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Is incoherence required for sustainability?

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Abstract

Unstoppable feedback loops and tipping points in socio-ecological systems are the main threats to sustainability. These behaviors have been extensively studied, notably to predict, and arguably deviate, dead-end trajectories. A core group of repeated and predictable patterns in all systems, called systems archetypes, has been identified. For instance, the archetype of escalation is made of two positive feedback loops fueling one another. Interestingly, none of the known archetypes provide sustainability: they all trigger endless amplification. In parallel, systems biologists have made considerable progress on the role of incoherent loops in molecular networks in the past 20 years. Such patterns in biological networks produce stability and a form of intrinsic autonomy for all functions, from circadian rhythm to immunity. Incoherence is the fuel of homeostasis of living systems. Here, I bridge both conclusions and propose that incoherence should be included in the list of systems archetypes, and considered as an operational way to buffer socio-ecological fluctuations. This proposition is supported by the well-known trade-off between robustness and efficiency: adaptability requires some degree of internal contradiction. This applies to both technical and social systems: incoherent strategies recognize and fuel the diversity of solutions; they are the essential, yet often ignored, components of cooperation. Building on these theoretical considerations and real-life examples, incoherence might offer a counterintuitive, but transformative, way out of the Great Acceleration, and possibly, an actionable lever for decision makers.

Keywords

efficiency—resilience trade-off, incoherent loops, robustness, sustainability, systems archetypes, systems thinking

Introduction: Systems thinking with the help of archetypes

Human behaviors are often the result of untamed amplification loops. A bit like in a crowd movement: everyone is responsible for the agglomeration, and everyone wants to get out. Unfortunately,

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beyond a certain threshold, the crowd movement acquires its own logic, becomes autonomous, and is strengthened by the will of everyone to escape the crowd. Now considering global changes, one could say that humanity is currently in a planetary crowd movement: our global socio-economic system is channeling our future trajectory through many amplifying loops. Efficiency becomes counterproductive. Alas, many of the proposed solutions do not fundamentally change this path. For instance, strategies relating to energy efficiency increments or to frugal smart technologies often ignore rebound effects, paradoxically leading to increased global consumption of resources and more global pollution in the end (Foster et al., 2010). Beyond energy, this applies to most of our products and activities, from concentrated detergents generating over-dosage to high-yield oil palm generating new needs in all sectors (Hamant, 2020). This also echoes Goodhart law: when a measure becomes a target, it ceases to be reliable (Strathern, 1997). For instance, many of the efficient solutions to the climate crisis are toxic to biodiversity. Sustainability is not necessarily correlated with efficiency. In turn, could inefficiency promote sustainability, to some degree? More generally, could incoherence, defined here as an internal contradiction in a given system, fuel sustainability?

To explore that question, one must dig into systems dynamics. As mentioned in *The limits to growth*, « running the same system harder or faster will not change the [trajectory] as long as the structure is not revised » (Meadows et al., 2009). This means that we need to deconstruct the interaction network behind the socio-ecological crisis: amplification loops must be identified for us to be able to counteract them. This systemic work might seem difficult, but a guide exists, and is even very well known to systems analysts: it takes the form of “archetypes” (Table 1) (Kim, 1994).

In a network, an archetype is a small logical module with a limited number of elements and interactions, which effect is predictable with high confidence. The word archetype refers to the fact that such modules are found in all systems. To take an analogy, if a sentence is composed of words, a system is composed of archetypes. More precisely, if a sentence has a meaning thanks to the syntax that links the words together, a system becomes predictable once the archetypes are articulated between one another. Such an approach is used widely, from the prediction of next day’s weather to the multiple IPCC scenarios for the end of the century. For instance, the “success to the successful” archetype can be applied to an anticyclone, which by its own existence, sets the conditions for its maintenance on the same site (heat stabilizes the anticyclone). Such prolongation can translate into a heat dome (weather forecast), and the frequency and duration of heat domes is expected to increase in the future, by IPCC, following the same logic (Milman, 2023).

