Between Armaments and Ornaments. Weak and Strong Emergent Patterns in Virtual and Real Cellular Automata

Erica Onnis

Abstract Despite the various criteria presented in the literature, most authors engaged in the debate about emergence agree on a fundamental distinction between strong/ontologically robust cases of emergence and weak/metaphysically innocent ones. The former typically involve entities that exhibit new causal capacities, while the latter are primarily associated with deductive unpredictability, conceptual novelty, and other qualities that highlight our epistemic limitations in understanding them. In this paper, I initially examine a paradigmatic example of weak emergence, namely the higher-level patterns generated by virtual Cellular Automata (CAs) as analysed by Mark Bedau. Then, I demonstrate that the same mechanism can be observed in real biological systems, such as the dynamics governing the pigmentation ontogeny of the ocellated lizard (*Timon lepidus*). Unlike virtual CAs, however, real CAs produce patterns that seem to perform non-reducible functions. Therefore, I propose that despite the similarities between virtual and real CAs, the pigmentation pattern of the ocellated lizard should be regarded as a case of strong emergence. Moreover, I suggest that this analysis may shed light on the nature of biological emergent entities in general. Finally, the paper includes an Addendum introducing an issue that, while not exhaustively addressed here, is highly relevant: how to metaphysically conceptualise the causal efficacy exhibited by the pigmentation patterns.

Keywords emergence, patterns, cellular automata, biological information, difference-making, causation.

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This is an accepted version of the manuscript. Please cite the published version:
Onnis, E. (2024). Between Armaments and Ornaments. Weak and Strong Emergent Patterns in Virtual and Real Cellular Automata. In: Martín-Villuendas, M., Gefaell, J., Cuevas-Badallo, A. (eds) *Life and Mind. Interdisciplinary Evolution Research* (pp 67–90). Springer, Cham. https://doi.org/10.1007/978-3-031-70847-3_4

1. Introduction

Over the past few decades, interest in the notion of emergence has grown steadily. As testified by several debates in philosophy and science (Bedau and Humphreys 2008; Gibb, Hendry and Lancaster 2019; Wuppuluri and Stewart 2022), emergence seems relevant in describing and understanding various natural phenomena such as spacetime (Crowther 2016; Wüthrich 2019), quantum entanglement (Silberstein 1999; Hüttemann 2005; Humphreys 2016), molecular structure and macroscopic properties (Luisi 2002; Hendry 2006), as well as stigmergy, flocking, and similar coordinated behaviour of insects, birds, fishes, and mammals (Grassé 1959; Theraulaz and Bonabeau 1999, Cucker and Smale 2007; Mitchell 2012). Despite its widespread application – or probably because of it –, no single, uncontroversial definition of emergence has been developed; rather, there are different models based on criteria that overlap only partially.[2] In his book *Emergence. A Philosophical Account* (2016), Paul Humphreys explores the reasons that might explain this lack of consensus; he identifies two main factors. The first is that "[…] the concept of emergence is not rooted within a single science" (2016, p. xvii), so there is no discipline that can have the final say on it. The second reason is that "[…] we do not have a firm pre-theoretical grasp of emergence in the way we do with something like causation" (*ibid*). In other words, we are incapable of pre-theoretically agreeing on what is emergent and what is not: hence the lack of universally accepted examples of emergent phenomena. As a result, there is now an extensive debate about the nature of emergent entities, as they seem to exhibit different features when observed in different contexts and approached by different disciplines. It has become customary, therefore, to speak of many forms of emergence: strong, ontological, or metaphysical; weak or epistemological; conceptual; flat; causal; diachronic; synchronic, *etc*.

As I suggested elsewhere (Onnis 2023), given the heterogeneity of emergent phenomena and the different theories proposed to model and explain them, adopting a pluralist approach, rather than attempting to reduce certain models to others, may be beneficial. In other words, rather than seeking universal features that all emergent phenomena should exhibit – for instance, for any case of strong emergence, possessing a novel causal power (Wilson 2022) –, it could be fruitful to identify the specific ways in which the general criteria associated to emergence are satisfied in particular cases. This approach would lead to the development of several "species-specific" models of emergence and supports the following intuition: that the word "emergence" refers, as a sort of umbrella term, to different states or processes characterised by different features that depend, in turn, on the ontological domain in which they appear and the nature of the entities composing their emergence base. General features such as novelty or ontological and epistemological irreducibility can still be recognised as important in defining emergence – indeed, essential for justifying why all these (different) phenomena should be considered emergent. However, in order to formulate better explanations and descriptions of why and how certain phenomena are emergent *specifically*, those criteria need to be contextualised and detailed. By doing so, it may be possible to produce a useful taxonomy of emergents appearing at different levels of organisation.

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[2] See, for instance, Wilson 2021 (pp. 7-15), in which the author offers a long list of the interpretations of the two criteria that she recognises as central for emergence, namely autonomy and dependence.

In this paper, I focus on biology, a domain in which emergent phenomena are abundant but also particularly difficult to frame using traditional emergentist outlines, and offer a model for these peculiar instances of emergence. To do so, in the next paragraph I briefly introduce the distinction between strong or ontological and weak or non-ontological cases of emergence. Then, in §3, I look into Mark Bedau's analyses of the macro-patterns emerging from the micro-dynamics of *virtual* cellular automata. Bedau defines these patterns as "weakly emergent" (1997, p. 375) because they are nomologically autonomous but causally ineffective, being nothing more than the aggregation of the causal states of the components (2012, p. 97). In §4, I propose to examine an *embodied* cellular automaton regulating a real biological process, namely the ontogeny of the labyrinthine pigmentation pattern of the ocellated lizard (*Timon lepidus*). The examination of this case aims to illustrate the functions performed by the higher-level pattern and whether those functions can be reduced to the causal contributions of the lower-level micro-components. Regarding the first issue, in agreement with recent studies in communication biology, in §5 I propose that ocellated lizards' pigmentation patterns perform genuine biological functions such as conveying information about the individuals displaying them. This may be further specified by considering the patterns as vectors of "informational difference-makers", namely as causal mediators based on biological information exchange (§6). In §7, I address the second issue, that of the possible reduction of these causal roles. I suggest that pigmentation patterns are not realised in the classic, functional way, which involves inheritance of causal powers, but rather in the way that David Yates defines as "qualitative". Qualitative realisation, however, is not a reductive relation, as the qualitatively realised entity retains the ability to perform new causal roles.

