modular brain; structured social communities, like corporations, academic institutions, governments and tribes; and even ecosystems (their informational aspect). IMNs provide a tool for investigation of this large intermediate realm.

(2) IMNs are a natural platform for modeling "division of labor" architectures for information system design. Because information media are dynamical systems with an additional level of organization related to information, they are a natural platform for investigating the interactions between the physical and the informational. The physical characteristics of a system, which includes its internal dynamics and its interaction with other systems, is a constraint on its informational nature. In an information network, the different characteristics of informational media can be exploited to create a system that can do what no single medium can do.

(3) IMNs allow a reformulation of SPI. In a network of interconnected dynamical/base systems, the informational characteristics of some media may be determined by other media, and possibly by the entire network. In other words, the medium may be determined by the network. I explore this idea in the next section.

## 5 From network to medium

Let us go back to the example of the CD. How do we analyze the CD with the formal definition? The dynamical system ($\mathcal{D}_{CD}$) is given by the set of possible states of the CD. (We fix sufficiently fine-grained states in light of the mechanisms that interact with a CD. Molecular level is probably too fine-grained, but the laser can be sensitive to micro-scale variations, so we probably need to get close.)

The dynamics is specified by the natural aging of the disc, but since it is a storage medium, it plays no role. We assume that the disc remains in the same state unless there is an external change.

What are the information-carrying states of the disc? The intuitive definition would be that $\mathcal{IC}_{CD}$ is the set of states with a spiral of lands and pits. States that do not include such a spiral — most random states would not — are not among any $\mathcal{IC}_{CD}$ states. We must be a bit careful, however. The lands and pits are important because of the way they reflect the light of the laser. Scratches also affect the reflectance; a disc with a one spiral and a scratch may look the same to the laser as another disc with a different spiral but no scratch. Thus, it is best to group disc states into $\mathcal{IC}_{CD}$ sets based on how they look after the laser would read them.[14]

The lesson of the CD example was that the information contained in a CD depends on the read and write operations to and from the CD. I described the various levels of error correction algorithms needed to recover the information (the unique string of zeros and ones) on the disc. The assumption is that the string is encoded with sufficient redundancy; that is, many different $\mathcal{IC}_{CD}$ states produce the same string. What string this is, however, depends on the decoding algorithm. The CD is functional as a container medium because, moreover, the encoding algorithm generates a sequence with sufficient redundancy to allow the decoding. Still, it is the decoding that determines what $\mathcal{IC}_{CD}$ states, and thus what dynamical states, contain the same information.

The decoding operations are just information transformations to other media. In the case of the CD, there are several media, some are hardcoded in the CD player, and other, virtual media are in the computer. The CD, then, acquires its informational states via its role in an IMN where the information management transformations are defined. In the most abstract level of description there are two media, one is the CD and the other a medium, $M$, whose informational states are binary strings of zeros and ones, and an information management transformation, $f$, between them. When we say that the CD contains information (string) $s$, we really mean that $M$ is in a state $s$. In effect, the function $f$, which captures the complex decoding process, is stipulated to be an information preserving transformation. Whatever the state of the CD, we care only about the output of $f$. We can use $f$ to define the informational states of the CD. Namely $\mathcal{I}_{CD}=\{f^{-1}(s)|s \in \mathcal{IC}_M\}$, where the inverse $f^{-1}(s)$ is the set of states of the CD that result in $s$. $f$ places a constraint on the encoding operations $e : M' \to CD$, where $M'$ is a medium similar to $M$. $e$ must be such that $f \circ e : M' \to M$ is a simple copy operation.

What are information preserving transformations, $\mathcal{F}_{CD}$, on a CD? Here are information non-preserving transformations: CD manufacturers place warning icons on CD boxes advising against bending, placing near a heat source, or drawing on the reflective surface. Such operations do not keep the CD in the same informa-

[14] Because a scratch may produce an undetermined result, not just a *bit* flip, the syntax of the disc also contains holes. Remember that the Eight-to-Fourteen Modulation rules constrain the possible lengths of lands and pits. A scratch may break the constraint and a portion of the spiral must be regarded as containing a hole. Thus, the $\mathcal{IC}$ sets must be distinguished based on the presence of holes as well. Moreover, if a disc is too scratched, it may be impossible for the algorithms to produce a unique string. Such states would not be included in any $\mathcal{IC}$ set, even though a spiral exists within the disc.

tion state. Regular handling, which might produce small scratches, constitutes an information preserving transformation of the CD.

What we have observed is a medium defined by its role in an information network — by what transformations to other media exist, and by which of them function as information preserving transformations. This is how technological media are ultimately always defined. The paper/ink medium is defined by its integration with the human cognitive system, and the human capacity to produce and distinguish between different swirls; language is determined by the capacities to produce, distinguish and comprehend linguistic tokens. It is this observation that supports the *structural principle of information*. With the notion of information media networks, SPI can be reformulated as follows:

SPI: The structure of information media is determined by the IMNs in which they enter.