In the literature, there is a limited number of archetypes, all describing amplification loops (Table 1, Kim, 1994; Meadows and Wright, 2008). For example, the “escalation” archetype best describes the crowd movement, as well as many other similar situations. Here is the case of intensive agriculture: ploughing, fertilizers and pesticides degrade soil structure and life; as agronomical yields decrease, more ploughing, fertilizers and pesticides are used to compensate for the decline in the short term, accelerating the agony of the soil in an endless escalation in the long term.

While the complexity of a system should not be reduced to its archetypes, archetypes can be considered as the core skeleton of the system. This means that modifying them is, by far, the most effective way to change the trajectory of a given system. For instance, once the archetype behind traffic jam emergence is identified (the tragedy of the commons), one can find effective ways to prevent them, for instance, by imposing a slower speed on certain highway sections to enforce a more homogeneous behavior. Identifying the archetypes in a system is the first step to change its structure.

However, before starting this work, one must be sure that the list of known archetypes is complete. Here, I argue that we are missing one archetype, and arguably, the most relevant one to support sustainability: none of the canonic archetypes are stabilizing factors, whereas, in

Table 1. The main systems archetypes, with examples of their outcome in biology and in sustainability.

Archetype name	Example in biology	Example in sustainability
Drifting goals: lowering the goal instead of taking corrective action	The windshield phenomenon: each new generation forgets what a normal density of insects in the environment should be (Vogel, 2017)	The boiling frog phenomenon: certain stakeholders remain blind to a degraded environment because their wealth allow them to keep their lifestyle unchanged (Oswald et al., 2020)
Escalation: over-reaction to threats (arms race)	In plants, growth heterogeneity between adjacent cells is not dampened, it is instead actively promoted to prime organ emergence (Uyttewaal et al., 2012)	Arms race can increase global insecurity (Richardson, 1960)
Fixes that fail: fixing the symptom instead of the cause	Our brain tends to take shortcuts, especially when sugar levels are low (Baumeister et al., 1998)	Geoengineering reduces atmospheric CO_2 content, but may prevent us from questioning the root cause of our CO_2 emission (Parr, 2008)
Growth and underinvestment: lowering performance standards to justify underinvestment	Natural selection can lead to high levels of specialization, but this can also reduce the ability to explore alternative paths, an impasse in a changing environment (Gould, 1989)	The past success on the Ozone hole (Montreal protocol) can lead some to underestimate the efforts needed to face the more complex global socio-ecological crisis (Baldwin and Lenton, 2020)
Limits to success: growth increases pressure beyond which increasing efforts are useless	Algal blooms emerge when conditions are favorable, but their rapid growth also exhausts the resources and limits their ability to continue growing (Song et al., 2023)	Technological progress only provide limited solutions to the climate crisis, and often ignores the required efforts for equity and in education to become (really) sober (Rao and Baer, 2012)
Addiction: the side effect of the cure overwhelms the original problem symptom	Curing the symptoms with psychotropic medication does not fix the root cause of the problem and can instead generate an addiction (Nestler and Aghajanian, 1997)	Precision agriculture conveys the idea of frugality, but does not question monoculture and extends the dependence of farmers to digital technologies (Carbonell, 2016)
Success to the successful: initial success biases upcoming ones and channels resource allocation	Competitive species are more likely to colonize their biotope, to the detriment of biodiversity and long-term adaptability of the ecosystem (Pyšek and Richardson, 2010)	Focusing research on a hot topic will attract funding, but may also reduce creativity and innovation, which may reduce the array of solutions to global changes (Park et al., 2023)
Tragedy of the commons: focus on individual benefit leads the commons to be less productive	Certain parasites score an own goal when they are unable to maintain their host alive (Bayne et al., 2001)	Renewable energy with lithium-based batteries serves a happy few to the detriment of more distant ecosystems and people, potentially weakening everyone in the end (Chordia et al., 2021)

biological networks, there is increasing evidence that incoherent loops take on such a role. Should incoherence be included in the list of archetypes? Could it become a relevant lever for sustainability?