Finally, in §8, I conclude that if one agrees on the irreducibility of their causal roles and adopts Bedau's model of emergence, the pigmentation patterns of the ocellated lizard appear to be an example of strong emergence by virtue of the following features: (i) patterns are *physically composed* and *qualitatively realised* by their components and are therefore *dependent* on them; (ii) they are *autonomous* because their evolution is *theoretically unpredictable* (derivable but just by simulation); (iii) they are *novel* because they instantiate the *novel* and *causally efficacious property* of conveying biological information. Moreover, pigmentation patterns, like any other biological trait, must have an evolutionary origin, which means that they must be the result of an evolutionary process during which they have been selected because of their functions. This last feature suggests something that should be considered every time a biological case of emergence is under scrutiny, namely that biological systems are open systems and their surroundings, as well as their diachronic evolution, must be taken into consideration. In biology, in short, no synchronic analysis of emergent phenomena viewed as isolated systems can do the job.

The paper includes an *Addendum* about how the causal novelty exhibited by the lizard's pigmentation patterns can be conceived from a metaphysical point of view. This is an issue that cannot be exhaustively discussed in this paper, given its complexity; but I mention it here to indicate its importance and the need to explore it in future research. I outline two possible ways in which informational difference-makers can be interpreted metaphysically. The first is by admitting that the causal processes at issue involve an actual transfer of an actual entity, i.e., "biological information". As I will show, this view exhibits similarities with transference theories of causation. The second is by adopting a power ontology and by understanding the exchange of biological information in terms of the exercise of at least two mutually dependent causal powers, i.e., the power to inform, exerted by a source (the pattern), and the power of being informed, exerted by a receiver (who decodes the information). I conclude that both these theories provide insights into the causal processes at issue but have relevant metaphysical costs, and, for now, leave open the question of whether a new metaphysical framework is needed to model the case that biology confronts us with.

2. Ontological and non-ontological forms of emergence

Despite the various criteria and models offered by the literature, most authors agree on a basic distinction between strong or ontological cases of emergence and weak or "metaphysically innocent" ones. The former typically involve novel and unprecedented causal capacities that make them non-epiphenomenal and ontologically relevant (O'Connor 1994; Kim 1999; McLaughlin 2008; Yates 2016; Gillett 2016; Baysan 2020; Wilson 2021). For example, Carl Gillett's most sophisticated account of emergence, which he calls *S-emergence* (Gillett 2016, pp. 187 et seq.), posits that S-emergent properties are *realised* but *determinative* high-level properties. Gillett defines emergent determination as "non-productive" because he wants to keep the distinction between causation as production or "role-filling" and causation as determination or "role-shaping". To do so, he introduces the term *machresis* to capture this second type of determination. Regardless of the distinction between causation and determination, however, what Gillett is emphasising is that S-emergents are entities able to make a difference to the world and this feature makes them ontologically robust. Another example is Jessica Wilson's recent and influential proposal for metaphysical emergence, which requires the fulfilment of two conditions related to causal efficacy which she calls the *New Power Condition* and the *Proper Subset of Powers Condition*. According to Wilson, to be metaphysically emergent an entity should possess a causal power not had by its components (a *new* power) or a causal profile different from that of its components (which means, in Wilson's framework, a *proper subset* of their powers).

On the other hand, weak or metaphysically innocent emergent phenomena do not require novel causal efficacy but exhibit other notable features, such as conceptual novelty (Humphreys 2016), unpredictability or underivability (Bedau 1997; Humphreys 2016; Gillett 2016), predictability through simulations (Bedau 1997).

To explain weakly emergent properties, for instance, the elaboration of new conceptual frameworks is required, and this suggests that every special science property is an example of this kind of "conceptual" emergence (Humphreys 2016). As for unpredictability and underivability, it may be useful to recall what was pointed out by Jaegwon Kim, who distinguished between *inductive* predictability and *theoretical* predictability (1999). One can inductively predict the appearance of an emergent property in a system that one already observed in the past, but one cannot theoretically (i.e., deductively) predict it before its first appearance, starting from the knowledge of its emergent base alone. In addition to this knowledge, adds Humphreys (2016), there have to be some experiments and at least an "inductive generalization".

Despite their unpredictability and the need for novel concepts, weakly emergent phenomena do not – apparently – exhibit the capacity to causally contribute to their bearers and to the world. Consequently, they are usually excluded from the category of ontologically or metaphysically relevant forms of emergence.[3]

In the following discussion, I consider a paradigmatic example of weak, non-ontological emergence: the macroscopic patterns produced by a virtual cellular automaton (CA) as presented by Mark Bedau (1997). Bedau argues that the system does not exhibit novel causal powers and appears to be ontologically innocent; furthermore, the macro-dynamic of the system is predictable – albeit only through simulation –, so the system seems to manifest a *weak* form of emergence. However, when this process, originally examined as an abstract computational model, is observed in the natural world as a real, embodied biological process, its ontological relevance becomes evident, raising the question of how to conceptualise it.

3. Mark Bedau's weak emergence

In 1997, Mark Bedau wrote a paper identifying "underivability without simulation" as the hallmark of a particular kind of emergence that he defined as "weak". Unlike ontological or strong emergence, weak emergence is metaphysically innocent because it does not imply any form of ontological dualism (neither substance nor property dualism) and is consistent with materialism. Therefore, it represents a useful tool for describing reality without conflicting with a scientifically informed view of nature.

Bedau's weak emergence can be observed in systems composed of a certain number of lower-level components in certain microstates that produce higher-level macro-states through a microdynamics *D*. The microstates are the intrinsic states of the components, while the macrostates are the structural properties of the system. When the macro-states cannot be derived from the microstates without a real simulation, the system exhibits what Bedau calls "weak emergence".[4] The need for a real, step-by-step simulation to assess the evolution of the system is due to the absence of a possible compression or shortcut to derive it. Indeed, some years later,

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[3] This distinction rests upon an underlying metaphysical assumption known as the Eleatic principle. The principle owes its name to the visitor from Elea who converses with Theaetetus in Plato's *Sophist* (Oddie 1982). Towards the end of the dialogue, the Eleatic Visitor describes the theories of some materialist philosophers living in his town and tries to make their thesis more understandable. In this context, he enunciates the principle according to which everything that *really is* possesses some power or capacity (246a). The equivalence between being/existing and possessing causal capacities has persisted throughout the centuries, and in Jaegwon Kim's opinion, it was explicitly adopted by Samuel Alexander, one of the so-called "British Emergentists", the authors that introduced the notion of emergence in the philosophical and scientific debate in the nineteenth and twentieth centuries (John Stuart Mill, George Henry Lewes, Conwy Lloyd Morgan, Charlie Dunbar Broad and, indeed, Samuel Alexander; see Mclaughlin 2008). Alexander even gives the name to the other expression by which the principle is known, namely "Alexander's Dictum". The expression, coined by Kim (1993), suggests that, in Alexander's view, emerging phenomena such as the mind cannot be mere epiphenomena but are instead capable of exercising genuine causal efficacy. This is because, if they were not, they would have no reason to exist. I believe that the more or less explicit adherence to Alexander's Dictum (which Alexander did not really formulate, as I noticed in Onnis, 2022) is one of the most significant legacies left by Kim to the second emergentism.