This principle raises two philosophical difficulties: (1) Does it mean that an information medium changes when it enters in different networks, or as the network changes? and, (2) Does SPI lead to a foundational gap, where the IMN is defined by the media, the media are defined by the IMN, and therefore no conception serves as a foundation?[15]

Problem (1) must be answered affirmatively. Indeed, the medium changes as it enters in different networks. The important question is: *Does the change paralyze the use of information media?* One reason for being able to successfully sell CDs is that they contain the same information regardless of what CD player one uses. While this is true, it is just as much a statement about the medium — the CD — as it is about the players. If every player manufacturer used proprietary algorithms for decoding the CD, then the CD would not be regarded as containing fixed information, and sales would suffer. Users of CDs and player manufacturers enforce strict ISO standards to assure that indeed, a CD behaves in the same way in different IMNs. The implementation and enforcement of standards requires work and has an energy cost. This energy cost can be seen as evidence for the network dependence of information media. It is the cost of maintaining the illusion of immanence of the information in the CD.

More generally, the medium dependence of information — i.e. the phenomenon where it appears that the medium alone suffices to determine the contained information — is a result of network coordination. Many media with which humans interact depend heavily on interpersonal regularities in cognition, human experience, and culture. Language succeeds in acting as a communication medium to the extent that such regularities exist, and it fails to meet the ideal of a stable, immanent information carrier to the extent that such regularities fail. Such failures of language are inevitable because of the differences of the vast IMNs in human cognition. The Russelian concept of a logically perfect language is well defined, as far as information media are concerned, but it captures little of the nature of language because it depends on an artificial information network. The formal theories of semantics and syntax define exactly such a network, implemented in the virtual environment of a meta-language. The great advantage of such formal networks

[15] The problem is not merely that there may be a circular definition, which is often acceptable, but that if the notions are only co-determined, the theory of information media may lack foundation. This may be a problem if we intend to use the notions to analyze physically instantiated systems.

is that conformity is easy to maintain. One network instance can be matched to another network instance by a reliable process of recognition and copying of symbols. Such networks, however, eliminate the connection to the human cognitive system. They do not solve the problem of maintaining conformity among the natural networks; they just shift the problem to the *integration* of the formal network into a natural network. Such formal networks, nonetheless, offer a technological improvement. For special domains of human enterprise the problem of integration is simpler to solve than the global problem of natural language network integration. In domains like mathematics and science, where one restricts and regulates the use of language and its connection to practice, the integration problem is simpler. In other cases, the problem can be simplified by forcing human practice to conform to the formalism of the language. Legal systems are partially organized in this way. All of these considerations are meant to be suggestive only. A detailed argument for each is beyond the scope of the paper. They are offered only as real and important examples of problems that can be illuminated by an information network approach.

Problem (2) is an ontological, not a logical problem. It is not a problem about the definition of a medium and information network. This is because SPI is not a logical principle. It is a principle about where to look for the ontological origin of information media. As presented here, and as I have argued in (Vakarelov, 2010) about information more generally, both information media and IMN are ontologically secondary to the underlying dynamical systems. In this sense, SPI is a statement about how the $\mathcal{IC}$ states and the information preserving transformations are defined. Because all transformations are ultimately defined on the underlying dynamical systems, it is perfectly legitimate to first define transformations between the dynamical system of the media, and only after analyze what transformational invariance justifies treating the functions as information transformations. In this way, it is perfectly acceptable to define an information management transformation and use it to define informational states or information preserving transformations — in effect defining the $\mathcal{IC}$ sets of one medium from those of the other. Note, however, that this is not sufficient as a recipe for getting the definition process started. The question of how the process can get started is beyond the scope of this paper. I say more about this in (Vakarelov, 2010), but ultimately, in technological IMNs at least, the start comes from pragmatics — from how the network is integrated in the informational media of human cognitive systems, and in human interactions with the world and other humans.

## 6 Conclusion

In this paper I provided a foundation for a general theory of information media and information medium networks. The discussion demonstrated that many technological and natural systems normally associated with information containment, processing and management are subsumed under the notion of information medium. The goal is to use the notions of information medium and IMN as a general framework for investigation of all informational phenomena. The goal will be a subject of further research, to which this paper offers a first step.

The paper also endorsed a structural approach to information, suggesting that information is not a basic notion but is derived as an invariance under information transformations. A future goal is to understand information, including its semantic and pragmatic aspects, as a phenomenon in the interaction and coordination of large networks of information media, implemented in the highly organized dynamics of the world, and interacting with the world at a causal level. Central role in such networks is given to human cognition. It ultimately endows the information networks with the kind of semantics relevant to human experience and action.

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