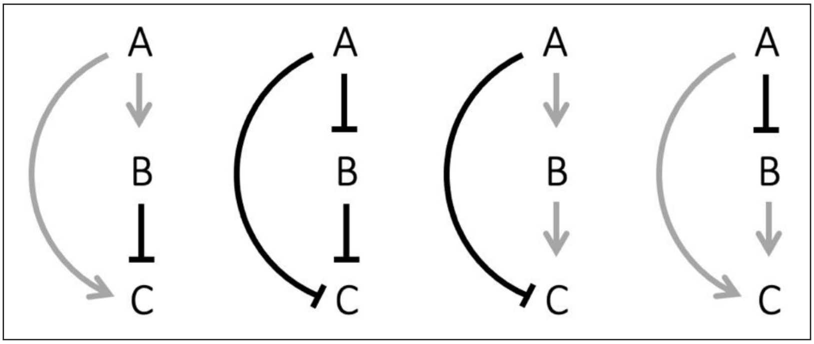

Figure 1. Incoherence defined as an internal contradiction in a system. The diagram illustrates the four possible incoherent loops for a 3-element system.
Source: Adapted from (Reeves, 2019).

Incoherence is an essential ingredient of biological robustness

How to define incoherence? Here I take the concept of incoherence at its roots, that is, an internal logical contradiction in a given system. For a 3-element system, this corresponds to a set of interactions that makes A induce and inhibit C at the same time. To be complete, in that case, there must an odd number of negative interactions in the system: this means 1 or 3 inhibitions (Figure 1). Because this definition is simple and based on logic only, it can be formalized and tested algorithmically. This is particularly pertinent in systems where many elements and interactions have been identified. Typically, this corresponds to gene networks in biological systems, especially in the best described model species such as drosophila, yeast or the plant *Arabidopsis thaliana*. The power of this approach, together with the availability of large dataset, close to exhaustivity, might be why such incoherent loops have become a central focus of study in biology in the past two decades (Shen-Orr et al., 2002; Lee et al., 2002; Milo et al., 2004).

Taking a step back, what does the analysis of such biological network teach us? Two conclusions: amplification loops are very frequent in all gene networks, and these loops are almost always built in such a way that one branch has the opposite effect of the other, that is, they are incoherent (e.g., Chakravarty and Csikász-Nagy, 2021). Interestingly, these incoherent loops have three main effects (Reeves, 2019): (i) they allow the system to return to its original stable state after a perturbation, (ii) they are rather inhibitory to avoid endless exponential amplifications, (iii) they improve very significantly the inhibition dynamics, and thus the induced stability (Figure 2).

More simply said, incoherent loops produce stable outcome, through autonomous oscillatory behavior that also dampen external perturbations. This is for example the case of circadian rhythm in living beings: (i) an amplification loop in the molecular network generates two possible outputs (active metabolism during the day and slow metabolism at night); (ii) an inhibition loop generates oscillations; (iii) when combined, they generate an oscillating biostability (day/night metabolism in alternation). This behavior is very robust in the long term, that is, little disturbed by external elements, thanks to the incoherent loop structure of the system. This type of behavior is now formally established in mammals, insects, fungi or plants (Joanito et al., 2018; Ueda et al., 2005).

Many other examples can be found in biological systems. For instance, plant growth is driven by their internal hydrostatic pressure (Peters and Tomos, 1996). This is obvious when one stops watering them: plants wilt, that is, they deflate. When they are inflated, they grow. However, in these conditions, plants are using photosynthesis to build stiff walls around their