[4] "Macrostate P of [the system] S with [local] microdynamic D is weakly emergent iff P can be derived from D and S's external conditions but only by simulation" (Bedau, 1997, p. 378). See also Assad and Packard (2008, p. 232): "Weakly emergent behaviour is deductible in hindsight from the specification after observing the behaviour".

Bedau slightly modified his definition of weak emergence by explicitly focusing on the notion of *incompressibility* (Bedau 2008).

It should be noticed that underivability without simulation, as well as incompressibility, are not features a system has because of the observer's cognitive limits. On the contrary, they reflect a *real* feature of certain systems whose dynamics can be derived only by simulation because of its nonlinearity – i.e., interdependence between components and correlations between variables (MacKay 2008; Bishop 2010).

The possibility of derivation/explanation, albeit by simulation, contrasts with a frequently required feature of emergent phenomena, which is epistemological irreducibility. This renders Bedau's weak emergence very weak because, even if just in principle and through the appropriate procedure, systems exhibiting weak emergence have a derivable evolution. Moreover, as said, Bedau's weak emergence is metaphysically innocent because the macrostates are exhaustively realised and determined by the microstates, therefore no novel causal powers appear in the systems.[5]

A question that arises at this point is why one should still use the term "emergence" if Bedau's account is so different from historically received ones (a question Bedau himself poses at the end of his 1997 paper). As a matter of fact, British Emergentists considered the presence of genuine causal efficacy and the impossibility of providing good theoretical predictions about emergent phenomena as their distinctive marks. Bedau's account, in contrast, does not attribute these features to the cases that he acknowledges as instances of weak emergence. Nonetheless, he points out that in more recent literature, two other important hallmarks have been assessed as typical features of emergence:

> (1) Emergent phenomena are somehow constituted by, and generated from, underlying processes.
> (2) Emergent phenomena are somehow autonomous from underlying processes (1997, p. 376).

Considering these two hallmarks, weak emergence seems to be a proper example of emergence. First, as stated by (1), the macrostates are generated from the underlying microstates. Second, as stated by (2), their behaviour is somehow autonomous at the macro-level. On the one hand, the necessity of a simulation descends from the impossibility of a derivation based solely on the microstates and the external conditions; on the other hand, Bedau emphasises another relevant feature of these systems, namely that "the sciences of complexity are discovering simple, general macro-level patterns and laws involving weak emergent phenomena" (1997, p. 395). From a nomological point of view, therefore, higher-level macro-phenomena seem partially autonomous because they are governed by distinct macroscopic natural laws.

Bedau's example of systems exhibiting weak emergence involves cellular automata (CA): spatially and temporally discrete dynamical systems composed of regular grids of cells that hold a finite number of possible states (for an introduction, see Berto and Tagliabue 2017). For each temporal step t_1, $t_2 \ldots t_n$, every cell of the system synchronously updates its state as a

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[5] "[…] the ontological and causal state of a cellular automaton macro-structure is nothing more than the aggregation of the ontological and causal states of its micro constituents" (Bedau 2011, p. 97).

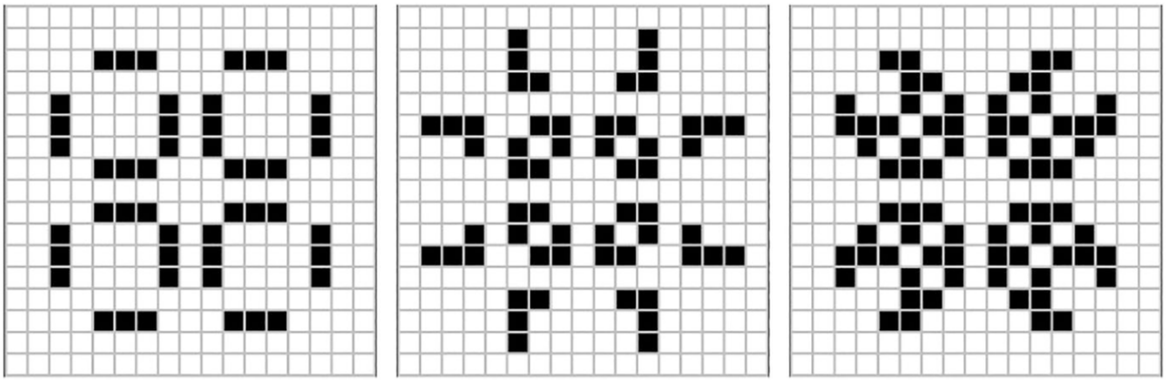

Fig. 1 The temporal evolution in three phases of a Pulsar, a recurrent pattern in the *Game of Life*. Pulsars belong to the category of "oscillators", namely patterns that repeat themselves after a certain number of time phases called "generations". Pulsars repeat themselves after three generations, meaning that after the third phase, the first pattern is generated again

function of the previous states of its neighbouring cells. The laws governing these interactions are simple, deterministic, *local* rules, but as the system develops, they produce sophisticated *global* patterns that are weakly emergent.

The simplest CA is called *elementary cellular automaton* (ECA). It is a one-dimensional model in which cells have only two possible states and the relevant neighbouring cells are the two in close proximity (range=1). A more complex CA is the *Game of Life* invented by the mathematician John Horton Conway in 1970. Unlike the ECA, the *Game of Life* takes place in a two-dimensional scenario and consists of a grid of cells extending in width and length, where each cell updates according to the states of the eight cells around it. These models produce complex and sophisticated macro-level patterns, such as those represented in Fig. 1.

In Bedau's framework, these macrostates – the CA's macro-level patterns – are emergent because they reflect the two hallmarks previously mentioned: (i) constitution and dependence upon micro-level components and processes; (ii) autonomy due to the impossibility of a deductive derivation/explanation. In Bedau's framework, therefore, incompressibility due to nonlinearity is responsible for the emergence of macrostates that are autonomous at the macro-level but also exhaustively constituted and generated by the lower-level microstates. Moreover, the powers of the macrostates are realised by those of the microstates, so the adjective "weak" for this kind of emergence seems appropriate, given that no novel powers, in addition to those of the components, appear at the macro-level.

In conclusion, macro-patterns indeed have a sophisticated structure and even Gestalt features, but in Bedau's opinion, they are simply the by-products of their microdynamics. However, what happens when these very dynamics are "embodied" in real biological processes? Do the macro-patterns remain inactive by-products of a microscopic dynamic, or do they start performing different and autonomous (i.e., emergent) functions?