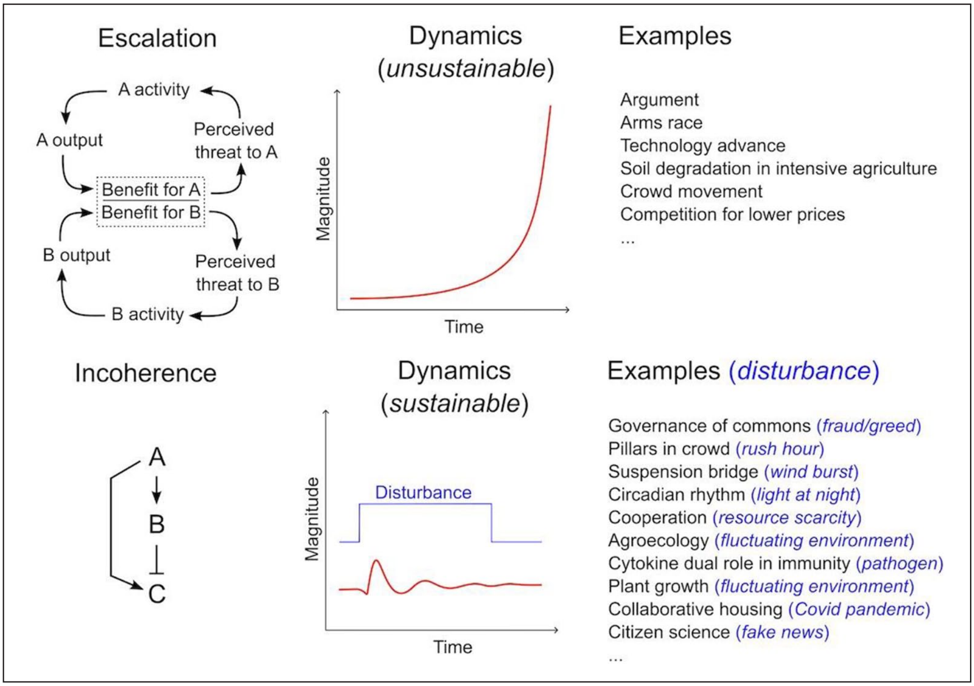

Figure 2. Incoherence as a sustainability systems archetype. Top: Escalation is a well-established systems archetype where A's output is perceived as threat by B, which in turn over-reacts, leading to a perceived threat from A, in a feedback loop (Kim, 1994; Meadows and Wright, 2008). The resulting dynamics is unsustainable, unless A or B drops the fight. Examples are listed on the right. Bottom: The example of the incoherent feedforward loop (well-established in biology). Such incoherence produces a form of robustness, the system becoming more resistant to internal or external disturbance. Many examples exist in biology (e.g., circadian rhythm (Ueda et al., 2005; Joanito et al., 2018), immunity (Hart et al., 2014), or plant growth (Vidal et al., 2010)). Incoherence is also an overarching factor in the governance of commons (Ostrom, 1990), addressing the shortcoming of the tragedy of the commons. Agroecology, citizen science or collaborative housing all exhibit incoherent features (slowness in a time of urgency, redundancy in a time of scarcity, heterogeneity in a time of rationalization) than more optimized and centralized approaches (intensive agriculture, academic/applied science, real-estate housing) but they are more robust to perturbations including environmental or economic fluctuations (through farmer's technical autonomy and biodiversity promotion in agroecology), fake news (through transdisciplinary debunking in citizen science) or psychological impact of Covid-imposed confinement (through increased interactions in collaborative housing). Incoherence's apparent weaknesses appear as systemic remedies to unsustainable amplifying loops.

cells, to resist their own turgor pressure. In other words, plants drive their growth with the handbrake on (Creff et al., 2023). This incoherence is a key to their robustness: many studies show that this constant balance allow them to constantly adapt to their environment, and to better use external and internal fluctuations to shape their organs (Moulia et al., 2021).

Such biology insight is an opportunity to revisit the definition of stability though systems dynamics: stability is not a flat line; it is instead a dynamic oscillation, alternating action and reaction around a baseline (Glass and Pasternack, 1978). In other words, the autonomous oscillation of the system can protect against unforeseen and random fluctuations. For instance, the cells of the gut are renewed periodically (in a few days) and this allows resistance to a great number of external aggressions. Conversely, the non-renewal of teeth limits the range of possibilities. In these cases, the degree of renewal scales to the degree of life-threatening aggression from the environment: a breach in the gut is certainly more harmful than a breach in a tooth, and calls for increased dynamics. This conclusion can be generalized using Ashby's law of requisite varieties: systems robustness does not emerge from its further consolidation (i.e., increasing coherence), but instead from promoting its own variability (i.e., fueling incoherence) (Ashby, 1958). While coherence feeds amplifying loops and generate instability, incoherence-fueled oscillation in biological systems is an effective shield against turbulence in a fluctuating environment.