4. A “living” CA made of coloured skin scales

Classic examples of biological structures that follow the development rules of CAs are the shells of many marine molluscs. These animals display a wide variety of pigmentations that sometimes derive from simple pattern-forming mechanisms, and at other times result from the superposition of multiple mechanisms leading to complex irregular patterns (Meinhardt 2009) (Fig. 2a, b, c). One notable example of the latter cases – noticed, among others, by Stephen Wolfram (2002) – is the shell of *Conus textile*, a beautiful and highly venomous sea snail. In this shell, at least two pigmentation systems seem to be superimposed, creating a mixture of parallel and oblique lines, as well as an alternation of differently coloured regions (Fig. 2c). Additionally, as shown by Fig 2d, the pigmentation of *Conus textile* is remarkably similar to the pattern generated by the evolution of an ECA following “Rule 30”.

However, despite these interesting features, it remains unclear how mollusc shell pigmentation patterns are influenced by evolutionary pressure. Some studies suggest that colour evolution is linked to camouflage, aposematism, as well as thermal or sexual selection. Yet, many species presenting these patterns live buried in sand or mud, have poor vision, develop patterns in the

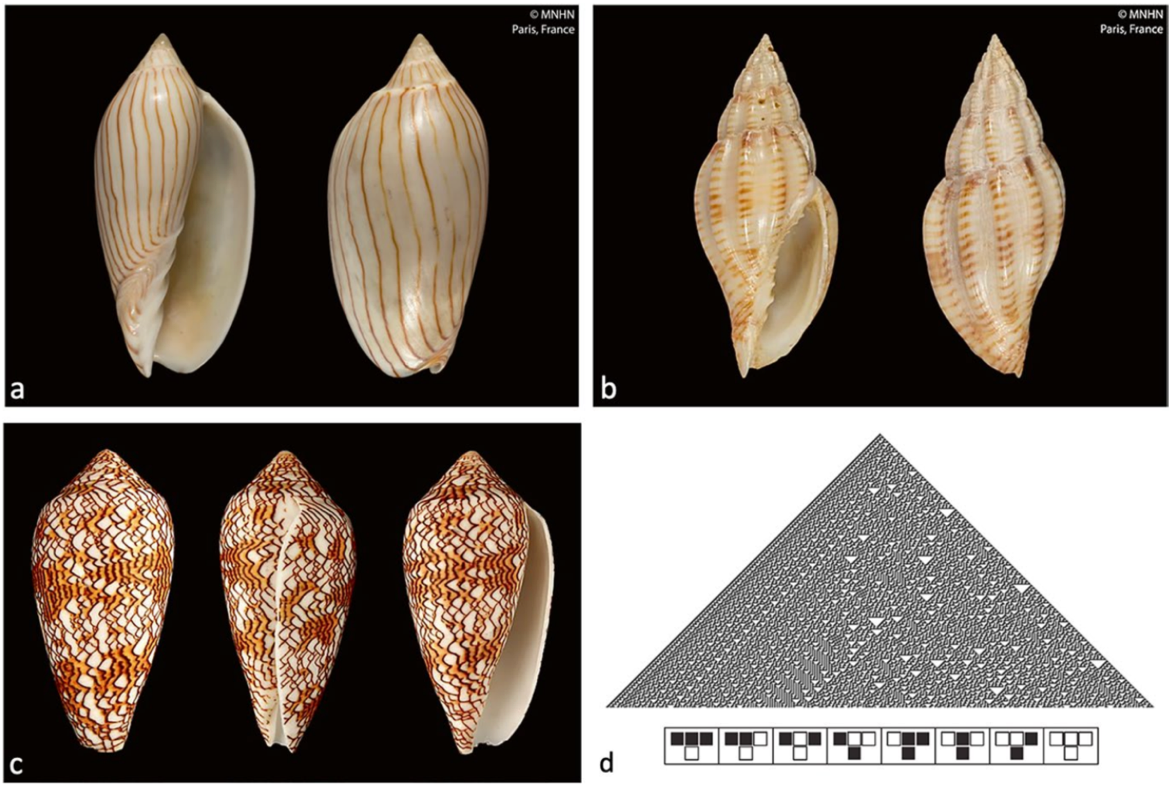

Fig. 2 Above, two species presenting simple pattern-formation systems: an *Amoria ellioti* (**a**) showing stripes parallel to the growing edge, and a *Lyria planicostata* (**b**) showing stripes perpendicular to the growing edge. Below, a *Conus textile* (**c**), and a CA following “Rule 30” (**d**) (Elementary Cellular Automata, Rule 30. From The Wolfram Atlas of Simple Program, https://mathworld.wolfram.com/Rule30.html). Credits: (**a**) M. Caballer, MNHN—Muséum national d’Histoire naturelle, 2020; (**b**) M. Caballer, MNHN—Muséum national d’Histoire naturelle, 2020; (**c**) H. Zell, private collection

inner part of the shell, cover themselves with algae, or have a thick periostracum (the outermost layer of the shell), obstructing pattern visibility (Williams 2016). For these reasons, some studies suggest that pigmentation patterns, in some species, may be mere relics or "incidental by-product[s] of metabolism or of structural requirements of the shell" (Saenko and Schilthuizen 2021, p. 3). Given this possible functional and causal "neutrality", I will not consider shell pigmentation in this paper, but rather focus on another recently studied case of a "living" CA: the ontogenetic mechanism of pattern pigmentation in the ocellated lizard (*Timon lepidus*) (Manukyan et al 2019).

It is worth noting that, like molluscs, reptiles – as well as most vertebrates – exhibit several types of colour patterns, namely "symmetry-breaking regularities […] such as stripes, spots, tessellations, meanders and labyrinths" (Manukyan et al 2019, p. 173). However, the processes through which patterns are produced in molluscs and vertebrates are different. While in shells patterns are "built up one line at a time" (Wolfram 2002, p. 425) because of the growing structure of the shells themselves, in other animals, patterns develop over surfaces. Therefore, while pattern formation in shells reflects the dynamics of a unidimensional ECA, in reptiles and vertebrates it is similar to a two-dimensional CA like the *Game of Life*. What follows will clarify this last statement.

Lizards are exothermic (cold-blooded) reptiles characterised by a body covered in scales. Their size varies considerably among the thousands of existing species, as do their diet, feeding techniques, habitat, and coloration. As for the latter, lizard skin colours depend on both structural and pigmentary cells. The former interact with light, while the latter contain pigments such as melanin or carotenoids. Typically, therefore, pigmentation is produced by cell-level interactions. However, in ocellated lizards, pigmentation patterns emerge at a higher anatomical level, as the relevant interactions occur not at the level of the cells but at the higher level of the scales (which are made of cells). This is why the authors of the study define as "mesoscopic" the process responsible for pigmentation ontogeny: because it is localised *between* the microscopic level of the cells and the macroscopic level of the patterns.

The coloration mechanism exhibits all the relevant features characterising a two-dimensional CA. Firstly, CAs like the *Game of Life* are composed of a regular grid of discrete cells holding finite possible states. Similarly, lizard skin is composed of discrete scales that can display a finite number of colours. Secondly, and most importantly, in CA, the state of a cell is updated as a function of the states of its neighbouring cells, following simple local rules. The pigmentation mechanism of the ocellated lizard operates in a similar manner: each scale updates its colour as a function of its neighbouring scales. During the transition from juvenile to adult patterns, the number of black scales surrounding green scales increases until it reaches a value of three, while the number of green scales surrounding black scales increases until it reaches the value of four (Manukyan et al 2019, p. 175). The result of this dynamic is the intricate labyrinthine pattern visible in Fig. 3.

In conclusion, "the ocellated lizards' lattice of mesoscopic scales behaves as a CA that computes a macroscopic pattern", and this demonstrates that this class of computational systems is not just "[…] an abstract concept but corresponds to a process generated by biological evolution" (Manukyan et al 2019, p. 174). With that said, a question naturally arises about the biological functions that pigmentation patterns serve in nature.

Fig. 3 Ocellated lizard (*Timon lepidus*). Male (above); pigmentation patterns (below). Credits: Fabio Pupin

5. The adaptive value of pigmentation

Generally speaking, animal coloration has various adaptive functions, some of which have already been mentioned in relation to molluscs. First, pigmentation is related to intraspecific communication, serving as an "ornament" to attract mates or as a sort of "armament" aimed at deterring sexual competitors. However, it is also relevant to interspecific communication, as shown by aposematism, where bright colours signal toxicity or distastefulness. Other adaptive functions include concealment and camouflage, photoprotection against the damaging effects of sunlight, and thermoregulation (for an overview, see Protas and Patel 2008; Hubbard et al 2010).

The significance of pigmentation is equally evident in its absence. Hypogean species, which live in underground ecosystems, exhibit common morphological characteristics despite inhabiting different geographical areas and belonging to different groups: no eyes and lack of pigmentation. This is an example of convergent evolution, as eyes and pigmentation are useless in total darkness, so they gradually disappeared over time, while other structures, such as appendages, have become more prominent (Culver and Pipan 2019).

Regarding lizards, pigmentation patterns perform at least two functions. Firstly, they contribute to what is called disruptive coloration, "a phenomenon in which a color pattern breaks up the animal's form so that it is difficult to identify the real outline of the animal" and distinguish it from its surroundings (Protas and Patel 2008, p. 427). Pigmentation, therefore, serves as *camouflage*. Secondly, in lizards, like in many reptiles, patterns can be ornaments as well as armaments, playing a crucial role in sexual selection and survival (Whiting et al 2003). In these cases, patterns carry information about the individual displaying them and serve as "badges-of-status", namely features conveying social standing signals. These markings are particularly important in male competition, where competitors can settle conflict by *fighting*, which is a costly solution, or rather by *signalling* their dominance, fighting abilities, and level of aggressiveness. The latter strategy avoids actual fight as well as consequent injuries and energy expenditure, and is often preferred to physical confrontation, especially in those cases where there is a relevant asymmetry between the competitors, or when the value of the contested resource is low (Maynard-Smith and Harper 1988).

Given the above, it is not straightforward to consider the emergent pigmentation patterns displayed by ocellated lizards as instances of weak emergence. It is true that the macroscopic pattern is exhaustively determined by its lower-level components and dynamics, as happens in virtual CAs, and it is also true that the evolution of the system can only be derived by simulation. However, stating that the pattern does not exert any form of autonomous causal efficacy – being, therefore, ontologically innocent – seems to contrast with what biology teaches about the effectiveness of animal signalling and communication. This leads to two questions. The first one is how to conceptualise the causal efficacy of animal signalling; the second one is whether this causal efficacy can be somehow reduced to the lower-level or not. Answering the former question may provide new insights into causation; answering to the latter would clarify whether the pigmentation pattern produced by the embodied CA really represents an instance of weak emergence or rather a case of strong, ontological emergence. Let us now turn to the first problem.

6. Pigmentation patterns as vectors of informational difference-makers

In the field of communication biology, also known as biocommunication, it is customary to consider two possible ways in which animals communicate: through *cues* and through *signals*. A cue is a physical feature of the world that can elicit a reaction in the receiver. However, cues – which can be both phenotypic and abiotic properties – have not evolved *because of* these functions. Cues convey information to the receiver accidentally. On the other hand, signals evolve specifically because of their ability to influence the receiver. A signal is defined as "any act or structure which alters the behavior of other organisms, which evolved because of that effect, and which is effective because the receiver's response has also evolved" (Maynard Smith and Harper 2003, p. 3).

To understand how cues and signals do what they do, however, it is necessary to introduce the concept of "correlational information", because what cues and signals do is convey this type of information (Fresco, Ginsburg, and Jablonka 2020, p. 550). For example, a cloud in the sky is a cue that conveys information about the possibility of rain because clouds and rain are correlated. Similarly, the honeybee waggle dance is a signal that conveys information about the richness and distance of a food source. There is a correlation between these features: the longer the dance, the more distant the food.

It should be noted that in biocommunication there is no consensus on the exact meaning of the term "information". There are different interpretations (Stegmann 2013), and starting from the 1970s, some authors have even suggested banishing this notion from communication biology, describing cues and signals without referring to information exchange (Dawkins and Krebs 1978). This viewpoint often takes an anti-realist stance, with its supporters stating that talking about information exchange is just using a metaphor to describe a process that can be described through less mysterious concepts like manipulation or influence (Owren, Rendall and Ryan 2010). Without delving too deeply into the debate, it is worth noting that while the nature of information surely requires a detailed analysis, this does not mean one should discard a concept that successfully describes numerous biological processes. Furthermore, those who use the concept of information exchange to explain animal communication are not always realists or ontologically committed to the reality of information (Stegmann 2013). They employ it as a good heuristic tool, and even if *what information is* still is an open question, an "informational stance" about animal signalling is evidently successful.

The different interpretations of "information" are only partially relevant to the focus of this work. Information can encompass mere correlation, uncertainty reduction, or more complex mental representations. This pluralism, however, simply reflects the existence of different kinds of signals and different forms of communication in nature. Some of them are representational, while others are not. Vervet monkeys' alarm calls are referential because they allow the monkeys to understand whether the danger is represented by a leopard, an eagle, or a snake (Seyfarth et al 1980). These signals, therefore, convey representational, correlational and uncertainty-reducing information. Many other signals, however, are less sophisticated and operate in different ways.[6] Animal communication, moreover, is just one area among many in

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[6] Examples of signals not involving mental representations are ant pheromone trails: "there is no need for the ant's nervous system to construct an internal representation of some rudimentary 'idea' of food [...] you do not need a map if you are traveling by rail" (Johnson-Laird, 1990, p. 3).

biology where information plays a role. In other frameworks, information is seen as genetic, further highlighting the challenges of providing a general and unambiguous definition of biological information.