Incoherence fuels robustness in technical systems too

Since we are dealing with systems, and therefore only with logical links, this conclusion also applies to other contexts. For instance, there is strong interest in engineering for these incoherent loops, in particular to avoid uncontrollable exponential behavior. Beyond elaborate examples in electronics or robotics, one can think of the simpler case of suspension bridge. It displays a fundamental contradiction: the bridge piers are in compression while the deck cables are in tension. Two destructive forces in a bridge, for what benefit? Because they oppose each other, the forces—compression and tension—create a mechanical balance. This allows the bridge to have its own mechanical autonomy, and thus to resist external fluctuations: when subjected to wind, the bridge oscillates but does not break, at least up to a certain deformation threshold (Chen and Duan, 2014; Nawy, 1989). Needless to say, such a balance of force also exists in (robust) biological systems, and typically in cells, with a membrane under tension and a content under compression (Ingber, 2008), or in plants, with an epidermis under tension and internal tissues under compression (Kutschera and Niklas, 2007).

Beyond suspension bridges, technical systems must take into account the trade-off between efficiency and resilience. This means that some degree of inefficiency is required for their long-term sustainability. This is well described in many technical fields, such as computer science (Shannon and Weaver, 1949), cybernetics (Ashby, 1956), synthetic biology (Filo et al., 2022; Reeves, 2019) or infrastructure design (Markolf et al., 2022).

Could incoherence, as a stabilizing archetype, help us design sustainable technical strategies counteracting the amplification loops of the Anthropocene? Let us consider the rise of low tech (Bihouix, 2014). While the world is experiencing more pressing issues, this could be viewed as an incoherent idea: creating suboptimal solutions, through slow participatory research with citizens, and with reduced economic growth (e.g., the all-repairable), instead of favoring the most efficient solution. The contradiction is resolved when considering that the race toward efficiency also reduces our path to a limited number of options (i.e., the most efficient ones) and makes us forget or discard the less efficient ones (e.g., more traditional, often less complex and more sober, options). In a changing environment, such a drive towards efficiency makes our socio-economic increasingly vulnerable. For instance, a smart electricity grid is more efficient, but any disruption in the system might not be resolved by citizens but, instead, could involve a distant technocratic entity. This is very fragile. Efficiency in technology can become an alienation, and can also reduce our adaptability by narrowing the options: smart cities do not necessarily make citizens smart. Robustness emerges from suboptimal processes, and prevails over efficiency, in a fluctuating environment (Aubin, 2009; Hamant, 2024a). Optimization is relevant to a stable environment, only.

Could incoherence feed sustainability beyond technical solutions? In an increasingly fluctuating world, the key, shared, values is no longer efficiency, it is adaptability (Hamant, 2024a). Can incoherence be used as a tool to stabilize our turbulent world?

Figure 3. A rice field in China, as an example of sustainable system requiring the governance of the commons, and associated incoherence. Coordination between upstream and downstream farmers requires cooperation, that is, a shared objective that may conflict short-term immediate interests. Elinor Ostrom's principles from the governance of the commons embed several incoherent components, which in the end, ensure the sustainability of the resource. See main text for details. Credit photo: O. Hamant.

Incoherence fuels robustness in organizations too

Incoherence, as an effective lever for sustainability, also applies to (sustainable) organizations. Consider the archetype of "the tragedy of the commons": each individual pursues their own goals in a selfish manner, and in the end, the commons (e.g., in pastoral areas: a shared aquifer, a shared grazing plot or a shared irrigation system (Figure 3)) no longer fulfill their function to the detriment of all (Hardin, 1968). The principles that prevent the emergence of the tragedy of the commons have been identified by economist Elinor Ostrom and her team, through a global analysis of robust commons over time (Ostrom, 1990). Most of these principles are fundamentally incoherent: (i) a commons which primary value could be its openness, instead needs limited access; (ii) the rules to maintain a fragile resource could be strict, but the analysis of robust commons over time shows instead that these rules must be modifiable in a participatory manner; (iii) sanctions, which one might want very strong to limit selfish behavior and fraud, must on the contrary be weak to guarantee the cohesion and belonging of group members; (iv) commons survive if they are managed by a self-organized and autonomous structure, but this structure must be recognized by an external entity in order to be maintained over time (Ostrom, 1990). Thus, it appears that incoherence might be a necessary, sometimes counterintuitive, ingredient to correct amplification loops, even in organizations.