However, this paper does not aim to define information in biology or in biological communication in general. Instead, it focuses on the specific case of ocellated lizards' pigmentation patterns, and Eva Jablonka's account of biological information appears particularly suitable in this regard (Jablonka 2002; see also Koonin 2016).

In Jablonka's framework, biological information relates to structure, meaning, and function. Unlike Claude Shannon's statistical notion of information or Solomonoff/Kolmogorov/Chaitin's algorithmic information theory, biological information does not just correspond to a system having different or more or less complex and incompressible possible states; rather, it is associated with the functional response that it elicits in a receiver[7]: "A source—an entity or a process—can be said to have [biological] information when a receiver system reacts to this source in a special way" (Jablonka 2002, p. 582). Here, "special" means "functional", and "functional" means able to causally contribute to the goal-oriented behaviour of the receiving system. This functional reaction, moreover, should be "beneficial over evolutionary time" (ibid, p. 581), otherwise it would not pass through the sieve of natural selection. In a recent paper, Jablonka, Nir Fresco and Simona Ginsburg (2020) explicitly highlight the effectiveness of biological information by talking about informational "difference-makers". A signal, in other terms, elicits a functional response in the receiver and that means that it should be recognised as its cause (Fresco, Ginsburg and Jablonka 2020; see also Jablonka 2002; Calcott, Griffiths and Pocheville 2020).

Peter Godfrey-Smith (2014) formulated a model that aligns with these ideas and can explain the signalling processes involving pigmentation patterns. Drawing from David Lewis' and Claude Shannon's models of communication, Godfrey-Smith identifies two rules governing communication processes. The first rule is the rule of the sender, who produces a signal in response to a state of the world. The second rule is the rule of the receiver, who responds to the signal by performing an action. This process can be represented as follows:

Fig. 4 A model of signaling processes (adapted from Godfrey-Smith 2014, p. 6)

Regarding ocellated lizards, their pigmentation patterns appear capable of transmitting biological information about the individuals' character to conspecifics. Following the aforementioned model, the state of the world corresponds to the features of the individual (e.g., its age, sex, or social status), the pattern represents the sender's signal, the signal is the piece of

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[7] This account of biological information is similar to Donald MacKay's (1969) and Gregory Bateson's (1972) definitions, which focus on the changes that information produces in the receiver.

biological information *about* the features of the individual, the receiver is a competing male or a female, and the receiver's potential acts correspond to its functional reactions and/or behaviours – e.g., fighting, fleeing, or being interested in mating.

This model suggests that animal signals, which are "made of" information, should be considered as biological or informational causal mediators, and this is rather undebatable among biologists. If these causal mediators cannot be reduced, moreover, the pigmentation pattern of the ocellated lizard should be reasonably recognised as an instance of strong emergence. In the next paragraph, I explore this possibility.

7. Causal efficacy between functional and qualitative realisation

In his work on CAs, Mark Bedau focused on computational models such as *virtual* CAs. Here, patterns have *computational* functions that Bedau considers exhaustively realised and completely determined by their microcomponents. In *real* CAs, emergent patterns have *biological* functions that have been selected by evolution to enhance the fitness of their bearers. This suggests that the causal relevance of these patterns must be taken into due consideration.

In the previous paragraph, I proposed to understand pigmentation patterns as vectors of informational difference-makers, serving as causal mediators of a special biological kind. This notion poses a challenge to classic theories of causation, as they do not encompass such phenomena. A strategy to avoid the problem of accounting for them (and for their higher-level causal efficacy) is therefore a reductionist one. A sceptic, in other words, may try to reduce the higher-level causal roles of the patterns to the lower-level causal roles of the components, stating that the powers of the former are in fact exerted by the latter. However, there might be good reasons to suppose that this is not a feasible plan, because classical models of ontological reduction such as realisation (Kim 1993 and 1998; Shoemaker 2007) prove ineffective in this case. To better clarify this point and illustrate the specificity of the causal roles in question, let me turn to a distinction introduced by David Yates.

Yates (2016) describes two types of realisation: *functional* and *qualitative*. In classical accounts of realisation, which Yates defines as "functional", "the powers of the realized property are derived from those of its realizers" (2016, p. 818). In qualitative realisation, in contrast, the "realizers do not realize it [the realised property] by bestowing causal powers" (*ibid*), but rather by meeting certain non-causal specifications. As examples of properties that are not functionally but rather qualitatively realised, Yates describes sphericality and the molecular geometry of the water molecule H_2O.

To be spherical or to have a particular geometry, an object composed of more elementary parts needs to have those parts arranged in certain spatial configurations. The lower-level components do not fill causal roles or transfer their causal powers to the higher-level entity; rather, there need to be specific spatial relationships among the parts. Yates defines this feature by saying that properties such as sphericality or molecular geometry have a "*non-causal* specification". I propose that having a certain pattern falls into the same category, as patterns are geometric properties.

To manifest a pattern, therefore, an object composed of more elementary parts, such as scales, must have those parts arranged in a specific spatial configuration. In this case, no causal roles must be inherited or realised by the lower-level components. However, these higher-level properties (sphericality, molecular geometry, or patterns) may exhibit novel causal efficacy. For instance, water molecules are polar, and Yates argues that polarity depends on both the nature of the atoms forming the molecule and its molecular geometry. Polarity, moreover, has considerable effects enabling the formation of hydrogen bonds, which allow water to have a significant surface tension; this allows for the phenomenon of capillarity. In Yates' view, finally, molecular geometry is an example of strong emergence because this property is both realised by its lower-level components and causally autonomous. The same can be said, I think, for pigmentation patterns, which are realised by (the colours of) the scales, while being effective in a distinctive, autonomous way. In fact, pigmentation patterns could be considered an even more compelling example of qualitative realisation than molecular geometry, as while in water molecules the components already have individual distinctive powers, in the case of the patterns the components do not possess powers of their own[8] and do not perform specific functions until they become part of the higher-level structure.

Ultimately, pigmentation patterns appear to possess genuine causal roles that cannot be realised (i.e., reduced) to the causal roles of the scales of which they are composed. If one agrees on this, and adopts Mark Bedau's model of emergence, the pigmentation patterns of the ocellated lizard can be seen as an example of strong emergence.

8. Conclusions. Pigmentation patterns as an instance of strong emergence in biology

In summary, the reasons for considering the pigmentation patterns of ocellated lizards as a case of strong, rather than weak, emergence, can be outlined as follows:

(i) DEPENDENCE. The patterns are *physically composed* and *qualitatively realised* by their components (the scales).
(ii) AUTONOMY. The evolution of the patterns is *theoretically unpredictable* (merely *derivable by simulation*).
(iii) NOVELTY. The patterns instantiate the *novel* and *causally efficacious property* of conveying biological information.

Pigmentation patterns exhibit features commonly associated with ontologically emergent phenomena: mereological composition, realisation, theoretical unpredictability, and (causal) novelty. However, this specific case of emergence has some distinctive characteristics.

First, the realisation of the pattern is qualitative rather than functional, involving structural and spatial specification rather than the transfer or inheritance of causal powers. Second, the property responsible for NOVELTY involves biological information, which is one of the features that typically characterises living systems and their interactions.

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[8] It can be said that the scales, being coloured, do have causal powers, since colours can be intended as powers. In the Addendum, for instance, I mention Anna Marmodoro's constitutional theory of colours, and she argues that colours are powers: the powers of appearing coloured. As I will show, even if one were to admit this idea, the causal roles of patterns do not seem to be derivable from those of scales, because colours and patterns are different entities with different causal capacities. See the Addendum below.

In addition to these qualities, it is pertinent to consider another feature:

(iv) EVOLUTIONARY ORIGIN. The patterns are the result of an *evolutionary process* during which they have been selected because of their function.

Pigmentation patterns differ from virtual CAs emergent patterns – and from any other artificial communication system – because they do not only acquire their features synchronically based on their components but also diachronically through a long, natural process of co-evolution with the receivers. The patterns emerge from the relational structure of the components and the interplay between this structure and the environment, and this is a feature that must be always considered when discussing biological cases of emergence. While the debate about emergence usually focuses on isolated systems, their properties, their powers, and the synchronic relationships between the different levels of organisation involved, biological systems are never isolated, so one must always consider their surroundings, as well as their diachronic evolution.

In addition to the specific conclusion that the pigmentation patterns of ocellated lizards should be considered as instances of strong emergence, this analysis may suggest two broader conclusions. First, when examining structures at the intersection of non-biological and biological systems, the property of conveying biological information should be regarded as a salient property sufficient for emergence. Second, emergence in biological systems should be understood in diachronic terms, as their synchronic structure alone cannot explain all their features.

In summary, when a physical system develops the ability to send or receive biological information as defined by Jablonka, Fresco and Ginzburg, it marks one of those discontinuities that have sparked discussions about levels of reality since the origin of the debate about emergence. At that moment, in other words, a transition to more complex levels of organisation takes place and can be identified.

Addendum

The issues discussed in this paper raise an important question that cannot be fully addressed here but deserves to be mentioned as a potential direction for future research to explore. The question is how the causal novelty of the lizard's pigmentation patterns can be conceived from a metaphysical point of view. I proposed to understand patterns as vectors of informational difference-makers, a description closely aligned with the vocabulary employed by communication biologists and philosophers working on these issues (such as Jablonka, Ginzburg and Fresco). Nevertheless, from a metaphysical standpoint, these causal processes, if taken seriously, should be better specified and related to existing models of causation. The key issue is the following: should the idea of an exchange of information be taken literally, or is it to be understood as a metaphor for something else?

In this addendum, I will provide a brief overview of two possibilities. The first is that informational difference-makers may refer to an actual transfer of an actual entity, called "biological information". The second is that they may refer to the exercise of at least two mutually dependent causal powers: the power to inform, exerted by a source, and the power to be informed, exerted by a receiver.

1.

The first hypothesis bears resemblance to the so-called “transference theories of causation”, proposed by authors like Jerrold Aronson (1971), David Fair (1979), and more recently, Phil Dowe (1992) and Max Kistler (1998). The central tenet of these theories is that causal relationships can be equated to transmissions of physical quantities such as energy, linear-momentum, or electric charge. Let us consider Fair's theory as a representative example.

The causal process on which Fair grounds his analyses is the classic interaction between billiard balls. The pool player hits the cue ball. Then, the cue ball “traverses the table top until it meets the eight ball head-on. The cue ball comes to a complete halt. The eight ball suddenly begins to move in the same direction that the cue ball had been moving, with apparently the same velocity. Its journey terminates in the aforementioned side pocket” (Fair 1979, p. 219). This is an example of a causal process where the cue ball is commonly recognised as causing the eight ball to fall in the side pocket. Fair presents several similar examples[9] and argues that science, particularly physics, has provided a clear explanation of the nature of these processes. Within this framework, causation corresponds to the flow of a certain conserved quantity of energy from one body or physical structure (the cause) to another body or physical structure (the effect): “The causal connection is a physical relation of energy-momentum transference” (ibid., p. 229). Returning to the example of the billiard balls, the cue ball transfers a specific amount of energy to the eight ball, and by doing so, it causes its movement.

Unlike regularity or counterfactual theories of causation, which do not open the causal black-box, Fair’s model – like Aronson’s, Dowe’s and Kistler’s – aims at accounting for the physical connection between a cause and its effect. Causation, therefore, is not merely seen as a matter of contiguity or regularity but corresponds to an actual interaction (or, in cases of omissions, to the absence of that interaction). While several causal processes can be easily described in terms of energy-momentum flows, others are more challenging to physically reduce, (allegedly) because of our ignorance. For instance, the physical description of a causal process like “John’s anger caused him to hit Bill” (ibid., 1979, p. 236) is incomplete due to our ignorance in neurophysiology. Similarly, we do not know how to physically describe a process like “antiwar demonstrations caused the Vietnam war to end” because of all the properties of the systems involved. However, Fair argues that these limitations are not a real problem for this analysis: they do not invalidate the theory, but only make it incomplete.

Returning to the pigmentation patterns of ocellated lizards, my first hypothesis suggests that their causal efficacy is grounded in their transmission of biological information to the receiver. At first glance, there are significant similarities with the transference theory of causation: the cause and the effect are connected by an actual interaction, and *something* is transferred from the patterns to the receiver. This transfer, moreover, makes a difference to the receiver, which

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[9] “John causes the door to move; the rotational energy of the door has its source in the chemical energy of ATP, transferred via the muscles of his arm. The internal combustion engine causes the car's forward motion; here the translational kinetic energy of the car (its ‘forward motion’) originates in the chemical bonds of the complex hydrocarbons of gasoline, transferred during combustion to the pistons and ultimately to the wheels. The sun causes the earth to warm, the energy of fusion transferred by photons becoming the thermal energy of terrestrial objects. The jet, in exceeding the speed of sound, causes a pain in Hector's ear, the energy having been transferred from the jet to the ear drum as pressure waves in the atmosphere” (Fair, 1979, p. 229).

receives that something, but also to the patterns, which lose it. While in the framework of traditional transference theories of causation the causal mediator is energy-momentum, in this example – and in many other biological processes with the same structure – the relevant causal mediator is biological information, which can be reasonably understood as something other than energy.[10] However, this hypothesis comes with a metaphysical burden, as it implies the need to expand our ontology and admit biological information as an entity with a *sui generis* existence. This may be fruitful because, given the ontological differences between energy and information, it should not be surprising that the transmission of the latter is not conservative as it must be in the case of energy, according to transference theorists. This might explain why biological information can sometimes be missed or "misunderstood": because it is not a conserved entity but rather something that can be created, transformed, and destroyed quite easily.