Taking a step back, social systems heavily rely on incoherent loops (Hamant, 2024b). For instance, governments must promote counterpowers (parliaments, independent journalism, anti-corruption associations) to maintain the perennity of democracy (Christiansen et al., 2021). Conversely, when journalism turns into advocacy, democracy is threatened (Fielding, 2023). Weak police often better keeps the peace, for example, in Taiwan (Martin, 2020). The medical secret is essential to the work of physicians; the secret of the source is essential to the work of journalists, especially in the digital age (Posetti, 2017). Despite the appeal for more transparency, the State secrecy can also contribute to peace (Schudson, 2015). Randomly picked members of a jury legitimize the work of the judge (Schwartzberg, 2018). The list goes on. We have evolved social systems, building on internal contradictions. Such a strategy echoes the work on loosely coupled systems, which are well-known for their incoherence and robustness (Orton and Weick, 1990). In fact, this conclusion has solid theoretical and mathematical ground in many sectors, that is, in economy (viability theory by (Aubin, 2009)) or when dealing with self-organization principles (Atlan, 1972). The analysis of incoherent loops in biological systems only follows this trend, while providing a more concrete narrative to explain the values of incoherence, and their relevance to social organizations. Robustness does not emerge from tighter interactions, but instead from increased noise and more oil in the wheels.

Conclusion: Incoherence is required for cooperation

The power of incoherence can be illustrated with the difference between collaboration and cooperation. When people collaborate, they each move forward on their respective projects, hoping that the addition of these contributions will be synergistic. The hidden hypothesis is that individual efficiencies add up. However, a successful collaboration often masks destructive effects for unidentified third parties, typically the environment. Collaboration can thus hide a form of competition, which often induces the exhaustion of external resources. On the contrary, when people cooperate, the success of the collective project outweighs the success of individual projects. Cooperation therefore implies an acceptance of incoherence, even to the point of having to score an own goal. For instance, in participatory research (Vaughn and Jacquez, 2020), scientists will go slower to explain what they do and this will negatively impact their H-index. But conclusions will be more robust (because the studies deal with increased variability) and the outcome will help counteract the spread of conspiracy theory, by improving the dialogue between science and society at the root (Kerrigan et al., 2023). Choosing cooperation over collaboration means understanding, as in Michel Serres' Natural Contract (Serres, 1995), that any transaction between humans involves multiple social and environmental interactions, including incoherent ones, that go beyond short-term interests, for the survival of the group.

With these examples, I hope to raise awareness in sustainability science and policy: sustainable policies tend to align with efficiency, at the expense of robustness. To counteract this trend, one needs to consider the added-values of inefficiency. More generally, internal contradictions in systems, that is, incoherence, can provide a way out of amplifying loops. Considering incoherence as an actionable archetype in a system could be a step in that direction. Beyond the examples mentioned above, one can evoke the amplifying loops generated by social networks and artificial intelligence, through which the same information is distributed based on the coherent profiles of users (Vosoughi et al., 2018). To break such regimentation, one needs to depart from the shared beliefs in the group, and thus own some degree of incoherence.

In the end, incoherence might be ignored because efficiency is so attractive, and because the trade-off between efficiency and robustness is often limited to technical systems. By bridging systems science and biology, I hope to provide a new narrative to this conclusion. One could consider incoherence to be the most relevant nature-inspired innovation for sustainability, that is, by providing an intrinsic break to the Great Acceleration (Steffen et al., 2015). Going back to the opening example, to prevent crowd movement, one can install fixed pillars on the walking path beforehand to slow down everyone at rush hour, another incoherent solution (allowing people to escape faster by slowing them down). Incoherence provides an answer to our over-optimized, and thus vulnerable, civilization, through apparent inefficiencies (heterogeneity, slowness, errors, conflicts, randomness, etc.) (Hamant, 2024a and 2024b). It is an effective remedy to unstoppable amplifying loops and an actionable tool for decision-makers.

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