Serious theoretical work should be done in this regard, and not everybody will be eager to expand ontology in this manner; still, the effort could prove worthwhile, as it might contribute to the formulation of a new causation model suitable for analysing biological phenomena such as (human and nonhuman) animal communication and signalling.

2.

The second hypothesis, which posits that the causal efficacy of the pigmentation patterns corresponds to the exercise of causal powers, has a metaphysical cost as well, which is that of accepting a power ontology. This is a wager that not everyone feels inclined to take because there is metaphysical controversy around powers. However, given that the power-based approach to causation is receiving increasing attention, it is worth exploring it.

Various theories of powers have been formulated in recent years (Molnar 2003; Mumford 2004; Marmodoro 2010; Heil 2003; Williams 2019). Among these, Anna Marmodoro's "constitutionalist" account, which has already been applied to colours and their perception (Marmodoro and Grasso 2020), appears the most suitable for the purposes of this paper, since pigmentation patterns are made of colours and their effectiveness relies on perception.

Constitutionalism is a metaphysical, power-based theory according to which objects have qualitative features such as colours, smells or tastes. Within this framework, in other words, objects have the powers to appear coloured, to have a certain scent or taste, etc. These subjective or "qualitative" properties, however, can only be activated by – and become manifest thanks to – partner-features that are the powers of a perceiver. For instance, an object's power to appear coloured is fully activated by a perceiver's power to see colours (and conversely, the perceiver's power to see a colour is activated by the qualitative feature of the object). This theory establishes a relationship of *co-activation* or *co-realisation* between the powers of the object P and the powers of the perceiver Q.[11] On the one hand, this relation allows one to recognise colours as actual properties of objects, rather than something which solely exists "in our heads". On the other hand, it recognises the perceiver as the essential condition for the manifestation of these

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[10] See, for instance, Norbert Wiener: "Information is information, not matter or energy" (1948, p. 132).

[11] The connection between P and Q is not *ad hoc* but reflects a general tenet of Marmodoro's account of powers, namely that "a power's manifestation always happens as mutual manifestation of partner-powers, which act reciprocally as necessary conditions for each other's powers" (Marmodoro and Grasso, 2020, p. 68).

properties. Constitutionalism, therefore, “does justice to our intuitions about both the objective and subjective features of colors” (Marmodoro and Grasso 2020, p. 74), resolving many of the issues affecting the contemporary debate on their nature (see Chalmers 2006; Marmodoro 2006; Maund 2022).

Another central tenet of Constitutionalism is that some causal powers are multi-track and multi-stage. Some powers, in other terms, have multiple types and stages of manifestation. The multi-stage feature is particularly relevant to the present analysis. Powers like colours have different degrees or stages of manifestation, ranging from the less full to the fullest. For example, the colour of a lemon may be *unmanifested* when the lemon is in a dark room (even though the lemon still has the power of being yellow), *partially manifested* when it is illuminated but no perceiver is seeing its colour, and *fully manifested* when it is both exposed to light and perceived. The authors suggest calling these three phases of manifestation as stage 0, 1 and 2 of the power’s actuality. This graduality of actualisation depending upon the context is useful to explain why the manifestation of a power is not always the same.

This theory of co-activating, multi-staged powers can be applied to the causal processes involving pigmentation patterns. It is possible to advance the hypothesis that these processes involve the patterns’ power to inform the receiver and the receiver’s power to be informed by the patterns, with no reference to – and necessity for – an additional and ontologically controversial entity such as biological information. Moreover, the multi-stage feature of causal powers can justify some characteristics of the interaction between patterns and receivers. In short, a pattern may be unmanifested when invisible, partially manifested when no one is looking, or fully manifested when a perceiver is informed by it.

Given the complexity of the causal process at issue, however, this analysis overlooks at least one crucial point. To be informed by a biological pattern, mere visual perception is not enough. The pattern may be visible and perceived, yet still fail to effectively inform the receiver. This may happen because of the inherent differences between colours and patterns. The power to appear coloured only requires perception to become fully manifest. You cannot avoid seeing yellow if you’re a normally sighted individual who is looking at a yellow lemon illuminated by natural light. Moreover, in those same circumstances, the lemon cannot avoid manifesting its being yellow. In contrast, to be informed by a pattern requires perception plus some form of understanding.

The power of being informed by a pattern exerted by a lizard would allow for the full manifestation of the power to inform exerted by the pattern of another lizard, but what about you, reader, assuming you are not a herpetologist? Do you have the power to be informed when you look at the pigmentation pattern of an ocellated lizard? While you possess the power to see the pattern and the pattern can be seen by your visual system, its power of informing you is not fully activated because even if you have the power to perceive it, you don’t know what it means (and this is the relevant way in which that pattern informs the receiver: by transmitting a message about the world). This may suggest that a third stage of manifestation might be needed in cases like this or, more probably, that the partner-powers to be coloured and to see a colour are different from the partner-powers to inform and being informed by a pattern even if the pattern, from a physical point of view, is nothing more than a coloured shape.

I will not elaborate on this issue here, but I believe it would be worth exploring further to better understand communication and enrich power ontology.

3.
At this stage, I do not have a particular preference for either the first or the second hypothesis. Both provide valuable insights into certain aspects of the causal process under consideration, but also require additional investigation and come with significant metaphysical costs, such as the ontological commitment to biological information as a *sui generis* entity or to causal powers as real, non-metaphorical fundamental properties of the world. It is possible that in-depth analyses will clarify which model is best. Otherwise, as is often the case in philosophy, it is also plausible that choosing among these hypotheses (or formulating new ones) boils down to personal metaphysical and metametaphysical preferences.

Acknowledgments
I am grateful to Anna Marmodoro, Michele Paolini Paoletti and two anonymous reviewers for their valuable comments. This research was generously funded by the German Bundesministerium für Bildung und Forschung during my research stay at the Käte Hamburger Kolleg Aachen: Cultures of Research (RWTH Aachen University).

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